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Multi-Criteria Decision Models for Forestry and Natural Resources Management: An Annotated Bibliography

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Abstract

Foresters and natural resource managers must balance conflicting objectives when developing land-management plans. Conflicts may encompass economic, environmental, social, cultural, technical, and aesthetic objectives. Selecting the best combination of management uses from numerous objectives is difficult and challenging. Multi-Criteria Decision Models (MCDM) provide a systematic means for comparing tradeoffs and selecting alternatives that best satisfy the decisionmaker's objectives. First developed during World War II by the U.S. military for strategic decisionmaking, MCDM have since been applied to such diverse fields as energy and financial planning, manufacturing, real estate investment, reservoir control, solid waste management, and water distribution. In recent years, the use of MCDM in forestry and natural resources management has generated a substantial body of literature. This annotated bibliography includes 124 important references ranging from theoretical studies to real-world applications of MCDM.

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Introduction

Foresters and natural resource managers must balance conflicting objectives when developing land-management plans. Conflicts may encompass economic, environmental, social, cultural, technical and aesthetic objectives.[1] Selecting the best combination of management uses from numerous objectives is difficult and challenging. Fortunately, Multi-Criteria Decision Models (MCDM) provide a systematic means for comparing tradeoffs and selecting alternatives that best satisfy the decisionmaker's objectives.

First developed during World War II by the U.S. military for strategic decisionmaking, MCDM have since been applied to such diverse fields as energy and financial planning, manufacturing, real estate investment, reservoir control, solid waste management and water distribution. In recent years, the use of MCDM in forestry and natural resources management has generated a substantial body of literature. This annotated bibliography includes 124 important references ranging from theoretical studies to real-world applications of MCDM.

Overview of MCDM in Forestry

MCDM refers to quantitative techniques used to facilitate decisions that encompass competing management objectives. Because they comprise numerous analytical methods, MCDM often are classified for convenience as Multi-Objective Decision Models (MODM) or Multi-Attribute Decision Models (MADM). MODM support the design of a range of separate decision alternative[1] techniques such as linear, goal, and integer programming. MADM support the "best" decision from among several alternatives using the Analytic Hierarchy Process and Multi-Attribute Utility Theory.

Forestry applications of MODM are concerned primarily with mathematical optimization techniques. The literature on the use of MODM for forest management can be divided into four developmental phases. Early studies, or Phase I, of MODM use in forestry explored "modeling to generate alternatives." Those who supported this approach believed that mathematical programming could be used to construct a range of possible decision solutions. These alternatives would be presented to decisionmakers, who would then select the alternative that best met the established criteria. Research on generating alternatives was especially popular during the 1980's, a period that coincided with the introduction of the linear programming model FORPLAN by the USDA Forest Service. FORPLAN was designed to meet the long-term requirements of the National Forest Management Act of 1976.

Phase II began in the early 1990's and focused on the connection between strategic and tactical forest management planning. Tactical- or stand-level planning requires significantly more detail and data than strategic forest-level planning. Analysts found that FORPLAN could not accommodate both stand- and forest-level plans because it generated excessively large models. As a result, stand-level planning was left to individual national forest districts to develop. A related branch of research attempted to find effective ways to bridge tactical and strategic planning.

Phase III was characterized by efforts to incorporate spatial constraints into MODM. These studies, which accounted for the major portion of MODM research during the 1990's, resulted from FORPLAN's earlier ineffectiveness with respect to spatial concerns, particularly those relating to wildlife habitat. This research addressed the need for more complex spatial considerations, for example, requirements for the regrowth of vegetation prior to subsequent reharvesting, i.e., "green-up constraint," edge effects, and habitat fragmentation.

[1]De Montis, Andrea; De Toro, Pasquale; Droste-Franke, Bert; Ines, Omann; Stagl, Sigrid. 2000. Criteria for quality assessment of MCDA—methods. In: 3rd biennial conference of the European Society for Ecological Research; 2000 May 3-6; Vienna, Austria. Vienna, Austria: International Institute for Ecological Economics. [http://www.kfunigraz.ac.at]

The fourth and current phase of research concerns heuristic methods, that is, techniques for problem solving through experimentation and trial and error. Interest in heuristics was developed after analysts realized that spatial programming formulations for real-world management situations were difficult if not impossible to apply with conventional linear programming algorithms, i.e., they typically required enormous computing capability. Supporters of heuristic methods contend that they can solve large, complex problems efficiently while approximating optimal solutions.

Proponents generally believe that MODM have been useful for natural resource planning and management. Their research has focused on ways to modify MODM to improve realism and efficiency. Unfortunately, these researchers failed to consider the response to these models. Indeed, a major failure of FORPLAN was its lack of acceptance by public interest groups (and perhaps by many Forest Service employees). To many of these groups, models such as FORPLAN were difficult to comprehend and were associated with an enigmatic "black box" approach to planning.

MADM constitute a newer and perhaps more acceptable method for quantifying and evaluating public preferences. These models already have been used extensively in military, corporate, and medical applications. However, few studies have applied MADM to forestry or other natural resource situations. The Analytical Hierarchy Process within MADM is receiving special attention for natural resource applications. It is not known whether such techniques can improve public involvement, collaboration, and acceptance of land management plans—or the planning process itself. To capture the benefits of both MADM and MODM, some researchers have tried to combine them. Another recent trend has been to combine MADM and/or MODM methods with Decision-Support Systems.

Despite many years of effort, there is still much to do. Only about half of the citations in this bibliography refer to empirical tests of the utility or feasibility of the MODM approach. Further, in most of the studies, researchers used hypothetical data or, at best, simplified decision situations; relatively few applied MODM to actual working forests. In fact, few studies were designed to implement a MCDM-generated management strategy.

The section on MODM applications in forestry that follows is divided into nine subsections. These are followed by sections on MADM applications in forestry and land planning, applications of combined MODM/MADM models, applications of MCDM to water resources, fisheries, and other environmental entities, and to decision-support systems. The bibliography includes an author index and a glossary.

MODM Applications in Forestry

General

1. Bare, B. Bruce; Briggs, David G.; Roise, Joseph P.; Schreuder, Gerard F. 1984. **A survey of systems analysis models in forestry and the forest products industries.** European Journal of Operational Research. 18(1): 1-18.

A comprehensive survey of the range of problems related to forestry and the forest products industry that have been addressed using decision models such as linear, dynamic, goal, mixed-integer, and nonlinear programming. Applications are divided into forest management (timber production), forest products, product yield, and process applications. Linear programming models have been used to facilitate nursery operations and seedling allocation for individual forest; optimize the cutting of trees to maximize product output and match that output with demand; integrate forest management, transportation layout, and product allocation for private wood-products companies; allocate fire control or harvesting equipment; and minimize the loss of material in paper-trimming processes. Citations for more than 70 systems analysis and forestry references are included.

2. Bell, Enoch F. 1977. **Mathematical programming in forestry.** Journal of Forestry. 75(6): 317-319.

Describes linear programming (LP) that is illustrated using straightforward terminology. Each of the assumptions required by LP are reviewed, and limitations that result from these assumptions are discussed. The author suggests that LP often is used in situations where the assumptions of the model are not met

3. Buongiorno, J. 2001. **Quantifying the implications of transformation from even to uneven-aged forest stands.** Forest Ecology and Management. 151: 121-132.

Discusses the role of optimization and simulation to achieve multiple economic and ecological objectives in choosing a target stand, and in converting an initial stand to this target.

4. Buongiorno, J.; Gilless, J. K. 2003. **Decision methods for forest resource management.** San Diego, CA: Academic Press. 439 p.

Introduces multi-criteria decision models for forestry and natural resource management, including linear programming models with economic and environmental objectives in even-aged forests. Also discusses the economic and environmental management of uneven-aged forests, introducing a MAXMIN criterion of diversity, multiple-objective management with goal programming, and simulation models of even or uneven-aged forests, to include ecological and economic criteria. Reviews the use of Markov models to address uncertainty in managing for landscape diversity, biodiversity, and financial returns.

5. Garcia, Oscar. 1990. **Linear programming and related approaches in forest planning.** New Zealand Journal of Forestry Science. 20(3): 307-331.

Single-use forest planning (managing for timber) entails decisions regarding what management treatments and which spatial and temporal patterns of harvesting will best achieve output objectives. Presents several alternative formulations for the forest planning model, which is divided into the forestry model and the utilization model. The first is related to the physical impacts of various management treatments and the response of the forest to these actions. Three methods for formulating this model are discussed: a state space approach and the traditional Model I and Model II classifications.

6. Nieuwenhuis, Maarten. 1989. **Operations research in forestry.** Irish Forestry. 46(1): 51-58.

Discusses the general characteristics of the six most commonly used formulations in forest applications. These include linear, integer, goal, and dynamic programming, network analysis, and simulation. The major uses of each method are included, as are references for each method in forestry/forest-industry applications.

Linear Programming

7. Boscolo, M.; Buongiorno, J. 1997. **Managing a tropical rainforest for timber, carbon storage and tree diversity.** Commonwealth Forestry Review. 76(4): 246-254.

Discusses the use of linear programming and MAXMIN methods to analyze tradeoffs among various objectives in managing a rain forest for timber, carbon storage, and tree diversity.

8. Buongiorno, J.; Dahir, S.; Lu, H. C.; Lin. C. R. 1994. **Tree size diversity and economic returns in uneven-aged forest stands.** Forest Science. 40(1): 83-103.

Discussions of linear and nonlinear programming models illustrate tradeoffs related to diversity of stand structure (tree size), and economic returns in managing northern hardwoods.

9. Ingram, D.; Buongiorno, J. 1996. **Income and diversity tradeoffs from management of mixed lowland dipterocarps in Malaysia.** Journal of Tropical Forest Science. 9(2): 242-270.

Linear programming with MAXMIN criteria was applied to determine the short- and long-term effects of current management regimes on economic returns and diversity of tree species and size. Criteria included the Shannon-Wiener index of diversity, minimum number of trees by species and size, soil rent, forest value, internal rate of return, and annual yield. Regimes were compared in the steady state (long term) and during convergence (short term) of stands with different initial conditions.

10. Jamnick, Mark S. 1990. **A comparison of FORMAN and linear programming approaches to timber harvest scheduling.** Canadian Journal of Forest Research. 20: 1351-1360.

Timber harvest scheduling in the United States is accomplished primarily with linear programming (LP) or binary search. In Canada, simulation often is used to create harvest schedules. Harvest schedules produced using a Model I LP approach were compared with those generated by simulation (the FORMAN model). The models were applied to two hypothetical forests, each about 130,000 ha in size, over sixteen 5-year planning periods. The only harvesting activity allowed was softwood clearcutting and harvest could be followed by natural regeneration or one of three replanting options.

11. Johnson, K. Norman; Tedder, Philip L. 1983. **Linear programming vs. binary search in period harvest level calculation.** Forest Science. 29(3): 569-581.

Compares two general categories of procedures that can be used to determine periodic harvest levels: binary search and linear programming, highlighting the advantages of each approach. The search for a method to combine the best features of each procedure is discussed.

12. Lu, H. C.; Buongiorno, J. 1993. **Long- and short-term effects of alternative cutting regimes and economic returns and ecological diversity in mixed-species forests.** Forest Ecology and Management. 58: 173-192.

Six cutting regimes were compared by linear programming with respect to soil rent and ecological diversity obtained in the short and long term in uneven-aged northern hardwood forests.

13. Omi, Philip N.; Murphy, James L.; Wensel, Lee C. 1981. **A linear programming model for wildland fuel management planning.** Forest Science. 27(1): 81-94.

Linear programming (LP) was applied to optimize the timestream of fuel management investments in forest watersheds in southern California. Historical approaches for evaluating fire management planning are outlined, limitations of these approaches are discussed, and the importance of minimizing costs through optimization is stressed. An LP formulation also is presented that maximizes reduction in a "wildfire damage-potential" index. LP provided general guidelines for fuel management planning but was inappropriate for tactical-level, site-specific evaluations.

14. Roise, Joseph; Chung, Joosang; Lancia, Richard; Lennartz, Mike. 1990. **Red cockaded woodpecker habitat and timber management: production possibilities.** Southern Journal of Applied Forestry. 14(1): 6-12.

Examines alternative management strategies using multiple-objective linear programming to mitigate the negative effects of financial timber rotations on red-cockaded woodpeckers. The financial consequences of providing cavity trees and protected areas also are examined.

15. Rowse, John; Center, Calum J. 1998. **Forest harvesting to optimize timber production and water runoff.** Socio-Economic Planning Sciences. 32(4): 277-293.

