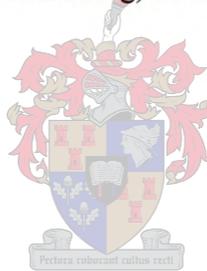


MULTI-CRITERIA DECISION MAKING AND GEOGRAPHICAL INFORMATION SYSTEMS: AN EXTENSION FOR ARCVIEW

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Thesis presented in partial fulfilment of the requirements for the Master's degree (in GIS for Spatial Analysis and Decision-making) at the University of Stellenbosch.



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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that it is not previously in its entirety or in part, been submitted at any university for a degree.

F J Bester

SUMMARY

Multi-criteria decision-making (MCDM) is a set of techniques designed specifically for the analysis of complex problems. Geographical Information Systems (GIS) focus on spatial problem-solving and spatial analysis. The integration of these methodologies offers a powerful approach to decision making. Despite the fact that most spatial decision problems are multi-criteria problems by nature, the process of MCDM is not well established or effectively integrated into the field of spatial analysis and GIS.

This research focuses on bridging the gap between MCDM and GIS. To this end, a generic MCDM extension was designed and implemented in ArcView. As a result, a first version MCDM extension is offered. The extension expands ArcView's functionality with a limited set of MCDM methods. This functionality is illustrated on two problems involved with developing the tourism potential at Coutada 16 Wildlife Reserve in Mozambique.

The MCDM extension facilitates procedures that allow the evaluation of spatial problems and includes the ability to deal with both raster and vector data. This system offers a generic problem-solving environment, which can be used to evaluate geographical problems of any nature. This research identifies a number of improvements to the developed functionality and successfully illustrates the potential problem-solving capabilities associated with MCDM integrated with ArcView.

OPSOMMING

Multi Kriteria Besluitneming (MKBN) is n versameling metodes vir die analise van komplekse probleme. Geografiese Inligtingstelsels (GIS) fokus op geografiese probleemoplossing en analise. Die integrasie van hierdie twee metodologieë bied 'n kragtige benadering tot besluitneming. Ten spyte daarvan dat die meeste geografiese probleme in wese meerveranderlik van aard is, is MKBN nie effektief binne die raamwerk van GIS geïntegreer nie.

Hierdie studie fokus op die oorbrugging van die gaping tussen MKBN en GIS. Met hierdie doel voor oë is 'n generiese MKBN-uitbreiding vir ArcView ontwerp en geïmplementeer. Die resultaat is 'n eerste- weergawe MKBN-uitbreiding. Die uitbreiding brei ArcView se funksionaliteit uit om 'n beperkte versameling MKBN-metodes in te sluit. Die nuut ontwikkelde funksies word geïllustreer aan die hand van twee probleme wat die ontwikkeling van die toerismepotensiaal vir die Coutada 16 Wildreservaat in Mosambiek aanspreek.

Die uitbreiding maak voorsiening vir 'n MKBN-evaluasie van geografiese probleme en besit die vermoë om beide vektor- en roosterdata te analiseer. Hierdie stelsel verskaf 'n generiese omgewing vir probleemoplossing wat gebruik kan word om byna enige geografiese probleem te analiseer. Die studie identifiseer verbeteringe op en uitbreidings van die ontwikkelde funksies en slaag daarin om die potensiaal van probleemoplossing wat deur die integrasie van MKBN-tegnieke met ArcView moontlik gemaak word, te illustreer.

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ABBREVIATIONS

AHP	Analytic Hierarchy Process
CDP	Criterion Decision Plus
CR	Consistency Ratio
GCI	Geometric Consistency Index
GIS	Geographical Information Systems
GLTFCA	Greater Limpopo Transfrontier Conservation Area
KNP	Kruger National Park
GKG	Gaza Kruger Gonarezhou Transfrontier Park
MADM	Multi-attribute Decision-making
MCA	Multi-criteria Analysis
MCDM	Multi-criteria Decision-making
MCDM_AV	MCDM for ArcView extension
MCE	Multi-criteria Evaluation
MODM	Multi-objective Decision-making
OWA	Ordered Weighted Average
RMS	Root mean square
SAW	Simple Additive Weighting
SDSS	Spatial Decision Support System
SMART	Simple Multi-attribute Rating Technique
WESSA	The Wildlife and Environment Society of South Africa

CHAPTER 1: INTRODUCTION

1.1 GIS-BASED MULTI-CRITERIA DECISION-MAKING

In general, decision-making can be seen as a choice between alternative courses of action. While simple decisions can be made *ad hoc*, complex issues and problems with severe impacts require an extensive evaluation process (Malczewski, 1999a). The problem complexity is measured in terms of the number of people involved, the number of alternatives to choose from and the number of criteria used. The severity of a problem outcome can be weighed in terms of economical, social, environmental and/or political impacts.

Multi-criteria decision-making (MCDM) includes a set of techniques designed specifically for solving complex problems (Malczewski, 1999a). As a basic strategy, the method divides the problem into small understandable parts, evaluates the parts independently and then integrates the subsets to indicate an overall solution for the problem. From a technical point of view, Geographical Information Systems (GIS) are defined as a set of tools for the input, storage, retrieval, manipulation, analysis and output of spatial data (Malczewski, 1999a and Demers, 2000). Defining GIS as a system rather than merely as software, describes it as a spatial problem-solving and analysis tool (Malczewski, 1999a) or a spatial decision support system (Demers, 2000).

These two distinctive areas of research, GIS and MCDM, can benefit from each other. On the one hand, GIS techniques and procedures have an important role to play in analysing MCDM problems. They offer unique capabilities of automating, managing and analysing a variety of spatial data for decision-making. On the other hand, MCDM methodologies offer a rich collection of techniques and procedures to reveal decision makers' preferences and to incorporate them into GIS-based (or spatial) decision-making.

Spatial MCDM evaluates a problem with scientifically proven methods and includes evidence for the selected solution as part of the output. This not only improves the confidence in the solution, but also in the decision-maker (Malczewski & Jackson, 2000). Further, the process acts as a consensus-building tool and promotes participatory action (Villa, Ceroni & Mazza, 1996; Jankowski, Nyerges, Smith, Moore & Horvath, 1997; Van den Honert, 1998; Malczewski, 1999a; Malczewski, 1999b; Ferrarini, Bodini & Bechi, 2001), which supports the ideals of Agenda 21 (ICLEI, 1992). The representation of results as maps also proves to be more efficient and effective than traditional outputs from MCDM procedures (Villa et al., 1996; Klimberg & Cohen, 1999 and Jankowski, Andrienko & Andrienko, 2001).

1.2 THE PROBLEM

While both MCDM and GIS are well-established methods and fields of research, their integration, is at best, an emerging field (Zhao & Garner, 2001). Laaribi, Chevallier & Martel (1996) recommend such an integration while Densham (1991) sees the integration of GIS and MCDM methods as a concrete illustration of what could be a future Spatial Decision Support System (SDSS). It is estimated that at least 80% of data used by managers or decision-makers are of a geographical nature (Worall, 1991). Despite the fact that most spatial decision problems are multi-criteria problems by nature, the process of MCDM is not well established or effectively integrated into the field of spatial analysis and GIS (Malczewski, 1999a and Maniezzo, Mendes & Paruccini, 1998).

The widespread use of ArcView as desktop GIS software (Zhao & Garner, 2001 and GIS Software & Resources, 2003) makes it an obvious choice for the incorporation of MCDM methods. The integration of MCDM with ArcView is however still limited and consists primarily of specialised and/or commercialised products (Faber, Wallance & Cuthbertson, 1995; Ganter & Smith, 1995; Jankowski & Ewart, 1996; Jankowski et al., 1997; Geoscience Information Services, 2000; Zhao & Garner, 2001 and Heather, 2003).

The research is focused on further bridging the gap between MCDM and GIS (specifically ArcView). The goal of this research is to develop a set of tools that allows spatial MCDM in the context of ArcView. The proposed MCDM extension is a generic, open source and free extension, which distinguishes it from the existing software. For the purposes of this research, a limited set of techniques is implemented. Future expansion of the extension can lead to a complete range of options, which will make it a one-of-a-kind all-purpose decision-making tool.

The aim of this study is formalised as: “The development and implementation of a MCDM extension in a common desktop GIS, ArcView”. The objectives identified for this aim are to:

- a) perform a literature study of the most common techniques used in spatial MCDM procedures;
- b) develop and implement the MCDM extension for ArcView;
- c) illustrate the functionality of the newly created extension on a hypothetical problem; and
- d) evaluate and discuss the decision-making capability of the created extension.

1.3 RESEARCH METHODOLOGY AND FRAMEWORK

In this chapter, the concept of spatial MCDM was introduced very briefly and the research aim and objectives were formalised. The main findings of the literature review, as identified for the first objective follows in the next chapter. The chapter includes a general discussion of the literature search, the most relevant theoretical views on the topic, the predominant focus of research on MCDM procedures, a summary of existing software packages and extensions with spatial MCDM capability and concludes with an overview of the spatial MCDM process.

This is followed by a discussion of the second objective, which sets out to develop and implement the MCDM extension, in Chapter 3. An overview of the development and implementation of the extension is provided and the system's processing capabilities and included functionality are described in detail. This is followed by an illustration of the implemented functions to a real-world problem, as set out by the third objective, in Chapter 4. The two examples discussed show a typical MCDM evaluation of raster and vector data with the developed software.

Finally, an evaluation of the created extension's validity and potential use as formalised for the fourth objective are dealt with in Chapter 5. The validation procedure is based on aspects of the system's error-free functioning and the appropriateness of its developed interface. The discussion proceeds with some recommendations for the improvement and expansion of the existing functions and in conclusion, offers some final remarks on the research process and the developed extension. The chapter layout is diagrammatically illustrated in Figure 1.1.

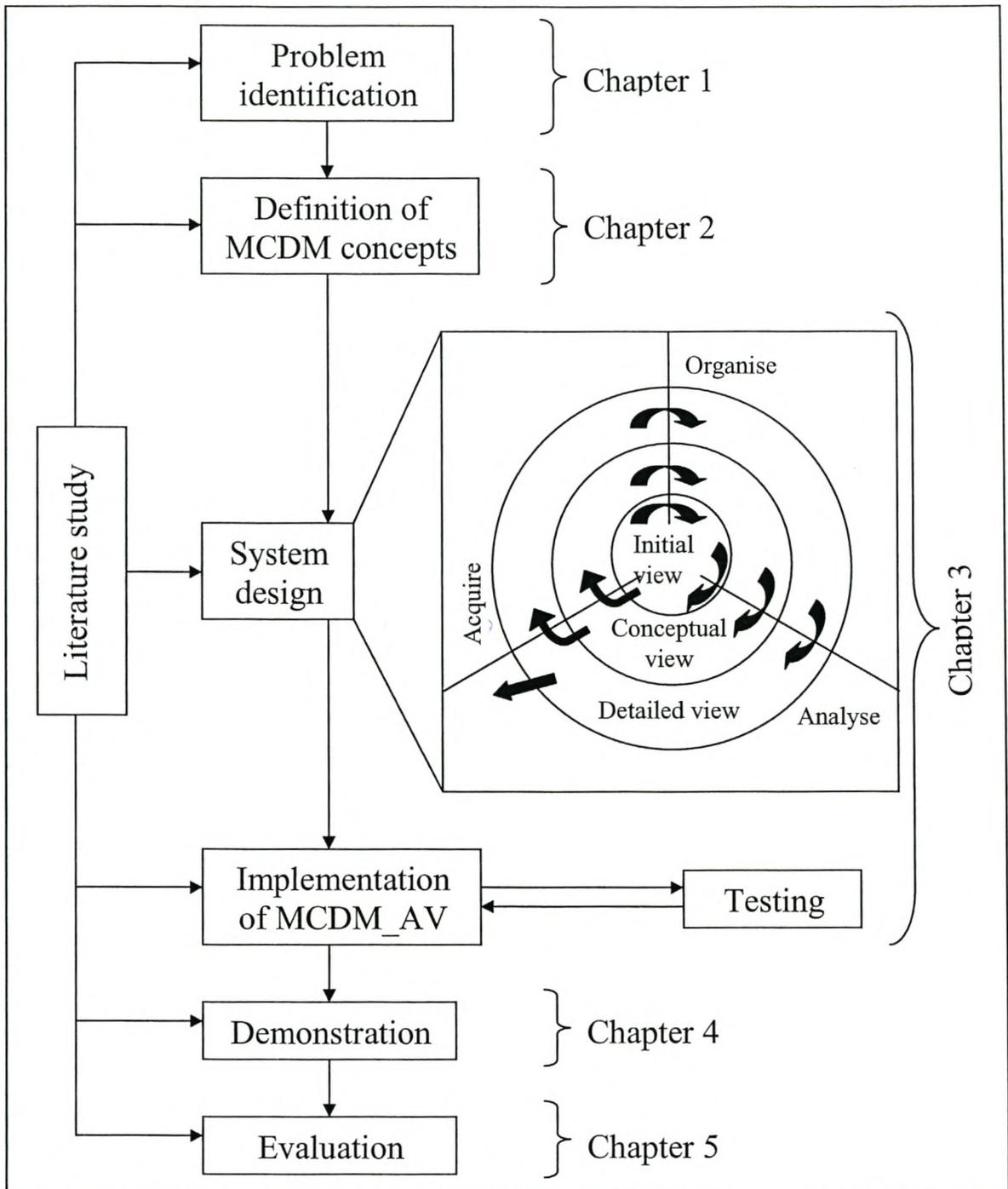


Figure 1.1: Research methodology and framework

CHAPTER 2: LITERATURE REVIEW

The literature review played a dual role in this research. First, it established a background for multi-criteria decision-making (MCDM) and spatial MCDM, exploring the literature that covers existing research and highlighting the opinions held by experts in the field. To this end, the review fulfils the tasks normally associated with a literature review. Second, the literature review was refined to double as textual analysis of the detailed theory involved in spatial MCDM. The textual analysis component summarised the methods and aided in the process of identifying methods and their computational needs, required to develop the MCDM extension. Figure 1.1 illustrates how information from the literature study ties in at various stages during the research process.

2.1 LITERATURE SEARCH

The abundance of literature on MCDM proved to be a constraint to the exhaustive coverage of the topic. This abundance is illustrated in an overview of the literature on MCDM combined with finance (Steuer & Na, 2003), which revealed 265 references. On most Internet search engines the keywords MCDM, multi-criteria analysis (MCA) or multi-criteria evaluation (MCE) resulted in over a million hits. Refining it by means of spatial or GIS-based keywords only reduced the number to about 100 000 hits. Because of this abundance, the literature review became an iterative process with each cycle focusing on a more detailed level of the areas identified in the previous repetition.

The data required for the intended research consist of mainly secondary information of a textual nature. Published scientific literature, either journal articles or specialised books, formed the focus of the initial data-gathering process. From the wide range of initially identified material, only the most relevant topics were researched in greater detail. This iteration continued until the researcher was satisfied with the coverage of the selected topics. In aspects where published data failed to satisfy the required levels of detail, unpublished sources retrieved from the World Wide Web were utilised.

The literature search was done with the use of the University of Stellenbosch, Gericke Library's electronic resources (Geobase, Cab-abstracts, African studies, SA studies, Nexus, Sabi-net, and Science Direct) and book catalogue, as well as various Internet search engines. While all the literature search tools retrieved multiple sources, Science Direct proved especially useful for identifying the most recent articles. This search engine includes the ability to download full text articles and offers access to many articles even before they are published in the respective journals.

2.2 TERMS AND DEFINITIONS

MCDM and the above-mentioned terms, MCA and MCE, are often used interchangeably throughout the literature. In a strict sense, MCDM is used as an enveloping term, including all aspects of multi-criteria decision theory. MCA and MCE on the other hand are limited to a description of a single method of multi-criteria problem-solving. The use of the terms analysis and evaluation, which respectively refer to a single process, accounts for this. However, the terms MCA and MCE can also be used as a reference to a decision-making process (the actual process rather than the technique used).

Criteria form the basis for the evaluation of alternatives. Decision criteria consist of a set of features common to all alternatives. Each alternative is assigned a criterion score, a value that specifies the alternative's relative performance on the associated criterion. Criteria can be of two kinds, i.e. factors and constraints (Eastman, 1999). While factors refer to criteria that enhance or detract from the alternative's overall suitability, constraints only offer the limited description of excluding unsuitable alternatives as possible solutions. Factors and constraints can also be referred to as 'hard' or 'absolute' and 'soft' or 'fuzzy' factors (Pettit & Pullar, 1999). A final classification of criteria is the distinction between objectives and attributes (Malczewski, 1999a). An attribute refers to a single physical feature regarding the alternative. The measured or assigned performance rating for an attribute is used to evaluate the alternative's performance. Objectives on the other hand are statements regarding the desired performance of an alternative. Each objective consists of a number of attributes that specify the degree to which an alternative satisfies the desired state.

As defined above, the criterion score is a value that indicates the level of desirability for an alternative with regard to the criterion. On its own, the numerical value is meaningless, but as part of a measuring scale, it can be interpreted as a rate of performance. Scales can be defined as natural or constructed scales. A natural scale is an objective unit of measure that enjoys common usage and interpretation. Distance, temperature and time, for example, are measured on natural scales. Constructed scales on the other hand are devised specifically for specifying performance on certain criteria. These scales are often subjective and used for specifying performance on criteria such as scenic quality. Both natural and constructed scales can be further divided into direct or proxy scales. Direct scales are attributes measured directly in terms of the degree of achievement. Cost, for example, illustrates a direct scale. When there are no direct attributes defining the achievement, proxy scales are used. A cause, consequence or partial indicator indicates the performance for the corresponding objective when rated on a proxy scale. Ambulance response time, for example, can be used as a proxy measure for minimising death on arrival.

The decision-maker, or group of decision-makers, accounts for the human component in MCDM. People affected by the decision's outcome, stakeholders or persons with expert opinions are considered as decision-makers. Decision-makers are involved in all aspects of the process, particularly in the stages involved with defining the structure of the problem (the set of alternative and evaluation criteria) and in assigning the relevant importance to the evaluation criteria. Group decision-makers can be classified as either a team or a coalition. The term 'team' refers to a group where all persons involved have a mutually consistent set of preferences for all outcomes, while a 'coalition' is made up of individuals who compromise their outlooks for a resulting group decision.

One of the most attractive aspects of MCDM methods is the ability to control how certain elements influence the decision's outcome. In MCDM, weights are applied to distribute the relevance among the various components. Weights, for example, are used as an indication of a decision-maker's influence or the importance of a criterion that is included in a MCDM process.

The ultimate aim of the analysis is to combine the elements using the multi-criteria decision rule. The decision rule serves two major purposes. It firstly dictates how decision-maker preferences and criteria are combined into a single composite index and secondly, defines the technique used to order the alternatives in terms of their achievement.

2.3 THEORETICAL VIEWS

MCDM techniques can be widely applied to all fields of study (Keeney & Raiffa, 1976 and Hsing-Yeh, Deng & Chang, 2000). Literature on MCDM describes it as a process to provide intuition, insight and understanding, which supplement those of the decision-maker (Massam, 1991). Decision support systems not only indicate what information was used and where it came from, but also how the information has been used and why this means that the decision taken is the best one. In fact, decision support systems are not intended to replace the decision-maker in solving the problem. They are constructed to help the user to make responsible and clearly documented decisions (Maniezzo et al., 1998).

2.3.1 Complexity in decision-making

In recent years, decision-making has evolved from a single person solving a problem based on an incomplete set of criteria, to a decision environment where problems are evaluated based on a set of all possible criteria with all stakeholders voicing their unique points of view (Triantaphyllou, 2000 and Joerin, Theriault & Musy, 2001). The growing awareness of environmental, political and social issues stemmed this evolution (Jankowski & Richard, 1994). Controversies such as NIMBY (not in

my back yard), LULU (locally unwanted land-use) and CAVE (Citizens Against Virtually Everything), illustrate the difficulties that often arise when a development project significantly modifies its surrounding environment (Couclelis & Monmonnier, 1995; Dente, 1995; Wexler, 1996 and Jankowski & Stasik, 1997).

In addition to the increase in complexity associated with the decision-making process, today's problems are more complex. This is partly due to greater awareness, which gives rise to a plethora of new laws and regulations (Jankowski & Richard, 1994) that even further raises the number of criteria required to perform a complete analysis. Problems are also more ill-structured, fuzzy and include qualitative factors (Vessey, 1991 and Vessey & Galletta, 1991).

The decision-maker's attitude towards decision-making accounts for a further complexity. Decision-makers are no longer willing to accept only the traditional management science philosophy of finding a single optimal solution, but rather want to examine the problem under a variety of conditions and assumptions in order to consider several possible outcomes (Vessey, 1991 and Vessey & Galletta, 1991).

