MULTIPLE CRITERIA AND DECISION SUPPORT SYSTEMS IN WATER RESOURCES PLANNING AND RIVER BASIN MANAGEMENT.

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1 INTRODUCTION

In this paper I look at a systems approach to decision making in general, multi-criteria methods, what constitutes a decision support system (DSS), I briefly review what has been done in the past, examine the current state of the art and make some predictions about future directions and uses for DSS with a specific emphasis on those used in water resources planning and river basin management.

1.1 Systems Approach to Decisions

It is essential to understand the various activities involved in making decisions related to large infrastructural projects. The classical paradigm for a systematic approach to decision making contains five steps, de Neufville & Stafford (1971):

Definition of Objectives: For every project there will be a person or group of people who make the final decisions in relation to what (if anything) gets done and when. Each decision maker will have a set of objectives, which must be taken into account. The decision maker's objectives dictate a set of criteria, which are used to assess all possible options. Large-scale water resources problems usually involve a considerable range of objectives and thus assessment criteria and a scoping exercise is required to identify all their attributes. In relation to river management systems, some of the objectives would be related to (ii) flood control, (ii) preserving/restoring ecological integrity (not just threatened by pollution by also by changes in hydrologic or hydraulic regime) (iii) providing contact and non-contact amenity/recreation (iv) water supply (v) navigation (vi) hydropower (vii) efficient use of resources (money, land, manpower etc.) (viii) equity, e.g. in the distribution of benefits (ix) regional and national development. Many criteria arise because of the context of the design problem, i.e. an individual flood related design must be seen in the overall context of river basin management.

Measures of Effectiveness: Procedures must be established for assessing each objective or criteria. They may be quantitative (e.g. cost) or qualitative (e.g. visual impact, amenity etc.)

Generation of Alternatives: A list of possible types of solution is generated, possible from a brain-storming session. It is important to get as complete a list as possible. In relation to flooding, both structural and non-structural measures (e.g. source control, planning/zoning, risk assessment, forecasting, flood-proofing etc.) should be considered.

Evaluation of Alternatives: All of the possible types of solution are evaluated in relation to the measures of effectiveness for each criterion. This invariably requires modelling and produces an assessment matrix. Each alternative design is modelled and its performance and impacts predicted.

Decision or Recommendation: The results of the evaluation are analysed and decisions or recommendations are formulated. When there are many objectives/criteria this may involve some trade-off between objectives and multi-criteria decision support techniques can help here.

This is a linear procedure, illustrated in the right hand side of Figure 1. The final two steps depend on the results of the three preceding steps so the steps must be completed in the order listed. This paradigm is valid today in certain circumstances, but does have some limitations, particularly when applied to complex problems with large environmental considerations. This is because it assumes that