Linear programming (LP) was used to assess the optimal size and shape of harvest blocks to maximize net present value from timber production and watershed runoff. Model parameters, decision variables, objective function, and constraints are detailed. The application of LP to a section of the Canadian Crow-Bow Forest over twenty-five 10-year planning periods is discussed. Eight different scenarios are described.

Goal Programming

16. Buongiorno, J.; Peyron, J. L.; Houllier, F.; Bruciamacchie, M. 1995. **Growth and management of mixed-species, uneven-aged forests in the French Jura: implications for economic returns and tree diversity.** Forest Science. 41(3): 397-429.

Linear and goal programming were used to find management regimes to achieve various objectives of diversity and economic efficiency. Criteria were Shannon's index of tree diversity by species and size, minimum number of trees by species-size class, basal area, present value of harvests, and rate of return on capital.

17. Chang, S. J.; Buongiorno, J. 1981. **A programming model for multiple use forestry.** Journal of Environmental Management. 13: 45-58.

Goal programming and input-output analysis for multiple-use planning on public forests were combined to specify goal levels, allow experimentation with management intensity and management priorities, and determine tradeoffs between management activities.

18. de Steiguer, J. E. 2000. **Applying EXCEL Solver to a watershed management goal-programming problem.** In: Ffolliott, Peter F.; Baker, Malchus B., Jr.; Edminster, Carleton B.; Dillon, Madelyn C.; Mora, Karen L.; tech-coords. Land stewardship in the 21st century: the contributions of watershed management; 2000 March 13-16; Tucson, AZ. Proc. RMRS-P-13. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 325-329.

Demonstrates the application of EXCEL® spreadsheet linear programming (LP) solver to a watershed management multiple-use goal programming (GP) problem. Data used to demonstrate the application are from a watershed study in northern Colorado. One of the desirable features of LP/GP problems formulated on spreadsheets is the highly visible display of the problem, which seems to invite inquiry and experimentation. Also, with the spreadsheet method, problems can be structured and solved in different ways.

19. Hotvedt, James E. 1982. **Application of linear goal programming to forest harvest scheduling.** Southern Journal of Agricultural Economics. 15(1): 103-108.

An early application of goal programming (GP) to timber harvest scheduling on an 84,000-acre management area in the Southeast. The model was designed to minimize deviations from desired total harvest volume, discounted and undiscounted cash flows, and discounted cost. Target levels for each of the four goals were determined by solving four linear programming models to determine the optimum level of achievement for each goal. The model developed a schedule that within 50 years would convert an "irregular forest structure" into a highly regulated one. In addition, managers were made aware of possible tradeoffs with respect to harvest volume and financial goals.

20. Julio, Berbel; Zamora, Ricardo. 1995. **An application of MOP and GP to wildlife management (deer).** Journal of Environmental Management. 44: 29-38.

In forest modeling, wildlife decisions often are disconnected from management criteria and considered indirectly as constraints on a financial objective function. An alternative approach, that makes wildlife concerns the primary goal of a management model is a linear formulation that includes both economic and ecological goals as objective functions. The model was applied to hunting reserve management in Spain, specifically, to maximize the value of roe deer hunting while ensuring the sustainability of the population. Because these two goals are incompatible, a multiobjective generating technique was used to identify the non-inferior solutions and determine the tradeoffs for each alternative. To demonstrate the usefulness of this approach, the problem was reformulated as a lexicographic goal program (GP) and solved. Using the GP method rather than maximizing the number of roe deer in each period stabilized the number of deer across all periods and improved the political acceptability of the solution.

21. Nhantumbo, I.; Dent, J. B.; Kowero, G. 2001. **Goal programming: application in the management of the miombo woodland in Mozambique.** European Journal of Operational Research. 133: 310-322.

Goal programming (GP) was applied to a regional land planning problem in Mozambique in which public participation was a significant component. The goals modeled included protection of natural parks and reserves, timber harvesting, tourism, firewood collection, anddemand for animal, plant, and nonwood forest outputs. The model also included constraints on land area, labor, and capital and constraints relating to the diversity and adequacy of local diets. Both lexicographic GP and weighted GP are discussed and the rationale for using the weighted approach is presented. The lexicographic GP model was run using four different sets of goal weights. The model was an effective and appropriate alternative.

22. van Kooten, G. C. 1995. **Modeling public forest land use tradeoffs on Vancouver Island.** Journal of Forest Economics. 1(2): 191-217.

Discusses the use of goal programming to determine whether and to what extent the level of outputs, i.e. benefits to residents of Vancouver Island, can be improved over the currently proposed forest management plan. The model formulation and four scenarios for which the model was run are discussed.

The plan proposed for the area will result in a loss to society of approximately $440 million per year over the scenarios that were evaluated in this study.

Interactive Mathematical Programming

23. Steuer, Ralph E.; Schuler, Albert T. 1978. **An interactive multiple-objective linear programming approach to a problem in forest management.** Operations Research. 26(2): 254-269.

A linear programming (LP) and vector maximization model was applied to unit-level management plan preparation at the Swan Creek subunit of the Mark Twain National Forest. Five management objectives were identified and rank-ordered. Desired attainment goals were determined for each. There were three constraint types related to acreage, budget, and sustained yield. Goal programming achieved limited success due to a lack of clarity between decisionmakers' criteria preference weights and "tradeoff weights in the region of optimality." A fuzzy LP approach with interval weights also was rejected. The procedure that was chosen is a modification of the interactive LP model. This model is more flexible and easier to use than previous models.

24. Tecle, Aregai; Duckstein, Lucien; Korhonen, Pekka. 1994. **Interactive, multiobjective programming for forest resources management.** Applied Mathematics and Computation. 63: 75-93.

An interactive and a fuzzy approach to forest management was applied to the 1.65 million-acre Beaver Creek watershed in Arizona. Five potential treatments and a "no action" alternative were considered. A standard linear programming formulation was used for five of the six objective functions and one constraint; fuzzy set theory was used to address the remaining functions and constraints. PARETO RACE software was used to facilitate a "free search" procedure that does not require assumptions about the decisionmaker's utility function. The sensitivity of the gross economic benefit achieved from each alternative to changes in the fuzzy variable values also was assessed. The model was easier to use than more structured methods and allowed for imprecise data. The authors note that this type of approach can not guarantee "convergence toward a 'satisfaction'."

Dynamic Programming

25. Anderson, David J.; Bare, B. Bruce. 1994. **A dynamic programming algorithm for optimization of uneven-aged forest stands.** Canadian Journal of Forest Research. 24: 1758-1765.

Dynamic programming (DP) was used for uneven-aged stand management despite demanding computational requirements. The method presented is formulated as a forward recursion, discrete, two-state DP. State variables were trees and basal area per acre. The "neighborhood storage concept" was used to reduce the number of possible states that must be considered at each stage. There were four harvest parameters that differed in the harvesting method applied and the width of neighborhood classes. Detailed results are examined with respect to solution times and objective function values, i.e., present net value. The objective function of one run exceeded a previous "best solution" generation.

26. Lin, C. R.; Buongiorno, J. 1998. **Tree diversity, landscape diversity, and economics of maple-birch forests: implications ofMarkovian models.** Management Science. 44(10): 1351-1366.

Markov decision-process models solved by dynamic programming were used to choose managements with multiple objectives. Criteria included landscape diversity (variety of stands in the forest), diversity of tree species and tree size, annual income, and present value.

27. Puumalainen, Janna. 1998. **Optimal cross-cutting and sensitivity analysis for various log dimension constraints by using dynamic programming approach.** Scandinavian Journal of Forest Research. 13: 74-82.

A forward recursive dynamic programming (DP) model was applied to tree bucking. DP can accommodate both nonlinear and linear relationships and computation is better with DP than with linear programming. The model was applied to the bucking of 3,282 stems of Scots pine in three sawtimber grades and a pulpwood class. Four sets of constraints for minimum diameter and log length were used for each quality category. The DP model was useful for bucking optimization and the solution time was satisfactory.

Modeling to Generate Alternatives

28. Allen, Julia C. 1986. **Multiobjective regional forest planning using the noninferior set estimation (NISE) method in Tanzania and the United States.** Forest Science. 32(2): 517-533.

The noninferior set estimation method (NISE) was used to generate several feasible and nondominated solutions to a multiobjective forest planning problem that was formulated as a linear programming model with two objectives: minimize wood production and transportation costs. Constraints included area, tree growth, and wood volume. In Tanzania, NISE generated

14 feasible solutions using three sets of model assumptions. Because NISE does not rely on a prior elicitation of decisionmaker preferences, it is effective for real-world situations. Potential problems include a tendency for this technique to be computationally demanding and represent less than the full range of possible solutions.

29. Bare, B. Bruce; Mendoza, Guillermo. 1988. **Multiple objective forest land management planning: an illustration.** European Journal of Operational Research. 343: 44-55.

An alternative generating technique known as the step method (STEM) is examined, and the rationale for generating multiple feasible solutions versus a single optimal solution is discussed. Applied to a mixed fir forest in western Washington, the model generated alternatives that represent levels of achievement for seven objective functions, including maximization of harvest volume and populations of "indicator species" and minimization of populations of pest species. Outputs of the generated alternatives are compared using payoff tables; the range of difference between each solution is discussed. STEM is a powerful tool for forest planning in situations in which the complexity of the system prevents the capture of effective elements by optimization techniques.

30. Boscolo, M.; Buongiorno, J. 1997. **Simulating options for carbon sequestration through improved management of lowland tropical rainforest.** Environmental and Development Economics. 2: 241-243.

Simulates a tropical forest stand in Malaysia in its role as a source of income and as a carbon store, and quantifies the potential for and cost effectiveness of carbon sequestration by modifying current management practices.

31. Buongiorno, J.; Kolbe, A. 2000. **Economic and ecological effects of diameter-limit and BDq management regimes: simulation results for northern hardwoods.** Silva Fennica. 34(3): 223-235.

Long-term financial and ecological effects of diameter-limit and basal-area-diameter-q-ratios (BDq) in mixed northern hardwood stands in the Lake States were compared by using simulation.

32. Mendoza, Guillermo A.; Bare, B. Bruce; Campbell, Gene E. 1987. **Multiobjective programming for generating alternatives: a multiple-use planning example.** Forest Science. 33(2): 458-468.

Presents modeling-to-generate-alternatives (MGA) approach to decisionmaking in forest planning. The general structure of this approach, known as a Hop, Skip, and Jump algorithm, was applied to multiple-use planning. Five objective functions, including maximization of timber volume and forage production and consideration of water production and recreation opportunities were considered. The technique generated four solutions related to output in a payoff matrix. Unlike optimization methods, MGA techniques are effective in situations in which one or more objective is omitted from the analysis or where the model is formulated incorrectly.

33. Schulte, B.; Buongiorno, J. 1998. **Effects of uneven-aged silviculture on the stand structure, species composition, and economic returns of loblolly pine stands.** Forest Ecology and Management. 111: 83-101.

The consequences of management regimes for economic and ecological criteria were predicted with the Southpro simulation program for mixed hardwoods and loblolly pine stands in the Southern United States.

34. Volin, V. C.; Buongiorno, J. 1996. **Effects of alternative management regimes on forest stand structure, species composition, and income: a model for the Italian Dolomites.** Forest Ecology and Management. 87:107-125.

Simulation methods were used to compare the effects of extracting mortality only, applying Susmel's guides, diameter-limit cuts, saving beech, and continuing current harvest. Ecological criteria included forest cover and stand composition; economics were judged by net present value.

35. Willis, C. E.; Perlack, R. D. 1980. **A comparison of generating techniques and goal programming for public investment, multiple objective decision making.** American Journal of Agricultural Economics. February: 66-74.

Compares goal programming (GP) and two generating techniques—the weighting and constraint methods—in terms of computational expense, explicit quantification of tradeoffs, quantity of information generated, and validity of the interaction between decisionmaker and analyst. GP was more efficient computationally but generating techniques provided explicit tradeoffs between objectives as well as much more information to the decisionmaker than GP. Also, unlike GP, generating techniques determine feasible relationships but leave the evaluation process to the decisionmaker.

Hierarchical Planning

36. Cea, Christian; Jofre, Alejandro. 2000. **Linking strategic and tactical forestry planning decisions.** Annals of Operations Research. 95: 131-158.

A multilevel model is proposed that links strategic-level investment decisions with tactical-level planning in private forestry companies. The first step is the development of a general integer programming (IP) model that specifies the strategic planning problem. The objective function entails the maximization of present net value subject to constraints regarding harvest volume, harvest area, and timber demand. Once this model has been solved, results for the macro-stands are used to set goals for individual stands in the tactical-level problem, also formulated as an IP problem. The tactical model is decomposed into two submodels for road-building and transportation decisions. The road-decision model is solved using simulated annealing and the transportation problem is solved using LP, a secondary algorithm is used to improve the solution.

