



MULTI-CRITERIA DECISION-MAKING IN FOREST MANAGEMENT PLANNING

— AN OVERVIEW

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ABSTRACT

Forest management planning comprises multiple products, goods, and services and is characterized by multiple conflicting interests. Thus, multi-criteria decision-making (MCDM) immediately suggests itself. However, reports on MCDM seem to be dispersed. It is attempted to provide a generally accepted metaphor, to increase the understanding of, to relate MCDM to traditional methods, and to suggest a ranking of the methods with respect to beneficial use within forest management planning. It is concluded that MCDM methods, with focus on duality values, comprise great prospects for application to multiple-use forestry, alleviating some of the shortcomings associated with the traditional "one-criterion" management paradigm.

Keywords: Forest management planning, multi-criteria decision-making.

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BACKGROUND

Multi-criteria decision-making (MCDM) achieves increasing recognition within the application of operations research in forest management planning (FMP). The production environment in forestry is often characterized by multiple products, goods, and services and is therefore subject to multiple interests, many of which are conflicting. This situation has led to the need for consideration of an increasing number of goals in FMP. It is therefore a prerequisite that elements of decision support systems applied in FMP are able to address many different goals simultaneously in the planning process. To conform with the demands of usual planning problems it immediately suggests itself to apply one of the methods belonging to MCDM.

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Reports on application of *MCDM* methods in *FMP* seem to be dispersed and do not provide a clear picture of potential advantageous *MCDM* methodology. They mainly represent examples of application of specific methods. In this way, a single publication may give the false impression of expressing the state-of-the-art. A general overview of *MCDM* is needed to be able to classify the increasing number of specific examples of application. *MCDM* covers such a great variety of methods, concepts, and approaches useful for *FMP* that a holistic presentation is held appropriate.

The aims of this paper are:

- to contribute to a generally accepted metaphor for *MCDM*,
- to contribute to better understanding of the characteristics of *MCDM*,
- to relate *MCDM* elements to more traditional *FMP* methods, and
- to suggest a ranking of the *MCDM* methods in relation to prospects for beneficial use within *FMP*.

INTRODUCTION

Khaynish & Vlasov (1983, p. 144) and Carlsson & Kochetkov (1983) view the major problems in management science as complex and ill-structured. Therefore, descriptive models and interactive systems are needed.

Starr & Zeleny (1977a, p. 13) distinguish between attributes and objectives, the latter being closely identifiable with the decision maker's values and needs: objectives are not the actual attributes but can be viewed as being functionally related to or derived from some of the attributes.

MCDM aims to give the decision maker some tools enabling him to advance in solving a decision problem where several — often contradictory — points of view must be taken into account. The advance towards a solution will arrive at a compromise action, and it must be emphasized that the decision depends strongly on the decision maker's *personality*, on the circumstances in which the decision-

aiding process takes place, on the way in which the problem is presented, and on the analytical method used (Vincke, 1992, p. 29).

Vincke (1992, p. xvi) views *MCDM* as still being at its very beginning and proposes the following three families of *MCDM* methods:

- (i) multiple attribute utility theory,
- (ii) outranking methods,
- (iii) interactive methods.

Multiple attribute utility theory usually makes use of an additive utility function of the analytical form

$$U(a) = \sum_{j=1}^n U_j(g_j(a)),$$

where U_j are strictly increasing real functions, g_j are criteria, and a is an alternative action. Thus, the evaluation of action a according to criterion j is written $g_j(a)$.

Outranking methods are founded on a general idea of evaluating the relation between two alternative actions, a and b . It is linked to the situation where the arguments suffice to determine the preference relation between the alternatives, e.g. a is at least as good as b , while there is no sound reason to refute that statement (Roy, 1974; Vincke, 1992, p. 58).

An interactive method consists of alternating computation steps and dialogue with the decision maker. The first computation step provides a first solution, which is presented to the decision maker who reacts by giving extra information about his preferences. Injecting the latter information into the model allows a new solution to be found (Vincke, 1992, p. 79). Interactive methods are classified according to: (i) a search-oriented conception, or (ii) a learning-oriented conception (Vincke, 1992, p. 103).

However, a general feature of interactive methods is the use of preference information, which leads to potentially improved compromise solutions (Vincke, 1992, pp. 79–105). Preference information usually comprises trade-off estima-

tions, i.e. dual values, or shadow prices. Thus, another general feature of interactive methods is the focus on dual information.

Choosing a multi-criteria aggregation method is in fact equivalent to choosing a type of "compensation" among the criteria. Up to now, this fundamental concept has not been thoroughly studied. Intuitively, the compensation aspect of a method is more or less the great possibility to counterbalance a disadvantage on one criterion by an advantage on another (Vincke, 1992, p. 111). It is clear that this area of research could yield very promising results. In support of this observation, Keen (1977, p. 53) and Starr and Zeleny (1977b) mention that *MCDM* requires a shift from objectives to constraints as the base for analysis. The characteristics of a two-person zero sum game is presented by Schlichtkrull (1993, p. 119), and the use of duality information from linear programming (*LP*), assuming a gain/loss matrix, is illustrated.

MacCrimmon (1973) delineates multiple-objective decision methods into:

- (i) weighting methods,
- (ii) sequential elimination methods,
- (iii) mathematical programming methods,
- (iv) spatial proximity methods.