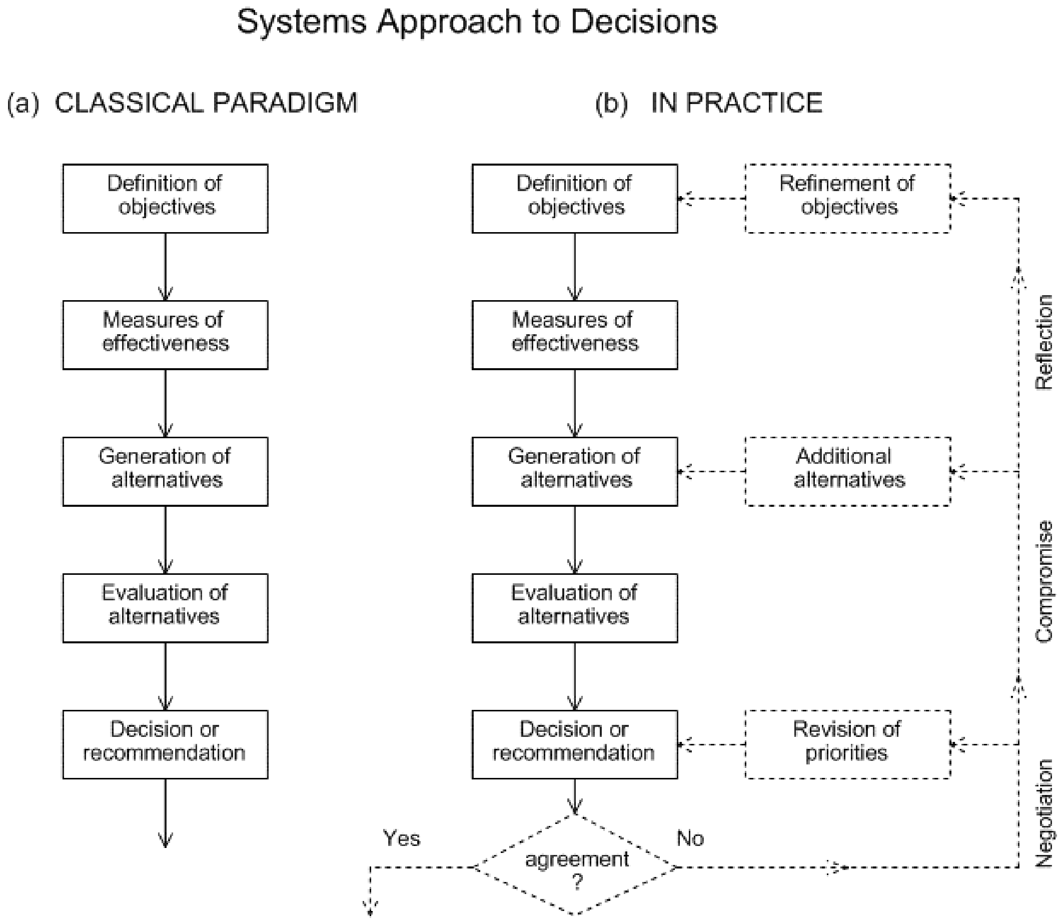

Figure 1 Classical vs Existing structure of systems analysis

the decision maker(s) are readily identifiable and that their objectives (and priorities) can be readily obtained at the outset of the analysis. This may be true in many circumstances, for instance for most private companies and for many public agencies. However, many decisions relating to large scale activities or infrastructure related to water resources have significant environmental impacts and the objectives and priorities of the general public must be taken into account. Scoping and public consultation activities are important and essential features of decision making in these situations. What happens in practise at the moment is more closely represented by the steps shown on the right hand side of Figure 1. The ultimate aim is to find an acceptable compromise between the various, invariably competing, objectives, and this involves negotiation, compromise and perhaps even some rethinking of the project objectives. This was understood at a comparatively early stage, e.g. by Jamieson & Fedra (1986) who recognised that, "River basin management can be characterised as an exercise in conflict resolution".

This “reality” has both advantages and disadvantages. The advantage is that there is more scope for stakeholders to contribute to decisions than in the classical systems parading. However, two major disadvantages are

(i) Stakeholders contribution often comes so late in the analysis. This has a number of consequences, not least of which is that the voices of objectors are far more prevalent at this stage than the voices which support a decision/design.

(ii) that the negotiation is primarily about the final decision (design) itself and not about the underlying objectives or criteria which its represents. Final designs are the results of many complex analyses. Even if such a design is optimal there is no guarantee that small perturbations of the design remain close to optimality, nor even that they do not violate any constraints which may have been imposed on the original design.

I believe that there is a need to involve stakeholders as early as possible in the analysis and to focus that involvement on refining objectives and criteria, rather than on adjusting a proposed solution. Because this is a more abstract level, it is more difficult to achieve and decision support tools are necessary to facilitate the involvement of stakeholders. What are now called decision support systems (DSS) have the potential to fulfill this role.

The ordinary meaning of the phrase "decision support system" includes any system which helps someone with any aspect of making a decision. A system is " any structure, device, scheme or procedure, real or abstract, that interrelates in a given time reference, an input, cause, or stimulus, of matter, energy, or information, and an output, effect, or response, of information, energy or matter" (Dooge, 1973). A decision is a choice between a number of options (always including the "do nothing" option). Combining these definitions covers a vast range of objects and concepts under the term "decision support system", including calculators, spreadsheets (Savenije, 1995). However, the practice in the past has been to reserve the description for systems which help with some (i.e. more than one) aspects of making a decision. Purists might insist that the description be reserved for systems which help with all aspects of decision making, but that is not yet accepted usage of the phrase.

