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MULTIOBJECTIVE DECISION THEORY - DECISION SUPPORT SYSTEMS WITH EMBEDDED SIMULATION MODELS

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Abstract

The concepts of multiobjective decision making utilizing embedded computer simulation models and dimensionless scoring functions are described in the context of a decision support system (DSS). This methodology consists of procedures to help make practical decisions using simulation models when the decision makers are faced with multiple, often conflicting, objectives. An example application describes a decision support system for design or remediation of shallow land burial systems to control release of radioactive and hazardous chemicals into the environment. Applications under development include selection of best farming practices to minimize water pollution from nutrients and pesticides.

Introduction

Modern design of complex systems such as shallow land burial facilities for low-level radioactive waste involves a variety of considerations including the interactive nature of processes controlling performance of a proposed system (Nyhan and Lane, 1982; Hakonson, et al., 1982; Gershey, et al., 1990). Often, design changes to mitigate one possible mode of system failure can induce failure through another component or process. A simple example might be the interaction between erosion of trench covers (which could potentially expose the buried wastes) and percolation of infiltrated water through the trench cap and into the buried wastes. Erosion control measures which reduce runoff and erosion by increasing infiltration of precipitation into the trench cap could exacerbate percolation below the trench cap.

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Similarly, agricultural management practices designed to maximize crop yields may exacerbate transport of sediment and agricultural chemicals to receiving surface waters. Management practices, such as reduced tillage or no-till cultivation, may reduce erosion but accelerate movement of water and agricultural chemicals to groundwater (e.g. SCS, 1984; Leonard and Knisel, 1988).

In both of these examples, designing the best landfill system or selecting the best management practice (BMP) for an agricultural system, the decision maker is faced with a multiobjective decision problem. The multiple objectives typically consist of controlling or optimizing decision variables (measured data or simulation model predictions of variables) with different units and various levels of uncertainty.

Examples of decision variables from a farming operation are runoff volume in mm, percolation below the root zone in mm, soil loss from the field in t/ha, evapotranspiration in mm, crop yields in t/ha, nutrient or pesticide concentrations in mg/l, and profits and losses in dollars. The value, or utility, of the magnitude of the decision variables is determined from an individual's expert knowledge, from a knowledge base, or from an expert system utilizing more extensive knowledge and data bases.

With recent developments in simulation modeling (e.g., Knisel, 1980; Beasley, et al., 1980; Schroeder, et al., 1984; Williams and Renard, 1985; Williams, et al., 1984; and Leonard, et al., 1987) technology now exists to compute decision variables describing performance of landfills and cultivated fields.

Commensurate with these developments has been the development of expert systems in agriculture (Harmon, et al., 1988) and in design of shallow land burial systems (Ascough, 1989 and Lane, et al., 1990). Decision support systems (DSS) technology is growing and finding practical applications (e.g., see Andriole, 1989). The main purpose of a DSS is to support decision makers in solving problems that are poorly structured or defined, as is often the case in environmental problems. Multiobjective decision techniques that incorporate dimensionless scoring functions have been developed (e.g., see Wymore, 1988) to facilitate comparison of alternatives within a DSS.

In summarizing the proposed methodology, the concepts of multiobjective decision making utilizing embedded computer simulation models and dimensionless scoring functions are described in the context of a decision support system (DSS). This methodology consists of procedures to help make practical decisions using simulation models when the decision maker is faced with multiple, even conflicting, objectives.

An example application of the methodology is presented for the optimal design of a shallow land burial system for low level radioactive or other hazardous wastes. This example is used to suggest that the multiobjective decision methodology presented can be valuable in optimal system design and in selecting the best management practice (BMP) from among a suite of alternatives.

Overview of the Methodology

The proposed methodology consists of a number of steps from definition of the problem, to selection of the proper analysis techniques, to helping make a decision about a design or selecting the best from among several management alternatives. The general methodology can be described in the following sequence of steps.

1. Defining the Problem
    a. User Needs
    b. Selection of Conventional or Baseline Conditions
    c. Selection of Alternatives for Consideration
2. Determining the Decision Variables
3. Selecting the Simulation Model to Predict the Decision Variables
4. Selecting the Experts, Knowledge Base, & Data Bases
5. Selecting the Scoring Functions & Weighting Factors
    a. Expert Judgment
    b. Risk Analysis
    c. Applicable Regulations
6. Evaluating the Alternatives
7. Recommending a Decision

These steps are not specifically sequential and are not at all independent. The entire process from Step 1 to Step 6 will be interactive and more or less repetitive until a recommendation is made (Step 7).