The principles of sustainable development promoted by the globally adopted Agenda 21 (ICLEI, 1992) perfectly illustrate the paradox of contradictory objectives that most decision-makers face. Development must reflect economic realities while maintaining all environmental, social and political needs (Jankowski & Richard, 1994; Van Lier, 1998 and Joerin et al., 2001).

In the face of this complex and risk-prone decision-making environment, decision analysis has become a necessity (Jankowski & Richard, 1994). The demand for tools supporting decision-making has increased (Joerin et al., 2001). In 1995, an initiative in this respect was led by the National Centre for Geographical Information and Analysis (NCGIA) (Densham, Armstrong & Kemp, 1995 and Carver, Frysinger & Rietsma, 1996). The general opinion among land planners is that progress in computing sciences, especially GIS and MCDM (or the combination thereof) can help handle this complexity (Pettit & Pullar, 1999 and Joerin et al., 2001).

2.3.2 Spatial MCDM as a suitable problem-solving tool

While conventional MCDM methods assume a spatial homogeneity for all alternatives, the reality is that the suitability of alternatives is influenced by many spatial attributes. When used in conjunction with GIS, the resulting process includes the varying spatial relationships in the analysis. In addition to the advantages of combining GIS and MCDM, as listed in section 1.1, the literature revealed a number of factors that make spatial MCDM a very powerful approach to spatial analysis.

The first factor worth mentioning here is the simplicity that the approach brings to the process. When dealing with multiple decision-makers, multiple objectives and many different criteria, the components are decomposed, evaluated separately and then recompiled to derive the solution. This decomposition allows the decision-maker(s) to focus on small, comprehensible subsets of the overall problem. This is particularly useful when dealing with the public or groups that lack the technical background to fully appreciate the importance of the different components (Jankowski & Richard, 1994 and Pereira, 1996). The ability to represent criteria and alternatives as maps further strengthens this communication between planners and decision-makers.

Many countries have spent considerable amounts of money to develop large geographical databases describing their territories. These existing data sets reduce time delays in the decision-making process, while simultaneously improving the coordination between ongoing projects in the same territory (Joerin et al., 2001).

2.3.3 Concerns about spatial MCDM

While the benefits of spatial MCDM far outweigh its disadvantages, a few sources have raised some concerns about this approach. The major problem addressed is that of uncertainty (Hsing-Yeh et al., 2000 and Lee, Park & Kim, 2002). Precise descriptions of weights and/or features are not always possible. The imprecision resulting from this is what causes alarm. MCDM deals with this problem through consistency estimation use of fuzzy techniques and sensitivity analyses. Much of the current research is focused on this problem. Aguarón, Escobar and Moreno-Jimenez (2003), for example, focus on the evaluation of consistency in the Analytic Hierarchy Process (AHP) where they develop a row geometric mean method, a geometric consistency index (GCI), to replace Saaty's original consistency ratio (CR). Lee et al. (2002) suggest a more interactive approach, while Hsing-Yeh et al. (2000) call for further development of fuzzy techniques to address this issue.

Another concern stems from the fact that the choice of method considerably influences the outcome (Joerin et al., 2001). This issue revolves around the question of which method is the best one. Consensus on this is that there is no best method. With the complexity of many problems, it is even felt that approaches should be more flexible to include a combination of the existing methods (Aguarón et al., 2003).

2.4 RESEARCHED AREAS OF MCDM

As mentioned earlier, MCDM is a well-researched topic with a large database of knowledge. While the initial research was aimed at developing new methodologies, it quickly progressed to a phase of

evaluation and refinement of the existing techniques. In 1980, most of the methods used today were already defined. Roy's ELECTRE method (1968), for example, was followed by a series of refinements (ELECTRE II, ELECTRE III, ELECTRE IV and PROMETHEE) (Won, 1990). On the other hand, one of the most widely applied methods, the analytic hierarchy process (AHP), developed by Saaty (1977, 1980), is still used in a manner very close to its original design.

The "electronic revolution" (Papageorgiou, 1983) and the beneficial aspects of integrating MCDM techniques into GIS gave new life to research in this area. Current research is aimed at selecting the most appropriate methods for particular problems, the modification of existing methods to better suit specific problems and the evaluation of decision-making systems where MCDM has been applied. Recently adopted approaches focus on the development of more interactive procedures (Lee et al., 2002) and problem-solving through a combination of methods (Pöyhönen & Hämmäläinen, 2001).

2.5 APPLICATIONS OF SPATIAL MCDM TO THE REAL WORLD

"Several approaches for integrating GIS with MCDM models have been developed" (Zhao & Garner, 2001). These range from a simple integration based on the loose coupling of one or more MCDM models with GIS (Carver, 1991; Pereira & Duckstein, 1993; Jankowski & Richard, 1994 and Jankowski, 1995), to a closely integrated system where MCDM models become an integral part of the GIS (Janssen & Rietveld, 1990; Eastman, Kyem, & Toledano, 1993; Tkach, 1997 and Heather, 2003).

Both MCDM and GIS are well-established tools but essentially separate fields of research. The state-of-the-art software now available may be used directly when loosely coupled. This integration technique is the basis of most approaches that involve the integration of systems (Parks, 1993). Loose coupling is further favoured by the simplicity of integrating software systems, compared to the daunting and costly task of starting from scratch when implementing MCDM procedures as an integral part (Zhao & Garner, 2001). Laaribi et al. (1996) however consider loose coupling as only a short-term solution to the long-term goal of GIS systems based on decision-maker orientated decision-making.

Spatial MCDM has been applied in various areas to generate alternative routes (Jankowski & Richard, 1994; Pereira, 1996), evaluating urban transportation projects (Won, 1990 and Tsamboulas & Mikroudis, 2000), finding locations of solid waste transfer stations (Massam, 1991), modelling air quality in a super city (Teng & Tzeng, 1994), risk assessment of water pollution (Giupponi,

Eiselt & Ghatti, 1999) and land-use suitability assessment (Joerin et al., 2001). Table 2.1 summarises the most common methods and their application.

Table 2.1: Applications of spatial MCDM

Name/Type of MCDM	MCDM method	GIS capability	Application
Collaborative planning support system	Fuzzy compromise group decision-making	GRASS	Water resource management
Stand-alone MC-SDSS	SAW, reference point method	Geographical display module	Solid waste management
MCDM/GIS coupling	Ideal point, lexicographic, concordance	PC ARC/INFO	Nuclear waste disposal facility location
Internet-based MC-SDSS	SAW	PC ARC/INFO	Nuclear waste disposal facility location
MODM/GIS coupling	Techniques for generating non-dominated alternatives	Geographical display module	Corridor location problem
MODM/GIS coupling	Techniques for generating non-dominated alternatives	Geographical display module	Land-use planning
IDRISI/decision support module, full-featured MC-SDSS	SAW, ideal point, OWA	IDRISI	Land suitability and use analysis
DOCLOC, MADM and GIS coupling	TOPSIS	ArcView	Health care resource allocation
Active response GIS (AR/GIS)	Voting, ranking, linear programming	ArcView	Land resource planning
Stand-alone MC-SDSS	Reference point method	Geographical display module	Land-use analysis
MPATHav, MODM/GIS coupling	Techniques for generating non-dominated alternatives	ArcView	Routing in transportation risk assessment
Spatial Group Choice (Choice Explorer Group Facilitator, Geo Visual)	Group decision-making voting, ideal point, SAW	ArcView	Habitat site development
MADM/GIS coupling	Multi-attribute value function	Geographical display module	Agricultural land use
MODM/GIS coupling	Interactive goal programming	ArcView	Water resource management
MADM/GIS coupling	Ideal point method	Geographical display module	Locating fire stations
MADM/GIS coupling	Concordance	Map info	Water resource management
MODM/GIS coupling	Goal programming	Geographical display module	Locating banks
Internet-based MC-SDSS	Reference point method	INTEGRAPH/MCE GIS	Site development
Stand-alone MC-SDSS	AHP	Geographical display module	Landfill siting
SimLand, MADM/GIS coupling	AHP	ARC/INFO	Land development

(Source: Malczewski, 1999a: 336-337)

In addition to the methods listed, the literature revealed two more applications where MCDM has been integrated with ArcView. The first, Criterium Decision Plus (CDP), is a tool specifically designed to prioritise bank branch closure procedures (Zhoa & Garner, 2003). CDP runs as a Windows application to assist decision-makers in the making and presentation of decisions. The analysis is based on two models, the Simple Multi-attribute Rating Technique (SMART) and the Analytic Hierarchy Process (AHP). The procedure is limited to vector-based analysis and the interface and functionality are designed specifically for the problem of bank closures.

The other ArcView application of MCDM, called the multi-criteria decision-making tool, “provides decision-makers with multi-criteria analysis tools for performing site suitability analyses and for finding multiple least-cost path corridors over a suitability grid surface” (GIS Software & Resources, 2003). The features included are adding record numbers, joining tables intersecting, standardising values, calculating mean values, weighting values, summing values, finding maximum values, making fields invisible, classifying data, dissolving data, splitting/quartering shapes, unioning shapes and producing histogram charts (Heather, 2003).

2.6 A REVIEW OF SPATIAL MCDM

Many specialised fields offer guidelines and protocols of performing MCDM procedures in their context. The C&I Toolbox Series (CIFOR, 1999) for example, offers a set of ten publications for MCDM in sustainable forest management. These are listed in Table 2.2. Another example is the Multi-criteria Analysis manual by the Department for Transport, Local Government and the Regions (United Kingdom) (2001). This manual provides guidance for Government officials and other practitioners on how to undertake and make the best use of MCDM for the appraisal of options for policy and other decisions.

Even with extensive guidelines such as those offered by these examples, it is still required to adjust the components (standardising methods, weighting methods and decision rules) to fit the problem-specific needs. The remainder of this section summarises a general approach to spatial MCDM, summarising the relative methods as structured and discussed by Malczewski (1999a).

Table 2.2: C&I Toolbox Series

C&I Tool No.	Title
1	Guidelines for developing, testing and selecting criteria and indicators for sustainable forest management.
2	The CIFOR Criteria and indicators generic template.
3	CIMAT (Criteria and indicators modification and adaptation tool) (CD-ROM + user manual).
4	The CIFOR criteria and indicators resource book database (CD-ROM + user manual).
5	The BAG (Basic assessment guide for human well-being).
6	The Grab Bag: Supplementary methods for assessing human well-being.
7	Scoring and analysis guide for assessing human well-being.
8	Who Counts Most? Assessing human well-being in sustainable forest management.
9	Guidelines for applying multi-criteria analysis to the assessment of criteria and indicators.
10	Methodologies for assessing ecological indicators for sustainable forest management.

2.6.1 Classifying multi-criteria problems

Spatial MCDM involves a complex panorama of theory and method. Evaluating the problem-specific needs can aid the decision-maker in selecting the appropriate MCDM methods. To this end, spatial problems can be classified into groups with a limited set of MCDM procedures defined for the type of processing required. The structure is based on the three major dichotomies involved in MCDM. These are:

- multi-objective versus multi-attribute decision problems
- individual versus group decision-makers, and
- decisions taken under certainty (deterministic) versus uncertainty (probabilistic and fuzzy).

The classes can be illustrated as a hierarchical structure with MCDM defining the top level and the three dichotomies as subsequent levels to result in four discrete sets of deterministic, probabilistic and fuzzy decisions. Figure 2.1 shows this arrangement.

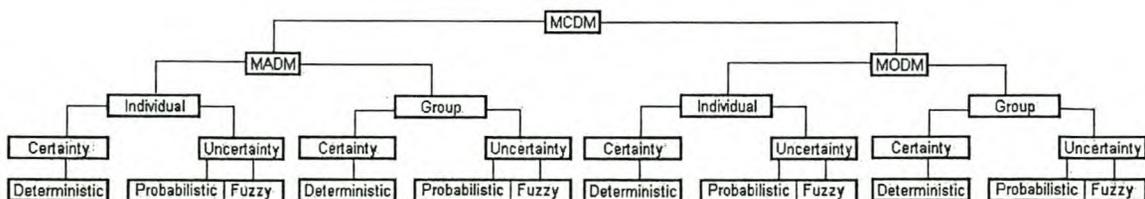


Figure 2.1: Classification of multi-criteria decision problems

(Adapted from Malczewski, 1999a: 84)

The main difference between multi-objective decision-making (MODM) and multi-attribute decision-making (MADM) is that the former distinguishes between alternatives based on attributes, while the latter distinguishes between alternatives based on objectives. Further differences between the two methods are listed in Table 2.3.

Table 2.3: Comparing MODM and MADM approaches

	MODM	MADM
Criteria defined by:	Objectives	Attributes
Objectives defined:	Explicitly	Implicitly
Attributes defined:	Implicitly	Explicitly
Constraints defined:	Explicitly	Implicitly
Alternatives defined:	Implicitly	Explicitly
Number of alternatives:	Infinite (large)	Finite (small)
Decision-maker's control:	Significant	Limited
Decision-modelling paradigm:	Process-orientated	Outcome-oriented
Relevant to:	Design/search	Evaluation/choice
Relevance of geographical data structure:	Vector-based GIS	Raster-based GIS

(Source: Malczewski, 1999a: 86)

Individual and group decision-making are distinguished by the number of decision-makers involved in the process. With multiple decision-makers voicing their preferences, some conflict can be expected. This conflict can be defined as either competitive or independent. Competitive conflict occurs when there is a direct conflict between decision-makers' preferences, while independent conflict occurs when a decision-maker's actions have consequences for other decision-makers.

There are two main sources of uncertainty. They are the validity of information (error-free and appropriateness to achieve desired goals) and the possibility of future developments that lead to differently preferred outcomes. For a decision made under certainty, the term 'deterministic' is used. This type of problem is experienced in a situation where all aspects contributing to the outcome are measurable attributes of the alternative and not all uncontrollable outside events influence the outcome. A decision for a certain alternative that is optimally based on measured physical attributes can therefore be deemed to be deterministic. In most complex problems however, at least a degree of uncertainty exists. When uncertainty is part of the problem, it can be evaluated by either a probabilistic or a fuzzy approach. The probabilistic problem assumes values based on the probability that it belongs to a certain uniquely identified class, while the fuzzy approach defines classes as a range of possible values.

2.6.2 Framework for spatial MCDM

The intelligence, design and choice phase can be identified in all forms of decision-making. The intelligence phase consists of scanning the environment in search of conditions calling for

decisions, whereas the design phase involves inventing, developing and analysing a set of possible solutions. The choice phase is where a particular alternative or set of alternatives is selected.

For spatial MCDM, each of these phases includes a number of methods that guide the decision-maker through the decision-making process. These methods typically involve:

- a) problem recognition;
- b) identifying a set of evaluation criteria;
- c) identifying a set of alternatives;
- d) defining criteria weights;
- e) applying the decision rules;
- f) performing a sensitivity analysis; and
- g) making recommendations.

Figure 2.2 illustrates this general framework for spatial MCDM. It identifies the major processes, how they fit into the three phases and specifies the major methodologies utilised during each phase.

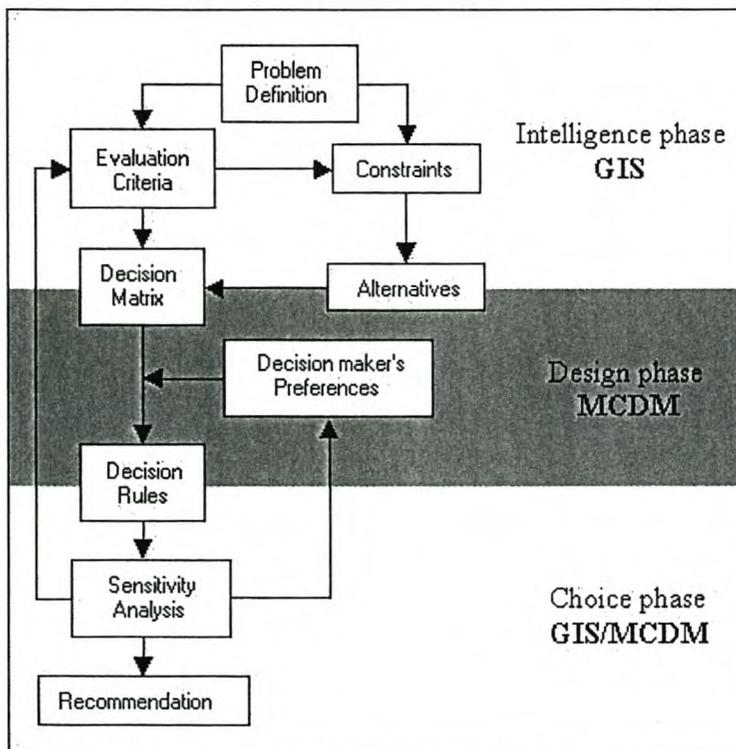


Figure 2.2: Framework for spatial MCDM
(Source: Malczewski, 1999a: 96)

2.6.2.1 The intelligence phase

The intelligence phase involves problem recognition, identification of criteria to include in the analysis, the initial process of constructing a decision matrix and selecting alternatives. Problem recognition is the first step in all decision-making processes. It involves the processing and examination of raw data that allow the decision-maker to identify opportunities or problems. This step is followed by the selection of evaluation criteria.

While a constraint was earlier defined as a specific kind of evaluation criterion (see section 2.2 above), it is distinguished here (see Figure 2.2) as a separate entity requiring a separate process of identification. The distinction of constraints is based on its boolean nature, restricting its analysing capabilities to the exclusion of non-viable alternatives. All other criteria offer the ability to rate the remaining alternatives' performance, while constraints mainly serve a screening purpose. For the purpose of this research and the accompanying MCDM extension, constraints and criteria will be referred to as separate entities.

Criteria and constraints are problem-specific and should be selected to achieve the specific goals. The identification process is a multi-step procedure with each cycle allowing the inclusion of overlooked criteria, elimination of redundant criteria, combination of two or more criteria or the decomposition of a criterion. Criteria and constraints are generally identified through examination of the relevant literature, analytical studies, or expert opinions on the problem. Appendix A lists a set of rules for the selection of appropriate criteria. In spatial MCDM, constraints and criteria are represented as GIS data layers (maps) in either raster or vector format. This format depends on the problem-specific analysis requirements and the software capabilities. Criterion maps include a range of values representing positive or negative impacts. Constraint maps only distinguish two classes, one for viable and another for prohibited alternatives.

Alternatives are represented as geographical features in a data layer (map) in also either vector or raster format. In vector format, point, line or polygon features represent the possible alternatives. These only store information for the specifically identified geographical area. For raster-data, each of the cells is interpreted as an alternative. A raster-based analysis therefore eliminates the need for predefined alternatives. In this sense, vector-based analysis can be seen as a discreet evaluation of the predefined geographical alternatives, while raster-based evaluations perform a continuous analysis on the entire mapped region.

The construction of a decision matrix signals the transition from the intelligence phase to the design phase. The decision matrix formalises how the alternatives are related to one another, how the

alternatives are related to the criteria, how the criteria are related to one another and how the criteria will contribute to the overall solution of the problem. This step defines the entire problem as a single matrix and serves a useful purpose of visually representing the problem components to be analysed during the design phase.

2.6.2.2 The design phase

Steps taken during the design phase is where normal GIS analysis is regarded as lacking. While traditional GIS problem-solving often eliminates the human component, spatial MCDM includes decision-maker preferences as a component in the outcome. MCDM procedures offer a structured and scientifically designed approach to include all the relevant aspects in the decision-making process. The techniques included in the design phase are procedures to standardise criterion scores, derive criteria weights from decision-maker preferences, and combine all the elements into a single composite index.

The MCDM process often involves a comparison of conflicting criteria expressed on different scales. It is therefore necessary to transform the criteria to a common scale. The process performing this transformation is termed standardisation. Malczewski (1999a) discusses standardisation as part of the criteria selection process, the author however regards it as part of the design phase and consequently includes it at this stage. The necessity of standardisation can be illustrated through a hypothetical example of comparing two alternatives (A1 and A2) based on their performance on two criteria (C1 and C2). If the one criterion (C1) is measured on a scale ranging from 0 to 1 and the other (C2) on a scale from 0 to 1 000, the score obtained from the second criterion (C2) will overshadow the other criterion's (C1) score. With this approach, the second criterion (C2) will dominate the selection process. If both criteria are however transformed into a common range, the criterion scores will contribute equally to the overall suitability of the alternatives. From the variety of standardisation techniques, the most common are linear standardisation, value utility approaches, probability approaches and fuzzy set membership. From these, only the linear scale transformation will be discussed.