2 MULTIPLE CRITERIA METHODS

In the last step of the classical systems analysis paradigm shown above, all the information gathered in the previous 4 steps is used in forming a decision (design) or a recommendation. In practice, the considerable effort and resources expended on modelling the alternatives and predicting their performance and impacts (step 4) is not matched by the methods used in step 5 to make decisions. This weakness is becoming increasingly important as such decisions are questioned or challenged more frequently and in a wider range of fora. Rigorous and transparent methods are required and they exist. Some of the potentially useful techniques are described briefly below.

2.1 Multi-Attribute Utility Theory (MAUT)

Multi-Attribute Utility Theory (MAUT) (Keeney and Raiffa, 1976) is a methodology which, within the context of an engineering project, allows possible consequences to be 'traded off' against one another. The closely related ideas of value and utility have a long history and are used in a wide variety of decision-making contexts. Engineers and planners use them when considering the best options for large-scale projects; especially those related to infrastructural development. Economists use them when analysing the operation of enterprises, markets and economies and especially in the field of welfare economics. Psychologists and social scientists use them in the study of how people behave and the reasons for the choices they make. Many of the concepts, assumptions and methods used are very similar in all these applications although some of the technical terms may be different or have different meanings in each subject area. The goal is to improve understanding of peoples' preferences, both as individuals and in groups, and to develop tools to assist in making decisions which correspond to these preferences. It is assumed that such decisions are good ones and that they will be accepted by a large number of the people affected by them.

MAUT involves devising a function 'U' which will express the "utility" or level of satisfaction with a project alternative. This function is constructed from a knowledge of the impacts and of the decision makers attitudes to various levels of impact. The decision-makers preference from a range of project options will be based on which one maximises the value of the function U. Estimating the form of this function is fundamental to the problem solving mechanism in MAUT. While this technique is often argued to be more rigorous than the others, in practice it is limited to cases where there are a small number of impacts to be considered.

2.2 The Analytic Hierarchy Process

The Analytical Hierarchy Process (Saaty, 1980) is a multicriteria decision-aid methodology which allows qualitative data to be transformed into pairwise comparison data. It is essentially the formal expression of the decision maker's understanding of a complex problem using a hierarchical structure. Saaty (1980) describes the theme of the Analytic Hierarchy Process (AHP) as a combination of 'decomposition by hierarchies and synthesis by finding relations through informed judgement'. Its purpose, as with most other decision-aid methods, is to develop a theory and provide a methodology for modelling unstructured decision choice problems in economic, social and engineering sciences. It reduces a decision problem to a series of smaller self-contained analyses. The relative merit of each project option is determined from a pairwise analysis of the relative performance ratings for all combinations of project options, separately for each decision criterion involved. The relative importance of each criterion is also determined from a similar pairwise analysis of decision makers preferences. The result of the overall process is a ranking of all options on an interval scale, enabling the optimal one to be selected.

2.3 Concordance Analysis

Concordance Analysis is a non-compensatory, multi-criteria decision-making method. The term 'non-compensatory' implies that if some alternative 'a' is better than alternatives 'b' or 'c', there is no need to determine preferences between 'b' and 'c' **-** they remain uncompared without endangering the decision-aid procedure. Even if 'b' and 'c' are incomparable, the procedure remains valid. Individual criteria are not traded-off against on another.

The technique has already been applied to problems in transport investment choice, land-use planning and energy investment. In recent years, there have been applications of it in the area of environmental management. It is most useful when a large number of competing schemes need to be short-listed to a smaller number of 'preferred' ones, in order to facilitate further detailed consideration and evaluation. Using the technique to select a single 'best' alternative is less straightforward, due to it's susceptibility to changes in importance weightings of the criteria, and weaknesses in the levels of outranking of one alternative over another, both of which of which can lead to inconsistent conclusions regarding the single 'best' or rank order solution between competing alternatives.