37. Church, Richard L.; Murray, Alan; Barber, Klaus. 2000. **Forest planning at the tactical level.** Annals of Operations Research. 95: 3-18.

Examines the decomposition of optimal strategic-level solutions to optimal tactical-level plans on forests. This is known as hierarchical planning. Three linear programming (LP) models are presented. The first, the coordinated allocation of choice model, is an LP formulation that combines the use of a strata-based noncontiguous planning structure and a zone-based contiguous planning structure. It maximizes the present value of choices determined both on a zone basis and on the basis of individual decisions made within analysis areas (strata). Also discussed are two Bridging Analysis Models. In the first model, strategic-level goals are allocated proportionately to tactical planning units subject to implementation constraints. The goal is to maintain the acreages of each prescribed treatment as close as possible to the strategic levels. The second model allocates tactical outputs based on strategic output goals in two ways. The min-area formulation minimizes the number of constraints that are binding in the tactical solution, while the equiv-risk model attempts to maximize the distance from the most constraining conditions for each analysis area to preserve flexibility in future planning.

38. Nelson, John; Brodie, J. Douglas; Sessions, John. 1991. **Integrating short-term, area-based logging plans with long-term harvest schedules.** Forest Science. 37(1): 101-122.

A three-stage model is proposed to link short-and long-term harvest planning in the development of optimal harvest schedules on a 4,000-ha, 62-unit forest with timber as the sole output. In the first stage, a linear programming (LP) model is used to maximize the present net worth of all harvesting decisions across the forest. The solution provides volume and revenue targets for the second stage, the use of integer programming (IP) to determine harvest scheduling and transportation at the stand level; the model is solved using the Monte Carlo heuristic procedure. After 200 feasible solutions were generated, 5 were selected, each with a different objective for value, timber volume, and net revenue. These five alternatives were used to generate 15-decade LP formulations that were entered into FORPLAN as a coordinated-choice allocation. By combining the strategic solution from a strata-based LP and the spatial distributions created using an area-based IP, one can create timber harvest plans that are spatially feasible over the short term and acceptable over the long term.

39. Weintraub, Andres; Cholaky, Alejandro. 1991. **A hierarchical approach to forest planning.** Forest Science. 37(2): 439-460.

Comprehensive forest planning has historically been accomplished through the use of “monolithic,” single-stage, linear or mixed integer programming models. Hierarchical planning is proposed that addresses the inability of traditional approaches to link strategic, operational, and tactical-level plans. In this study, the explicit linkage of strategic and tactical models is illustrated. Neither adjacency constraints nor explicit representation of roading variables are included. The land-use allocation, per-period level of timber production, constraint targets, and road-building budget derived from the model are used as direct inputs into the tactical model. Although the tactical model can be solved only with heuristic techniques, it is adequate for forest planning in complex situations.

Improving Spatial Capabilities

40. Church, Richard L.; Murray, Alan T.; Weintraub, Andres. 1998. **Locational issues in forest management.** Location Science. 6: 137-153.

Describes the most common “locational” forest issues. For each situation, a basic mathematical programming model is formulated, illustrating the typical objective function and constraint structure. Issues discussed include forest planning to maximize present net value, timber-harvest scheduling, transportation planning, and designating reserves to preserve biodiversity. The most common solution methods are discussed for each situation, as are alternative means of formulation and solution.

41. de Kluyver, C. A.; Daellenbach, H. G.; Whyte, G. D. 1980. **A two-stag, multiple objective mathematical programming approach to optimal thinning and harvesting.** Forest Science. 26(4): 674-686.

Dynamic programming (DP) and linear programming (LP) are applied to create timber-harvesting plans for large forests. A DP approach selects from all potential stand-management activities policies that are the most efficient for each type of forest stand. This reduced set of policies is then used in an LP model to schedule timber harvest across an entire forest. The decision variables represent collections of activities applied across the entire planning horizon rather than individual activities for each period. The use of both management "policies" and DP to limit the set of activities considered significantly reduces model size.

42. Epstein, R.; Nieto, E.; Weintraub, A.; Chevalier, P.; Gabarro, J. 1999. **A system for the design of short term harvesting strategy.** European Journal of Operational Research. 119: 427-439.

Applies linear programming (LP) to short-term harvest decisions by private forest companies, including what bucking patterns to use, how much volume to cut on a weekly basis, types of machinery to use, and where to harvest, that are influenced by changing product demand and the quality of previous harvests. An LP formulation is presented for maximizing present net value subject to volume, machine capacity, transportation capacity, and demand constraints. Dual variables associated with the bucking constraints are used to generate new bucking patterns to optimize product output. A flexible branch and bound algorithm is used to determine the best pattern. Both the structure of the algorithm and the rules that can be applied to control the selection process are described and selection approaches are compared with respect to product output derived from the resulting patterns. This approach has been used by Chilean companies to improve operations and realize significant savings.

43. Guignard, Monique; Ryu, Choonho; Spielberg, Kurt. 1998. **Model tightening for integrated timber harvest and transportation planning.** European Journal of Operational Research. 111: 448-460.

A method is proposed to improve solution capabilities of a mixed-integer programming (IP)model for integrating transportation and timber planning. IP models such as the IntegratedResource Planning Model cannot be solved easily or quickly because of the size of most forestmanagement problems and many 0-1 variables required. Suggestions are included for improvingsolution time through the use of trigger constraints, constraint lifting, and the prioritization of branching for double-contraction variables. Four model structures, each using a different combination of the three improvement techniques, were tested on three small data sets. For the second data set, the original IP formulation was solved to optimality only after 7 days had elapsed. Lifting the trigger constraints did not significantly reduce computation time but the addition of double-contraction priorities resulted in a solution time of several minutes. Using all three improvements together resulted in computation times of less than 15 minutes for all test cases.

44. Haight, Robert G.; Travis, Laurel E. 1997. **Wildlife conservation planning using stochastic optimization and importance sampling.** Forest Science. 43(1): 129-139.

Wildlife populations are particularly difficult to model with standard linear or integer programming approaches. A stochastic programming model is described that minimizes the cost of habitat protection subject to constraints related to species viability. The first half of the paper focuses on describing the formulation of the problem and details the search algorithm used to solve this model. To evaluate the approach, it is applied to a hypothetical problem related to the management of gray wolf. Simulation models are used to generate the survival probabilities for the wolf under different management plans. The model is run numerous times with different population targets to determine the tradeoff between cost and risk. The sensitivity of the model to changes in population growth and dispersal functions is assessed. In addition to its ability to incorporate uncertainty into the optimization process, this approach offers a high degree of flexibility in the types of wildlife functions that can be utilized. Although computation difficulty limits the size of problem that can be addressed, this model is a noted improvement over traditional deterministic approaches.

45. Hof, John; Bevers, Michael. 2000. **Direct spatial optimization in natural resource management: four linear programming examples.** Annals of Operations Research. 95: 67-81.

Discusses how to optimize wildlife populations based on their spatial dynamics. Four species-specific and site-specific linear programming (LP) models that incorporate wildlife issues intonatural resource planning are described. The objective function and all necessary constraints are outlined along with model assumptions and limitations. The first model attemptsto maximize the population of a species that is being raised in captivity and then released into thewild; the second maximizes a colonial species population given particular population movement(dispersal) tendencies; the third minimizes pest populations, given particular dispersingbehavior and specific management activities focused on reducing the population; the fourthis applied to the survival of a species given strict spatial constraints on habitat.

46. Hof, John; Linda Joyce. 1993. **A mixed integer linear programming approach for spatially optimizing wildlife and timber in managed forest ecosystems.** Forest Science. 39(4): 816-834.

A mixed-integer linear model is presented that addresses the potential for a nonconvex decisionspace that could prevent the identification of global optima; and the inability of nonlinearmodels to solve real-world problems or take into account the random nature of factors such ashabitat fragmentation. A grid-based approach is used that divides forest area into square subunits of equal size. The objective function includes the weighted sum of timber output andpopulations of both edge-dependent and area-dependent species. A nonlinear edge-effect model is presented and reformulated as a mixed-integer linear model; the same modification is used for habitat-fragmentation effects. Both of these model components and a linear habitat-size threshold constraint for area-dependent species are incorporated into the final formulation. Two scenarios are tested using sets of objective-function weights. Solution times ranged from 30 minutes to 2 hours. Although the model is designed primarily for relatively small problems, an optimal solution is guaranteed.

47. Hof, John G.; Joyce, Linda. 1992. **Spatial optimization for wildlife and timber in managed forest ecosystems.** Forest Science. 38(3): 489-508.

Although there have been attempts to incorporate nonlinear relationships in linear programs, for example, through piecewise approximations, most have achieved limited success due to significant increases in problem size and computation. Three formulations that can consider nonlinear functions related to wildlife habitat are presented. The first approach, which attempts to account for edge effects using a standard grid-based allocation, uses integer nonlinear programming to determine whether each cell will be harvested or left as wildlife habitat. However, real-world application of the model is limited by lack of effective solution algorithms. The same basic procedure is repeated in the second model but with a "geometric" allotment structure such that land uses are allocated using circles of varying diameters. This approach does not require an integer formulation. In the third model, the geometric structure is used to model fragmentation effects.

48. Hof, John G.; Raphael, Martin G. 1993. **Some mathematical programming approaches for optimizing timber age-class distributions to meet multispecies wildlife population objectives.** Canadian Journal of Forest Research. 23: 828-834.

The typical forest-scheduling model considers wildlife only indirectly. Three alternative models that optimize wildlife factors directly are presented. The first maximizes the total number of viable species and is considered the "most efficiency oriented," while the other two models maximize a specific measure of population viability. All three models are run using both linear and nonlinear viability functions. When nonlinear viability functions are used, the models must be solved with nonlinear programming. With linear functions, only the standard linear programming formulation is required. An exception is the second "viability" model, which has a nonlinear objective. The models, which were tested using data from a 1.1 million-ha forest in California, produced different optimal age-class distributions. Using the logistic (nonlinear) viability function was the most realistic approach, though the two viability models were more effective in spreading the risk of extinction equitably across all species. The "total species maximization" approach yielded the highest total number of viable species.

49. Hoganson, Howard M.; Borges, Jose G. 1998. **Using dynamic programming and overlapping subproblems to address adjacency in large harvest scheduling problems.** Forest Science. 44(4): 526-538.

Dynamic programming (DP) was used to solve a mixed-integer harvest-scheduling problem in three scenarios consisting of 40- by 25-unit "forests." The planning problem was decomposed into subproblems and thus increase the problem size to which DP can be applied. The objective of this specific formulation was to maximize net returns subject to adjacency constraints. The problems were solved using forward recursion. The application entailed planning over five 10-year periods with seven possible management alternatives. For comparison, each of the four problems also was solved using a simulation approach and an unconstrained (relaxed) DP. Solution times were satisfactorily short and this method provided better solutions than the simulation approach.

50. Jones, J. Greg; Meneghin, Bruce J.; Kirby, Malcom W. 1991. **Formulating adjacency constraints in linear optimization models for scheduling projects in tactical planning.** Forest Science. 37(5): 1283-1297.

Several approaches are presented for minimizing the computational requirements of mathematical programs by reducing the number of constraints needed to handle adjacency considerations. The formulations are based on the assumption that the forest management area is divided into polygons rather than structured as a grid, and are presented as constraints in an integer programming model. The constraints are first formulated for only one decision variable and one planning period. Type 1 formulation uses a group rather than pairs of polygons to restrict timber harvesting. Type 2 combines several Type I constraints. The formulations are applied to three planning areas consisting of 27, 112, and 279 polygons. Using Type 2 constraints could reduce the number of constraints by nearly 75 percent. If trigger inequalities are used, Type 2 formulations would reduce the number of constraints by 27 percent.

51. Murray, Alan T. 1999. **Spatial restrictions in harvest scheduling.** Forest Science. 45(1): 45-52.

Discusses two common approaches to modeling adjacency constraints in harvest scheduling that are used when irregularly delineated units represent the forest management areas. Both approaches are presented as binary integer programming models. The Unit Restriction Model is applied when management units are so large that the harvest of two adjacent units would necessarily violate adjacency constraints. If management units are significantly smaller than the area limit of the adjacency constraint, harvesting of adjacent units does not necessarily violate the constraints and the Area Restriction Model is used. Both exact and heuristic solution methods for solving these models are discussed, and the issue of spatial unit definition in minimizing modeling and computation requirements is addressed.

52. Murray, Alan T.; Church, Richard L. 1995. **Measuring the efficacy of adjacency constraint structure in forest planning models.** Canadian Journal of Forest Research. 25: 1416-1424.