Linear scale transformation is the simplest standardisation technique. The values are transformed from one scale to another so that they maintain their relative position in the range. A value of 1 on a scale of 0 to 10 could for example be converted from or to a value of 0,1 on a scale of 0 to 1, or a value of 10 on a scale of 0 to 100. Figure 2.3 illustrates a linear transformation from a scale of 0 to 10 to a scale of 0 to 1.

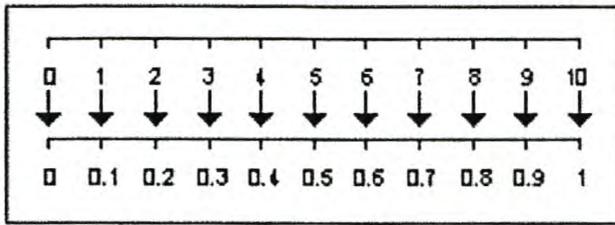


Figure 2.3: Linear transformation

Decision-makers usually have some kind of preference towards certain criteria. Intricate problems with multiple criteria make it impossible for a decision-maker to simply assign weights that express their preference towards a criterion. Weighting methods supply a structured approach to deriving weights from decision-maker preferences. The most common and well-established methods include ranking, rating, pairwise comparison and trade-off analysis. As it is not incorporated in the extension, trade-off analysis will be excluded from this discussion. Issues regarding the selection of the appropriate weighting method and dealing with multiple decision-makers will however be discussed.

Three types of ranking can be distinguished. They are the normal rank sum, the rank reciprocal and the rank exponent methods. For the rank sum and rank reciprocal techniques, the decision-maker is only required to arrange the criteria in an order of importance. The weights are computed from the ranked criteria. For exponential ranking, an additional variable, the exponent, must be supplied. The exponent specifies the rate of change between weights of consecutively ranked criteria. When the exponent is 1, the resulting weights will be similar to weights derived with the sum ranking method. As the exponent increases from 1, more weight is given to the higher-ranked criteria. If the exponent is reduced from 1, the weights are focused on the lower-positioned criteria.

Point allocation and ratio estimation are the most popular rating methods. The point allocation procedure is based on a direct approach. Decision-makers are allowed a certain number of points. The decision-maker allocates the points among the criteria. The weights are calculated as the percentage of the total, awarded to a criterion. The ratio estimation process similarly requires the decision-maker to allocate points among the criteria. The weights are then determined as the ratio between the criterion being weighted and the criterion with the lowest number of points allocated.

The eigenvector approach is the best-known pairwise comparison method. This technique was designed by Saaty (1980) as an integral part of the analytic hierarchy process (AHP). Decision-makers compare all criteria against one another in a pairwise matrix. A predefined scale from 1 to 9 and its reciprocals are used to assign preference. Each value in the scale is associated with a

linguistic term to aid the user with the appropriate preference allocation. In general, a value of 1 indicates equally preferred criteria, higher values indicate a more preferred criterion and the reciprocals a less preferred criterion. Table 2.4 illustrates the nine-point scale and the associated linguistic terms.

The eigenvectors, which can be substituted as weights for the allocated preferences, are calculated from a completed preference matrix. Further computations are aimed at a consistency evaluation for the preference matrix. Estimating the consistency ensures that the criteria are awarded consistent preferences and count towards the trustworthiness of the weighting procedure.

Table 2.4: Saaty's nine-point scale

Preference	Linguistic class
1/9	Extreme less importance
1/8	Very to extremely strong less importance
1/7	Very strong less importance
1/6	Strong to very strong less importance
1/5	Strong less importance
1/4	Moderate to strong less importance
1/3	Moderate less importance
1/2	Equal to moderate less importance
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extreme importance

(Source: Saaty, 1980)

Recent developments in the pairwise comparison weighting procedure revolve around using different scales or different techniques for consistency estimations. The Geometric Consistency Index (GCI), for example, is an alternative approach to estimate consistency. Saaty (1994) however maintains that when his original scale is used for specifying preferences, the estimation procedure is appropriate.

One of the paradigms in MCDM is the selection of the appropriate weighting method (Jacquet-Lagrèze & Siskos, 2001). An Internet-based study compared a variety of MCDM weighting methods (Pöyhönen & Hämäläinen, 2001). Among these were four versions of the analytic

hierarchy process (AHP), direct point allocation, simple multi-attribute rating technique (SMART), swing weighting and trade-off weighting. In earlier studies, these methods have yielded different weights. Schoemaker and Waid (1982) for example, showed that the weights derived with three of these methods were different. The study by Pöyhönen and Hämäläinen (2001) however concluded that the difference in weights is a result of the interpretation of the different sets of preference scales associated with the methods. They further state that, if used appropriately, the different techniques should essentially offer similar weights (an expression of preference).

“The choice by the decision analyst of an appropriate methodology for aiding multi-criteria decisions will be affected by many factors, such as the nature of the problem, the characteristics of the decision-maker, availability of software support, and simply familiarity with the methodologies” (Stewart, 1999). This choice can be made based on outside considerations with confidence that it will not substantially affect the decision outcome. The following table (table 2.5) offers some of the techniques’ properties that aids in the selection of the appropriate weighting method.

Table 2.5: Weighting methods

Feature	Ranking	Rating	PW-comparison	Trade-off analysis
Number of judgements	N	N	$n(n-1)/2$	$<n$
Response scale	Ordinal	Interval	Ratio	Interval
Hierarchical	Possible	Possible	Yes	Yes
Underlying theory	None	None	Statistical/heuristic	Axiomatic/deductive
Ease of use	Very easy	Very easy	Easy	Difficult
Trustworthiness	Low	High	High	Medium
Precision	Approximations	Not precise	Quite precise	Quite precise
Software availability	Spreadsheets	Spreadsheets	Expert choice	LOGICAL DECISIONS (LD)

(Source: Malczewski, 1999a: 190)

The issue of multiple decision-makers can be addressed in two main approaches. The first is through either finding a consensus on weights among the decision-makers or in combining decision-maker preferences by a statistical process such as averaging. In addition to combining preferences, statistical procedures can also be applied to obtain a single weight from weights derived by separate weighting processes by decision-makers. Combining weights or preferences through either consensus or statistical calculations is an iterative process requiring continuous re-evaluation of the weights until all the decision-makers are satisfied. A second approach is to use methods specifically designed for group input. Multiple comparisons are an example of a method based on this principle.

The decision rule defines how the components are compiled and the way in which alternatives will be ranked. While some decision rules are limited to procedures for combining data layers, others structure an approach of decomposing and recompiling data layers. Decision rules are available for

both multi-attribute decision-making (MADM) and multi-objective decision-making (MODM). The most common MADM procedures are boolean intersection (Eastman, 1999), simple additive weighting (SAW), value/utility functions, analytic hierarchy process (AHP) and ordered weighted average (OWA). The MODM procedures consist of value/utility functions, goal programming, interactive programming, compromise programming and data envelopment analysis. This discussion is limited to three of the MADM procedures: boolean intersection, SAW and OWA.

Boolean intersection (Eastman, 1999) is the simplest decision rule. It only considers constraints as elements and combines these data layers through a simple overlay process. Since the constraints are boolean layers, output from this decision rule only distinguishes prohibited from viable alternatives. This procedure offers no further insight into the suitability of the remaining alternatives. Because of the limited analysis capability of this method, it is often used in combination with other decision rules. In such a combination, boolean intersection merely serves as a screening process to reduce the evaluation's computational requirements. Figure 2.4 illustrates how the boolean decision rule combines two data layers.

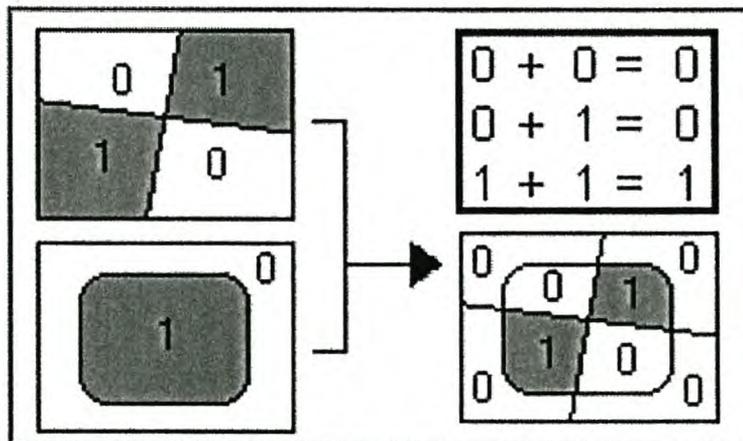


Figure 2.4: Boolean intersection

The SAW method includes user preferences in the compilation procedure. The weights are applied before the criteria are combined so that the various criteria accounts for different proportions of the resulting compiled index. Weights are applied by multiplying the assigned score with the weight expressed as a fraction of 1. The combination of criteria then follows by adding together the proportioned criterion scores for each alternative. The compiled index allows the alternatives to be ranked into an order of preference. For criteria associated with negative attributes, higher values are interpreted as less desirable and must therefore be ranked ascending. If the criteria however express a positive influence on the alternatives' suitability, higher values show a better performance and are therefore ranked descending. Figure 2.5 illustrates two criteria combined with the SAW approach.

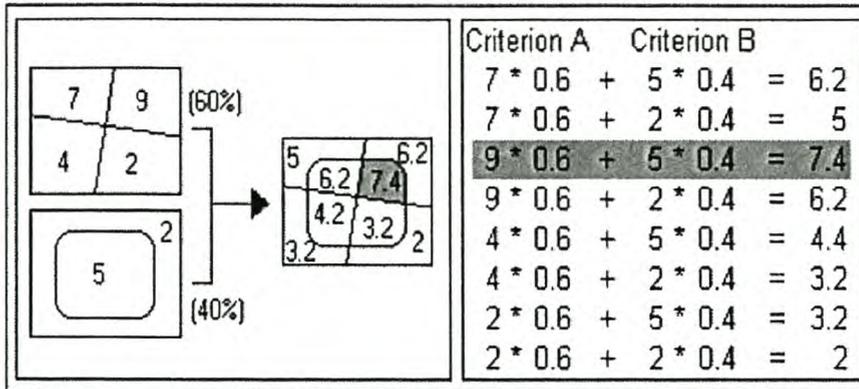


Figure 2.5: Simple additive weighting

When compiling criteria, there is a possibility of selecting alternatives that are performing poorly on certain criteria as optimal solutions. When, for example, an alternative performs excellently on two criteria and poorly on a third criterion, it could be considered as more suitable than an alternative performing well on all three criteria. In certain decision environments, the second alternative would be preferable. In these types of problems, the decision-maker can control the risk of recommending alternatives that are performing poorly in certain respects by using the OWA method (Yager, 1988, 1992, 1993).

The OWA decision rule includes a trade-off between criteria in the analysis. This capability is attributed to an additional set of weights, namely order weights, specified for the process. At each alternative, the criteria performances are ranked and assigned the weight corresponding to their order position. Order weights for the same criterion can therefore vary among alternatives and result in the same criterion contributing different proportions to the compiled index for each alternative.

Assigning higher weights at the bottom-ranked order positions accounts for lower-scoring criteria, contributing more to the overall suitability of the alternative. At the extreme, the full weight can be assigned to the lowest-scoring criterion. This results in the overall performance to be represented as the lowest-scoring criterion's score. Performing an analysis at this extreme excludes all risk from the process. Assigning full weight to the highest-scoring criteria, on the other hand, greatly increases the risk. At this extreme, the alternative's overall suitability will be represented as the score of the highest-scoring criterion. The exact order weights are problem-specific. It is the decision-maker's responsibility to define the appropriate set to meet their specific needs. Figure 2.6 illustrates an OWA procedure for combining two criteria to a compiled index.

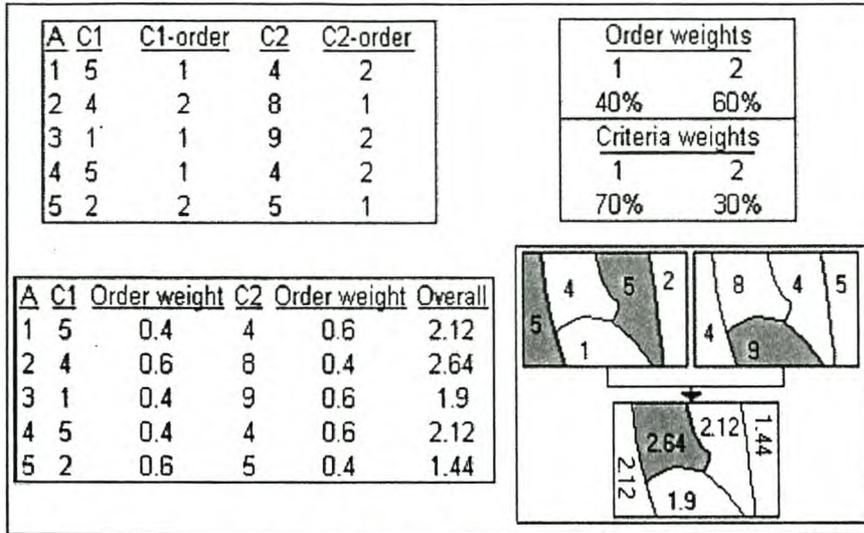


Figure 2.6: Ordered weighted average

With the exception of the MODM decision rules, the procedures for the design phase listed (but not discussed) in this chapter are summarised in Appendix B. For a more detailed discussion on these methods, the interested reader is referred to Malczewski (1999a).

2.6.2.3 The choice phase

The choice phase concludes the decision-making process and involves processes for a sensitivity analysis and the provision of recommendations.

The sensitivity analysis is a process to evaluate the MCDM procedure performed, on the basis of the possibility of errors included in the decision outcome. The sources of errors are attributed to errors in geographical data or the uncertainty associated with the preferences expressed by the decision-makers (Malczewski, 1999a and Márkus, 2003). Errors in geographical data are specified as RMS errors, and uncertainty in decision-maker preferences are specified as the percentage of uncertainty.

Error propagation methods simulate the aggregation of errors through the process (Malczewski, 1999a and b). Propagated errors associated with each alternative can be calculated in this fashion. The alternatives are then re-ranked, taking the possibility of errors into account. One alternative is then ranked as more suitable than another, only if the lowest possible performance is better than the other one's best possible performance. Spreadsheet functions like error bars on a scatter plot can be used for visual interpretation of these results. Another approach to sensitivity analysis is through performing Monte Carlo simulations (Malczewski, 1999a and b). This method performs the evaluation process repetitively, each time with a random set of possible values (as defined by the

possible error associated with each component). The outcome is recorded for each simulation and after a minimum of a hundred simulations, averaged for a most probable solution.

During the final stage of the MCDM process recommendations for future actions are made (Malczewski, 1999a). The recommendations must be based on the analysis. It can include descriptions of the best alternative or set of alternatives. The decision-makers must specify the level of confidence in both the decision-making process and the results. If the process has produced unsatisfactory results or is perceived to be lacking in the consideration of relative aspects, it must be stated. Where shortcomings account for the problem goal not being reached, further analysis can be recommended. A recommendation for further analysis must be accompanied by a detailed description of specific aspects where exploration is required.

CHAPTER 3: MCDM FOR ARCVIEW

The MCDM for Arcview (MCDM_AV) extension was developed as a first version generic MCDM tool. MCDM_AV includes MCDM procedures to standardise criteria, assign relative weights to criteria and apply decision rules. This chapter will supply an overview of MCDM_AV's development (design and implementation) (see Figure 1.1) and discuss the functionality offered by the developed extension.

3.1 THE SYSTEM DESIGN

MCDM_AV was developed using a spiral model (Demers, 2000). This design is a flexible, multi-level approach to system design. It separates the three tasks of acquiring, organising and analysing information and imposes three levels of detail. The first level, the initial view, explores the feasibility of implementing the proposed system. The second level, the conceptual view, initiates the discussion on the required functionality of the system. Finally, the detailed view engineers a detailed description of the system integration. The three cycles are followed by the implementation phase, which consists of coding and testing.

3.1.1 The initial and conceptual views

The feasibility of integrating a generic MCDM with ArcView was evaluated based on three concepts. These involved establishing the validity of spatial MCDM as a decision-making tool, the suitability of ArcView as a GIS for the development of such a system, and the existing applications where MCDM has been integrated with ArcView. Findings from the initial view concluded that an endeavour of this nature would be profitable.

It was established that spatial MCDM delivers the decision-making needs demanded by today's decision-making process of ever-growing complexity. The widespread use of ArcView as a desktop GIS, the easy-to-customise environment and the interfacing capabilities provided by the dialog designer extension, distinguishes it as a good choice for MCDM functionality integration. The existing applications of this nature proved to be limited to specialised decision support systems. The most recent development, MCE extension (Heather, 2003), allows a more open approach to problem-solving. The MCDM methodology included is however restricted to a single standardising and compilation method. The majority of this extension's use is focused on the interactive use of the GIS's existing capabilities.

A textual analysis of the compatibility of MCDM methods with GIS and the computational requirements for these methods initialised the process of selecting the methods to include in the extension. Chapter 2 summarised the most common MCDM methods and explored their use in a GIS environment.

The literature review revealed that a vast amount of programming is required to develop a generic system. As an alternative strategy, MCDM_AV was proposed as a ‘first version’, an extension with limited capabilities, but with the potential for future expansion. The conceptual phase resulted in the identification of criteria standardisation, weighting methods and compilation methods as three procedures essential for the implementation of a ‘first version’ MCDM extension. Without at least one method from each of these categories, the analysis capabilities would be incomplete.

3.1.2 The detailed view

During the detailed view, the intended functionality was formalised. The aspects discussed in this view consisted of the choice of an integration technique, the identification of the data format processing ability and the selection of the procedures/functions that would be included.

3.1.2.1 Integration method

While the literature indicates the many advantages of integrating MCDM with GIS through loose coupling, this is not considered as the appropriate method for this particular design. The reasoning here is based on the intended purpose of the extension. The goal is to create an extension with limited ability, but the potential to be expanded for a full range of functions. The future expansion of loosely coupled systems holds two drawbacks. First, unless the MCDM software originally integrated or software with a very similar data structure is used to expand the functionality, the expansion process will require a repetition of the process that was performed to create the original system. Additionally, the various interfaces for different functions could add confusion to the already complex decision environment. The second aspect is of an economical nature. With each expansion, the end user has to carry the cost of the commercial MCDM software.

Jankowski et al. (2001) state that all GIS's have the basic functionality to perform most MCDM procedures. Computations required by weighting methods and standardising procedures can easily be simulated in a GIS environment; the compilation of data can be accomplished through modifications and atomisation of overlay procedures, while a sensitivity analysis can be accomplished through Monte Carlo simulations. The system proposed here will therefore embark on the “daunting task” (Zhao & Garner, 2001) of creating MCDM procedures as an integral part of ArcView.

3.1.2.2 Data formatting capability

The analysis of both vector and raster data includes unique advantages. While vector data limit the data-gathering process and offer the ability to evaluate explicitly defined alternatives, raster data eliminate the need for alternatives and can assess an entire mapped region. ArcView is primarily a vector-based GIS, but with the extended functionality of Spatial Analyst, an astonishingly large range of raster data processing is available. With the GIS software capable of handling both data formats, it seems a waste to restrict the MCDM capabilities to a single format. MCDM_AV will therefore be developed to include both these data structures.

Data analysis is however restricted to a single format per evaluation. With the existing ArcView functionality of vector to raster and raster to vector conversions, data layers can easily be transformed into a single format. While an automated format-conversion as part of MCDM_AV's functionality could prove valuable in saving time for the end user, it will add an extra layer of complexity to the already gruelling task of developing this system. To avoid this complexity MCDM_AV will be designed to only allow the user to add a single data format during each evaluation.

For raster data, each cell is treated as an alternative and the criteria are represented as different layers. The cell value is interpreted as the criterion score and is used to rate the alternative's performance on the particular criterion. For vector data, all information is included in a single theme. In this theme, each record represents an alternative and the criteria are stored as separate fields. For both types of data, the criterion scores must be defined as numerical values. Figure 3.1 illustrates how the different formats store the required information.