Blin (1977, pp. 133–134) investigates the relationship(s) between fuzzy set theory and *MCDM* and finds that the problems raised by the multiplicity of evaluation criteria are intrinsically fuzzy set problems, and that many of the proposed solution procedures are simply methods to "defuzzify" the problem. We now must deal with a problem which is qualitatively different from simple maximization — as von Neumann and Morgenstern (e.g. 1953) have emphasized in the game context. It is noted that such a problem is a perfect illustration of the general theory of fuzzy sets (Blin, 1977, p. 130; Borglin, 1992; Borglin, 1993).

Yu (1977) identifies four elements in decision-making, viz.

- (i) the set of feasible solutions or decision alternatives,

- (ii) the set of criteria,
- (iii) the outcomes of each feasible solution, measured in terms of the criteria (by numbers or by ordering and ranking, or possibly descriptive measurements),
- (iv) the decision maker's preference concerning the outcomes, expressed in terms of the criteria.

The final decision should be selected from the set of non-dominated alternatives at the end of the decision-making process (Yu, 1977, pp. 168–169).

A negotiation problem may be regarded as a dynamic *n*-person game. However, there seems to be no result in game theory, in characteristic form, normal form, or extensive form, which can be used to obtain a satisfactory solution to a negotiation problem (Isaacs, 1965; Luce & Raiffa, 1967; Rapoport, 1970; Howard, 1971; Yu, 1977, p. 174).

The concept of convex sets has played an important role in optimization techniques, such as in mathematical programming, optimal control, and game theory. The relevance of and practical solutions to non-convex problems are identified by Swallow *et al.* (1990).

In decision problems, one is quite likely to face problems with multiple non-commensurable objectives. In this situation, it is logical that a good decision should not be dominated by other alternatives in the sense that there should not be other feasible alternatives which yield a greater satisfaction for the decision maker (Leitmann, 1976; Yu, 1976, pp. 11, 2).

Overview articles on *MCDM* have been presented by, e.g. Roy (1971); MacCrimmon (1973); Huber (1974). A comprehensive review of various goal programming (*GP*) methods and forestry applications has been made by Mendoza (1987).

A brief review of *MCDM* techniques with reference to forestry applications is given by Howard (1991). *MCDM* methods are well suited for poorly structured problems

prevailing in current forestry. A similar study, including a review of applications in forest management of pay-off matrices, compromise planning, the step method, and interactive multiple goal planning is presented by Krawiec *et al.* (1991). Each method is applied to a multi-purpose woodland.

The term "multi-criteria optimization" is used as a synonym for multiple objective mathematical programming. Multiple criteria optimization and multi-attribute decision analysis are from the field of *MCDM* (Steuer, 1986, p. 5).

Cohon *et al.* (1979) have proposed a multi-objective programming method called the non-inferior set estimation, which permits a quick and good approximation of the efficient set when the number of objectives under consideration is usually no more than two. The method is based on an iterative approach comprising the solution of a series of weighted *LP* programs.

It is noted that *LP* may be viewed as a multiple attribute decision method. The values of the variables represent a combination of the attributes, the linear constraints are conjunctive constraints on combinations of attributes, and there is a linear compensatory objective function. In contrast to the usual multiple attribute methods, there is not a small, explicit list of alternatives from which to choose, but rather an infinite set of alternatives implicitly defined by the constraints. The procedure thus involves a design problem rather than choice problem, since the purpose is to design a basis for selection of the optimal alternative by putting together the best combination of attribute values (i.e., values of the variables) (MacCrimmon, 1973, p. 33).

An overview of *MCDM* methods/approaches is given in Table 2 (see page 297), some of which are presented in detail in this paper.

A PHILOSOPHIC BASIS FOR *MCDM*

Researchers were at first only interested in finding efficient solutions, then, little by little, they turned to the interactive search for a compromise solution. This evolution clearly illustrates the transition from what was called *MCDM* to what is more and more often called multi-crite-

ria decision-aid.

Roy (1977, p. 179) defines decision-aid as the activity of a scientist who tries, by means of more or less formalized models, to help a decision maker improve his control (this word having its cybernetical connotation) of the decision-making process.

Modelling is closely linked to decision-aid. Four classes for the modelling may be considered, depending on feasibility/non-feasibility combined with mutually exclusive/non-exclusive actions (Roy, 1977, pp. 180f).

As noted by Angehrn (1991, p. 3), one of the main problems with the traditional approach to support human decision-making is the neglecting of the "human", or cognitive aspects. The traditional perspective tends to reduce the influence of human components such as subjectivity and creativity, and it approaches decision-making processes as if they were identical to technical problem-solving processes. Instead, a continually evolving, individual learning process is suggested as the framework for description of the decision-making process.

It is noted (Angehrn, 1991, p. 5) that "user first – technology second" support is seldom applied in multi-criteria decision support systems — these systems still remain strongly technology-driven. In such a set-up, "solving" techniques only play a secondary role. The primary support component consists of helping decision makers to progressively gain insights into the situation they are facing.

As a result, a multi-criteria decision support system should primarily have the characteristics of a flexible environment in which individual learning about a decision situation can take place. The development of individual strategies in exploring and generating decision alternatives through a concept of "modelling by example" is emphasized (Angehrn, 1991, pp. 5–6).

Visual interaction is mentioned as an important tool in a multi-criteria decision support system. E.g., visual interaction may be applied for representation/expression of a preference structure (Angehrn, 1991, p. 11).