Reviews the traditional approach to adjacency constraint structure (pairwise comparison), suggests eight improved formulations, and compares computational efficiency of these new approaches using six harvest-scheduling scenarios that are based on the planning horizon considered (single or multiple period), number of harvest units included in the analysis, and whether road building is considered in the problem. The different approaches are compared according to the number of constraints required, optimal solution generated, number of branches, and iterations, and solution time required. The most significant findings are that: (1) the traditional pairwise comparison method does not necessarily result in the tightest constraint structure, (2) methods that most significantly reduce the number of constraints may have longer solution times, and (3) methods that rely on constraint tightening are particularly efficient.

53. Murray, Alan T.; Church, Richard L. 1996. **Analyzing cliques for imposing adjacency restrictions in forest models.** Forest Science. 42(2): 166-175.

A network theory-based technique known as the Type I constraint approach was first used in conjunction with quadruplet cliques, i.e., one constraint constructed for each group of four cells. A modification to Type I constraints that allow this formulation to be used with cliques with more than four cells is discussed. Two additional constraint-reduction techniques are presented. The first focuses on the elimination of dominated clique constraints and the second reduces the constraints to a "minimal subset." All three approaches were applied to nine forest planning problems. For eight problems, the minimal clique constraint set resulted in the fewest adjacency constraints. All three methods resulted in the same number of constraints in the ninth example, though the nondominated approach required significantly shorter computation times. This reduction technique is recommended where the number of constraints generated is sufficiently small that it is not binding; otherwise, the minimal set approach is an effective alterative.

54. Roise, Joseph P. 1990. **Multicriteria nonlinear programming for optimal spatial allocation of stands.** Forest Science. 36(3): 487-501.

Draws on the "four color theorem" to develop a nonlinear programming model for timber-harvest scheduling. For problems that require adjacent units to be harvested no less than a specified number of years apart (the exclusion period), the theorem suggests a feasible solution is possible so long as the project period length divided by the exclusion period length is less than or equal to four. Where a feasible solution is not possible, the adjacency constraint can be used as the objective function, thus maximizing the length of time between harvesting of adjacent units. The basic nonlinear model is presented and the objective function and constraints are applied to four increasingly complex problems. As the number of stands included increases, the solution time for the models grows exponentially. This technique is applicable only to forests with fewer than 200 stands, but allows optimization of harvest decisions at both the forest and stand level.

55. Snyder, S.; ReVelle, C. 1997. **Multiobjective grid packing model: an application in forest management.** Location Science. 5(3): 165-180.

Presents a method of integrating timber harvesting and wildlife habitat goals subject to spatial constraints. A binary integer programming (IP) model was applied to a hypothetical and static data set comprised of a 25- by 25-cell forest grid. The objective is to develop a harvest schedule that maximizes both harvest volume and wildlife habitat acreage. Adjacency constraints are evaluated by 2 by 2 grid-blocks rather than by individual pairs of cells. The study's two objectives were combined using the weighting method. Three of the possible weight combinations were used to solve the IP, and the impact of various weights on the spatial distribution of management activities is discussed. The model was reformulated with additional constraints and the process repeated. This approach was successful in obtaining exact, optimal solutions in a minimal amount of time.

56. Snyder, Stephanie; ReVelle, Charles. 1996. **Temporal and spatial harvesting of irregular systems of parcels.** Canadian Journal of Forest Research. 26: 1079-1088.

A binary integer programming (IP) model was applied to a forest with irregular harvest-unit systems. Unlike regular (grid) systems, irregular systems require more than one type of constraint structure. The method for formulating constraints for irregular systems is demonstrated and the effect of such a set of constraints on the computational efficiency of the IP model is assessed. With the maximization of timber volume as the objective, the model is then applied to five hypothetical and five real scenarios. Data sets representing irregular parcel systems of varying sizes and configurations are evaluated using both static and multiple-period models. Adjacency constraint formulations for the two models are presented separately, and the multiple-period model is run for various planning horizon lengths. For the static model, the IP model performed well, requiring little, if any, branching and bounding. In some cases, considerable branching and bounding was required for the multiple-period model.

57. Snyder, Stephanie; ReVelle, Charles. 1997. **Dynamic selection of harvests with adjacency restrictions: the SHARe model.** Forest Science. 43(2): 213-222.

Discusses the need to develop models that allow harvest plans to be subject to spatial constraints and temporal management considerations to be integrated. A binary integer programming (IP) formulation is presented that is the "shortest path network flow" model, which is a means of structuring "relaxed" models that can be solved to exact integer solutions. Several general formulations of adjacency constraints that can be used in this approach are discussed, and a binary IP model is introduced that includes both spatial constraints over multiple periods and the shortest-path-network structure. The model is formulated for an area represented by a grid of cells of equal size. A set of hypothetical data is used to evaluate the approach, with multiple runs conducted using different grid sizes, time-horizon lengths, initial forest-age structures, and adjacency restrictions. The results of each run along with solutions times are reported.

58. Weintraub, Andres; Barahona, Francisco; Epstein, Rafael. 1994. **A column generation algorithm for solving general forest planning problems with adjacency constraints.** Forest Science. 40(1): 142-161.

Describes a method for solving forest-planning problems with multiple periods and a significant set of constraints, representing a large forest area that is realistic. A two-stage approach is applied to both simplified and expanded problems. The first entails scheduling units within a single, homogenous harvest area; the expanded problem entails unit scheduling across multiple areas. The first stage of the approach is the formulation of an integer-programming (IP) model, which is solved without the integer constraint (relaxed form) and then by heuristic procedure to improve the relaxed continuous solution. This simplex-based procedure identifies a "stable set" of subproblem alternatives that satisfy adjacency constraints; a three-step process is used to solve the stable set problem. First, a greedy heuristic method is used to identify a near optimal solution. If it is not successful, a linear programming (LP) technique is used to find an integer solution. If the LP is unsuccessful, the problem is solved by the branch and bound method. The latter approach was applied to two problems, each with three forest configurations, over a 10-year planning horizon. On average, the solutions were within 3 percent of the optimal solution for the relaxed IP.

59. Weintraub, Andres P.; Epstein, Rafael; Murphy, Glen; Manley, Bruce. 2000. **The impact of environmental constraints on short term harvesting: use of planning tools and mathematical models.** Annals of Operations Research. 95: 41-66.

Seven planning models currently being applied to real situations in New Zealand and Chile are described, including the typical planning horizon used and types of information required by each model. Also discussed is how forest management is facilitated by these models which range from short-term and small-scale operational applications to long-range planning formulations used for harvest scheduling, wood-processing investment decisions, and forest-management planning. The impact of modification to better include environmental protection measures in the planning process is illustrated for five of the models using these case studies. Impacts are assessed in terms of changes in net values and harvest volumes resulting from the mitigation measures.

Heuristic Methods

60. Bettinger, Pete; Boston, Kevin; Sessions, John. 1999. **Intensifying a heuristic forest harvest scheduling search procedure with 2-opt decision choices.** Canadian Journal of Forest Research. 29: 1784-1792.

Describes a method for improving the performance of tabu search for solving a harvest-scheduling problem. Tabu search operates by making iterative changes, or moves, to a selected solution based on specified search rules. The relative benefits of using 1-opt versus 2-opt moves in this search process is evaluated. In 1-opt moves, only one attribute of one decision choice is altered, i.e., a unit is removed from the harvesting schedule. In 2-opt moves, that attribute is changed for two decision choices simultaneously, i.e., one unit is added to the harvest schedule while another is removed. The objective of this application is to maximize of harvest volume subject to adjacency and even-flow constraints. Hypothetical 5 by 8 and 28 by 25 forest grids are generated. The problem is solved as a relaxed linear programming (LP) model and as an integer program (IP). Two versions of tabu search, one that allows only 1-opt moves and one that allows both 1-opt and 2-opt moves, are used. The solution time for tabu search was significantly less than for the IP model; the combined (1- and 2-opt) tabu model had a slightly longer solution time than the 1-opt model. The tabu models had objective function values within 3 percent (1-opt) and 1 percent (both) of the relaxed LP solution.

61. Bettinger, Pete; Johnson, K. Norman; Sessions, John. 1996. **Forest planning in an Oregon case study: defining the problem and attempting to meet goals with a spatial-analysis technique.** Environmental Management. 20(4): 565-577.

Spatial allocation is an important consideration in natural resource management, but it is difficult to optimize activities in a spatial context. An operational-level harvest-scheduling program called SNAP II+ uses the more common integer programming formulation and a heuristic solution algorithm approach. The model was evaluated based on whether it could model management goals well and was flexible in evaluating alternatives when applied to a small watershed in the upper Grand Ronde River Basin in Oregon. The model was formulated to maximize net present value over four 10-year planning periods. SNAP II+ generated feasible management plans and was effective in addressing spatial allocation.

62. Bettinger, Pete; Sessions, John; Boston, Kevin. 1997. **Using tabu search to schedule timber harvests subject to spatial wildlife goals for big game.** Ecological Modelling. 94: 111-123.

A tabu search heuristic is used to solve a large harvest-scheduling model that includes both temporal and spatial constraints for wildlife habitat. No other technique can directly incorporate habitat-quality considerations while developing feasible harvest schedules. The objective function in this model minimizes the sum of the squared differences between the target level of harvest and the actual level of harvest for each period, and contains penalty functions that prevent: (1) adjacent units from being harvested in the same period (adjacency constraint); and (2) blocks of units assigned as wildlife cover from being reduced below a minimum aggregate size (wildlife habitat constraint). The data used were based on a hypothetical landscape of 1-ha units (20 by 20 grid). Two scenarios were run that represented differences in forage age limitations and minimum harvest age. The algorithm was run for 1,000 iterations for the first scenario and about 400 iterations for the second. In both scenarios, a temporally and spatially feasible solution was obtained.

63. Bettinger, Pete; Sessions, John; Johnson, K. Norman. 1998. **Ensuring compatibility of aquatic habitat and commodity production goals in eastern Oregon with a tabu search procedure.** Forest Science. 44(1): 96-112.

Describes the use of tabu search to simultaneously optimize land-management plans and assess their impact on aquatic habitat. A basic linear-programming formulation with an objective function that optimizes net present value was applied to a 6,000-ha watershed in eastern Oregon. This method was able to optimize timber and aquatic habitat goals simultaneously, though it may not generate a global optimal solution.

64. Bos, Jan. 1993. **Zoning in forest management: a quadratic assignment problem solved by simulated**

annealing. Journal of Environmental Management. 37: 127- 145.

Zoning-based management is based on the assumption that conflict can best be reduced by separation of land uses. Traditional planning models do not explicitly include zoning decisions partly because they require integer variables that make the models difficult to solve. A forest zoning problem in the Netherlands is addressed using a quadratic assignment formulation in which the objective function comprises two elements. The first element is a function of both the suitability of a forest unit for each alternative use and the relative preference for those uses. The second considers the use of adjacent forest units and maximizes the grouping of uses that complement each other. The model also considers actual or potential land uses that border the forest when making zoning decisions. A heuristic algorithm (simulated annealing) is used to generate solutions. Data were obtained for 84 units within the Waterbloem National Forest and 80 "environmental" units that adjoin the forest. The model effectively considered the spatial relationships of various land uses and the solution algorithm provided acceptable results.

65. Bullard, Steven H.; Sherali, Hanif D.; Klemperer, W. David. 1985. **Estimating optimal thinning and rotation for mixed-species timber stands using a random search algorithm.** Forest Science. 31(2): 303-315.

Describes a method for generating "good" thinning regimes in even-aged, mixed-species stands, specifically, a growth model consisting of up-growth and mortality functions that generates data on stand structure and volume. Growth information is used in a nonlinear integer-programming model that addresses the thinning problem. The model was formulated to maximize present net value of both current and future income. A comparison of simple and multistage random search heuristics is given for two hypothetical samples. Both yielded nearly optimal solutions in several seconds to several minutes. In both cases, the multistage algorithm outperformed the simple algorithm.

66. Kangas, Jyrki; Pukkala, Timo. 1996. **Operationalization of biological diversity as a decision objective in tactical forest planning.** Canadian Journal of Forest Research. 26: 103-111.

Describes HERO, a utility-based heuristic method designed to address harvest-scheduling problems that consider biodiversity. The major premise of this method, which entails estimating an additive utility function and optimizing that function, is that all constraints and objectives can be formulated as preference and utility functions. The method was applied to a 43-ha, 37-unit forest in eastern Finland with two 10-year planning periods and 129 treatment schedules. Four scenarios with varying degrees of biodiversity importance were tested. The strengths of this approach are its flexibility and ability to consider nonlinear relationships, and make biodiversity commensurable with other objectives.