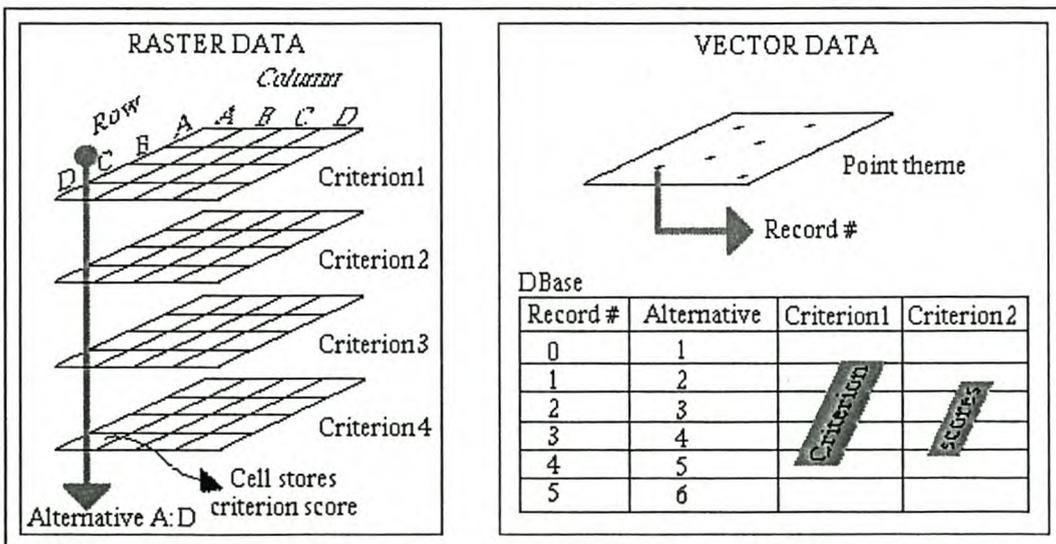


Figure 3.1: Criteria and alternatives in the different formats

When applying the decision rule, the various layers representing the criteria are combined to a single output grid. The extent and cell size for this output grid is defined by the input grids. The resulting theme will contain only information for areas represented in all input grids and the cell size will be similar to that of the biggest cell size from the input grids. The compilation procedures for vector data is carried out in the theme's database. An additional theme is added where each alternative's overall performance is calculated. Figure 3.2 illustrates how the different data formats are combined to calculate the overall performance.

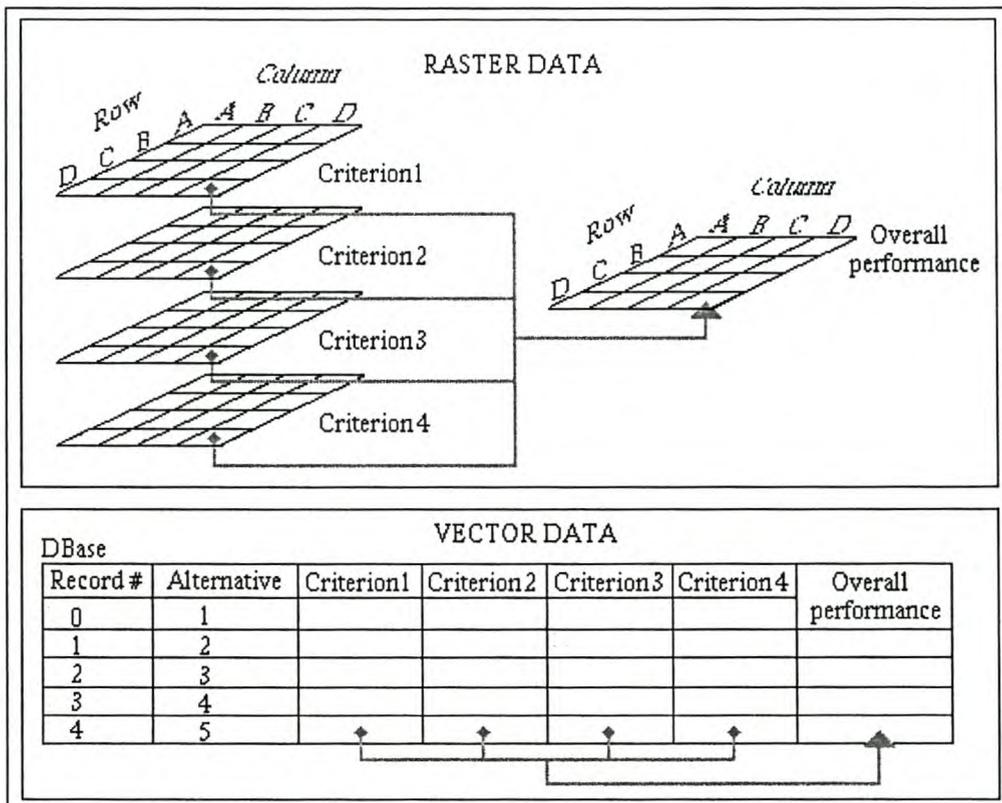


Figure 3.2: Calculating overall performances on raster and vector data

Constraints can also be represented by both data formats. These data layers are defined with only two numerical values as criterion scores, either 1 (possible) or 0 (prohibited). While constraints represented with raster data requires a separate layer for each constraint, vector data can represent constraints in either separate themes or separate fields in a single theme. When evaluating constraints only, the format is restricted to raster data. This restriction was imposed to avoid the complexity involved in evaluating constraints represented by different vector features (point, line or polygon). Furthermore, the processes where only constraints are evaluated serve the purpose of a screening process to identify the viable options for which the raster data structure is more appropriate.

When evaluating a problem on both constraints and criteria, the same format is required for criteria and constraints. Allowing constraints as separate data layers when evaluating vector data, allows the constraints to be represented as different features from used to represent the alternatives. Alternatives defined as points, for example, can be combined with constraints represented as lines or polygons. It is however important to realise that where constraints are used, nodata/null values will be interpreted as prohibited. When the constraints and alternatives are not represented by the same point or line features (separate fields in the theme) it requires an extremely high spatial accuracy. Using separate point or line themes as constraints should therefore be avoided.

3.1.2.3 The selected functions

The MCDM methods included were largely based on the functionality provided by the IDRISI software. The functions selected for MCDM_AV are:

- linear transformation as standardisation method;
- ranking, rating and pairwise comparison as weighting procedures;
- boolean intersection, SAW and OWA as compiling methods (decision rules);
- a function to evaluate alternatives represented in vector data on performance values stored in raster data ('evaluate options'); and
- a help file that assists the user with MCDM_AV's functionality.

Because of its simplicity, linear transformation was selected as the standardisation method. The function is designed to perform a normal or an inverted transformation procedure and transforms values to an output range of discrete (0 to 255) or continuous (0 to 1 with a user-defined precision) values. These data options are similar to those described by Eastman (1999) for the use in IDRISI. The standardisation function is initiated from a menu choice and all input is achieved through message boxes. The active themes are regarded as input themes and no restrictions are imposed regarding the simultaneous standardisation of both vector and grid data. As output, a new grid is created for each criterion when dealing with raster data, and new fields are added to the original theme for vector data.

The calculations for the normal and inverted transformations are mathematically expressed in equations 3.1 and 3.2. Both these formulas result with a new range of 0 to 1. A transformation to the desired range (discrete or continuous) is achieved by a multiplication of the desired range's maximum (r^{\max}). Equation 3.3 mathematically expresses this calculation.

$$x_{ij}^* = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} \quad \text{Equation 3.1}$$

$$x_{ij}^* = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}} \quad \text{Equation 3.2}$$

Where:

x_{ij}^* is the standardised score for alternative i on criterion j ;

x_{ij} the criterion score for alternative i on criterion j ;

x_j^{\max} the highest possible score for criterion j ; and

x_j^{\min} the lowest possible score for criterion j .

$$x_{ij}^* = x_{ij}^* r_j^{\max} \quad \text{Equation 3.3}$$

The three weighting methods are run from separate menu choices and include a separate dialog, specifically designed to handle the input of user preferences as required by the respective technique, for each weighting function. The active themes are interpreted as input for the weighting functions. The restrictions that are imposed allow the weighting of only a single vector data layer or multiple raster data layers. The weighting procedures do not change the data, but rather associates a weight with each of the input criteria. The weights are expressed as a fraction of 1 and the criteria weights assigned during a weighting process, summarises to 1. The fraction associated with each criterion therefore expresses its relative importance in the set of criteria.

The ranking methods include three variants, namely the rank sum, rank reciprocal and exponential ranking. This function allows the user to arrange the criteria into an order of importance based on their preferences. From this ordered list, the criteria weights are derived. The exponential ranking method additionally requires the input of an exponent. Equations 3.4, 3.5 and 3.6 respectively represent the calculations required for the rank sum, rank reciprocal and exponential ranking methods.

$$w_j = \frac{n - r_j + 1}{\sum (n - r_k + 1)} \quad \text{Equation 3.4}$$

$$w_j = \frac{1/r_j}{\sum (1/r_k)} \quad \text{Equation 3.5}$$

$$w_j = \frac{(n - r_j + 1)^p}{\sum (n - r_k + 1)^p} \quad \text{Equation 3.6}$$

Where:

w_j is the derived weight;

n the number of criteria;

r_j the rank assigned by the decision-maker;

p the exponent; and

$\sum (n - r_k + 1)$, $\sum \left(\frac{1}{r_k} \right)$ and $\sum (n - r_k + 1)^p$ the respective equation's total of all weights.

The point allocation procedure is included as a rating method. This function requires the user to specify a number of points and then allocate them among the criteria. The calculation for this function is expressed in equation 3.7.

$$w_j = \frac{a_j}{\sum a_j} \quad \text{Equation 3.7}$$

Where:

w_j is the derived weight;

a_j the allocated point; and

$\sum a_j$ the total points allocated.

The pairwise comparison method is based on the eigenvector approach. This method requires the most user interaction, but offers the most reliable results. Two variants are offered as part of MCDM_AV. These differ according to the scale used to assign user preferences. The options are to use Saaty's nine-point scale (Table 2.4) or a scale of any real values. The user is required to complete a preference matrix, from which the criteria weights are derived. Equation 3.8 mathematically expresses how weights are calculated from the matrix.

This weighting function also includes a consistency estimation procedure. The consistency ratio (CR) is calculated through the equations represented in equations 3.9, 3.10, 3.11 and 3.12. For MCDM_AV, the CR is interpreted to be unacceptable for values greater than 0.1 (10% error).

$$W_i = \frac{\sum_j \left(\frac{C_{ij}}{\sum_i C_{ij}} \right)}{n} \quad \text{Equation 3.8}$$

$$CV = \sum_j C_{ij} \times W_i \quad \text{Equation 3.9}$$

$$\lambda = \frac{\sum CV}{n} \quad \text{Equation 3.10}$$

$$CI = \frac{\lambda - n}{n - 1} \quad \text{Equation 3.11}$$

$$CR = \frac{CI}{RI} \quad \text{Equation 3.12}$$

Where:

W_i is the derived weight

C_{ij} the preference awarded for criterion i in column j ;

$\sum C_{ij}$ the column total of the awarded preferences;

n the number of criteria.

CV the consistency vector;

λ the average of the consistency vectors

CI the consistency index

CR the consistency ratio; and

RI the random index.

MCDM_AV includes boolean intersection, SAW and OWA as decision rules. It also allows the combination of boolean intersection with either the SAW or OWA decision rule. These approaches to compile data are facilitated by an atomisation of the calculation and grid calculator functions. Interaction is allowed from a single interface accessed by selecting the analysis choice on the MCDM menu or is opened automatically from the weighting procedures. Input criteria are restricted to a single vector theme or multiple raster layers and must be manually loaded or passed from a weighting function. Section 3.1.2.2 discussed how MCDM_AV handles data in the different formats. Boolean intersection combines constraints by determining the product of the boolean (0 and 1) data layers. The SAW decision rule combines data as expressed by equation 3.13 and the OWA as expressed in equation 3.14. Figures 2.4, 2.5 and 2.6 graphically illustrate these compilation techniques.

$$A_i = \sum_j w_j x_{ij} \quad \text{Equation 3.13}$$

$$A_i = \sum_j w_j x_{ij} w_r \quad \text{Equation 3.14}$$

Where:

A_i is alternative i ;

w_j the weight of criterion j ;

x_{ij} the criterion score at alternative i for criterion j ; and

w_r the order weight for the order r

This function produces a new theme representing the overall performance. When analysing raster data, the output is in the form of a new raster layer where the cell values express the overall performance. This grid can be interpreted as the final product, or serve as input for further analysis of the problem. For vector data, a new theme is also created. This theme has fields for each of the input criteria, the constraints, the overall performance and the rank awarded based on the overall performance. Both these data formats are displayed with a graduated legend, ranging in colour from green for the preferred alternatives to red for the alternatives not performing well. When the input data includes constraints, the prohibited alternatives are displayed in a grey colour. Additionally, an option to automatically add the alternative's awarded ranks is included for vector data.

The amount of processing required for the compilation procedures (particularly OWA on raster data), makes this a time-consuming process. An additional dialog was created to show that data is being processed. This dialog allows the user to cancel the running procedure.

In addition to the MCDM functions described above, two more functions were included in MCDM_AV. The first, 'evaluate options', is a function to aid in the choice phase. This function can be used to further evaluate grids offered as output from previously analysed raster data. It has options to evaluate alternatives represented as points, lines and polygons. Points are awarded the direct value of the underlying grid, the performance for lines is calculated by a multiplication of the length with the associated performance, and polygons are assigned a performance based on the average performance for the area it represents. This function generates a new vector layer with fields representing the performance and associated rank. These data are displayed in a legend similar to the one used for the output of an evaluation of vector data. The final function included for MCDM_AV is a help file containing background information on the MCDM process and a systematic explanation of the extension's use.

3.2 IMPLEMENTATION

The extension was developed as an integrated part of ArcView with no additional software requirements. It is compatible with all versions of ArcView 3.x and only dependent on the Spatial Analyst extension. All scripting was done in Avenue, ArcView’s development environment, and the extended functionality of the dialog designer was used to construct the dialogs. A total of fifty eight scripts and six dialogs (five for functions and one to indicate working status during the analysis phase) were compiled.

An object model illustrating the added functionality for ArcView is included as Figure 3.3. The object model identifies MCDM as an extension of the application (ArcView) and illustrates the addition of a menu for the View document. The six new functions (‘Standardization’, ‘Rating’, ‘Ranking’, ‘Pairwise comparison’, ‘Analysis’ and ‘Evaluate options’) are included as additional choices offered by the MCDM menu. Finally, Figure 3.3 also illustrates the developed dialogs and its interaction with the weight files.

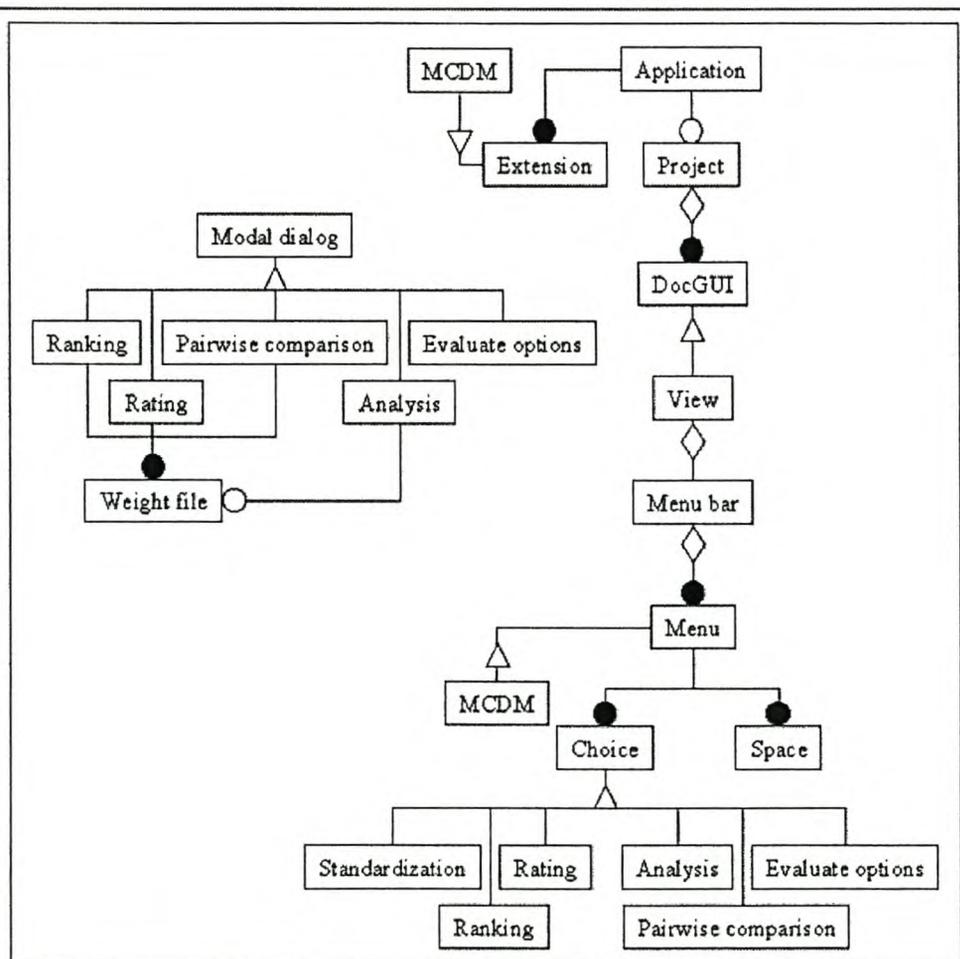


Figure 3.3: Object model for the extended functionality provided by MCDM

The flowcharts in Figures 3.4 to 3.6 illustrate scripts performing the various requests as initiated from the menu choices or dialog controls. Figure 3.4 illustrates the design for the ‘Standardization’, ‘Ranking’, ‘Evaluate options’ and ‘Help’ functions. For both the ‘Standardization’ and ‘Help’ functions, the entire procedure is performed through a single script. The ‘Ranking’ and ‘Evaluate options’ choices however triggers dialogs allowing the user to perform the required interaction for the various procedures. Figure 3.4 shows the associated script for each of the dialog buttons and also where any further scripts might be initiated from these associated scripts. Similarly, Figure 3.5 outlines the design and interaction of the ‘Rating’ and ‘Pairwise comparison’ dialogs with their associated scripts and Figure 3.6 for the ‘Analysis’ dialog and its associated scripts. Source code for the scripts are not included in this report, but can be accessed from the CD included as Appendix D.

In conclusion, this chapter have supplied an overview of the design and implementation of MCDM_AV (see Figure 1.1). The system’s design was discussed in terms of the three levels of detail. The discussion focussed on the detailed view where the integration method, the data formatting capabilities and the selected functions are included. A description of the implemented extension then followed as the final section for this chapter.