The new approach suggested by Angehrn (1991, p. 14) could be characterized by

- (i) the high level of human-computer interaction,
- (ii) the explicit objective to help users understand and communicate better their decisions rather than to solve them.

Multi-criteria decision-aid and multi-criteria decision support systems may be regarded as a philosophic basis for development and use of more specific *MCDM*/operations research methods.

GOAL PROGRAMMING

MCDM is also termed multi-objective decision-making. The most commonly used *MCDM* method is *GP* (Romero & Rehman, 1989, p. 31).

Initially conceived as an application of single objective *LP* by Charnes *et al.* (1955) and Charnes & Cooper (1961), *GP* gained popularity in the 1960s and 1970s due to the works of Ijiri (1965), Lee (1972), and Ignizio (1976). *GP* is now an important tool for multiple criteria optimization (Hazell & Norton, 1986, pp. 71–72; Steuer 1986, p. 282).

An *MCDM* problem in the form of *GP* may be mathematically represented in the following way, e.g. Oestermarck (1986, pp. 5–23), Steuer (1986, pp. 285–292), and Romero & Rehman (1989, pp. 22–62):

$$\begin{aligned}
 & \text{Min} \sum_{k=1}^m (w_k^+ y_k^+ + w_k^- y_k^-) \\
 & \text{s.t. } \mathbf{c}_k \mathbf{x} - y_k^+ + y_k^- = g_k \quad \text{for } k = 1, 2, \dots, m. \\
 & \quad \mathbf{Ax} \leq \mathbf{b} \\
 & \quad w_k^+, w_k^-, y_k^+, y_k^-, \mathbf{x} \geq 0,
 \end{aligned}$$

where

w denotes the weights assumed for deviations, y , from goal components, “+” indicates positive deviations, “-”, negative deviations,

\mathbf{c}_k is the goal parameter row vector of objective k ,

\mathbf{x} is a decision variable column vector,

g_k is the target level of objective k ,

\mathbf{A} is a technology parameter matrix,

$\mathbf{Ax} \leq \mathbf{b}$ defines the feasible set of decision variables \mathbf{x} .

The use of deviational variables depends on the characteristic of the goal, whether it comprises a lower bound, an upper bound, or a goal where both positive and negative deviations are undesirable.

GP may be applied as lexicographic *GP*, so-called preemptive *GP*, or weighted *GP*. When lexicographic *GP* is applied, the fulfilment of the goals takes place in a specific priority (Steuer, 1986, p. 292; Romero & Rehman, 1989, p. 36). A sequential linear method for lexicographic *GP*, as shown by Romero & Rehman (1989, pp. 47–51), may be applied.

When weighted *GP* is applied, the deviational variables may be converted to percentage deviation measures. In this case all the goals are considered in a composite objective function, which minimizes the sum of all the deviations among the goals and their aspiration levels. The deviations are weighted according to the relative importance of each goal to the decision maker (Steuer, 1986, p. 286; Romero & Rehman, 1989, p. 51). Weighted *GP* is also called Archimedean *GP* (Oestermarck, 1986, p. 5). Knowledge of a corresponding optimal dual LP solution may be applied as weights in the objective function of a *GP*.

MULTIPLE OBJECTIVE LINEAR PROGRAMMING

Multiple objective linear programming (*MOLP*) is distinct from (single objective) *LP* by having more than one objective function. According to Steuer (1986, p. 138), *MOLP* could be mathematically illustrated as follows:

$$\begin{aligned} & \text{Max } \mathbf{c}^1 \mathbf{x} = z_1 \\ & \cdot \\ & \cdot \\ & \cdot \\ & \text{Max } \mathbf{c}^k \mathbf{x} = z_k \\ & \text{s.t.} \\ & \mathbf{Ax} \leq \mathbf{b} \\ & \mathbf{x} \geq 0, \end{aligned}$$

where

c^i ($i=1,2,\dots,k$) is a row vector of dimension n of the i -th objective function coefficients,

z_i ($i=1,2,\dots,k$) is the value of the i -th objective function associated to \mathbf{x} ,

\mathbf{x} is decision variables represented by a column vector of dimension n ,

\mathbf{b} is a column vector of dimension m ,

\mathbf{A} is a matrix of dimension $(m \times n)$,

$\mathbf{0}$ is a zero vector of dimension n .

It is assumed that the decision maker has a utility function, which is a function of the objectives.

The distinction between decision space (S) and criterion space (Z) is important for an understanding of the different *MOLP* approaches and is therefore illustrated in Figures 1 and 2. The definition of convexity is illustrated in Figure 2.