67. Lockwood, Carey; Moore, Tom. 1992. **Harvest scheduling with spatial constraints: a simulated annealing approach.** Canadian Journal of Forest Research. 23: 468-478.

The use of simulated annealing (SA) to solve large harvest-scheduling is proposed and the basic procedure for this heuristic technique is described. A unique characteristic of this formulation is that the objective function is designed to minimize deviation from the harvest-volume target as well as penalty costs associated with constraint violations. Procedures for developing the four penalty cost functions are presented and the process of applying SA to this specific formulation is described. Data were from a 240,000-ha subsection of a private forest six harvest levels and three harvest block sizes used in trial runs. This method generated feasible solutions for every run.

68. Murray, Alan T.; Church, Richard R. 1995. **Heuristic solution approaches to operational forest planning problems.** OR Spektrum. 17: 193-203.

Explores the ability of three heuristic methods- interchange, tabu search, and simulated annealing to generate near optimal plans for problems with considerable detail. These methods represent improvements on a Monte Carlo approach and were applied to two moderate-size forests in British Columbia. The first problem was a mixed-integer formulation with 300 decision variables (291 integer) and 740 constraints. In a previous study, this problem was solved analytically in about 60 hours. For each heuristic, the process began with the best Monte Carlo solution, which generate 1,300 additional solutions. The best objective-function value using the interchange method was within 2 percent of the optimal solution. The best solutions generated by tabu search and simulated annealing were within 1 percent of the optimal solution. For all three methods, objective function values were significantly better than the solution generated using Monte Carlo alone. Solution times were 30 hours for tabu search, 11 hours for simulated annealing, and 3 hours for interchange. Tabu search solutions were the most consistent and closest to optimal.

69. Nelson, John; Bodie, J. Douglas. 1990. **Comparison of a random search algorithm and mixed integer programming for solving area-based forest plans.** Canadian Journal of Forest Research. 20: 934-942.

Compares a Monte Carlo integer-programming heuristic and a mixed-integer programming (IP) model for solving harvest-scheduling problems at the tactical level. The Monte Carlo technique was applied to a 1,700-ha forest in British Columbia. The harvest problem was first formulated as a mixed IP model with the objective of maximizing discounted net revenue. The problem was solved using linear programming (LP) to determine the optimal solution, and then reformulated as a Monte Carlo IP model. This heuristic model was solved using three search techniques: all-period, first selective, and second selective. Of the 1,300 Monte Carlo solutions generated, 175 were within 10 percent of the optimal value, 12 were within 5 percent, and the highest valued was within 3 percent. The all-period search was the most effective of the search routines and Monte Carlo was effective in creating harvest schedules for forest problems that are medium to large.

70. O'Hara, Anthony J.; Faaland, Bruce H.; Bare, B. Bruce. 1989. **Spatially constrained timber harvest scheduling.** Canadian Journal of Forest Research. 19: 715-724.

The model SCRAM is the first algorithm that can generate feasible and "good" solutions to integer programming (IP) problems that include many units, multiple planning periods, and spatial constraints. The basic IP formulation that is to be solved and the biased sampling search algorithm developed to solve it are described. This heuristic is a modified version of the Monte Carlo IP that both randomly selects harvest units and allows the selection process to be biased toward those units more likely to result in good solutions. Three different pre-biasing techniques were used on data from a previous study of a 242-unit forest with a planning horizon of five 10-year periods. This model is an important innovation because it requires no special data beyond what is available for the average scheduling problem, produces feasible/good integer solutions, and does not lose accuracy as the problem size increases.

71. van Deusen, Paul C. 1999. **Multiple solution harvest scheduling.** Silva Fennica. 33(3): 207-216.

One of the most common heuristic methods is the simulated annealing algorithm. The core of this solution technique is a procedure known as the metropolis algorithm (MA). Also related to the Monte Carlo technique, MA focuses primarily on generating a large list of feasible solutions, with less emphasis on economic optimality. All problem constraints are incorporated directly into the objective function. This allows consistent treatment of problem criteria and locally optimal solutions can be identified by increasing the weight of a particular element in the objective function. This has been suggested as more appropriate type of approach for government agencies that wish to identify more than the most economically efficient alternatives. As applied to a forest data set of 419 stands, MA proved a flexible approach to forest planning.

72. Wientraub, Andres; Church, Richard L.; Murray, Alan T.; Guinard, Monique. 2000. **Forest management models and combinatorial algorithms: analysis of state of the art.** Annals of Operations Research. 96: 271-285.

The types of algorithms available to solve mixed-integer programming problems are reviewed and methods used to solve harvest-scheduling problems with adjacency constraints are discussed. Also discussed are algorithms that have been applied to the simultaneous planning of harvesting and road building. Although most applications have included the use of heuristic algorithms, the basic integer formulation can be strengthened to provide a good solution.

73. Weinttaub, Andres; Jones, Greg; Meacham, Mary; Magendzo, Adrian; Magendzo, Ariel; Malchuk, Daniel. 1995. **Heuristic procedures for solving mixed-integer harvest scheduling-transportation planning models.** Canadian Journal of Forest Research. 25: 1618-1626.

Discusses the use of heuristic techniques to address spatial constraints in harvest scheduling. The basic formulation, based on the Integrated Resources Planning Model, is given as an linear programming (LP) optimization of present net value, and the heuristic procedure for problems in which only road-decision variables are in 0-1 integer form is discussed. This iterative algorithm works with an LP solver to convert optimal LP solutions to integer solutions. This approach was applied using several small data sets and results were evaluated on the basis of the best solution using a mixed-integer programming (IP) model. An extension of the original formulation that considers both 0-1 road and 0-1 land-management variables is presented. Objective function values were about 40 percent higher with heuristic solutions than with the IP solution.

74. Yoshimoto, Atushi; Brodie, J. Douglas. 1993. **Comparative analysis of algorithms to generate adjacency constraints.** Canadian Journal of Forest Research. 24: 1277-1288.

The need to incorporate environmental concerns into harvest scheduling has led to the use of large number of spatial constraints in MODM problems. The conventional branch and bound algorithm has been so limited in use that efforts have been made to develop heuristic methods that can reduce the set of constraints that must be included in a standard integer programming model. Conventional solution algorithm and two heuristic algorithms that are used to reduce the number of constraints are reviewed and a simple analytical algorithm to reduce the constraint set is proposed. Three original algorithms and four versions of the proposed heuristic are evaluated for computational effort and number of constraints needed. Although the two original heuristic methods resulted in fewer constraints, computation time for each was greater than that for any version of the proposed heuristic. The latter method is preferred over conventional branch bound and other heuristic algorithms.

75. Yoshimoto, Atsushi; Brodie, J. Douglas; Sessions, John. 1994. **A new heuristic to solve spatially constrained long-term harvest scheduling problems.** Forest Science. 40(3): 365-396.

Describes a heuristic algorithm to solve integer programming (IP) harvest-scheduling problems. This two-stage algorithm eliminates scheduling alternatives that are infeasible over the entire planning period, and breaks down the scheduling problem into subproblems: only two successive planning periods are considered at any one time so that a selected schedule will be feasible both in the current period and in the next period. Data were from a forest containing 109 stands in 62 analysis areas and a second forest with 45 units. The objective was to maximize total present net worth for planning periods. The solution was compared with that from a branch and bound solution for the original integer formulation and a relaxed linear programming (LP) solution. Exception for the one-period schedule, the heuristic algorithm had significantly shorter solution times than the branch and bound method. The difference in objective function between the branch and bound and the heuristic solutions were less than 1 percent for all problems. The heuristic solution was significantly less than the relaxed LP solution in the 1- and 2-year planning problems, and was within 2 and 3 percent of the relaxed LP objective function value for longer planning problems.

76. Zanakis, Stelios H.; Evans, James R. 1981. **Heuristic "optimization": why, when, and how to use it.** Interfaces. 11(5): 84-93.

Heuristic methods are particularly applicable in situations where data are uncertain or limited or reasonable computation is not possible, or where there is an attempt to improve solutions through optimization. Ten features of the "ideal" heuristic method and eight guidelines for applying these features are presented.

MADM Applications in Forestry and Land Management

77. Choo, Eng U.; Schoner, Bertram; Wedley, William. 1999. **Interpretation of criteria weights in multicriteria decision making.** Computers & Industrial Engineering. 37: 527- 541.

A comprehensive assessment of the use of criteria weights in MADM models examining 13 interpretations that have been applied to these weights. Also examined are aggregation rules, measurement units, other comparative features of each interpretation, and the more common methods that use them.

78. Easley, Robert F.; Valacich, Joseph S.; Venkataramanan, M. A. 2000. **Capturing group preferences in a multicriteria decision.** European Journal of Operational Research. 125: 73-83.

Multi-attribute decision models are effective in quantifying the preferences of an individual decisionmaker, though natural resource decisions generally involve multiple stakeholders. As a result, the preferences of a wide range of groups must be considered. The effectiveness of the analytic hierarchy process (AHP), a variation of the standard AHP (FNAHP), and two pairwise voting techniques are evaluated for their ability to capture the preferences of multiple decisionmakers and supporting group decisionmaking. Three approaches are applied to the allocation of sales territory between two representatives. The resulting alternative rankings and decisionmaker perceptions were compared across the four decision methods. The hierarchical model was the most effective technique for capturing group preferences.

79. Gershon, Mark. 1984. **The role of weights and scales in the application of multiobjective decision making.** European Journal of Operational Research. 15: 244-250.

A major criticism of MCDM is that the results can be influenced, and any desired solution obtained, by manipulating the weights used in the analysis. Algorithms that do not require subjective weights have been developed, though subjective input still is required with these methods. Four MCDM compromise programming, cooperative game theory, multiattribute utility theory, and ELECTRE—were studied to determine the role played by their weighting schemes in the evaluation of alternatives. A general classification of the "proper" way in which weights can be determined is proposed. Differences among three types of weighting approaches are illustrated and the type of weighting scheme used, process of weight selection, and scalings and other subjective parameters for each MCDM are identified. Although these methods use the same input, each defines the concept of a "best" solution differently.

80. Hajkowicz, Stefan A.; McDonald, Geoff T.; Smith, Phil N. 2000. **An evaluation of multiple objective decision support weighting techniques in natural resource management.** Journal of Environmental Planning and Management. 43(4): 505-518.

Explores the use of five weighting techniques to better understand the implications of choosing a multi-attribute method choice for a particular natural resource problem. The weighting methods—fixed-point scoring, rating, ordinal ranking, graphical weighting, and paired comparisons—are described and then applied to prioritizing Australian National Heritage Trust projects for funding. The selection of decisionmakers, decision alternatives, and evaluation criteria for this problem are discussed, and weights obtained from each approaches are compared. Except for the paired comparison, all techniques resulted in the same ranking of criteria, though actual weights varied significantly. For ease of use, the ranking method is the most preferred and the fixed-point approach is the least preferred. The ranking technique clarified the decision situation the most and the graphical method the least. Decisionmakers should not rely on a single weighting approach as different methods may have an unknown bias.

81. Howard, Andrew F. 1991. **A critical look at multiple criteria decision making techniques with reference to forestry applications.** Canadian Journal of Forest Research. 21: 1649-1659.

Describes various MADM to include the components related to "procedural and mathematical formalities." These include scale transformations, criterion weighting, choice of criteria, and specification of alternatives. How each of these steps is approached affects the outcome of the MADM process, that is, the ranking order of the alternatives and the number of criteria that are used to assess the achievement of an objective, influence the weight of that objective in the analysis. Crucial issues that should be recognized and addressed before MADM are applied are described.

82. Lahdelma, Risto; Salminen, Pekka; Hokkanen, Joonas. 2000. **Using multicriteria methods in environmental planning and management.** Environmental Management. 26(6): 595 605.

MADM are appropriate and effective in environmental planning and management because of their ease of use and transparency to stakeholders. The three typical uses of MADM are the choice of a "best" alternative, ranking of several alternatives relative to each other, and analysis of the degree of acceptability of alternatives. The basic procedure for implementing MADM-driven decisionmaking is reviewed. The importance of early and consistent stakeholder involvement choice of evaluation criteria and selection of the most appropriate MADM technique are emphasized.

83. Martin, W. E.; Bender, H. Wise; Shields, D. J. 2000. **Stakeholder objectives for public lands: rankings of forest management alternative.** Journal of Environmental Management. 58: 21-32.