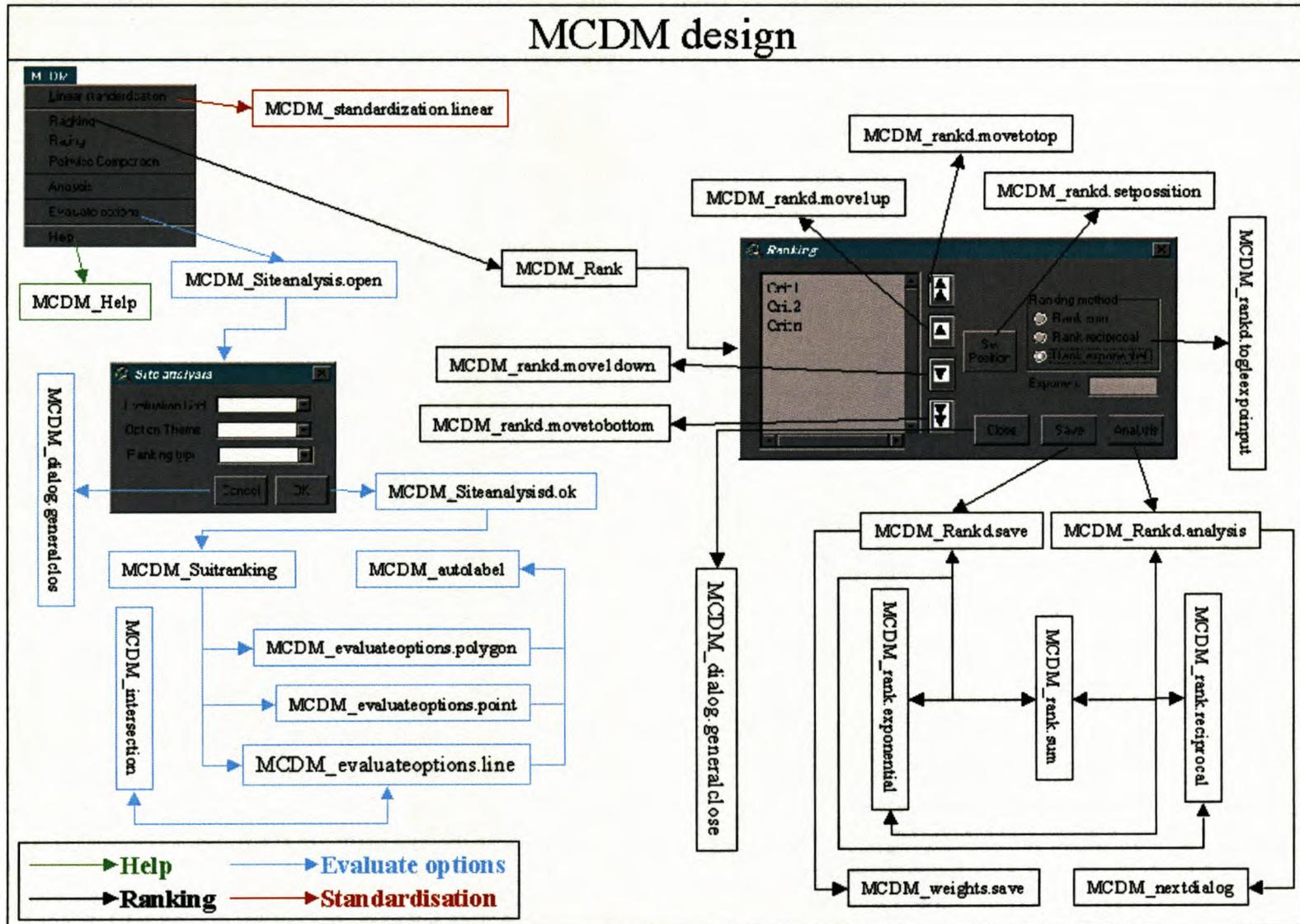


Figure 3.4: Standardisation, ranking, evaluate options and help functions

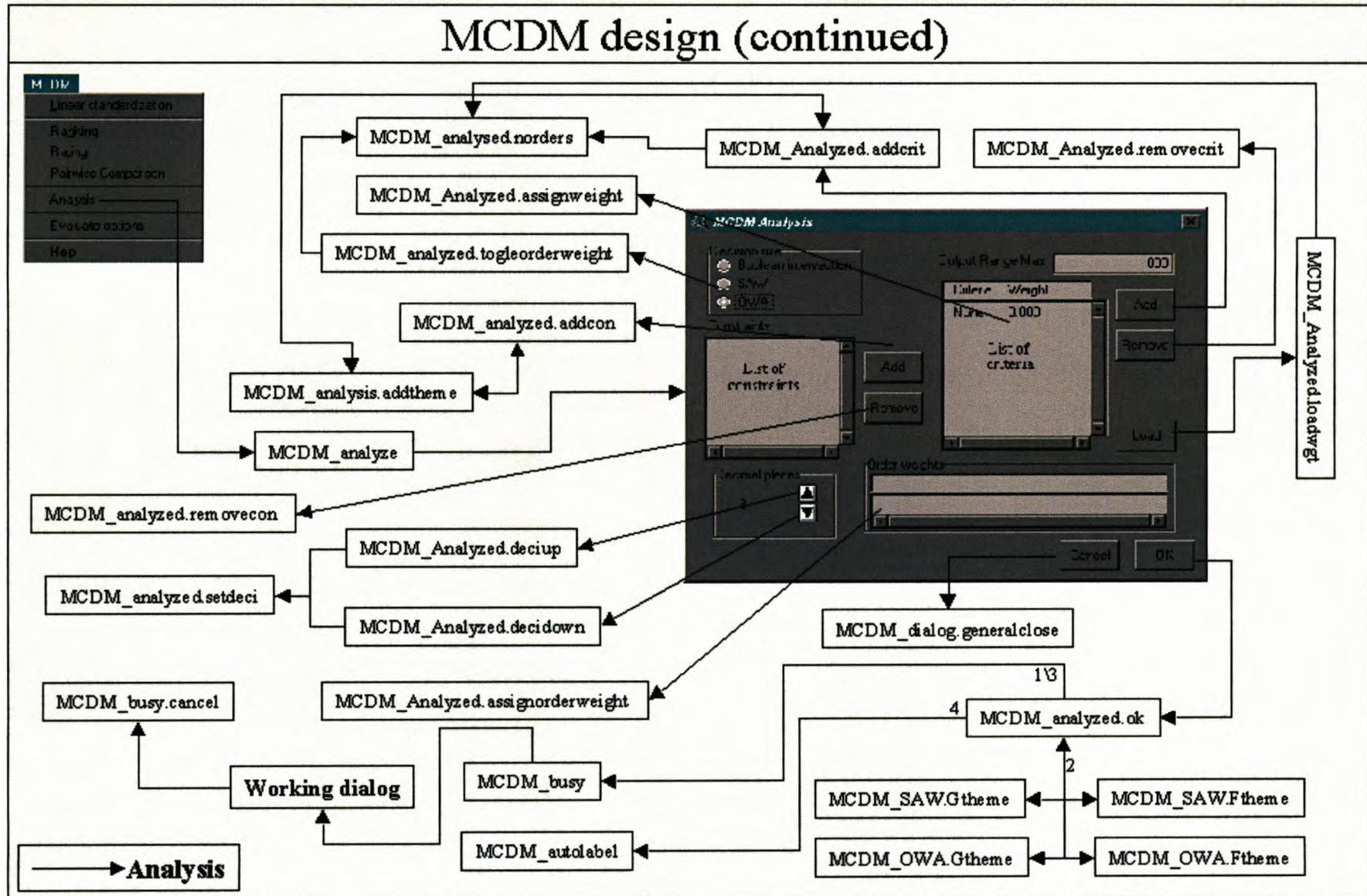


Figure 3.6: Analysis function

CHAPTER 4: AN APPLICATION OF MCDM_AV

In Chapter 4, MCDM_AV will be demonstrated (see Figure 1.1) through an application to some problems regarding the development of the Greater Limpopo Transfrontier Conservation Area (GLTFCA). The GLTFCA will create one of the most impressive conservation areas in the world (PPF, 2001). With a surface area of close to 100 000 km², it will become the world's largest protected area. The Gaza Kruger Gonarezhou Transfrontier Park (GKG) is situated at the heart of the GLTFCA. The GKG forms the core area of the GLTFCA and will be utilised for tourism. The GKG is formed by three components – Gonarezhou National Park in Zimbabwe, Kruger National Park (KNP) in South Africa and Coutada 16 (Limpopo Park since 2003) in the Gaza province of Mozambique. Merging these areas will be a phased process and, once completed, promises to re-establish traditional wildlife routes, economic equity and greater communication and cooperation between neighbouring countries taking part in this joint venture (Braack, 2000).

While the KNP component is a well-established wildlife reserve, Coutada 16 lacks the basic infrastructure demanded by tourism. Developing this component is vital for the equal distribution of the park's economic benefits. Figure 4.1 depicts the GKG and Figure 4.2 focuses on the inequity of tourist infrastructure between the components involved in the first phase, i.e. KNP and Coutada 16.

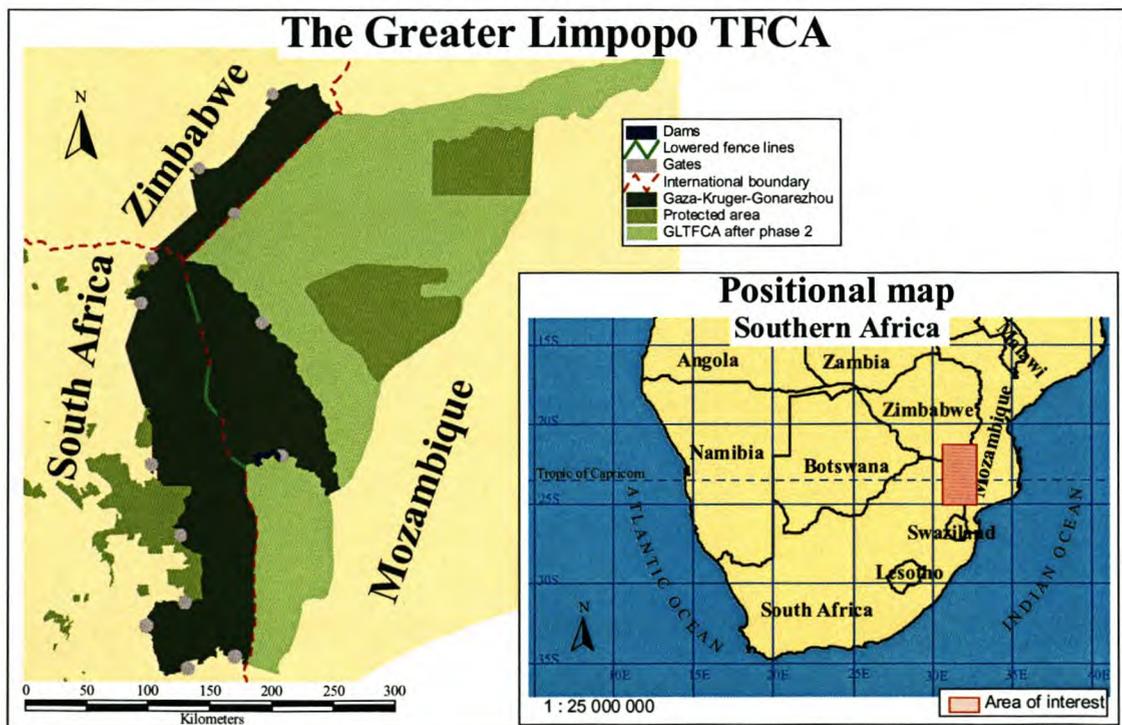


Figure 4.1: Greater Limpopo Transfrontier Conservation Area

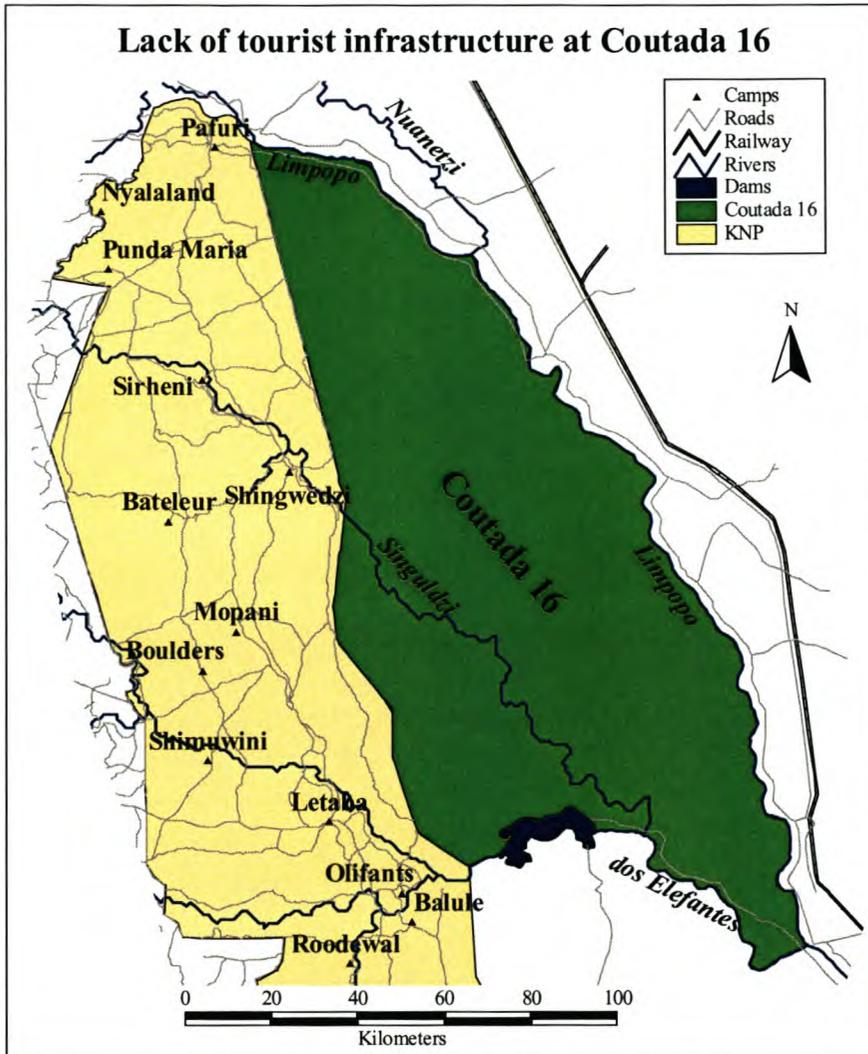


Figure 4.2: A comparison of tourist infrastructure between Coutada 16 and the KNP

The functionality of the developed MCDM extension will be illustrated through addressing some of the problems faced in the development of Coutada 16. As an initial step, the region must be zoned into areas of different land use. This process is discussed in “Land-use planning of Coutada 16” (PPF, 2001). The report is unpublished, but available on the Internet. Additionally, a copy of the report is included in Appendix D ([luplan&man.pdf](#)). Tourism, wilderness and community resources were identified as three broad zones. Figure 4.3 illustrates the proposed land use zones for Coutada 16 as determined by the Peace Parks Foundation (PPF, 2001). It distinguishes five zones: high intensity tourism, general tourism, community resources, wilderness and pristine wilderness. To illustrate the functionality of the newly developed MCDM extension, two problems regarding the development of Coutada 16’s potential for tourism will be discussed.

The first problem would be to demarcate of the area best suited for tourism use. The second task would be to select optimal sites for developing tourist accommodation. Results offered from these

examples are not intended for recommendations or conclusions. They simply serve as an illustration of MCDM_AV.

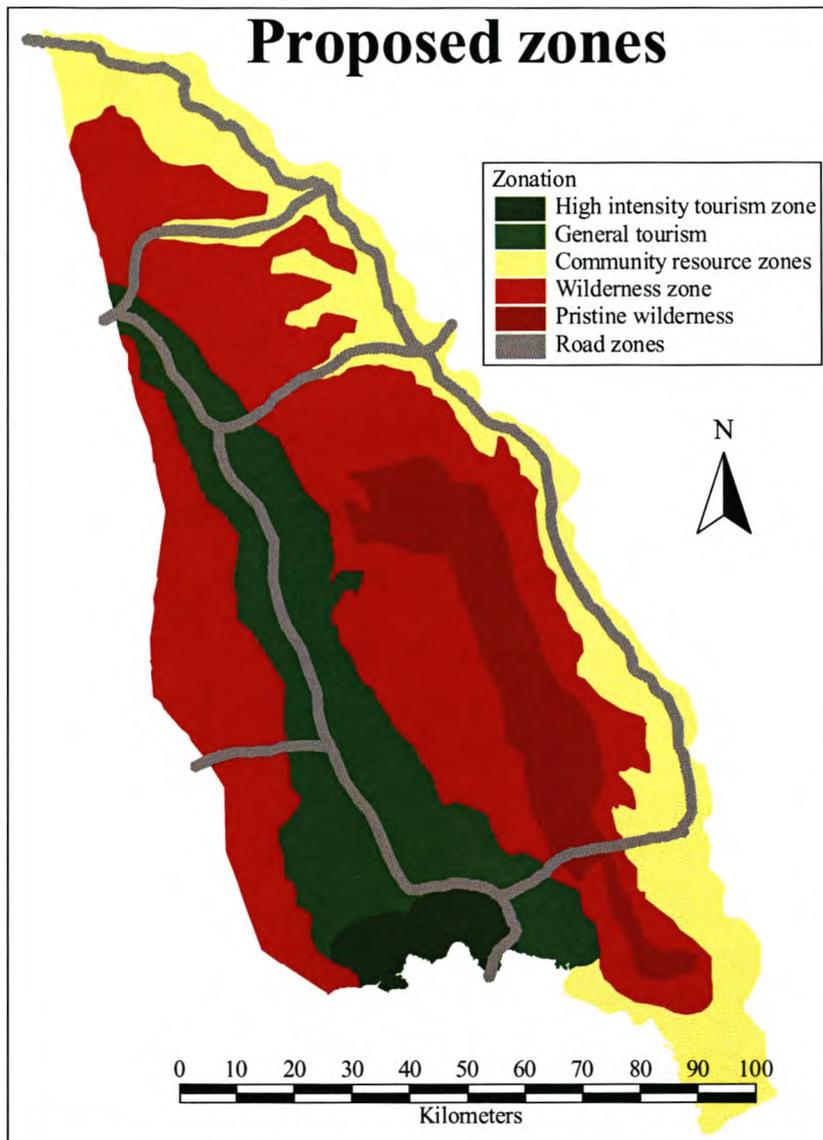


Figure 4.3: Proposed zonation of Coutada 16.

4.1 ZONING AN AREA FOR TOURISM

The first example shows a typical evaluation of raster data. Various standardisation, weighting and decision rules will also be illustrated. These capabilities will be used to demarcate an area in Coutada 16 for tourism use. This task was addressed in two phases. The first involved generating a grid that expresses the overall performance (as measured on the relative criteria) at the various alternatives (grid cells). The second makes use of the 'evaluate options' function to analyse a set of hypothetical alternatives.

The criteria selected to rate the initial grid for suitability as a tourism zone were based on the available data and are listed in Table 4.1. The first two criteria are similar to those used to demarcate the tourism zone as illustrated in Figure 4.3. These criteria were classified and awarded quantified values indicating their suitability as expressed in the report on Coutada 16's land use by the PPF (2001). The assigned values (criterion scores) are not exactly estimated figures, but rather values expressing the relative performance (as deduced by the writer) for the various categories. The accessibility criterion is based on the perceived quality of the nearest entrance. The quantified values expressing the accessibility of the entrance were also deduced from the information supplied in the report on Coutada 16's land use (PPF, 2001). Thiessen polygons were generated for the entrances and awarded the accessibility of the associated entrance. The resulting data layer was used as the accessibility criterion. The Wildlife and Environment Society of South Africa (WESSA) believes that all developments of infrastructure in natural or protected areas of South Africa should take place on the periphery of these areas (Brown, 2000). This will minimise the infringement on natural environments. To include this concept as a criterion, five-kilometre buffer zones were created and awarded performance ratings, decreasing by a constant value as the zones intrude further into the protected area. One of the major attractions for tourists is the ability to view animals in their natural settings. Wildlife hotspots are therefore a crucial component to be addressed during the demarcation of a tourism zone. This criterion can be decomposed into three separate attributes. Figure 4.4 illustrates the criteria as raster data layers.

Table 4.1: Criteria for selecting a tourism zone

Criteria
Soils, landforms and geology
Land cover
Accessibility
Peripheral areas
Distance from wildlife hotspots

The 'distance from wildlife hotspots' criterion required an independent compilation of the three components. Encounters with wildlife are more frequent at watering holes. Data for these features however were not available. As an alternative, water bodies (rivers and dams) were substituted for the watering holes. While Coutada 16 is rich in natural assets, wildlife (specifically mammals) is close to extinct in this region. A process of wildlife reintroduction is currently under way and the boma to which animals are being relocated is considered as a factor in the 'distance from wildlife hotspots' criterion. The relocation boma is however only a temporary measure and therefore can only be regarded as a representation of the current situation.