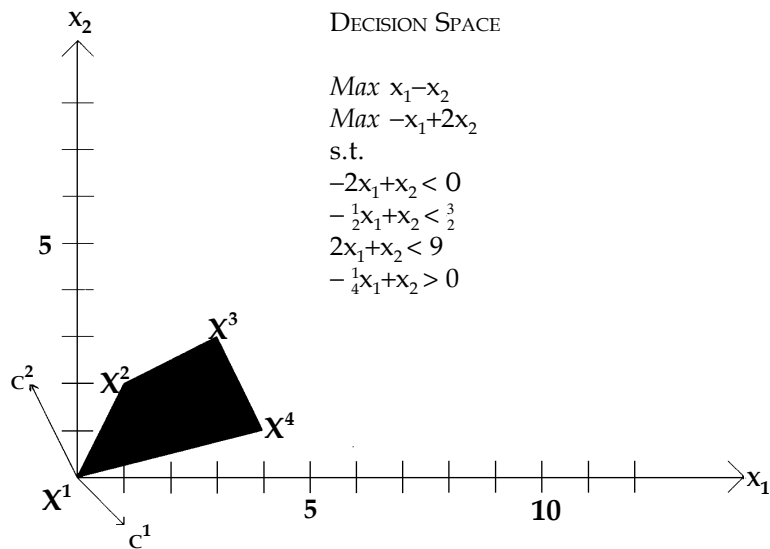


FIGURE 1. ILLUSTRATION OF DECISION SPACE

c^1 and c^2 are vectors of objective function coefficients for objective 1 and 2, respectively, X^1, \dots, X^4 are extreme points of feasibility. Source: Steuer (1986, p. 145).

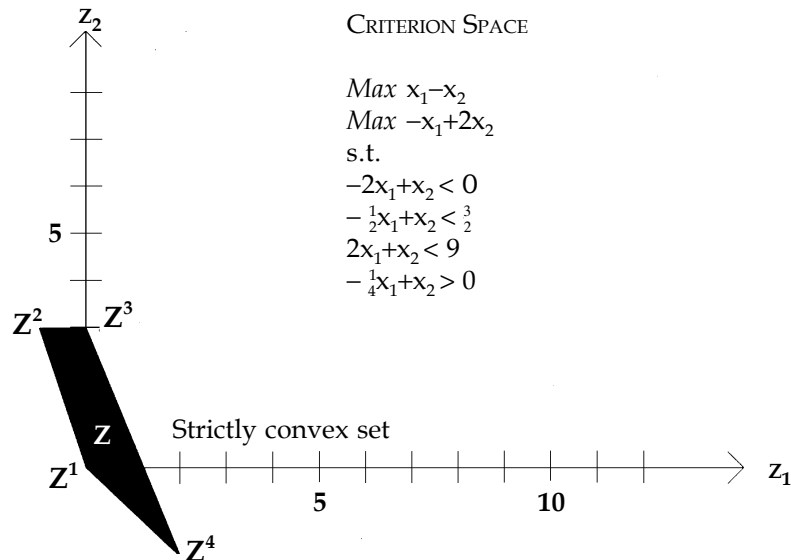


FIGURE 2. ILLUSTRATION OF CRITERION SPACE

Z^1, \dots, Z^4 are extreme points of criteria values. Source: Steuer (1986, p. 145).

A number of different *MOLP* procedures have been reported, of which *GP* is best known. The weighted-sum technique and vector-maximum algorithms are regarded as members of the more frequently applied *MOLP* approaches (Steuer, 1986, pp. 193–281, 419–483).

By use of the weighted-sum technique, the problem is transformed into a single objective problem with a composite criterion (Steuer, 1977, p. 226). One of the ways to avoid the inherent difficulties of the “static” weighted-sum model is to utilize an interactive approach as shown by, e.g. Benayoun & Tergny (1970), Benayoun *et al.* (1971), Dyer (1972), Geoffrion *et al.* (1972), Belensen & Kapur (1973), Zionts & Wallenius (1976), and Steuer (1977, p. 227). A numerical example of a three-objective *MOLP* problem is illustrated by Steuer (1977, pp. 236–239). The approach is based on the use of the so-called interval criterion weights.

The weighted-sum technique is linked to the formulation of a composite objective function that can be solved by application of conventional *LP* software. The method is

based on estimation and application of normalized weights to the objective functions. The set of possible weights is:

$$\Lambda = \left\{ \lambda \in R^k \mid \lambda_i \geq 0, \sum_{i=1}^k \lambda_i = 1 \right\}$$

Usually, the λ_i s are determined in form of the so-called interval criterion weights. Filtering (related to subsets of a larger finite set) and set discretization (related to characterization of a continuous set by selecting a finite number of points from it) may be applied for determination of the decision maker's extreme point of greatest utility (Steuer, 1986, pp. 311–335).

Then, by doing one's best to estimate a $\lambda \in \Lambda$, it is hoped that the composite (or weighted-sum) LP

$$\text{Max} \{ \lambda^T Cx \mid x \in S \}$$

where $C = (c^1, c^2, \dots, c^k)$, $S = \{x \mid Ax \leq b, x \geq 0\}$, and $\lambda^T Cx$ is the composite criterion function, will produce a solution that is optimal, or is close enough to the optimal (Steuer, 1986, p. 165).

The weighted-sum technique may be applied for finding an initial efficient extreme point in a vector maximum routine (Steuer, 1986, pp. 220–226). A number of different sub-problem tests for non-basic variable efficiency are described by Steuer (1986, pp. 233–244) in order to examine non-dominated efficient extreme points.

Some of the difficulties with use of *MOLP* techniques are:

- (i) the efficient set can be convex,
- (ii) the optimal point can occur at a non-extreme point,
- (iii) local optima may exist, because the decision maker's utility function is not concave (Steuer, 1986, p. 155).

The decision-oriented relevance of duality in *MOLP*, where the information gathered from the dual is employed in the course of an interactive decision process, is demonstrated by Isermann (1977). The so-called trade-off vectors of duality values are applied.

The linkage between *LP* and *MOLP* via objective row parametric programming is described by Steuer (1986, pp. 120–133). Such programming (in single objective *LP*) is essentially *MOLP*, with two objectives.