A major advantage of some versions of the method, and one which leads to it being usable within an environmental assessment framework, is it's ability to cope with data expressed in a variety of measurement scales, both qualitative and quantitative.

Comparison between options proceeds on a pairwise basis with respect to each criterion, and establishes the degree of dominance that one option has over another. Mathematical functions indicate this degree of dominance, determining the extent to which project outcomes and preference weights confirm or contradict the pairwise dominance relationships between alternative projects.

The method examines both the degree to which

1. the preference weights are in agreement with pairwise dominance relationships, and
2. the degree to which weighted evaluations differ from each other

These stages are based on what are defined as a concordance and discordance set. This twofold approach has the advantage that the available information is used as intensively as possible.
The result of the process is the selection of an optimum option or group of preferred options.

3 NEED FOR DECISION SUPPORT SYSTEMS

The multicriteria decision support techniques described above can be implemented, by experienced practitioners in a "stand alone" manner to address any particular design problem. However, if they are to be used as part of interaction with a non-technical general public then their use and interpretation must be made simple. This is most conveniently done by embedding them in a decision support system.

3.1 Pressures

Historically, there were many different pressures which contributed to the impetus to develop DSS:

Quantity of data involved: In large scale analyses, particularly for catchment-wide problems, very large quantities of data were involved, including spatial data and numerous long time-series. Although the analytical tasks required may have been straightforward and simple, the amount of calculation involved could not be done easily by hand and automated procedures were required. Geographical Information Systems (GIS) grew from this need in relation to geo-referenced or spatial data. Specialised database systems were also developed to meet this types of need, e.g. the USACE HEC's Data Storage System and Watershed Data Management systems (Lumb et al., 1988).

Complexity: More detailed and more complex analyses were required and involved the integrated use of increasingly complex and detailed models. Various types of simulation models, e.g. hydrological catchment models, river and floodplain hydraulic models and linked ecological and water quality models grew from this need. Techniques involving stochastic methods, Monte Carlo type simulations and ensemble forecasting are computationally demanding.

Requirements of decision makers: The need to demonstrate convincingly to the decision makers the performance and properties of the solutions (both the proposed and alternatives) emerging from the technical analyses. Good computer generated graphics, especially animations, facilitate this task. This need made the integration of models with multi-media software and graphical User Interfaces (GUI) more important. Apple Computer's Hypercard was an early and pioneering example of this.

Stakeholders perception of transparency and fairness: To persuade stakeholders to support decisions, especially when involving compromise, requires the decision making process to be transparent and manifestedly fair. Logical procedures which can incorporate all relevant factors are required. Multi-criteria decision analysis (MCDA) techniques can be used here (Rogers et al., 1999).

Public participation: The need to involve the public, as stakeholders, in the decision making process requires two-way communication. First the demonstration of proposed solutions and alternatives and secondly, the incorporation of feedback into the decision making process. There are many ways of doing this, but the internet provides some exciting new prospects.

3.2 For whom are decision support systems designed ?

The early DSSs were mostly designed as technical tools to be operated by technical people. They addressed the technical difficulties in dealing with large quantities of data and of integrating complex models, the first two elements in the above list. Later, because of its graphical output capabilities, the DSS became valuable in explaining the proposed solution and its properties to political or commercial decision makers. In projects with large environmental impacts, the ability of the DSS to help with explaining the solutions to the public and (where implemented) in using public feedback to inform and refine the decisions became apparent.

4 BRIEF REVIEW OF DECISION SUPPORT SYSTEMS

4.1 Functional Types of DSS

Whatever definition of DSS is preferred, the systems which are called DSS in the literature can be divided into a number of categories on the basis of their capabilities, with an emphasis (but not exclusively) on those related to flood management.