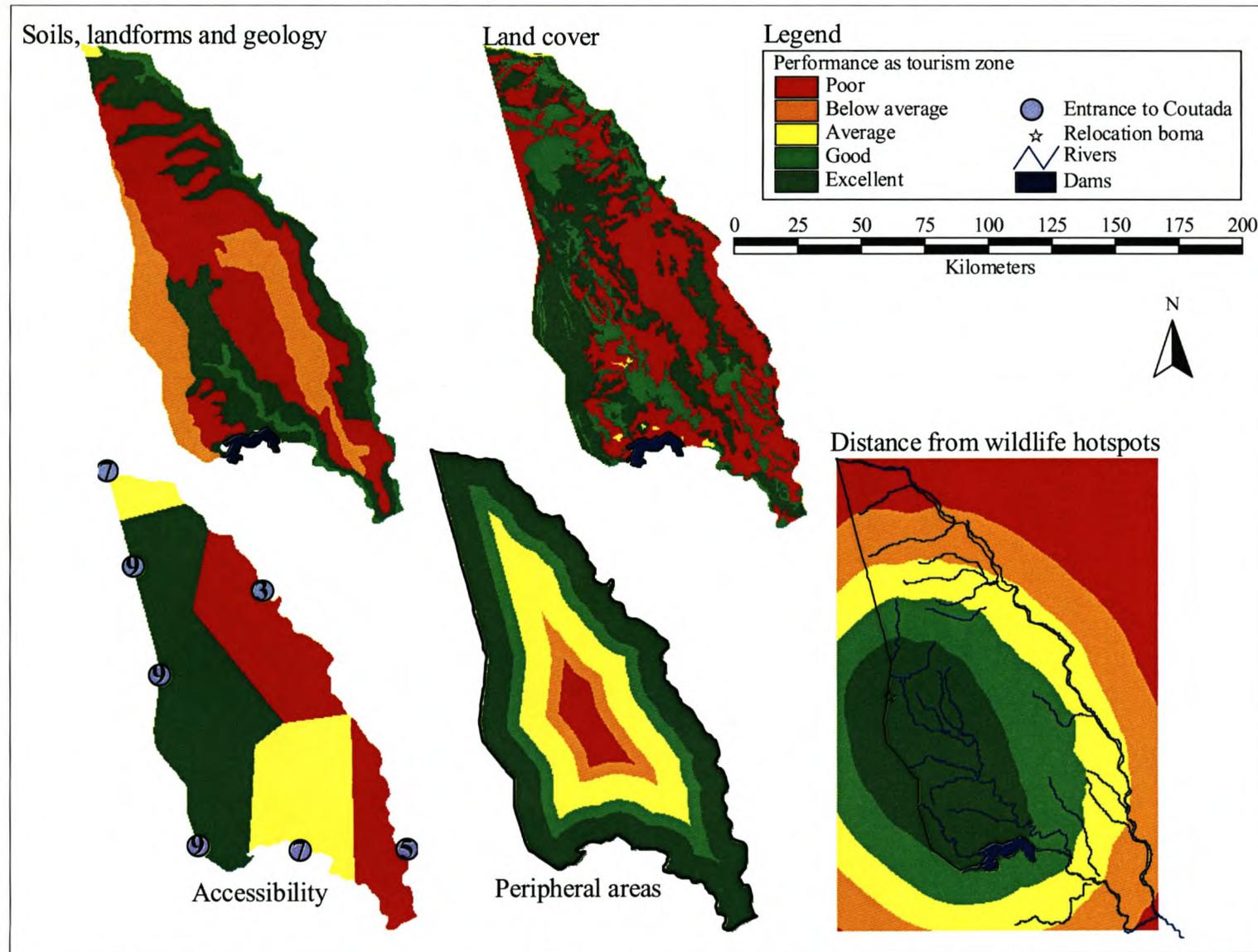


Figure 4.4: Criteria for allocating a tourism zone in Coutada 16

The three components were standardised to a continuous range with a precision of five (five decimal places). Because the desired output was for the criterion to express the benefit of each cell and an increase in distance is interpreted as a decrease in suitability for this criterion, an inversion was required. Both the measurements from the boma and the dam, where only one feature exists, include measurements much higher than obtained from the rivers dispersed through the region. Uniquely defining each set's maximum value accounts for the standardised criteria to express the worst performance as the maximum measurement in the original distance grid, thereby expressing a relative performance.

The three decomposed attributes were weighted by means of a point allocation process. The resulting weights of 0.5 for the boma, 0.35 for the dam and 0.15 for rivers were passed directly to the analysis dialog where the three attributes were compiled with the aid of the SAW method. Figure 4.5 illustrates the weighting and compilation procedure. Figure 4.6 illustrates the original distance grids, the inverted standardised grids and the resultant distance from the wildlife hotspots grid.

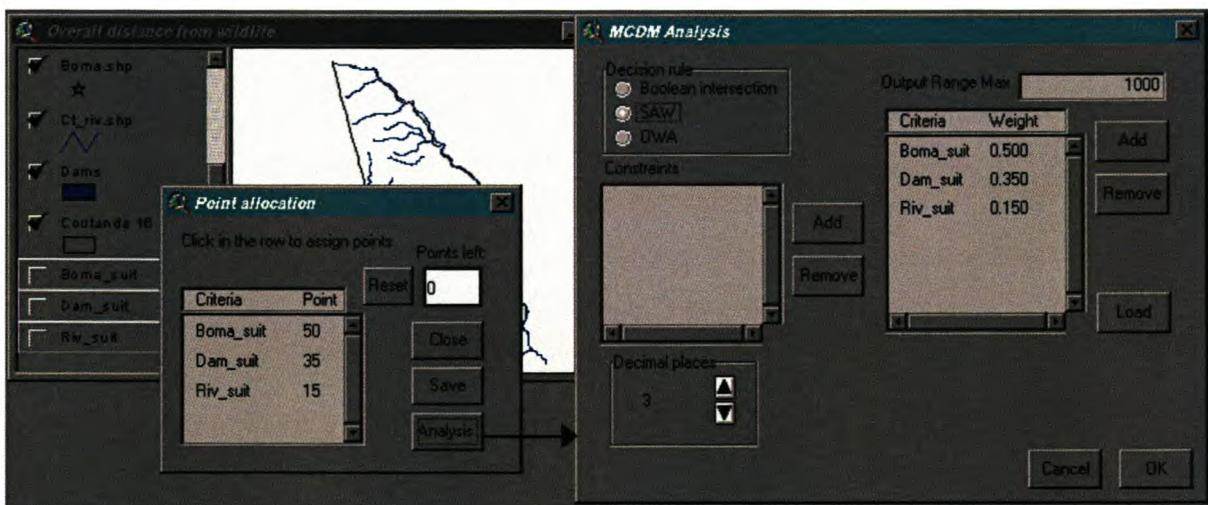


Figure 4.5: Point allocation and SAW compilation for the wildlife criterion

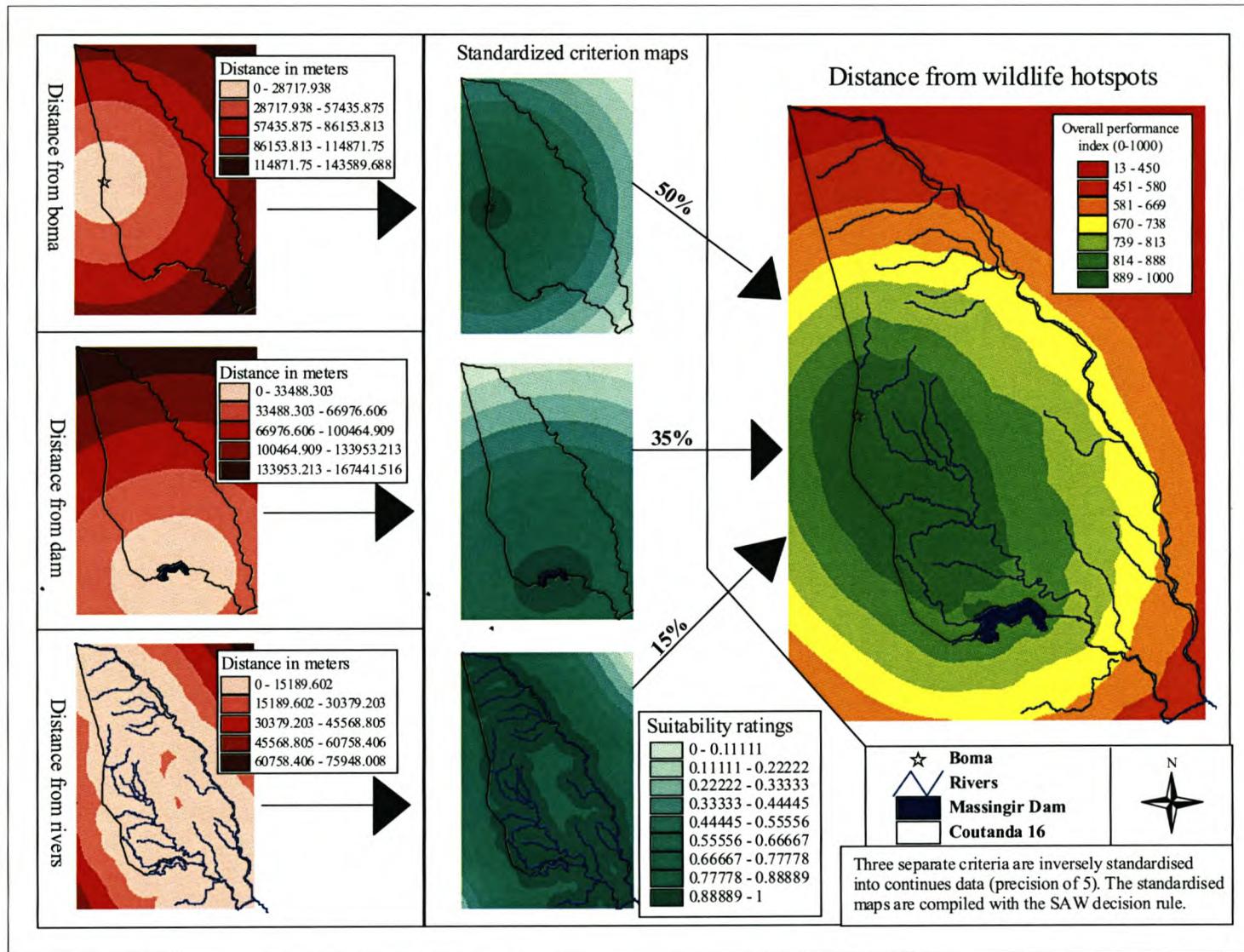


Figure 4.6: Creating the distance from wildlife criterion

Before the weighting process, the criteria were standardised with the normal option. The standardised criteria are mapped in Figure 4.7. To illustrate the full range of weighting features, the criteria for this analysis were weighted multiple times. Figure 4.8 illustrates the completed dialogs for the ranking, rating and pairwise comparison methods. The preferences assigned in the three ranking variants are similar and therefore only the exponential ranking, where the exponent is required additionally, is illustrated. The completed point allocation dialog represents the rating method. The pairwise comparison method is illustrated with both available preference scales. For the real scale, each criterion is associated with a value of importance and when compared, is specified as the one compared over the one being compared to. The results obtained from the various weighting procedures are listed in Table 4.2.

Table 4.2: Results from various weighting procedures

Criterion	Rank			Rate	Pairwise comparison	
	Sum	Reciprocal	Exponential	Point allocation	Saaty	Real
Landforms	0.333	0.438	0.455	0.350	0.448	0.307
Land cover	0.267	0.219	0.291	0.300	0.321	0.275
Accessibility	0.067	0.088	0.018	0.070	0.040	0.106
Peripheral areas	0.133	0.109	0.073	0.080	0.060	0.108
Distance from wildlife	0.200	0.146	0.164	0.200	0.130	0.204
Total	1	1	1.001	1	0.999	1

Weights derived from the pairwise comparison method using Saaty's scale were used during the application of the decision rule. Both the SAW and OWA methods were applied. Figures 4.9 and 4.10 respectively illustrate the completed dialogs for the SAW and OWA procedures. The resulting grids from the SAW procedure are shown in Figure 4.11 and those of the OWA are shown in Figure 4.12. For OWA the order weights were defined as 0.1, 0.15, 0.2, 0.25 and 0.3. Additionally, Figure 4.12 also illustrates the two extremes by applying the full weight to either the highest or the lowest order.

A set of vector alternatives of roughly equal size were defined and ranked using the 'evaluate options' function. Figure 4.13 illustrates the constructed alternatives and the resultant ranks obtained from the 'evaluate options' procedure. The ranking was based on the result of the SAW compilation of the raster data (Figure 5.11). From the resulting information it is possible to distinguish several alternatives best suited for tourism use. A typical conclusion from this data could identify the sites ranked as 1, 2, 3, 4 or 5 as possible tourism zones. Alternatively, high-scoring adjacent alternatives could be compiled and re-evaluated. A combination of alternatives ranked as 2 and 3 and those ranked as 1, 4 and 5 for example, will constitute two viable alternatives which can be re-evaluated. This example merely illustrates the MCDM extension's functionality. Formal conclusions regarding the demarcation of a tourism zone will not be discussed here.

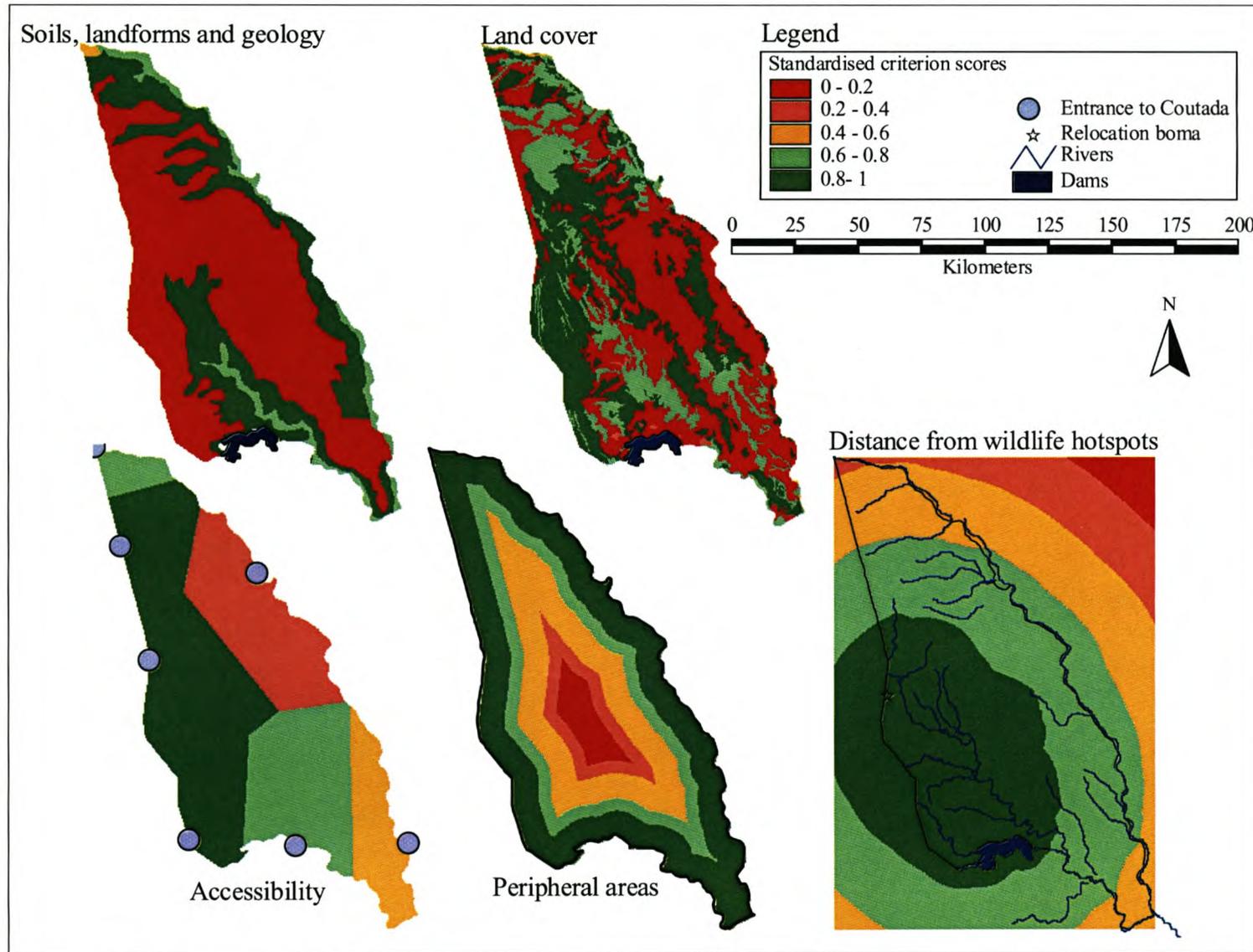


Figure 4.7: Standardised criteria

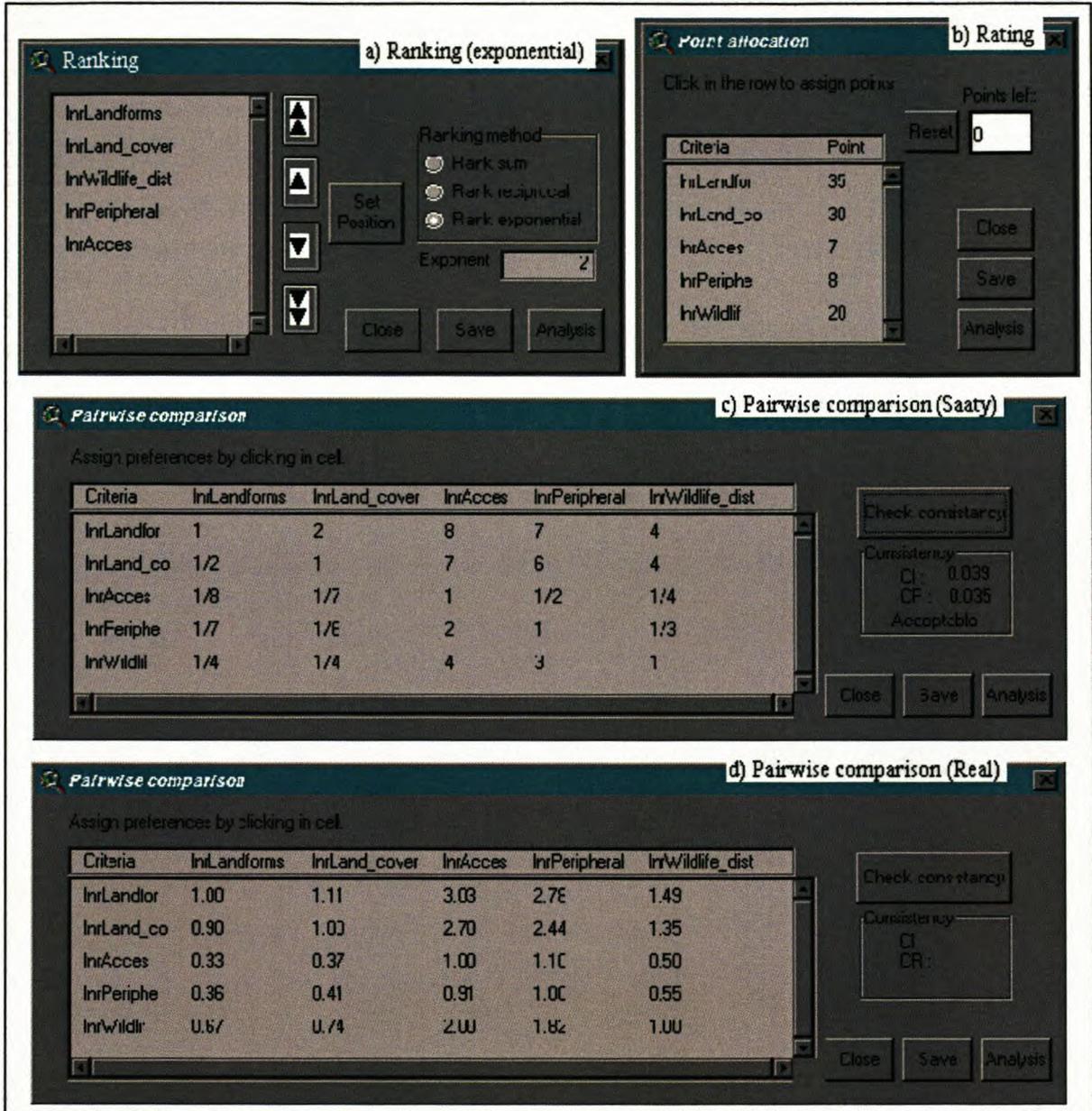


Figure 4.8: Weighting criteria for a tourism zone using a) Ranking, b) Rating, c) Pairwise comparison (Saaty's scale) and d) Pairwise comparison (Real scale)