Multiple criteria function *GP* with within-priority-level Archimedean weights may be solved as an *MOLP*. Each priority level is treated as an objective function and the endeavour is to search the space of trade-offs among the priority levels to find the best solution, all goals considered (Steuer, 1986, p. 300). An illustration of the solution of an *MOLP* using an automated package ADBASE and the optimization program MINOS is given by Steuer (1986, pp. 460–472), where a non-linear utility function was used.

Modelling of Markov decision processes by use of *MOLP* is demonstrated by Viswanathan *et al.* (1977).

Salminen (1992, p. 13) describes Zionts' discrete method which uses sets of multipliers for the criteria. The search for non-dominated solutions involves the formulation of additional constraints in an *LP*, until a test of the preference for alternatives compared to the currently best one is negative.

THE ANALYTIC HIERARCHY PROCESS

Generally, it is assumed that the decision maker chooses the alternative which most probably maximizes his utility, determined on the basis of his information available on the decision alternatives. The decision alternatives can be arranged in relation to ordinal utility, i.e. only one ranking is possible, or based on a ratio scale called cardinal utility (Camacho, 1980; Jarrow, 1987; von Winterfeldt & Edwards, 1988; Kangas, 1992a, p. 174).

Determination of weights of multiple criteria may be prepared by use of the eigenvalue technique in the analytic hierarchy process developed by Saaty (1977) and applied by Kangas (1992a) and Kangas and Pukkala (1992). A detailed description of the methodology is given in Kangas (1992b) with respect to multiple-use *FMP*. The resulting ratios of priorities can be interpreted as the marginal rates of substitution (Kangas, 1992a, p. 187). A graph of the decision hierarchy of this example is shown in Figure 3.

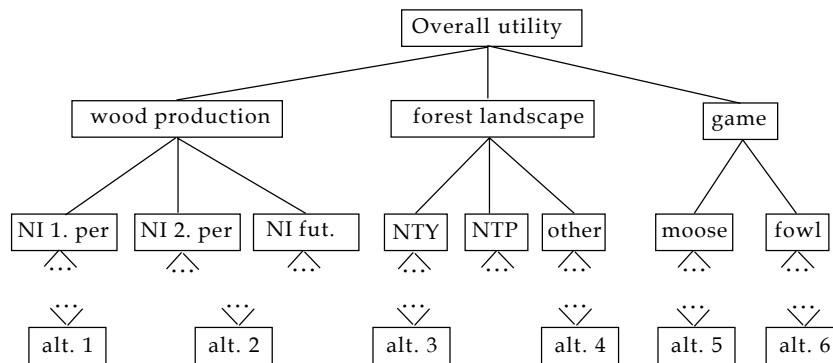


FIGURE 3. DECISION HIERARCHY OF MULTIPLE-USE FORESTRY PROBLEM

NI = Net income
 per = Period
 fut = Future after 2nd period
 NTY = Near to yard
 NTP = Near to path
 alt = Alternative

Source: Kangas (1992b, p. 264).

Using the analytic hierarchy process, a consistency ratio may be estimated as shown by, e.g. Kangas (1992b). Determination of the consistency ratio requires determination of the maximum eigenvalue of the matrix containing the pair-wise weight estimates. The computation of eigenvalues is illustrated by, e.g. Harsaae (1977, pp. 109–117). The task is not simple for non-mathematicians when the problem is solved manually. The problem may be solved by finding λ as a solution to the following equation (Yu, 1985, pp. 133–142; Kangas, 1992b, p. 262):

$$(A - \lambda I)q = 0,$$

where

A is the matrix (of pair-wise compared criterion estimates) that contains inconsistencies,

λ is the largest eigenvalue of matrix **A**,

q is the right eigenvector of the matrix **A**,

I is the identity matrix.

However, more user-friendly approximation methods are presented by Saaty (1990, pp. 17–21).

The right eigenvector \mathbf{q} constitutes the estimation of relative weights. If the matrix does not include any inconsistencies, i.e. the judgements made by a decision maker have been consistent, \mathbf{q} is an exact estimate of the priority vector.

Determination of eigenvalues of larger matrices, e.g. a (10×10) matrix, is possible with use of standard mathematical software such as MATHEMATICA (Schlichtkrull, 1994). As a rule of thumb, a consistency ratio of 10 per cent or less is considered to be acceptable (Kangas, 1992b, p. 262).

The analytic hierarchy process is viewed as an alternative to the traditional *MOLP* where different objectives are expressed with different physical and economic units. In the analytic hierarchy process, the weights for different objectives represent utility measures.

The analytic hierarchy process can deal with qualitative attributes as well as quantitative ones, e.g. it is possible to explicitly consider the attitude towards risk (Kangas, 1992a, pp. 186–187).

The maximum number of decision elements to be pairwise compared for estimating one preference function has been recommended as ten (Saaty, 1980; Kangas, 1993, p. 283). In practice a maximum number of five objectives is appraised to be worth considering (Salminen, 1992, p. 12; Kangas, 1993, p. 283).