In response to the National Forest Management Act and the National Environmental Policy Act, public participation has become an important component in Forest Service planning and decisionmaking. In quantifying public preferences, additive utility methodology identifies the decision context, stakeholders, and alternatives; elicits preferences from stakeholders regarding the alternatives and their attributes; and develops value functions for each stakeholder to rank alternatives. Additive utility functions were applied in the evaluation of alternative multiple-use management alternatives on the San Juan National Forest in Colorado. Alternatives were ranked by each stakeholder identifying the order of preference (ordinal ranking) and by cardinal value functions (cardinal ranking). Both methods produced inconsistent rankings, but the cardinal value functions generated the more useful evaluations.

84. Prato, T. 2000. **Multiple attribute evaluation of landscape management.** Journal of Environmental Management. 60: 325-337.

The use of multi-attribute models in landscape-level planning is proposed, and the multi-attribute decision procedure is described and applied to the following scenarios: a publicly owned watershed that is administered by a land agency, and a basin that is privately owned by multiple individuals. The most efficient alternatives are identified and decisionmaker preferences are then elicited to determine the most favored nondominated alternative. The multi-attribute model is useful for landscape-scale planning but might be difficult to implement as substantial input by the decisionmaker is required.

85. Pukkala, Timo; Kangas, Jyrki. 1996. **A method for integrating risk and attitude into forest planning.** Forest Science. 42(2): 198-204.

Demonstrates a method for incorporating intergenerational perspectives into forest planning. A heuristic method is proposed that integrates risk analysis and attitudes toward risk. The procedure incorporates stochastic simulation of stand development under different treatments and across various scenarios of tree growth and timber prices; pairwise comparison of objectives using the analytic hierarchy process technique; and an estimation of the decisionmaker's attitude toward risk. The method is applied to a case study that represents a typical planning situation facing a private forest owner. A solution is determined for three levels of risk (low, normal, and high) and across three risk perspectives (risk avoider, risk seeker, and risk neutral). The method can be applied to both tactical and strategic forest planning.

86. Tecle, Aregai; Fogel, Martin M.; Duckstein, Lucien. 1988. **Multicriterion analysis of forest watershed management alternatives.**m Water Resources Bulletin. 24(6): 1169-1179.

Two multi-attribute decision models, the outranking-based ELECTRE and the distance-based compromise programming method, are compared on the basis of how they select a preferred management alternative. Both are applied to a portion of the Beaver Creek watershed in Arizona. Compromise programming was preferred over the ELECTRE-based model for consistency and ease of use. Neither approach was overly sensitive to changes in criteria weights, and the most and least preferred alternatives were the same for both methods.

87. Teeter, Lawrence D.; Dyer, A. Allen. 1986. **A multiattribute utility model for incorporating risk in fire management planning.** Forest Science. 43(4): 1032-1048.

The use for multiattribute utility theory (MAUT) is important when uncertain information is incorporated into planning analysis. A method for evaluating Forest Service fire management strategies in terms of both economic efficiency and risk is proposed. Economic efficiency is represented by the direct costs of implementing a particular strategy plus any change in value of the forest that might result, and the risk associated with that strategy. Risk is considered not as variability in net returns but as potential loss or injury. The process of constructing utility functions and the technical aspects of their application are reviewed and seven alternative strategies, including the historical Forest Service fire management approach, are evaluated. These strategies consisted of combinations of particular activities, such as firebreak construction or surveillance, and their required resources. Utility models such as MAUT are valuable for incorporating risk/uncertainty into complex planning processes and are useful when outcomes are deterministic (known) and stochastic (unknown).

Combined MODM/MADM Applications

88. Malczewski, J.; Moreno-Sanchez, R.; Bojorquez-Tapia, L. A.; Ongay-Delhumeau, E. 1997. **Multicriteria group decision-making model for environmental conflict analysis in the Cape Region, Mexico.** Journal of Environmental Planning and Management. 40(3): 349-374.

The analytic hierarchy process (AHP) and integer programming (IP) are integrated into a model for conducting land-suitability planning. The AHP procedure incorporates the preferences of interest groups into the suitability analysis, and each geographic unit is weighted according to its suitability for various land-management activities. The weights can be used in the objective function of a binary IP model that maximizes the total weighted value of each land use for each unit. This approach is applied to a 19,000-km^2 area in Baja, Mexico with the goal of reducing conflicts among various interest groups over land use. Emphasis was placed on the "political" nature of actual interactions with these groups. The difficulties encountered in applying this approach in a real-world situation are discussed.

89. Mendoza, Guillermo A.; Sprouse, William. 1989. **Forest planning and decision making under fuzzy environments: an overview and illustration.** Forest Science. 35(2): 481 502.

Describes the use of fuzzy modeling-to-generate-alternatives (MGA) techniques and the analytic hierarchy (AHP) as a two-stage process for evaluating forest plans. The theory behind fuzzy decisionmaking and the procedure for converting a standard linear programming (LP) formulation a fuzzy LP are explained, and four alternative fuzzy MGA models—regular, selective, and weighted MAXMIN models and an additive model—are described. The second stage of this approach entails the use of AHP to evaluate and prioritize the alternatives generated with the MGA models. The basic AHP procedure of making pairwise comparisons and then synthesizing these priorities is examined. The method is applied to data from a real forest. Objectives were to maximize net revenue as well as areas suitable as wildlife habitat and for recreation; the planning horizon was ten 10-year periods. This approach is flexible and a more realistic alternative to optimization.

MCDM Applications to Water Resources

90. Belaineh, Getachew; Peralta, Richard C.; Hughes, Trevor C. 1999. **Simulation/optimization modeling for water resources management.** Journal of Water Resources Planning and Management. May/June: 154-161.

A combined simulation and optimization model is used as a hypothesis-testing devise to demonstrate whether an enhanced representation of surface water-aquifer interactions improves overall water-use management. This two-stage approach optimizes the water supply based on groundwater withdrawal and stream diversion factors, and then selects the optimal use strategy for this increased flow regime. The model was tested using five system scenarios. The improved surface water-aquifer interactions representation resulted in optimal solutions with 13 percent more surface-aquifer interflow, a 52 percent reduction in flow leaving the basin due to better use strategies, and an 80 percent increase in ground-water pumping. This technique is an effective alternative to optimization methods.

91. Bella, Aimee; Duckstein, Lucien; Szidarovsky, Ferenc. 1996. **A multicriterion analysis of the water allocation conflict in the upper Rio Grande basin.** Applied Mathematics and Computation. 77: 245-265.

Compromise programming (CP) and ELECTRE III are used to rank management alternatives for the Upper Rio Grande River Basin. Thirty alternative management actions and 18 criteria by which these actions could be evaluated were identified. Results for the two MADM approaches are compared with both equal and unequal weightings on the criteria. The CP method was run several times with varying "p" values to determine how attribute deviations from the "ideal" are treated in the analysis. Total rankings for all 30 alternatives are presented for both methods. Each produced approximately the same ranking order.

92. Chang, Ni-Bin; Wen, C. G.; Wu, S. L. 1995. **Optimal management of environmental and land resources in a reservoir watershed by multiobjective programming.** Journal of Environmental Management. 44: 145-161.

Presents a framework for incorporating economic, social welfare, and environmental quality factors into a multiobjective program for watershed planning in Taiwan. The processes of data acquisition, model building, and model solution are described and 6 objective functions, 10 constraints, and 15 alternative management techniques are identified. Compromise programming is applied to solve the resulting model, assuming equal weights on the objectives. This model was run twice, first assuming no pollution control measures and then considering the impact of these strategies. Sensitivity analysis was conducted to asses seven planning scenarios.

93. da Conceicao, Cunha; Sousa, Maria; Sousa, Joaquim. 1999. **Water distribution network design optimization: simulated annealing approach.** Journal of Water Resources Planning and Management. July/August: 215-221.

Due to limitations with other MODM techniques, a simulated annealing (SA) algorithm is proposed in designing a minimum-cost water-distribution network. The SA process is described and tested using simplified networks. Two test problems were chosen that had been evaluated by a variety of decision models. Results were compared with those from previous evaluations. In the first test case consisting of six studies, the SA approach tied for third place in terms of the objective function value (i.e., lowest cost) of eight evaluations. In the second test case, SA ranked fourth. This method is easy to use, can handle large, nonlinear, mixed-integer programming problems, and generates good results.

94. Das, Pransanta; Haimes, Yacov Y. 1979. **Multiobjective optimization in water quality and land management.** Water Resources Research. 15(6): 1313-1322.

The surrogate worth tradeoff (SWT) method is applied to a water-quality and land-management planning problem to demonstrate the ability of a MODM to integrate both nonpoint-source and point-source pollution into a single model. The two pollution submodels with a cost minimization objective and a third model with a water quality objective were integrated into a single optimization problem that was solved as a SWT problem using a generalized reduced gradient algorithm. Data, both actual and hypothetical, were generated for a basin in the Midwest that was nearly 9,000 square mile s. Four (noninferior) alternative plans were identified, and the level of attainment of each objective and tradeoffs among objectives were calculated for each alternative. The preferences of the decisionmaker are used to develop surrogate worth functions that are used to determine the preferred solution. This method can address large and complex problems and is easier to use than other MODM methods.

95. David, Laszlo; Duckstein, Lucien. 1976. **Multi-criterion ranking of alternative long range water resources systems.** Water Resources Bulletin. 12(4): 731-754.

An existing water resource system is compared to alternative systems to identify a scheme that meets economic and social requirements for a watershed in Hungary. A cost-effectiveness framework is used to guide the planning process, with alternative evaluation completed using ELECTRE techniques. The study site planning objectives, evaluation criteria, and alternative system plans are described and displayed in a "system versus criteria" matrix, and an incomplete ranking of alternatives is presented. This is a simple method for ranking alternative water-resource systems.

96. Duckstein, Lucien; Opricovic, Serafim. 1980. **Multiobjective optimization in river basin development.** Water Resources Research. 16(1): 14-20.

A combined cost-effectiveness and compromise programming (CP) approach was applied to the design of a water-resources system in Hungary. Cost-effectiveness methodology was used as the guidelines for evaluating and ranking alternatives; the CP method was incorporated to allow multiobjective evaluation of the alternatives. Results were compared with those using ELECTRE techniques and multi-attribute utility theory. Five alternatives were ranked on the basis of 12 criteria. For all three methods, two of the five alternatives tended to be ranked first or second; the exact order differed between approaches.

97. Flug, Marshall; Seitz, Heather L. H.; Scott, John F. 2000. **Multicriteria decision analysis applied to Glen Canyon Dam.** Journal of Water Resources Planning and Management. September/October: 270-276.

Presents a generic MADM method for evaluating flow alternatives for the Glen Canyon Dam in Arizona. This method was used to evaluate nine alternatives within several scenarios, each with a different weighting scheme. The analysis recommended that a new flow regime be adopted.

98. Gershon, Mark; Duckstein, Lucien; McAniff, Richard. 1982. **Multiobjective river basin planning with qualitative criteria.** Water Resources Research. 18(2): 193-202.

A combination of ELECTRE I and ELECTRE II is used to select a management solution for the Santa Cruz River in Arizona. The models were used to evaluate 25 discrete alternatives based on 13 evaluation criteria. ELECTRE I was used as a "screening" method to reduce the set of alternatives under consideration; ELECTRE II ranked the remaining alternatives. Sensitivity analysis was conducted by varying the scale intervals and the criteria weight. The impact of these changes on the final rankings is reported.

99. Gershon, Mark; Duckstein, Lucien. 1983. **Multiobjective approaches to river basin planning.** Journal of Water Resources Planning and Management. 109(1): 13-28.

Four MODM were applied to a 50-year planning problem affecting the Santa Cruz River in Arizona. Objectives were water supply, flood protection, "environmental," utilization of resources, and recreation, and five water-supply and five flood-protection options were identified and combined (total of 25 alternative management schemes). The problem was evaluated by ELECTRE, multi-attribute utility theory (MAUT), compromise programming (CP), and game theory. Results are presented as a set of rankings, one for each technique; sensitivity analysis was used to examine the impact on ranking order. Only MAUT and game theory had the same first-ranked alternative. Results showed that each method evaluated is appropriate to this type of decision situation and that results were reasonably similar.

100. Haimes, Yacov Y.; Hall, Warren A. 1974. **Multiobjectives in water resource systems analysis: the surrogate worth trade off method**. Water Resources Research. 10(4): 615-623.

Discusses the surrogate worth tradeoff (SWT) method as a decision tool for multiobjective water-resource planning. The rationale for the use of SWT in multiobjective planning, as well as the theory and basic formulation of the modes, are discussed. The model is recommended because it addresses noncommensurable objectives in a quantitative fashion and is computationally feasible.

101. Hipel, Keith W. 1992. **Multiple objective decision making in water resources.** Water Resources Bulletin. 28(1): 3-12.