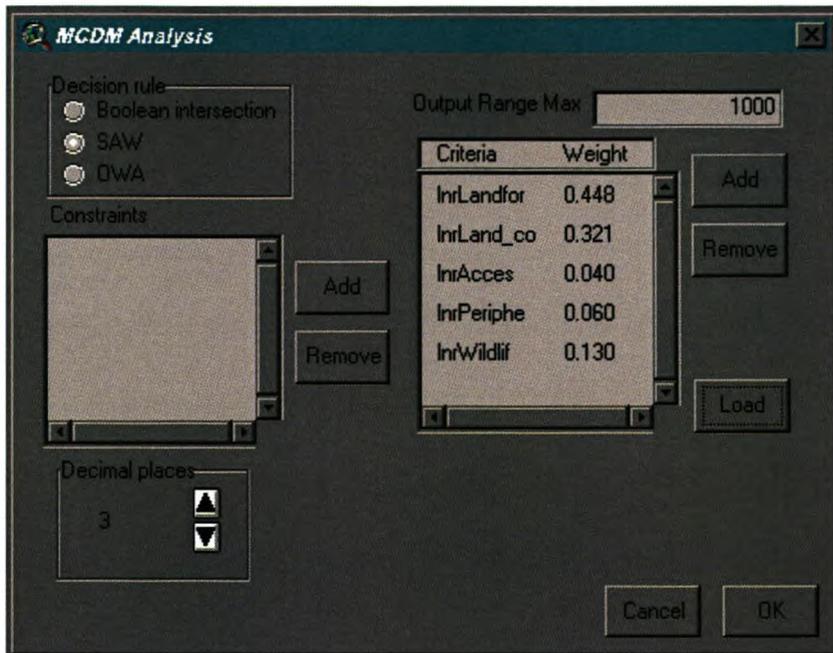


Figure 4.9: Analysis dialog for the SAW decision rule

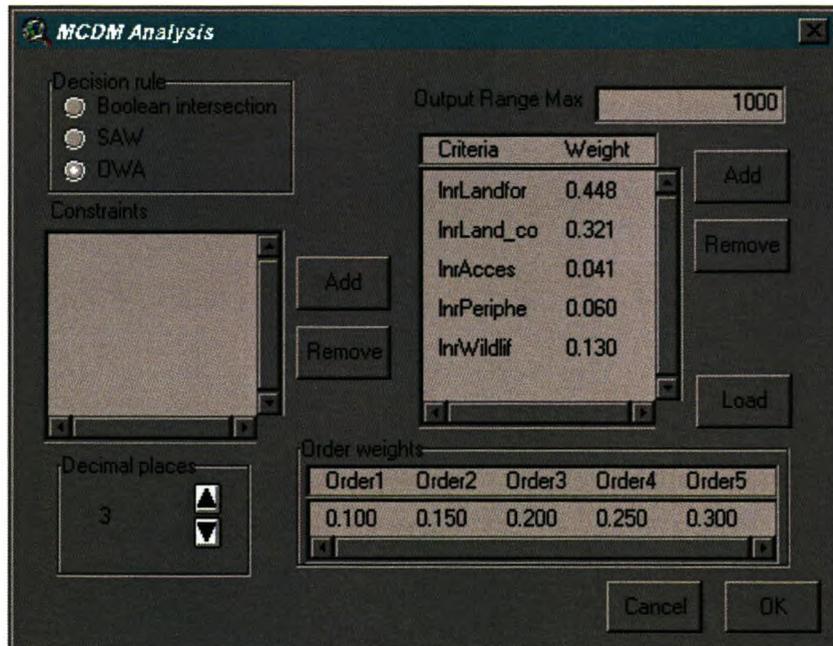


Figure 4.10: Analysis dialog for the OWA decision rule

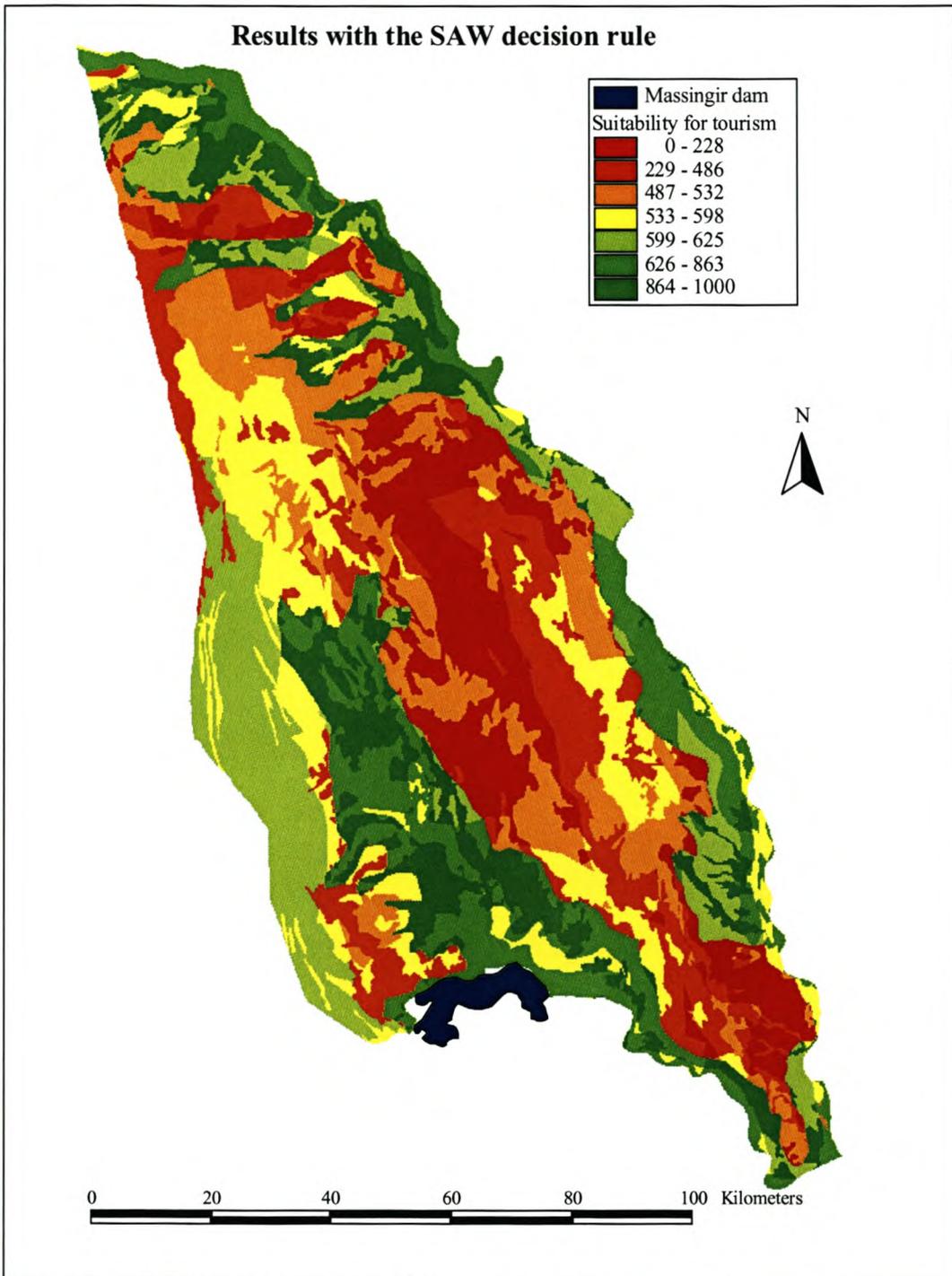


Figure 4.11: Coutada 16's suitability for tourism as derived with SAW

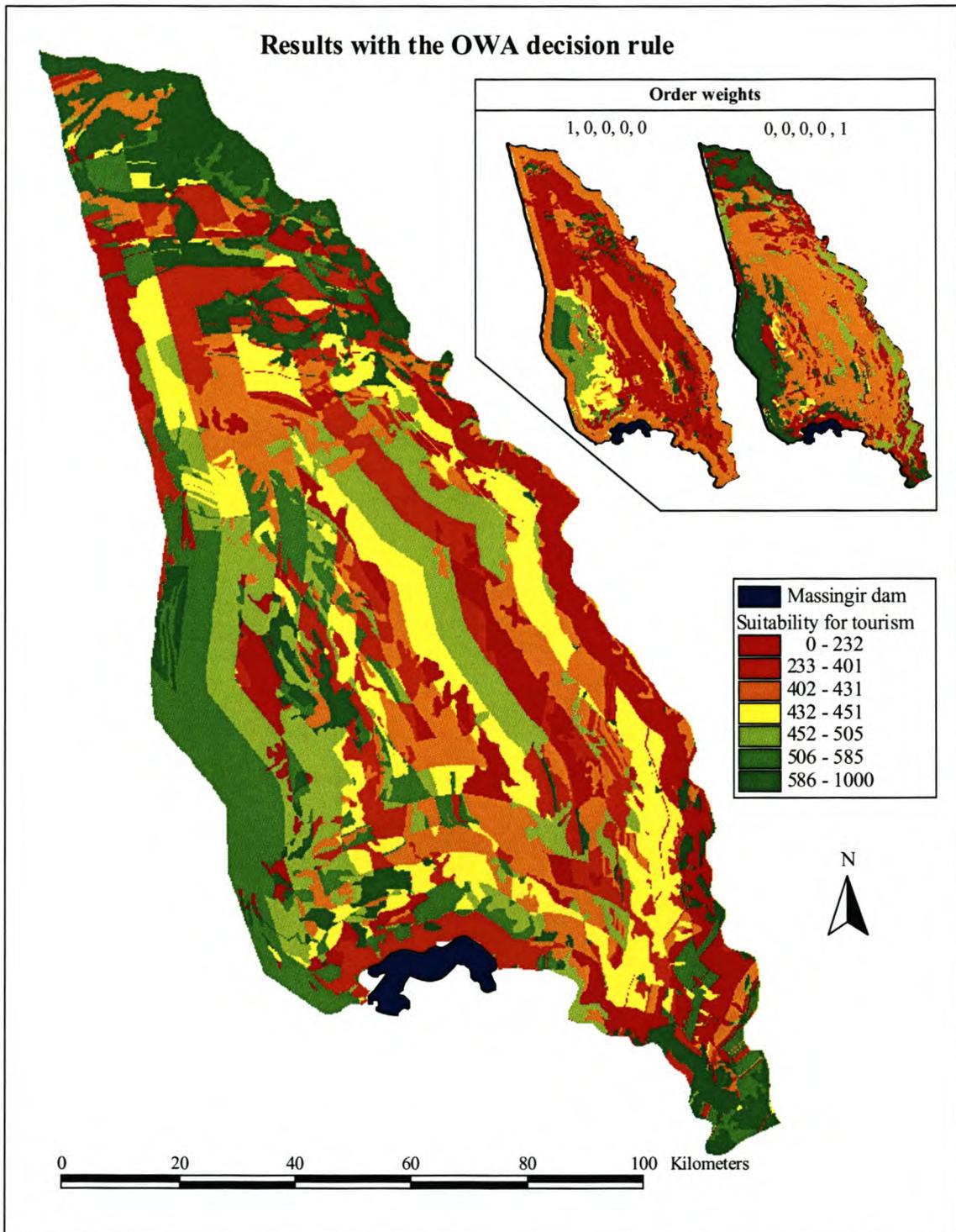


Figure 4.12: Coutada 16's suitability for tourism as derived with OWA

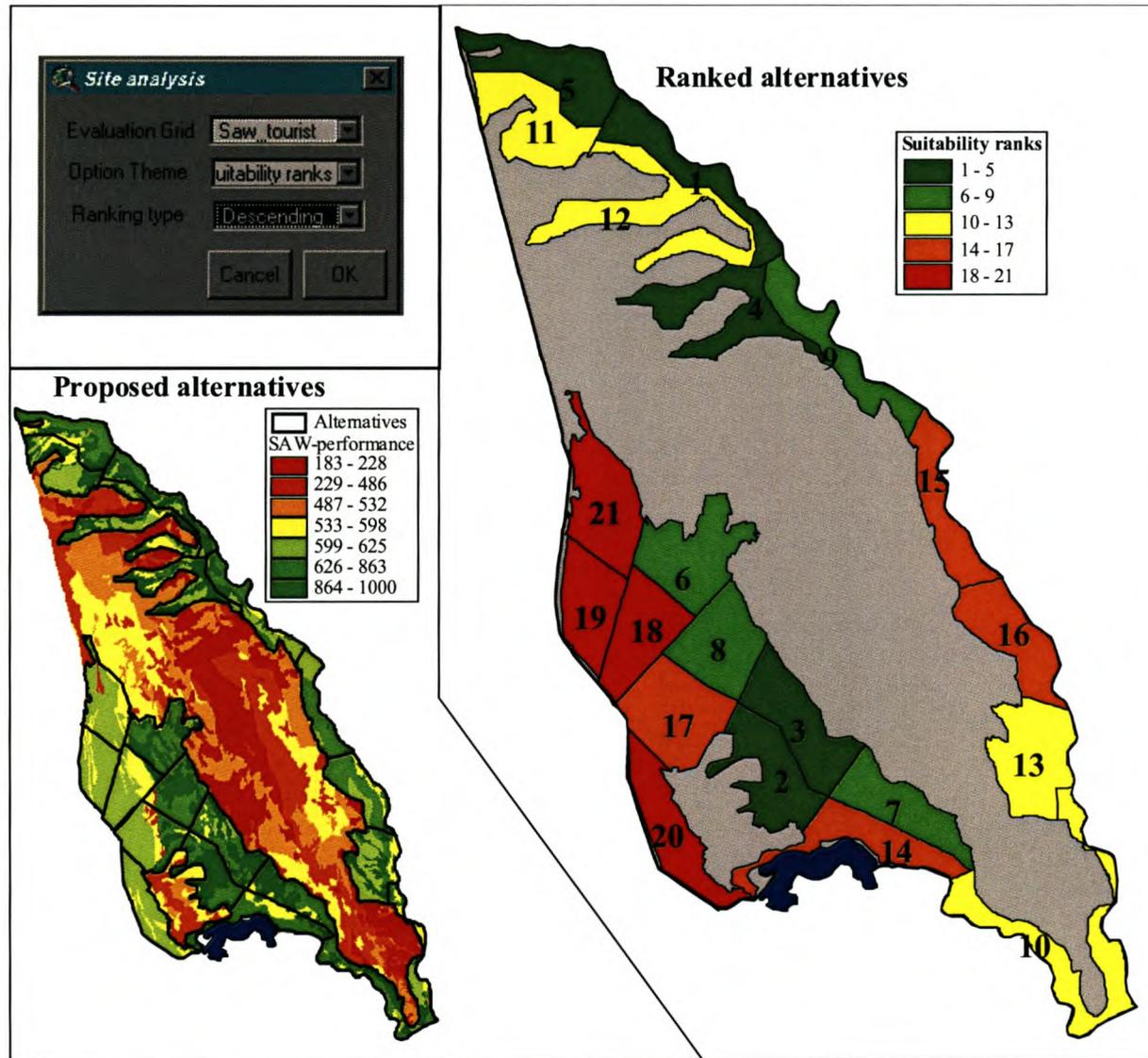


Figure 4.13: Ranked alternative zones

4.2 OPTIMAL LOCATION FOR TOURIST ACCOMMODATION

The problem of optimal location for the development of tourist accommodation is used to illustrate MCDM_AV's vector-processing capability. For this example, sites represented as a point theme are attributed with the relevant criteria. The criteria are standardised to a discrete range (0-255), weighted by means of the pairwise comparison method and combined with the SAW method. Table 4.3 lists the criteria and the associated weights. The criteria are based on the discussion of site planning in a natural setting by Gunn (1994). Both the selected criteria and alternatives however are purely hypothetical and results offered by this analysis are not intended for reaching any conclusions.

Table 4.3: Criteria for selecting tourist accommodation sites

Criterion	Weight
Overall performance from zoning analysis	0.489
Area in visual range	0.153
Significance of visual range	0.062
Negative attributes in visual range	0.062
Density of existing land cover	0.234

The results from this process are illustrated in Figure 5.14. In addition to the criteria, a constraint was used. This constraint is based on the original zoning (PPF, 2001) illustrated in Figure 4.3. For the constraint, the areas not zoned for tourism use were defined as prohibited zones. In the resultant ranked theme, alternatives regarded as prohibited (sites 1,2 and 10) are awarded a rank of 0. A typical conclusion from this data could be that sites 7, 8 and 3 (ranked as 1,2 and 3 respectively) are the three most suitable alternatives. Figure 5.14 also shows the standardised performance achieved at the ten proposed alternatives.

The performance from the SAW-compiled grid in the previous example, the area in the visual range and the significance of the visual range are standardised in the usual way and the remaining criteria are inverted. As a result, all criteria express attributes indicating the positive influence for each alternative. The performance from the zone analysis and the density of existing land cover are based on direct measurements. The area for the visual range was determined from a DEM modified to include the height of the associated land cover. The observer viewpoints were specified as the surface heights with an offset of three metres and a maximum view distance of 20 kilometres. From the computed viewsheds, visible areas were analysed and assigned values as estimated for both the negative and the positive aspects.

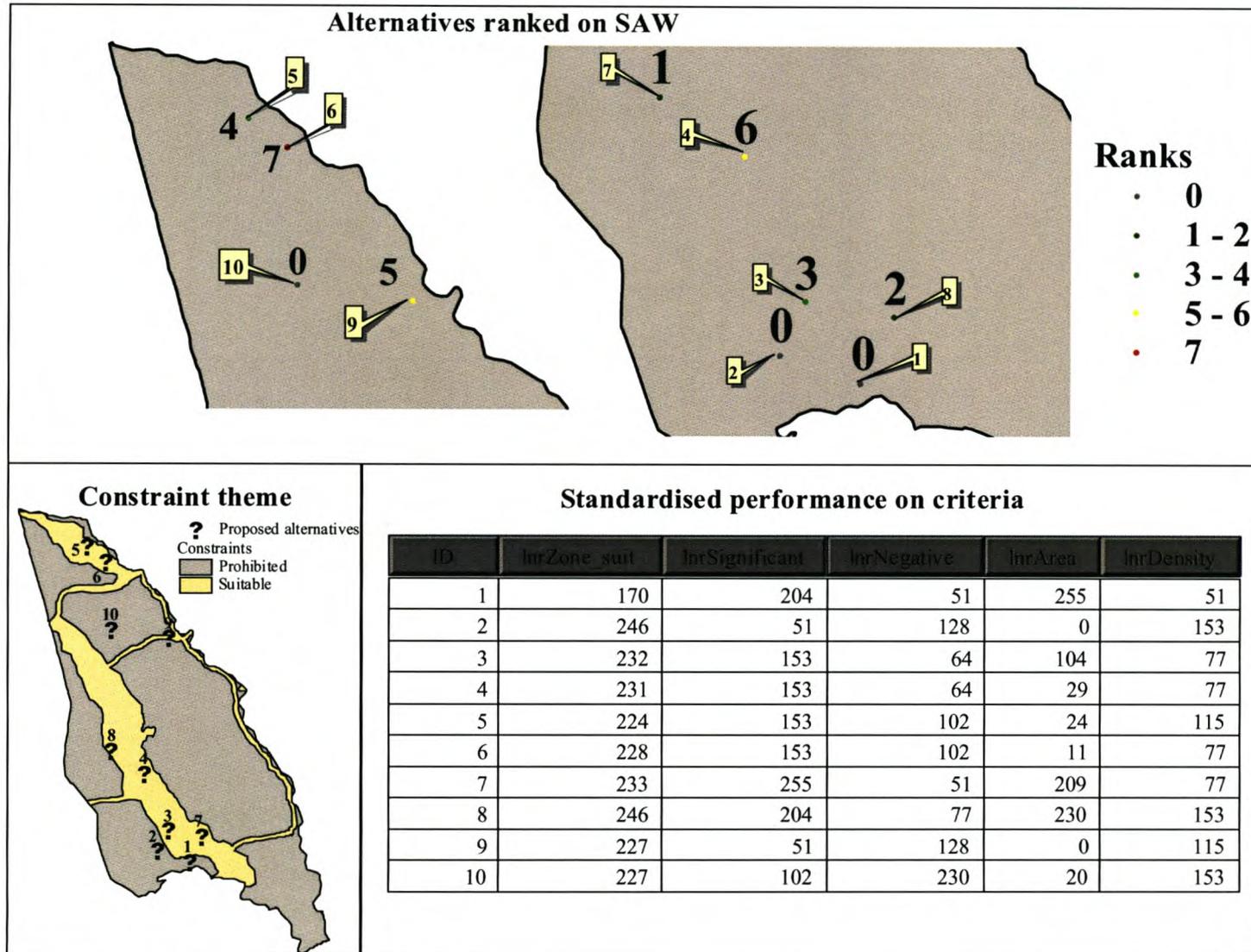


Figure 4.14: Site allocation with SAW compilation

During this chapter, MCDM_AV was demonstrated on applications to some real world problems. It included an evaluation of both raster and vector data to illustrate MCDM_AV's capability of handling both these data formats. The demonstration also illustrated the majority of the functions included by MCDM_AV, the outcome from the various procedures and how the results can be interpreted or used in further analysis.

The following chapter deals with the evaluation of the created extension's validity and its potential use as formalised for the fourth objective. This validation procedure is based on aspects of the system's error-free functioning and the appropriateness of its developed interface. The discussion proceeds with some recommendations for the improvement and expansion of the existing functions and in conclusion, offers some final remarks on the research process and the developed extension.

CHAPTER 5: THE PRACTICAL USE OF THE EXTENSION

The research was set out to implement MCDM procedures in the GIS ArcView software. The goal was successfully achieved and offered an MCDM extension as result. As indicated with this report, the MCDM extension expands ArcView's capability of spatial decision-making by introducing standardisation, weighting and compilation procedures from the MCDM methodology. The selected design allows the processing of either vector or raster data, but restricts a procedure to the use of a single data format. An additional function to evaluate vector alternatives on raster data is also included to aid the user in the choice phase. The final component, an extensive help file, offers user support on both the theory of MCDM and the functionality of the extension.