The evaluation using the analytic hierarchy process comprises determination of relative weights of criteria on each level in the decision hierarchy. The sum of the weights pertaining to a specific criterion on the next higher level is 1. The global weights of the next-lowest decision attributes are determined as the product of the local priority estimated at this level and the corresponding local priorities estimated at higher levels. At the lowest level of the decision hierarchy, the decision alternatives are evaluated comparing them separately with regard to each decision attribute. The global priority of a given decision alternative is computed as shown by Kangas (1992b, p. 266):

$$\sum_{j=1}^n gw(a_j)lp(a_j)$$

where

$gw(a_j)$ is the global weight of decision attribute a_j ,

$lp(a_j)$ is the local priority of the alternative with respect to attribute a_j ,

n is the number of decision attributes.

The alternative with the highest global priority comprises the optimal solution. An illustrative example is given by Saaty (1990, pp. 17–28). Four methods for estimation of the priority function are presented with an indication of the quality of the results.

Application of the analytic hierarchy process in conflict resolution is presented by Saaty & Alexander (1989). The outcome to receive the highest weight indicates an optimum that may be the most desirable result.

The analytic hierarchy process can be applied for analyzing benefit-cost estimates and resource allocation, as shown by Saaty (1982, pp. 194–223). Separate hierarchies are constructed for benefits and for costs to determine a benefit-cost ratio.

Conclusively, the analytic hierarchy process is useful for MCDM, but the method is appraised to be computationally and mathematically demanding. GP may be viewed as more constructive, because common LP software furnishes considerable computational advantages with respect to incorporation of a great number of numerical information that may support the evaluation of decision alternatives. However, an analytic hierarchy process software package called EXPERT CHOICE has been developed and increasingly applied to real-life problems (Vincke, 1992, p. 55).

DUAL DECOMPOSITION AND MULTI-CRITERIA DECISION-MAKING

In a dual context, multi-level multiple-criteria decomposition schemes are presented by Bogetoft & Tind (1990). They model how the headquarter of a large organization may

communicate with a division in an attempt to balance optimally the organization's wishes (as set by the head-quarter) against its possibilities (as delineated by the division). The decomposition of the overall decision problem into a sequence of subproblems allows the decision maker to clarify successively his wishes and to learn about his possibilities. A resource-directive procedure and a price-directive procedure are analyzed. It is noted that optimality is reached if a signal (e.g. a price response to a resource use constraint) is repeated. Upper and lower bounds on the optimal value are determined in each iterative step.

Despite its undeniable aesthetic appeal, the performance of the decomposition algorithm in practice has not been encouraging. It seems that it can be justified for problems that are too large to be solved directly, but can rarely compete with state-of-the-art general *LP* codes otherwise (Orchard-Hays, 1973; Ho & Loute, 1983; Garcia, 1990).

APPLICATIONS TO FORESTRY

The number of alternatives considered in forestry may, for practical reasons, be viewed as indefinite and the decision-making is usually multiobjective (Buongiorno & Gilles, 1987; Kangas, 1992a). Based on an evaluation of development of an appropriate information system in forestry the effects are (Tomanic & Novak, 1989, pp. 1–9; Pritchard, 1989):

- (i) less administrative and routine work,
- (ii) saving on space and equipment,
- (iii) elimination of conventional documentation,
- (iv) less data redundancy,
- (v) lower stock costs,
- (vi) shorter time and increased quality of data and information processing.

A fuzzy approach using *LP* is presented by Bare & Mendoza (1992). The objective function and selected constraints are viewed as soft, and satisfactory solutions were derived and discussed for several scenarios. The approach overcomes some of the potential problems related to

unfeasible harvest schedules, over-optimistic objective function values, and the need to strictly satisfy all constraints included in deterministic model formulations.

An elegant example of application of duality values for estimation of supply functions for products, goods, and services and demand functions for production factors is provided by Paredes & Brodie (1988).

A multiple objective programming framework focused on the generation of distinct solutions is presented by Mendoza (1988). The model integrates timber and wildlife management. Compared to traditional optimization methods, the wider range of alternatives considered enables the decision maker to appraise a wider variety of alternatives. Modelling to generate alternatives is presented and illustrated with a multiple-use planning example by Mendoza *et al.* (1987).

The integration of spatial optimization of wildlife in timber production forests is modelled by Hof & Joyce (1993) with use of mixed integer programming. Other functions related to landscape characteristics, hiking trails, camping grounds, and rivers are also included. The paper is viewed as a confirmation of MCDM being possible with application of a very wide range of operations research methods within FMP — some of which may not immediately be conceived as MCDM methods. An integer programming model for spatial and temporal optimization of wildlife populations in relation to forest management is shown by Hof *et al.* (1994). Weintraub *et al.* (1994) use fractional LP solutions rounded-off to integer values in a heuristic procedure for integration of adjacency constraints related to, e.g. wildlife and scenic beauty.

The importance of clarifying objectives as a means to constructing new, superior alternatives in decision analysis pertaining to old-growth forest conflicts is highlighted by McDaniels (1992).

With reference to sustainability of the tropical forestry sector as a whole, Gane (1992) suggests that computer modelling may help in the preparation of a development strategy in each country. A complex step-by-step approach is advocated. However, MCDM may be seen as a means to

address multiple objectives and then reduce the number of steps required to reach a decision.

A four criteria annual cut location model for preparation of felling schedules in mixed coniferous/beech stands is evaluated by Dragoi *et al.* (1988) and Dragoi & Blaj (1989). The criteria are related to the volume of advance growth, regeneration potential, accessibility, and length of felling period, showing how technical data may be applied as a representation of management objectives. An example of multiobjective modelling for timber production including consideration of regular employment is given by Bernetti (1990). The flexibility of GP models is emphasized.