Spatial Data analysis tools: These provided a way of inputting spatial data into a computer program which could manipulate, combine and analyse the data. Such capabilities are now usually built into most GIS packages in the form of a macro language, typically a version of Visual Basic. In such a language many of the combination and analysis tasks could be automated. DSSs for groundwater protection schemes are typical of this category. Used for example in delineating groundwater protection zones (Hammen & Gerla, 1994). ERAMS is a computer system which makes an initial assessment of the potential of land for rehabilitation and has been used in Algeria, China and Australia, (Squires, 1992). It uses satellite imagery, field surveys and soil tests and can be used with little training. Zandbergen (1998) describes a GIS-based DSS used for ecological risk assessment of urban watersheds.

Integrated model-base systems: These provided a spatial data environment integrated with a number of numerical models. As well as inputting and manipulating data, the integrated models allowed the user to perform numerical simulations for various alternative scenarios and to crudely compare the outputs. For instance, Wilson (2000) reports on a survey of the needs of water resources managers which highlights the rapidly expanding range of scientific disciplines involved in planning for water quality management. They lists the tools required and recommends a DSS structure to meet future needs. Gijsbers (1999) describes the DelftMSS a model integration and data management system for use in a DSS. Earlier DSS were planned with the technical expert as the intended user (Pingry et al., 1991). Haagsma (1995) develops formats for data storage and discusses an integrated modelling approach which allows distributed modelling, with individual models running in different locations communicating over a network. Flug (1993) looks at areas where some criteria may not be easily quantifiable. Srinivasan et al (1998) describe the HUMUS DSS system designed for very large basin planning, covering the entire continental USA. Todini & Bottarelli (1997) describe the ODESSEI system.

AQUATOOL (Andreu et al. , 1996) is a DSS designed for use in planning for complex river basins (Tagus and Segura), but has since been expanded to include operational decision support. It has a number of modules for simulation, (Sahuquillo, 1997), optimisation and risk assessment. A variety of different localised DSS systems have been developed to meet a variety of different situations and objectives, including:

Tomik (1991) in Florida, Frevert et al. (1997) for the Colerado River, Reitsmaet al.(1995) for operational decisions for the TVA. Leslie et al. (1996) and Miller et al.(1994) describe systems for hydropower optimum operation. The financial returns from improving hydropower operations was an incentive for developing DSSs. Lindquist (1996) describes a system for optimal combined reservoir and hydropower operation.

A recently completed European Union project, EUROTAS, addressed the issues of integrated catchment modelling for Flood Forecasting. It chose the open ArcView GIS \& database as the framework in which the data and models were integrated and much of the data input, storage and output was through ArcView. It can

(i) export/import data, spatial, time-series and others.
(ii) delineate catchments and edit resulting maps
(iii) detect (from topology), edit and map watercourses.
(iv) associate cross-section information with spatial location on appropriate river branches.

(v) analyse and combine point data, e.g. rain via Theissen polygons.
(vi) build land-use scenarios
(vii) build climate change scenarios
(viii) build river engineering scenarios
(ix) map floodplains and identify vulnerabilities.

They used a limited number of hydrodynamic models (MIKE11, ISIS and SOBEK) and catchment models (CLASSIC, DCN and HBV) The last 4 elements of the above list allowed the simulation of the effects of land-use and climate change on flood risk and of certain, engineering structural management options, which included

(i) lower or change hydraulic characteristics of floodplain
(ii) deepen or widen main channel
(iii) change relationship between channel and floodplain (including with embankments)
(iv) various storage, lateral discharges or operation of dams (including hydropower) and lateral weirs.

Options other than river engineering measures were not considered and the framework does not, at present, have a multi-criteria decision support module.

Other model-base developers adopted different approaches. For instance, WATERWARE, was written in an object oriented langauge, using the rapid prototyping approach, and was not based on any proprietary GIS format, (Fedra & Jamieson, 1996a, 1996b).

Multicriteria decision support tools: In addition to spatial data manipulation and model simulation capabilities, a true decision support system can help with the decision making by implementing one or more multi-criteria decision support methods for comparing alternative scenarios when there are many criteria to be considered. These may also consider such general factors as risk and uncertainty.