Discusses the role of multiobjective decisionmaking in all phases of water-resources planning, including groundwater contamination management, water-quality monitoring, water allocation, and reservoir-system operation. MCDM techniques are divided into four groups depending on whether they are applied to situations with one or multiple objectives and whether they can be used with one or multiple decisionmakers

(DM). In this classification scheme, most operation-research methods are applicable in single-objective, single-DM situations. MADM can be used when there is a single DM and multiple objectives. Multiple DM situations are restricted to analysis using team theory and game theory.

102. Hobbs, Benjamin F.; Chankong, Vira; Hamadeh, Wael; Stakhiv, Eugene Z. 1992. **Does choice of multicriteria method matter? An experiment in water resources planning.** Water Resources Research. 28(7): 1767-1779.

Four multi-attribute models are applied to hypothetical water-supply projects and their appropriateness, ease of use, validity, and sensitivity of results are compared. The methods evaluated are ELECTRE, goal programming (GP), multi-attribute utility (MAUT) functions, and additive value functions. The latter method was assessed using three weighting approaches; eight hypotheses were tested. The first three hypotheses concerned the perceptions of users toward the usefulness of the models and how easy or difficult they were to use. The fourth pertained to the perceived appropriateness of the approach; the fifth and sixth addressed both the ability of the models to predict unaided choices among alternatives by the users, and the construct validity of the rating weights; and the eighth concerned the degree of sensitivity in the final rankings to differences in who applies a particular model and which model is used. GA was the most understandable method and the one with which users were most comfortable, though all four approaches were trusted by fewer than half of the users. Generally, users were unconvinced of the utility of MAUT; none of the four approaches was consistently preferred.

103. Kenney, Ralph L.; Wood, Eric F. 1977. **An illustrative example of the use of multiattribute theory for water resource planning.** Water Resources Research. 13(4): 705-712.

Proposes the use of multi-attribute utility theory (MAUT) as an alternative to linear programming in water resources planning, specifically, five alternative plans for water-resource development in a river basin in Hungary. A previous evaluation using ELECTRE did include uncertainty in the analysis and specified tradeoffs among attributes only implicitly. The five alternative plans and objectives are described and a procedure for utility function assessment is given along with methods for assessing component utility functions and scaling factors. A utility value is associated with each alternative, with the highest value indicating the most preferred option. This method of assessing utility functions also provides a measure of how much better (more preferred) an alternative is relative to others.

104. Needham, Jason T.; Watkins, David W., Jr.; Lund, Jay R. 2000. **Linear programming for flood control in the Iowa and Des Moines rivers.** Journal of Water Resources Planning and Management. May/June: 118-127.

A mixed-integer programming model was used to evaluate the Iowa/Des Moines River Reservoir System's flood-control operation. The goal was to determine whether optimizing the operation of the entire reservoir system would be an improvement over the optimization of reservoir subsystems independently. The model used was intended to minimize penalties associated with excessive or inadequate storage, flow, or release from and between reservoirs. Formulation of the objective function, the three penalty functions, and the constraints are discussed and the 10 years with the largest flood events from 70 years of flow data were chosen as the data set for analysis. Results indicated that the optimal operation procedure is controlling each reservoir independently. Optimization models are particularly useful in this context but are "only as good as their penalty functions and constraints."

105. Neely, Walter P.; North, Ronald M.; Fortson, James C. 1977. **An operational approach to multiple objective decision making for public water resources projects using integer goal programming.** American Journal of Agricultural Economics. February: 198-203.

Integer goal programming (GP) was applied to the selection of Tennessee Valley Authority (TVA) water resources projects. Benefit-cost data for TVA water projects from 1965 to 1973 were used to illustrate the usefulness of integer GP as an alternative decisionmaking tool. Two objectives—economic development and environmental quality—goal levels, and goal weights for the study are discussed. Several runs were conducted using different weights and levels, with the original run giving equal weighting to both objectives. Comparisons were made between: (1) a run in which the economic objective has a higher goal level and one in which environmental quality is the higher goal, and (2) a run in which both goal weights and levels favor economic development and one where both favor environmental quality. The resulting schedules, net present value (NPV), and output levels were compared for actual TVA project selections, an integer-programming model that maximizes NPV, and the integer GP model with equal weights and goal levels that favor economic development.

106. Pouwels, H. M.; Wind, H. G.; Witter, V. J. 1995. **Multiobjective decision making in integrated water management.** Physics and Chemistry of the Earth. 20(3-4): 221-227.

Examines the usefulness of a general MADM technique in evaluating alternatives for water management in the Netherlands. Problem formulation, criteria, measures, and the MADM algorithm used in the study are described, and the significant effect of uncertainties on the ranking of alternatives is discussed.

107. Yoon, Jae-Heung; Shoemaker, Christine A. 1999. **Comparison of optimization methods for ground-water bioremediation.** Journal of Water Resources Planning and Management. January/February: 54-63.

Compares the computational performance of three classes of algorithms in the selection of a cost-effective policy for ground-water bioremediation. Algorithm classes evaluated include: (1) evolutionary algorithms, specifically, real-coded genetic algorithms (RGA), binary-coded genetic algorithms (BIG), and derandomized evolutionary strategy (DES); (2) direct search methods, specifically, modified simplex (MSLX), Nelder-Mead simplex (NSLX), and parallel directive search (PDS); and (3) derivative-based optimization methods, specifically implicit filtering for constrained optimization (IFFCO) and a version of SALQR. The use of simulation to generate the impacts of alternative ground-water pumping policies on system characteristics of interest is described. This simulation model is linked to the optimization methods to determine optimal bioremediation policy. SALQR consistently performed the fastest, though no algorithm produced the best solution in all cases. The BIGA method was considered a poor choice for use in ground-water bioremediation.

108. Zsuffa, I.; Bogardi, J. J. 1995. **Floodplain restoration by means of water regime control.** Physics and Chemistry of the Earth. 20(3-4): 237-243.

ELECTRE II was used to evaluate several restoration techniques for a flood plain in Hungary. Results of the case study showed that ELECTRE II and MADM in general are effective in helping decisionmakers choose the "best compromise" alternative based on specific preferences.

MCDM Applications to Fisheries

109. Mardle, Simon; Pascoe, Sean. 1999. **A review of applications of multiple criteria decision-making techniques to fisheries.** Marine Resource Economics. 14: 41-63.

A comprehensive survey of MCDM that have been applied to issues related to fishery management case studies are categorized by multiple objective programming (MOP, MADM, and other MODM). MOP includes goal programming, generating methods, and nonlinear MOP. MADM include multiattribute utility theory and the analytic hierarchy process; multilevel programming is included as an "other" MODM. The basic formulation of each model and its application and limitations are discussed. MCDM have great potential for improving fisheries management policy because of their flexibility.

110. Önal, Hayri. 1996. **Optimum management of a hierarchically exploited access resource: a multilevel optimization approach.** American Journal of Agricultural Economics. 78: 448-459.

Presents a multilevel optimization method for choosing the best policy options for open-access resources that are subject to hierarchical decision processes. The method is applied to fisheries management planning, specifically, the perspectives of management authority and individual users (or user groups) in making decisions concerning shrimp harvests in Texas. A single-level mathematical program formulated to maximize total net revenue from all fishing activities and a multilevel formulation and potential solution methods are discussed. The model is applied to scenarios for both regulated and unregulated management.

Other Environmental Applications

111. Bonano, E. J.; Apostolakis, G. E.; Salter, P. F.; Ghassemi, A.; Jennings, S. 2000. **Application of risk assessment and decision analysis to the evaluation, ranking and selection of environmental remediation alternatives.** Journal of Hazardous Materials. 71: 35-57.

Presents a framework for combining risk assessment and a MADM for the selection of remediation alternatives at a hazardous waste site, and how it would be used to assess the impacts of alternatives, incorporate public participation, educate stakeholders regarding risks, and generate good, defensible solutions. Four framework components preliminary analysis, decision-analysis impact assessment and integration, and deliberation of integration results are described. Decision analysis entails: 1) structuring the problem as a decision hierarchy, specifically impact categories, objectives, and performance measures, and 2) the use of the analytic hierarchy process (AHP) and fuzzy theory to determine the relative importance of each element at each level of the hierarchy. Simple pairwise comparisons are used to rate impact categories and the objectives within each of those categories. Performance measures were evaluated by AHP and fuzzy logic to define utility functions that described the level of “goodness” for the range of possible performance for each measure. Impact assessment was used to evaluate the performance of each alternative on each performance measure. Risk assessment was used to convert these values into utility functions so that uncertainties could be captured. The result was a ranking of all remediation alternatives for each stakeholder and a mean ranking for each alternative from the group as a whole. The deliberation process was used to determine how consensus was reached among all stakeholders on a “best” solution.

112. Cooper, W. W.; Hemphill, H.; Huang, Z.; Li, S.; Lelas, V.; Sullivan, D. W. 1996. **Survey of mathematical programming models in air pollution management.** European Journal of Operational Research. 96: 1-35.

Describes current MODM research in air pollution management to include institutions involved, regulatory activity, risk management, and selection of management goals and attributes. Basic mathematical programming approaches that are surveyed include deterministic programming, which is illustrated using linear programming and goal programming, and stochastic programming, which is illustrated with a chance-constrained programming model. The application of these and two additional approaches to problems related to management are discussed.

113. Hokkanen, Joonas; Salminen, Pekka. 1997. **Choosing a solid waste management system using multicriteria decision analysis.** European Journal of Operational Research. 98: 19 36.

ELECTRE III was applied to the selection of a municipal solid waste-management system in northern Finland. This method was chosen because it is fast and easy to use, data were imprecise, and numerous decisionmakers were involved who provided little information on preferences. Results are presented as a ranking of the alternatives; the impact of sensitivity analysis on those rankings is discussed. This technique is useful for situations in which keeping decisionmakers informed is a requirement.

114. Tecle, Aregai; Fogel, Martin. 1986. **Multiobjective wastewater management planning in a semiarid region.** Hydrology and Water Resources in Arizona and the Southwest. 16: 43-61.

ELECTRE and compromise programming were used in the selection of the “best” design for a wastewater treatment facility in Nogales, Arizona. The same alternative was selected with both models.

Decision-Support Systems

115. Brack, Christopher L.; Marshall, Peter L. 1996. **A test of knowledge-based forest operations scheduling procedures.** Canadian Journal of Forest Research. 26: 1193-1202.

Solution outputs were compared for three knowledge-based search routines, two expert systems, linear programming (LP), mixed integer programming (IP), and simulation methods that were applied to two forest plantations in Australia. A set of operations schedules were compared for each site. An algorithm rated each alternative on the basis of timber-yield flows, scenic beauty, stand health, and water quality. The expert systems and search routines performed well relative to the IP and simulation techniques. The LP model generated higher timber flows than most of the other methods; one expert system produced an even higher flow using nonstandard management regimes. Knowledge-based approaches and expert systems do not attempt to create optimal plans, but their flexibility can generate good solutions.

116. Gurocak, Elizabeth Reilly; Whittlesey, Norman K. 1998. **Multiple criteria decisionmaking: a case study of the Columbia River salmon recovery plan.** Environmental and Resource Economics. 12(4): 479-495.

A salmon recovery plan for the Columbia River was used as a case study to compare the performance of two MCDM—simple additive weighting and the interactive method—with a fuzzy expert system. Each method ranked alternatives on the basis of five attributes. The methods are compared on the outputs obtained by the highest ranked alternatives. Unlike the MCDM solutions, alternatives selected by the fuzzy expert system always were appropriate, that is, decision rules were satisfied.

117. Hong, Hyoo B.; Vogel, Doug R. 1991. **Data and model management in a generalized MCDM-DSS.** Decision Sciences. 22: 1-25.

Describes a method for designing a decision-support system (DSS) that supports an organization in formulating and solving multi-criteria problems. The typical multi-attribute method of representing alternatives is reviewed. Multi-criteria models are categorized, and various choice methods are described. Whether compensatory or noncompensatory, the models are categorized according to the cognitive demands on decisionmakers. Choice rules discussed include the additive, additive-difference, dominance, conjunctive, disjunctive, lexicographic, and elimination by aspects models. A set of principles for guiding the selection of an appropriate choice rule is suggested, and the process of executing the chosen model is described. The basic DSS architecture and prototype model (ISBIS) are described, and two examples of the applicability of the approach are provided.

118. Malczewski, Jacek; Jackson, Marlene. 2000. **Multicriteria spatial allocation of educational resources: an overview.** Socio-Economic Planning Sciences. 34: 219-235.