5.1 VALIDATION OF THE EXTENSION

Validation is an important part of this research as it is the only means of evaluating the potential use of the extension. Validation methods include testing for predictive ability, assessment for face validity (the appearance of the software), comparison against performance standards, and examination of scope validity (Harrison, 1991; O'Keefe, Osman & Smith, 1991). MCDM is validated here under two main readings. First, the issue of error-free functioning and the functions performing the intended manipulation will be addressed. This is followed by a discussion of the interface's specific design to motivate the use of this system.

5.1.1 Error-free functioning

Under this first topic, two issues are addressed. Firstly, it is established whether the applied methods perform the appropriate calculations. Ideally, this evaluation should be based on a comparison between results obtained from this software and results obtained from established spatial MCDM software. Too much time spent during the implementation phase however precluded such a validation process within the allotted timeframe. As an alternative validation method, various random manual calculations were compared against results obtained from the developed functions. This process took place in the testing phase during implementation. Where errors occurred, functions were corrected. The values obtained from the standardisation, weighting and compilation procedures are therefore all deemed to be accurate.

The second issue addressed is the validation of the error free functioning of MCDM_AV's user interface. This validation was aimed at the technical functioning of the system and ensures that all procedures function as intended. This testing also took place during the implementation phase and

while most errors were corrected, some minor deviations are still present. Appendix C lists and briefly discusses the known problems and concerns regarding the use of MCDM_AV.

5.1.2 User-friendly decision-making

Together with error-free functioning, a system's interface determines the success of its adoption by users (Demers, 2000). MCDM_AV is provided with a single menu associated with the view document. Choices from the menu allow the user to initialise the developed functions. Each function includes a set of message boxes and/or dialogs (with a set of associated controls) to facilitate the required user interactions. Message boxes allow the user to choose options from dropdown menus, make multiple selections from lists and input the necessary data for various functions. The dialogs were used to offer specific controls as required by the techniques. In the author's opinion, the implemented interface components successfully establish a user-friendly decision-making environment. A discussion on how certain elements were specifically designed to promote user interaction and ultimately make MCDM_AV more likely to be adopted as decision-making system, follows in this section.

Default input values were used for a double purpose. It firstly illustrates the format of the required input, eliminating the frustrating task of repeating inputs until acceptable values are specified. Secondly, the defaults offer valuable time saving information during the process. On the one hand appropriate defaults can be accepted, eliminating the need to key in values and on the other hand, it offers information which must otherwise be calculated or looked up in the input theme(s) database. An example of this information is to be found at the standardisation function where original range parameters defaults to the respective minimum and maximum values of the input data. Other examples are to be seen at the rating procedure and manual weighting of criteria in the analysis dialog where the remaining allowable values are automatically calculated and given as the default values.

The use of active themes for input of criteria into the standardisation and weighting functions also improves the use of this system. This obliges the user to visually interpret the criteria selected as input to the procedures at this early phase, which reduces the risk of selecting incompatible data layers.

The separate dialogs created for the weighting methods each offer a unique set of controls for user interaction. When selecting the ranking method, the user is required to express his/her preferences by arranging the criteria in the order of desirability. To perform this ranking, the dialog includes a displayed list with entries that can be manipulated to the desired orders with the specifically

designed buttons. For the point allocation procedure, the allocation of points simply requires the user to click the displayed criterion and specify the number of points associated with it. The dialog also displays the remaining points. An automated approach to assigning preferences during the pairwise comparison procedure greatly reduces the required user interaction. Specifying the preference also simply requires a mouse click on the appropriate cell in the displayed comparison matrix. This weighting procedure offers two options for assigning weights. One where the user selects the preference that best describes the relationship between the criteria being compared from a predetermined list (Saaty's scale) and another where the user can key in any real value expressing his/her preferences. The pairwise comparison also includes a consistency check for the assigned preferences that improves assurance in the final decision outcome. All three weighting procedures include the ability to send the criteria and weights directly to the analysis dialog, eliminating the tedious task of manually loading input. This data can alternatively be stored on disk from where it can be accessed at a later stage.

In addition to the ability of passing criteria and calculated weights directly to the analysis dialog, the analysis dialog also includes a number of controls promoting user interaction. Data can be added here by either manually adding it or loading it from a previously saved file. Manually adding constraints and criteria can be specified as themes loaded in a view or as the source data stored on disk. To load a file the user need only navigate to its position and indicate the file name. The load procedure looks for the data by source name and if this has changed from the time when the weight file was saved, it prompts the user to indicate the appropriate source file. An additional dialog is used to convey the working status of the system when the compilation procedures are run. It includes a function to cancel a procedure, extremely important when dealing with large data sets (specifically when utilising the OWA decision rule). The processing required by a compilation of OWA, such as illustrated by the first example in Chapter 4 for example (a compilation of four grids, each about 1900 X 1200), require around three hours to complete. MCDM_AV also offers support for the visualisation of results. First, the ranking of features includes an auto label function that labels vector alternatives with the calculated rank order. This function clearly demonstrates the order of performance as labels in an onscreen display or hard copy of the results. Secondly, the unique legend, coloured green to red (best to worst) for performance alternatives and grey for prohibited alternatives, further increases visual interpretation. The use of these legends for all output establishes a standard colourisation of results. This firstly allows a user familiar with the extension to quickly visually interpret the output and secondly allows a comparison between results from separate procedures.

All the functions and coded interfacing are equipped with tests for the required input. When information lacks or does not comply with the desired format, error messages specify where additional input is required or initial input was rejected. The major aspect attributing to the usability of this system is the included help file. This file can be accessed from the MCDM menu and offers information on the background theory of the methods, a systematic explanation of performing the various procedures and the example applications discussed in chapter 4.

A major concern regarding the interface is attributed to user comprehension of terms used for some of the choices offered. These concerns are also discussed in the section on known problems included as Appendix C.

5.2 PROPOSALS FOR FUTURE EXPANSION

MCDM_AV is regarded as a first-version generic extension intended for future expansion. During this research, a number of possible improvements/expansions were identified. Some of these are:

- a dialog that allows the input of all required data for the entire evaluation process as an initial step;
- procedures that allocate cells to select optimal polygon or line features;
- tools automating the creation of criteria;
- an interactive procedure for evaluating alternatives;
- inclusion of techniques such as fuzzy set membership methods, to handle uncertainty in data;
- expanding the available range of MCDM procedures;
- developing methods that handle multiple decision-makers;
- incorporating MODM procedures; and
- a function that facilitates a sensitivity analysis.

5.3 CONCLUDING REMARKS

While previous applications integrating MCDM with ArcView are problem-specific software, this extension offers the unique freedom of a selection from a variety of methods for different phases of the process. This freedom is similar to the MCDM functionality provided with IDRISI software and establishes a generic environment for decision analysis. The options included in MCDM_AV's functionality provide the user with the freedom to generate results for his/her specific objectives.

Because the extension is developed as an integral part of ArcView, a basic knowledge of ArcView's functionality is a prerequisite for any potential users. The ability to load data into ArcView, an understanding of the data structures it uses and a comprehension of the information being displayed will enable a user to perform the functions provided by the MCDM extension. Generating input data or processing results however requires a more experienced use of ArcView functions. Creating raster input for example requires conversions, distance allocations or interpolations. Vector data requires the user to create appropriate fields and utilise various functions to determine the criterion scores. The examples in Chapter 5 use buffers, distance matrixes and the conversion of vector data layers to generate raster input and area calculations, viewsheds (quality of visible area) and measurements for the specific alternatives' criteria scores in vector data. Producing hard copies or including results in a report requires the user to be able to create layouts and/or exporting to image files. Further processing of data could involve creating charts, querying specific sites or refining alternatives for a second MCDM evaluation cycle.

An overall evaluation of the system illustrates that it offers great potential. While a number of refinements and expansions are still required, MCDM_AV version 1.0 offers a basis for the creation of a fully generic MCDM extension for ArcView. With ArcView being one of the most popular desktop GIS's, the chances of users adopting this system is greatly improved. MCDM_AV and future expansions on this extension will be a giant leap forward for the decision-making capabilities of the ArcView software. This research could revolutionise ArcView users from their traditional decision making strategies to a more informed and involved process of solving problems. A change that will improve confidence in both the decision maker and the decision outcome, without the tedious and costly task of training when buying new software components.

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APPENDIX A: RULES FOR SELECTING APPROPRIATE CRITERIA

Malcsewski (1999a) recognises the following set of rules for the selection of appropriate criteria:

- a) A criterion must be comprehensive and awarded scores must clearly express the alternative's level of performance.
- b) A criterion must be measurable. It must be both practical to quantify and hold the ability to objectively illustrate the level of performance.
- c) The set of criteria must be complete in the sense that it covers all relevant aspects for the pending decision.
- d) All criteria must be operational. They must be understandable and meaningful to all decision-makers.
- e) Criteria can be decomposable in the sense that they can be broken down into parts for simplification of the process.
- f) Criteria must be non-redundant. When a criterion is included more than once, its influence is exaggerated.
- g) The selected set must include the minimal number of criteria. When more than the absolutely necessary criteria are included, it results in unnecessary complexity and processing requirements in the decision-making process.

APPENDIX B: SUPPLEMENT TO SECTION 2.6.2.2

In the text the discussion of the design phase (Section 2.6.2.2) was restricted to the methods incorporated into the developed MCDM extension. With the exception of the MODM decision rules, the remainder of the listed techniques is summarised here as discussed in Malczewski (1999a).

STANDARDISATION METHODS

Value/utility approaches

With value/utility approaches (Keeney & Raiffa, 1976) the relative position of the criterion scores change during a transformation from the original scale to a standardised scale. This method applies a curve to represent the biased preference of criterion scores. The new values are calculated by applying to the original values the function that defines the curve. Figure B.1 illustrates a transformation based on an exponential curve, defined as $y=x^2$. This technique allows user preferences towards specified ranges of criteria measurements. The curve in the figure for example illustrates a preference for an increase in values. The curves could also include multiple peaks to express preferences towards multiple sections of the criterion range.

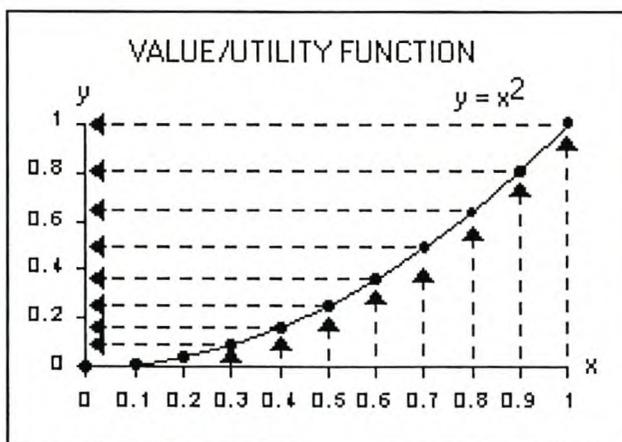


Figure B.1: Value utility function

Probability method

The probability method transforms values based on the specified condition's probability of occurring. This method requires multiple data sets for a single criterion, which are combined with the probability of each data set defining its contribution to the overall standardised score. A further refinement of criterion scores is achieved with the Bayesian approach, which includes further

probabilities in the transformation. Rather than transforming the criteria to comparable layers, it allows for expressing a degree of uncertainty in the data. To transform data into comparable layers, the method can be modified to include additional computations as described by the other standardisation functions.

Fuzzy set membership

The fuzzy set membership method is another approach used for handling uncertainty in data. The criterion scores are fitted to predefined linguistic terms and then substituted with a fuzzy set associated with each class. Performing this transformation requires the classes to be represented as overlapping trapezoidal or triangular shapes. These shapes are then fitted to a line representing the new range to derive the fuzzy set numbers for the classes. The shape junctions serve as reference points for the calculation of each class's four fuzzy numbers. This procedure is illustrated in Figure B.2 where triangular shapes are used to identify the fuzzy set of a scale 0 to 1 for three classes. The assigned fuzzy sets for each of the illustrated classes are 0, 0.2, 0.2 and 0.4 for low, 0.3, 0.5, 0.5 and 0.7 for medium and 0.6, 0.8, 0.8 and 1 for high. The original criterion score is then substituted by the four values associated with the class into which it falls. This technique transforms each criterion data layer to four data layers representing the original score's fuzzy counterparts.

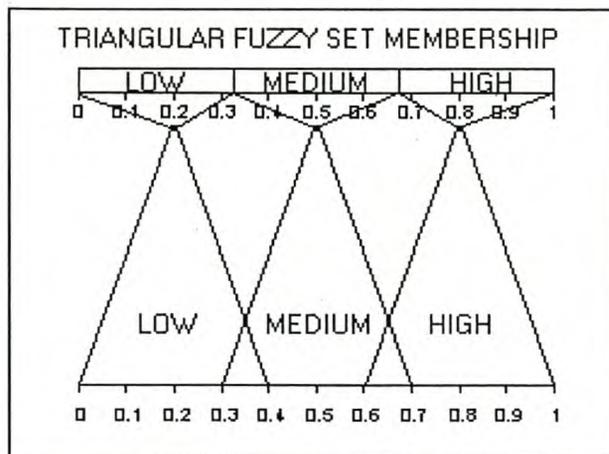


Figure B.2: Fuzzy set membership approach

WEIGHTING METHODS

Trade-off analysis

This weighting process makes use of the trade-offs that decision-makers are willing to make. The criteria are compared in groups of two so that each criterion is at some stage being compared to another. For each comparison, the decision-makers specify how much they are willing to sacrifice

on one of the criteria to maintain a full weight for the other. Criterion weights are subsequently calculated from the preferences expressed in the compared criteria pairs.

DECISION RULES

Value/utility functions

The major factor that distinguishes value/utility techniques (Keeney & Raiffa, 1976 and Keeney, 1992) from the other methods is attributed to the type of data expressed by the criteria. For the value/utility functions, the criterion scores are replaced by a value/utility as derived from a value or utility function. The value/utility functions are first categorised into individual or group functions and then further categorised based on the nature of information available. This categorisation accounts for a distinction of three approaches: the attribute value/utility function, group value/utility function and probabilistic additive weighting.

The attribute value/utility function is based on individual decision-making. Formally, this function is similar to the SAW method and only differs with the criteria scores being expressed as a value/utility rather than a normal criterion score.

The group value/utility function incorporates multiple values/utilities for a single criterion into the analysis process. The combination of criteria is preceded by combining different values/utilities expressed by the decision-makers, to a criterion expressing a group value/utility. The compiled criteria are further combined to a single index expressing the achievement at the alternatives. For deriving group criteria, weights specify the decision-maker's influence and while compiling the group criteria, the weights specify the criteria relevance.

Probabilistic additive weighting is based on the probability theory. Each criterion is decomposed into values/utilities expressing the worst, most likely and best outcomes for the pending decision. Each of the subsets is combined with the probability of the specified value/utility occurring and is recompiled into a single criterion. The resulting criteria are then finally combined into a single composite index that expresses the achievement rates for each alternative.

Analytic hierarchy process (AHP)

The AHP (Saaty, 1977; Saaty, 1980; Saaty, 1990 and Saaty, 1994) evaluates the problem in a hierarchical structure. The problem goal is defined as the top level and subsequent classes are formed from the decomposition of the goal. In its simplest form, the hierarchy can be represented on three levels, namely the goal, its objectives and attributes, to measure the alternative

performance. For complex problems, additional levels are added until the required decomposition and simplification of the process is reached. Figure B.3 illustrates the decomposition of elements and their associated weights for a simple AHP problem.

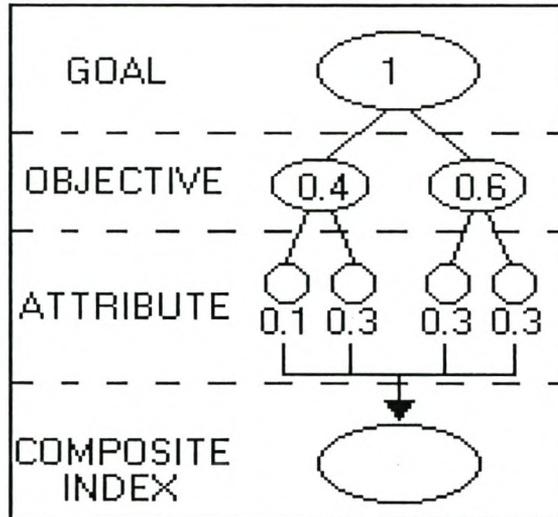


Figure B.3: A simple AHP hierarchy

The AHP makes use of the eigenvector method to derive weights from decision-maker preferences. Weights are expressed for all levels and represented as a counterpart of the associated element's parent class. The weights assigned at bottom levels can therefore be traced through the hierarchy, which allows visual conformation of weights at the lower levels. The SAW method is used to combine the criteria and associated weights to a compiled index.

APPENDIX C: KNOWN PROBLEMS

The problems included in this discussion are those identified during the evaluation of MCDM_AV as suitable decision-making system. The problems experienced are categorised into three classes; the function performing its intended task, the coded functions working error free and the comprehension of terms used to distinguish between certain options.

Even though all functions were corrected to perform the intended tasks, there is however concern regarding the use of the 'evaluate options' function. The problem experienced with this function is associated with the evaluation of line or polygon features. While the results offered from the techniques are as specified for the intended function, the practical application of this procedure has some errors. When performing an evaluation with line features for example, the results are influenced by the line length. While this is allowable when dealing with path costs, there is no basis for longer lines to be considered as more beneficial when dealing with benefits. The inverted problem occurs when dealing with polygon features. This method offers results in a per area basis, which means that when dealing with cost factors, there is no increase in cost with size. This problem can possibly be corrected with some minor adjustments of the source code. If it is redesigned so that area and distance influence the result when dealing with cost criteria and not (per area basis) the results of benefit criteria, the outcome will be more acceptable.

MCDM_AV also includes some minor glitches in its source coding. As a result, the following problems are experienced. The first is associated with the system warning of criteria not being in similar ranges at the weighting and compilation procedures. Allowing the user to specify input range maximums as values greater than those included in the data means that standardised criterion scores will not necessarily include the maximum value of the output range. The testing for criterion ranges is however based on the comparison of maximum values in the data sets specified as criteria. When criteria standardised to the same range do not include the same maximum values, they are interpreted as criteria with different ranges. The included option to continue circumvents this problem. A proposed solution is the creation of files storing range parameters for standardised criteria. The testing of ranges can then access a criterion's range from the information provided by these files.

A second problem is related to the weighting procedure. With the user specifying the output weight precision, the rounding of weights often cause reported weights not to add to 1. Results from the exponential ranking weighting method listed in Table 4.2 illustrate this error. For the compilation of data, criteria weights are tested for the total of 1. If they do not add up to 1, the procedure is

terminated. The reported error is however limited to the smallest fraction (± 0.001 for a precision of 3) and can easily be corrected manually.

The final area where there is cause for concern is with the comprehension of terms used to distinguish between some options. The choice between 'cost' and 'benefit' for the standardising function or the ranking of ascending or descending specified at the 'evaluate options' and 'analysis' functions illustrates these concerns. When a criterion is expressed as a cost criterion, the procedure inverts the data so that the output values are interpreted as higher values specifying better performance, whereas no inversion is performed for a benefit criterion. The terms 'normal' for benefit or 'inverted' for cost might be better suited for this distinction. These terms however lack the description of why the inversion is needed. For the compilation of data sets, it is crucial that the criterion data layers express the same type of data. The original terms of 'cost' and 'benefit' were therefore retained, although they fail to illustrate the use of the function to invert benefit data to cost data. This type of conversion requires benefit data to be specified as cost. This can be justified by defining a benefit criterion as a data set, expressing the cost it holds for the criterion to be expressed as a cost criterion. The terms used however remain a source of confusion.

The terms descending or ascending ranking is a further source of confusion. The terms describe the process of ranking a list of values from either the highest to the lowest (descending) or vice versa (ascending). The ranking procedure is however intended to always offer results ranked from best option to worst. The terms are used here to distinguish between the information expressed by the data sets. If cost criteria were compiled, the ranking should be ascending to rank the lowest cost as the best alternative. When benefit criteria are compiled, the highest values are the better-suited options and therefore require a descending ranking. To avoid confusion, the terms deemed as confusing and the results obtained from the various choices are all discussed in detail in the help file.

APPENDIX D: DATA INCLUDED ON CD

- ❖ A digital copy of this report in Adobe Acrobat Reader format (pdf).
- ❖ A digital copy of the land-use management report for Coutada 16 (PPF, 2001).
- ❖ A document with information regarding the developed extension (Readme.doc)
- ❖ The MCDM project file (MCDM.prj).
- ❖ The MCDM extension (MCDM.avx).
- ❖ The MCDM help file (MCDM.hlp, MCDM.cnt and MCDM.fts).
- ❖ Text files with source code for scripts and dialogs used in the extension (*.ave).