Shepherd (1997) describes some of the practical aspects of implementing interactive expert systems. Raman (1994) describe a knowledge based system for water supply management. Makowski (1996) describe a system, applied to the Nitra river, in which aspiration lead objectives can be modified as part of the MCDA process. Ramachandra et al (2000) describe a system which considers environmental and social cost and benefits for hydro electric schemes. Scoccimarro (1999) describe a system which includes social and ecological impacts in the development of upland catchments in Thailand.

Stakeholder Decision Support Systems: these are DSS systems which can be used by decision makers, technical experts and stakeholders to explore the consequences of combinations of preference schemes and alternative scenarios in the hope of achieving mutually acceptable compromises. These are often made available and used by stakeholders over the internet. Haemaelaeinen (2001) describe a framework for multicriteria modelling and support for a multi-stakeholder decision processes in relation to water level management in a regulated lake-river system in Finland. The stakeholders are involved in the decision process from formulating problem structuring stage to the group consensus seeking stage followed by a stage of seeking public acceptance for the policy. The framework aims at creating an evolutionary learning process. It also focuses on a new interactive method for finding and identifying Pareto-optimal alternatives. Role playing experiments with students are used to test the practical applicability of a negotiation support procedure called the method of improving directions. It describes the preference programming approach for the aggregation of the stakeholder opinions in the final evaluation of alternatives and consensus seeking. Bender & Simonovic (1996, 2000) describes positive results from a DSS which is specifically designed to facilitate interaction between stakeholders and decision makers in relation to hydroelectricity development projects. Simonovic (1999) describes a decision support system for flood management which is intended for use both by decision makers and stakeholders. It includes provision for emergency responses and public involvement as well as having flood prediction and monitoring capabilities. Jarman (1994) looks at the conflict resolution problem in relation to planning for disasters, with particular reference to water resources. Young (2000) describes a system developed for planning the sustainable development of the Murray-Darling basin. It is based on the RAISON DSS and allows user evaluation of development strategies.

5 THOUGHTS FOR THE FUTURE

5.1 Model-bases

With some notable exceptions, basic model components are comparatively cheap (in monetary terms) with many free. Model construction will not be a major future issue. And if the trend to write models as objects in an object oriented language continues then software issues relating to model integration will diminish in importance. Model libraries will be available on the internet. Such issues as appropriate modelling scale, adequacy of data and appropriate use of higher resolution data will remain.

5.2 Multi-criteria methods

As can be seen above, some effort has been made to include MCDA techniques in some DSS. Future DSS will have a major role in mediating compromise between stakeholders with competing objectives. The NAIADE (Novel Approach to Imprecise Assessment and Decision Environments) method (Munda, 1995) is a step in this direction. It is a discrete multi-criteria method which uses qualitative pairwise comparisons of alternatives. It analyses conflict by building a matrix which shows groupings of stakeholders on the basis of related interests.

5.3 Public Consultation and the internet

Sugumaran et al. (2000) describes a WWW based application which allows a wide variety of users to view a GIS based dataset relating to floods and floodplain mapping. There are suggestions that, when warned of an impending flood, the public look for confirmation from a second source before responding to the warning. This could be provided by a DSS via the internet. Davis (1991) describes a DSS designed to explore conflicts and policy options relating to nutrient management in catchments and its effect of water quality. It combines a module with allows a formal policy description with a catchment modelling module and a module for presenting the model results.

5.4 Public interaction and feedback

If public interaction is part of the role of a DSS it will be linked to the network and will be capable of responding to "what if" queries by either retrieving the required data from its memory or running the required simulation if necessary. The DSS will also be able to accept and record the opinions of public users and incorporate them into their MCDA analyses.

5.5 Updating and maintenance

The biggest long-term issue to be addressed for DSS users is how to ensure their databases are up to date. Such spatial characteristics as topology, soil type and geology are relatively static at the relevant time-scales, but land-use, including urbanisation, population, road and channel networks, precipitation, discharge and other data series do change at the relevant time scales. It seems to me that the only practical long term solution is to link the DSS (perhaps via the internet, but not necessarily so) with the primary organisation responsible for collecting and maintain the data. Thus links with ordnance survey, meteorological offices and environment agencies will be established, with automated updating procedures built-in.

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