Min-max GP and interactive multiple GP give more balanced solutions than weighted GP — the latter may produce extreme results between options. The step method seems to be particularly suitable for solving forest management problems which have a medium to large number of objectives among which only some, e.g. achieving targets or trade-offs, must be kept under “close control” (Krawiec *et al.*, 1992).

Pampanini (1990) emphasizes the importance of dual values used in an opportunity cost approach by consideration of willingness-to-pay factors related to the value of public functions of forestry. Criteria used to estimate the economic value of non-productive forestry functions such as tourism, recreation, hydrology, geology, landscape, and environment of wooded land are reviewed. Willingness-to-pay factors are recommended in economic analyses of environmental resources because the value of the above functions is likely to be far greater than that of the productive functions. A similar study of hedonic travel costs is reported by Hanley & Ruffell (1993). The emphasis on non-productive forestry functions calls for application of MCDM methods.

Pfister (1991) shows the importance of integration of multiple disciplines in FMP, exemplified by the effect of afforestation on development of land prices. A parallel observation is reported by Garrod & Willis (1993). These papers are seen as an argument for a holistic approach with inclusion of many factors exogenous to forestry. The inclusion of these additional elements in FMP may be accomplished by application of MCDM approaches.

A decision support system consisting of two forest level *LP* models and a geographical information system is presented by Davis & Martell (1993). The *LP* models account for strategic and tactical forest level silvicultural planning problems, respectively, and are linked together and to the geographical information system.

A few forestry-specific multi-criteria decision-aid references are given by Vincke (1992, pp. 123–125), such as Bertier & Montgolfier (1974) and Hallefjord *et al.* (1986).

With focus on agroforestry, Muetzelfeldt & Sinclair (1993, pp. 1139f) conclude that the effectiveness of modelling could be increased by the development of a modelling environment that enables interactive construction and modification of models by researchers.

The application of multi-resource forest management involves prior simulation, subsequent monitoring of the systemic response to management activities, and evaluation in biophysical and social terms. Short-term marginal adjustments, maintenance of options, and rational use of investment capital are required and lead to a product mix of substances that may change, but with a sustained flow of value. The importance of interaction in the planning process is emphasized and the characteristic of short-term marginal adjustments may be viewed as an advocacy for planning perceived as a continuous process (Behan, 1990, p. 16).

The application of a system dynamics model for analysis of land use development is presented by Klein (1989). The aim of the mathematical model is to perceive, acknowledge, and appreciate the dynamic interactions between people, the agricultural production system, and tree management, using system dynamics as an investigative tool. The report is seen as an example of *MCDM* methodology acting as an element of decision support with emphasis on a learning-oriented conception.

Application of a combination of multiobjective dynamic programming and MOLP for multiple-use forest resource management is presented by Gong (1992). All non-dominated solutions are given for each beginning state. The trade-offs between timber production and non-timber serv-

ices are clearly presented. However, the number of constraints and decision variables in the *MOLP* are equal to the number of states and the number of possible actions, respectively. Large-scale problems may need a capacity higher than that of the available software.

A cardinal *MCDM* model with incorporation of the ending forest structure, annual volume increment at the end of the planning period, scenic beauty, and net income by period is presented by Pukkala & Kangas (1993) and compared with a heuristic optimization method.

An analytic hierarchy process model with consideration of biodiversity is presented by Kangas (1993), and an example of estimation of priority weights of strategies with respect to the suitability of wildlife habitats is presented by Kangas *et al.* (1993a). A suggestion for estimation of forest landowner's landscape preferences is presented by Kangas *et al.* (1993b).

A list of some of the various studies in different method categories is provided in Table 1.

MORALITY AS A VALUE CRITERION

Because morality is so elusive a concept, a careful researcher may be inclined to exclude it from his considerations, arguing that it is largely a matter of personal or cultural style. A researcher is seen on the side of law and order if these best serve societal goals. The use of discounting opposed to the use of e.g. insurance values for estimation of real values may be viewed as having a moral content (Churchman, 1973, pp. 3–8; Cochrane & Zeleny, 1973). A definition of morality introduces very obscure problems for the decision theorist: In its negative mood form, the definition says that it is immoral to treat people like machines; in its positive mood form, it says that joyous morality consists of loving each individual for herself. The more phlegmatic capturing of these two moods says that people should not be categorized, classified, evaluated along scales. It attacks as immoral our cultural desire to reward and punish by comparisons and scales. The incorporation of human feeling — which is the essence of human values — in formalized model-building may be seen as a great challenge within *MCDM*.

TABLE 1. MCDM APPLICATIONS TO FORESTRY

LP	Weintraub <i>et al.</i> (1994) Davis & Martell (1993) Bare & Mendoza (1992) Paredes & Brodie (1988)
Mixed Integer Programming	Hof <i>et al.</i> (1994) Hof & Joyce (1993)
Dynamic Programming	Gong (1992)
Modelling to Generate Alternatives	Mendoza (1988) Mendoza <i>et al.</i> (1987)
GP	Krawiec <i>et al.</i> (1992) Bernetti (1990) Mendoza (1987)
MOLP	Gong (1992)
The Analytic Hierarchy Process	Pukkala & Kangas (1993) Kangas (1993) Kangas <i>et al.</i> (1993a) Kangas <i>et al.</i> (1993b) Kangas (1992a) Kangas (1992b) Kangas & Pukkala (1992)
Overview	Howard (1991) Krawiec <i>et al.</i> (1991)

Perhaps the best option for environmentalists as well as the most sensible option for society, given uncertainty, is to (1) impose a constant environmental capital stock constraint on investment decisions across the public sector; and (2) adopt a maximin strategy to protect choice when there is uncertainty about assimilative capacity, substitution possibilities, and damage costs. The moral issues related to discounting are reviewed by Hanley & Spash (1993, pp. 127–151).