Evaluation of Alternatives by Scoring Functions

Given the information on how to describe the conventional or baseline conditions, the alternative designs or management practices, and the decision variables to be included in the analyses, it is possible to evaluate the alternatives. First, some preliminary definitions and notation are described.

A scoring function is a way of relating the numerical value of a decision variable (i.e. runoff volume, sediment yield, leachate production, etc.) to a measure of its value or utility (Wymore, 1988). Notice that the decision variables will have different units so that a scoring function which converts values of decision variables in various noncommensurate units to a dimensionless quantity, or score, would allow comparison of decision variables on a common, 0 to 1, basis.

Define a scoring function for a decision variable X_i as

$$SC_i(X_i) = SC_i \tag{1}$$

where X_i is the value of the i'th decision variable in its original units (i.e. mm, t/ha, Kg/ha, etc.) and SC_i is its score in the range 0 to 1.0. Mathematically, this is expressed as $0.0 \leq SC_i \leq 1.0$.

As an operational definition, the score for each decision variable for the conventional management practice, or baseline condition, is set at 0.5. When the corresponding decision variable for the alternative under consideration is scored by Eq. 1, its value may be less than 0.5 indicating a degradation from the baseline condition, its value may be 0.5 indicating no change, or its value may be greater than 0.5 indicating an improvement over the baseline condition. Notice that the comparison is for a single decision variable. If the procedure is repeated for each of the decision variables, then a weighted sum of the individual scores can be used to objectively compare overall system performance of the conventional and the alternative design or management practice.

Mathematically, the overall score is thus

$$SC_c = \mathop{SUM}_{i=1}^{n} [W_i*0.5] / \mathop{SUM}_{i=1}^{n} [W_i] \tag{2}$$

for the conventional or baseline and

$$SC_a = \mathop{SUM}_{i=1}^{n} [W_i*SCa_i(Xa_i)] / \mathop{SUM}_{i=1}^{n} [W_i] \tag{3}$$

for the alternative under consideration. The subscript c refers to conventional and the subscript a refers to the alternative and W_i are the individual weights.

If the decision makers making the evaluations can agree on the decision variables to include in the analyses, on the exact form and shape of the scoring functions, and on the weights, then the proposed evaluation procedure (the multiobjective decision) is repeatable and thus scientifically defensible.

Example Application

Applications currently under development utilizing the methodology include the following system design problem. This example is in the developmental stage and is indicative, not exhaustive, of typical applications.

Design of a trench cap configuration for a low-level waste disposal site is a multiobjective design problem. In this example for a waste burial site at Los Alamos, NM, the conventional design employes about a meter of backfill over the buried wastes followed by 15 cm of topsoil vegetated with warm season grasses. The alternative under consideration includes a denser vegetative cover consisting of grasses and evergreen shrubs. Decision variables are average annual values of surface runoff, evapotranspiration (ET), average soil water content in the plant root zone, soil erosion, percolation below the trench cap into the buried wastes, and deep seepage below the waste material.

The CREAMS model (Knisel, 1980) was used to compute an annual water balance using 20 years of observed weather data for the conventional and alternative designs. The water balance was then used to estimate average annual values of the decision variables described above.

Values of the decision variables and their associated scores are shown in Table 1. Notice that some decision variables are best when maximized, some are best when minimized, and average soil water is best when kept in a range between wilting point and field capacity.

Table 1. Values of the decision variables and their scores for the conventional and alternative trench cover designs at Los Alamos, NM.

Decision Variable	Units	Conventional		Alternative	
		Value	Score	Value	Score
To be Maximized:					
Runoff	mm	18.7	0.50	14.0	0.114
ET	mm	435.3	0.50	449.0	0.656
To be Minimized:					
Percolation	mm	13.9	0.50	5.8	0.993
Erosion	t/ha	0.410	0.50	0.226	0.978
To be Held Between Wilting Point and Field Capacity:					
Ave. Soil Water	mm/mm	0.126	0.50	0.102	0.918

Individual scores and the overall unweighted score were larger for the alternative indicating an improved and feasible design if hydraulic barriers or leachate collection systems are employed to control the remaining deep seepage. Finally, the scores shown in Table 1 are all equally weighted. As discussed earlier, different weighting schemes would result in a different overall weighted score for the alternatives.

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