Churchman (1973, p. 8) recommends to listen and read with appreciation, discuss without demanding for precise definitions, let your phlegmatic critical mind take a rest —

like in drama and the novel — meaning you allow your moods to exercise. Within the scope of *MCDM*, these recommendations should not be insurmountable. Morality may be incorporated as a value criterion by a so-called soft model application approach where the analyst observes requirements for additional constraints directed by moral values and the need to view some of the existing constraints as uncertain. Thus, a requirement of sensitivity analysis in relation to moral values is highlighted.

CONCLUSION

The prospects of *MCDM* in forest management planning are strongly dependent on the information system. However, *MCDM* methods could be viewed as a potential element of the information system and in this way contribute to an improvement of the quality of management decisions.

Choosing a multi-criteria aggregation method is in fact equivalent to choosing a type of compensation between the criteria. Up to now, this fundamental concept has not been studied thoroughly, although it is a quite important tool if the aim is to advance toward axiomatics and a classification of multi-criteria methods.

Intuitively, the compensation aspect of a method is the more or less great possibility to counterbalance a disadvantage on one criterion by an advantage on another (Vincke, 1992, p. 111).

These statements are taken as clear and strong arguments for the emphasis that ought to be placed on duality in optimization in *FMP*. Some practical procedures using duality values are demonstrated by Benson (1977). With this clear and precise priority it will be possible to advance constructively on applied methodology within this area of research, and it may eventually produce strong support and improvements to operationally applied planning methods and models. The development process should appropriately begin with focus on optimization methods such as *LP*. Then, a methodological skeleton could be built, which could serve as the offspring for more exploratory methods within the field of *MCDM*.

An overview of operations research and *MCDM* methods in decision support systems is presented in Table 2 with

emphasis on application options and advantages.

By order of decreasing priority, a classification of *MCDM* methods for successful application in *FMP* is suggested below, with addition of some basic characteristics:

- 1) Dual *LP* comprises an alternative to all other *MCDM* approaches and may be applied to obtain explicit dual financial estimates.
- 2) *GP* may be applied by use of indirect dual financial estimates.
- 3) Modelling to generate alternatives may become more flexible than dual *LP*.
- 4) Dynamic programming requires programming ability. Lagrange multipliers may be estimated.
- 5) Multiple attribute utility theory has wide generality and may be combined with environmental impact assessment.
- 6) The analytic hierarchy process is strongly utility oriented.
- 7) Mixed integer programming is computationally demanding.
- 8) *MOLP* does not assure optimality and is mathematically demanding.

Systems analysis, simulation, network analysis, and a geographical information system may act as support elements in decision support systems based on the methods above.

None of these methods should be excluded from further research, but due to the present state-of-the-art in forest management planning the above priority is assumed to be appropriate.

It seems evident that *MCDM* methods offer a wide array of different techniques that have great prospects for beneficial application to the problems inherent in multiple-use forestry. The focus on duality values and opportunity costs seems to be a theme general to all *MCDM* methods, placing dual *LP* and *GP* foremost among this group. It may be appropriate to extend the traditional grouping of

TABLE 2. OPERATIONS RESEARCH AND MCDM METHODS IN DECISION SUPPORT SYSTEMS

METHOD	TYPICAL APPLICATION	ADVANTAGE
<i>Traditional</i>		
LP	Stand and forest level	Dual information
Mixed integer programming	Spatial analysis/adjacency	Easy formulation
Dynamic programming	Stand level	Age independent
Simulation	Growth models	Non-linearity allowed
Systems analysis	Enterprise/sector	Non-economic entities allowed
Network analysis	Harvest scheduling	Graphical representation
Stochastic optimization	Price analysis	Market relevance
GIS and alike	Spatial analysis	Reveals goal conflicts
<i>Exploratory</i>		
Decomposition	Centre and units	Solves large problems
Game theory	Optimization	Decision oriented
Chaos theory	Systems analysis	Feed-back considered
Optimal control and alike	Dynamic optimization	Non-linearity allowed
<i>Explicit MCDM</i>		
GP	Production/management	Transparent
MOLP	Optimization	Interactive
MGA*	Multiple-use	Wide span of decision space
MADA*	Public policy	Subjectivity allowed
MAUT*	Utility modelling	Handles qualitative information
AHP*	Utility modelling	Consistency measures
Outranking	Strategy formulation	Subjectivity allowed
Interactive and alike	Sensitivity analysis	Continuous planning possible

* Acronyms not explained in the text:

AHP the Analytic Hierarchy Process
 GIS Geographical Information System
 MADA Multi-Attribute Decision Analysis
 MAUT Multiple Attribute Utility Theory
 MGA Modelling to Generate Alternatives

MCDM methods with more basic operations research methods, dependent on the manner in which they are used in decision-making. It is concluded that the application of MCDM methods makes it possible to work in a holistic context, including a consideration of moral values, and by this alleviating some of the shortcomings associated with the "one-criterion" management paradigm.

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