In response to criticism of optimization (MODM) techniques, decision-support systems are being used to facilitate the allocation of education resources. Typical allocational issues related to educational resources are reviewed, and basic multiobjective formulation and several models that have been applied to allocation issues are presented. Typical planning attempts use data envelope analysis (which is based on a mathematical programming model), parametric programming, and goal programming. As an alternative approach to educational resource planning, it is proposed that multi-criteria decision techniques and a geographic information system be combined into an interactive Spatial Decision-Support System (SDSS) to take advantage of the visualization capabilities of an interactive SDSS.

119. Naesset, Erik. 1997. **A spatial decision support system for long-term forest management planning by means of linear programming and a geographical information system.** Scandinavian Journal of Forest Research. 12: 77-88.

Describes SGIS, a decision-support system that integrates a geographic information system and linear programming into a strategic planning system. Although limited to areas with no more than 2,000 stands, SGIS simulates the effects of treatment schedules, selects the optimal schedule, and generates maps and tables. SGIS was applied to a 719-ha, 872-unit forest in southeast Norway to determine the impact of establishing restricted-use buffers around water bodies with respect to net present value (NPV) and timber volume. The buffer areas resulted in a reduction in NPV of nearly 7 percent and reduction in timber volume of about 10 percent. Although SGIS is a valuable planning tool, it is not applicable to large areas nor can it incorporate spatial constraints into the optimization process.

120. Olson, Craig M.; Orr, Bruce. 1999. **Combining tree growth, fish and wildlife habitat, mass wasting, sedimentation, and hydrologic models in decision analysis and long term forest land planning.** Forest Ecology and Management. 114: 339-348.

Discusses the trend toward using MCDM in conjunction with other processes and models to develop a more diverse and comprehensive approach to forest management planning. The methodology outlined is intended for landscape-scale management situations and has been applied to areas ranging in size from 50,000 to 230,000 acres. Models that were incorporated into this planning process include digital terrain models, site-quality information, vegetation-class data, timber growth and yield models, and a watershed risk index. Linear programming was used to maximize the present net value of management activities subject to numerous constraints.

121. Purao, Sandeep; Jain, Hemant K.; Nazareth, Derek L. 1999. **Supporting decision making in combinatorially explosive multicriteria situations.** Decision Support Systems. 26: 225-247.

Presents a decision support system based on multi-objective and multi-attribute decision theory as an effective method for addressing problems characterized by a “combinatorially explosive” number of solutions and many conflicting criteria. A weakness of three categories of solution procedures, analytical, genetic algorithm-based, and heuristic approaches, is their inability to support decisionmaker learning. The first step in the proposed decision support system entails a “broad exploration of the search space.” Information gathered on search space limits and behavior is given to the decisionmaker to facilitate educated preference input in later stages. The second step consists of deep probes into promising search space regions. The decisionmaker is guided in an iterative and systematic process of exploring alternatives, steering the direction of the search by the specification of his or her preferences. The model provides information about unexplored regions of the decision space to the decisionmaker by assessing the likelihood of improving on the current solution’s levels of attainment for each criterion. When applied to a client/server architecture problem, this method places only moderate demands on the decisionmaker and quantifies the risk of stopping the search process at any point.

122. Rauscher, H. Michael. 1999. **Ecosystem management decision support for federal forests in the United States: a review.** Forest Ecology and Management. 114: 173 197.

Presents a generic decision-support system (DDS) for ecosystem management on federal forests. The typical adaptive management process as it is applied to ecosystem management is discussed and 33 ecosystem management DSS are compared. Decision methods (MODM) are discussed as a single component in a much larger planning process.

123. Tecle, Aregai; Shrestha, Bijaya P.; Duckstein, Lucien. 1998. **A multiobjective decision support system for multiresource forest management.** Group Decision and Negotiation. 7: 23-40.

Describes FORMDSS, an interactive, multiobjective decision support system that incorporates both compromise programming and cooperative game theory into a single tool for resource management. Data are from a pine forest in north-central Arizona managed for multiple objectives. Five objectives, each of which is based on a single variable—square feet of tree basal area per acre—are intended to represent the views of a different interest group or decisionmaker. For each objective, a graph specifies the relationship between basal area and a particular resource goal, and indicates the level of utility that would be achieved by a group advocating the maximization of that resource. This relationship is described mathematically as a time-invariant continuous function. Tradeoffs that occur across different basal-area densities are demonstrated for both MCDM. The objectives were given equal weights to identify a narrow range of basal-area densities that all (hypothetical) decisionmakers found satisfactory. FORMDSS can handle any number of objective functions, allows for easy modification of preference structures and other model parameters, and facilitates understanding through graphical representation of model inputs and outputs.

124. Varma, Vive K.; Ferguson, Ian; Wild, Ian. 2000. **Decision support system for the sustainable forest management.** Forest Ecology and Management. 128: 49-55.

Describes a decision support system for forest management that combines geographic information systems (GIS), a heuristic, and linear programming (LP) in a flexible model that addresses uncertainty and maximizes the utility derived from the products generated through alternative management plans. LP generates the optimal land allocation solution and then the spatial distribution of these uses is solved with a heuristic algorithm. Although this heuristic does not guarantee that the optimal utility level generated in the LP model will be attained, this approach should be effective when sustainability in forest management is an issue.

Author Index

Glossary

0 — 1 Integer Programming (see **Binary Integer Programming).**

1 opt, 2 opt — concepts in heuristic timber harvest scheduling. With 1-opt moves, only one attribute of one decision choice is altered, i.e., a unit is removed from the harvesting schedule. In 2-opt moves, that attribute is changed for two decision choices simultaneously, i.e., one unit is added to the harvest schedule while another is removed.

Adjacency Constraints — constraints in mathematical programming that control the occurrence of spatially related activities, e.g., the harvesting of timber in adjacent forest plots.

Algorithm — in mathematics, any computational procedure (see Simplex Method as an example).

Analytic Hierarchical Process (AHP) — a decision method in which a complex problem is structured as a hierarchy involving goals, criteria, objectives and alternatives; pair-wise comparisons of criteria and alternatives result in the specification of a preferred solution.

Area-Restricted Model (ARM) — a concept in timber harvest modeling with adjacency constraints. If management units are significantly smaller than the area limit of the adjacency constraint, then harvest of adjacent units does not necessarily violate the constraints and the ARM is used (see URM).

Binary Coded Genetic Algorithm (BIGA). See Genetic Algorithm and 0 - 1 Integer Programming.

Binary Integer Programming — a form of integer programming in which the values of the decision variables are restricted to 1 or 0.

Branch and Bound Algorithm — a technique that uses an efficient search algorithm for solving integer programming problems.

Bridging Analysis Models (BAM) — a method for decomposing optimal strategic-level solutions into optimal tactical-level plans on forests.

Compromise Programming (CP) — a solution technique that uses distance metrics to weight various objectives to account for their different importance to the decisionmaker. The alternative with the lowest summed deviation from the objectives is designated as the "best" solution.

Constraints — limits placed on and thus defining a problem's solution space, usually in the form of equations stated as mathematical equalities or inequalities.

Cooperative Game Theory — a form of game theory in which the participants cooperate to find a solution as opposed to noncooperative solutions, i.e., participants compete against each other.

Decision Support Systems (DSS) — a class of interactive computer-based systems and subsystems that help decisionmakers use data, documents, knowledge, and/or models to identify and solve problems and make decisions.

Dominated Solutions (see **Inferior Solutions).**

Dynamic Programming (DP) — a problem-solving approach that allows a large problem to be broken into a series of smaller problems or stages. The solution of all the smaller individual problems results in an optimal solution to the large problem.

Economically Inefficient (efficient) Solutions — solutions to economic cost-benefit analyses where costs are greater (less) than benefits.

ELECTRE, ELECTRE 1, 2, 3 — MADM techniques that facilitate decisionmaking by reducing the number of feasible alternatives to be considered.

Feasible Solution — A solution that satisfies all of the specified constraints (see Infeasible Solution).

FORMDSS — an interactive, multiobjective decision support system that incorporates both compromise programming and cooperative game theory into a single tool for resource management.

FORPLAN — FORest PLANning model; a linear programming approach used by the USDA Forest Service for land management planning.

Four Color Theorem — related to timber harvest scheduling with adjacency constraints. For problems that require adjacent units to be harvested no less than a specified number of years apart (the exclusion period), this theorem implies that a feasible solution is possible so long as the project period length divided by the exclusion period length is less than or equal to four. The theorem name is derived from the four colors used in mapmaking, for example, to distinguish different political states on a map.

Fuzzy Logic — an approach to computing based on degrees of truth rather than the usual "true or false" (i.e., 1 or 0). Includes 0 and 1 as extreme cases of truth, but also the various states of truth in between so that, for example, the result of a comparison between two things could be not "tall" or "short" but " .38 of tallness."

Fuzzy Programming — mathematical programming that uses fuzzy logic (see Fuzzy Logic).

Generating Methods — Techniques for identifying tradeoffs that are necessary among each of the decision alternatives. This information is presented to the decisionmaker who selects the most preferred option.

Genetic Algorithm (GA) — a heuristic solution algorithm in which the first step is generating a "population" of random solutions that are represented as "strings" composed of binary values for each decision variable. Each value corresponds to an "allele" on the string, which represents DNA; hence the name.

Geographic Information System (GIS) — a computer system for entering, processing, analyzing, and displaying spatial data and information, often a map-like format.

Goal Programming (GP) — a technique for solving multiobjective decision problems within the framework of linear programming. Target values are established for a set of separate goals and the programming objective is to minimize the collective deviation from these targets.

HERO — a utility-based heuristic method for addressing harvest scheduling problems that explicitly considers biodiversity.

Heuristic Techniques — methods for problem solving through experimentation and especially trial and error. They are typically used for computationally hard-to-solve problems and seek a compromise between a quick feasible solution and a feasible solution that is optimal.

Hierarchy — a structure for a decision problem using various levels consisting of goals, criteria, objectives, and decision alternatives (see AHP).

Infeasible Solution — occurs when two or more constraints have been specified that cannot be satisfied simultaneously, for example, simultaneous satisfaction of $x > 100$ and $x < 75$ is infeasible.

Inferior Solutions — solutions that are not Pareto optimal; also known as locally efficient solutions or dominated solutions.

Integer Programming (IP) — a problem-solving approach like linear programming except that decision variables are integers rather than continuous values.

Integrated Resource Planning Model (IRPM) — an integer programming planning model used by the USDA Forest Service.

Lagrangian Relaxation — a mathematical programming technique for performing constrained optimization through the introduction of Lagrangian multipliers—which are arbitrary non-zero constraints—to the constraints.

Lexicographic Goal Programming — a technique that assigns absolute priorities to the goals. Also called preemptive GP, this approach satisfies the multiple objectives sequentially in the order established by the priorities.

Linear Programming (LP) — a mathematical problem-solving approach that entails maximization or minimization of a single linear objective function subject to multiple linear constraints.

MAXMIN Model — attempts to maximize the minimum payoff; generally said to be a betting pessimist's strategy. Some argue that MAXMIN finds a socially "just" solution in the sense that it identifies the best possible outcome for members of society who are most needy.

Metropolis Algorithm (MA) — a timber-harvest scheduling algorithm related to the Monte Carlo heuristic technique.

Mixed Integer Program — a mathematical program that uses both integer and continuous decision variable.

Model I Formulation, Model II Formulation — two methods for defining decision variables in a timber harvest scheduling problem. With Model I, decision variables are the same for both original and regenerated stands. With Model II, different decision variables are defined for the original and the regenerated stands.

Modeling to Generate Alternatives (MGA) — the use of mathematical programming models to generate a series of possible alternative decision choices from which the decisionmaker chooses the preferred alternative.

Monte Carlo Heuristic Techniques — heuristic solution methods using simulations analogous to the probabilistic outcomes of roulette played in the casinos of Monte Carlo.

Monte Carlo Integer Programming — a heuristic solution method for integer programs involving the use of probabilistic inputs generated by a Monte Carlo process.

Multi-Attribute Decision Models (MADM) — a subdivision of MCDM, MADM support the selection of the "best" decision alternative from among several possibilities. Examples of MADM methods include the Analytic Hierarchy Process and Multi-Attribute Utility Theory.

Multi-Attribute Utility Theory (MAUT) — assumes that an individual can select among obtainable alternatives in a way that maximizes the amount of satisfaction he/she derives from that choice. This theory assumes that individuals are aware of the alternatives available to them and are capable of evaluating those alternatives.

Multi-Criteria Decision Models (MCDM) — refers to a variety of quantitative techniques used to facilitate decisions involving multiple, competing objectives or goals. MCDM were first developed for military strategic decisionmaking but have been expanded to include such diverse fields as financial planning, real estate investment, reservoir control, water distribution, solid waste management, energy planning, manufacturing, and forest management. Often subdivided into MODM (Multi-Objective Decision Models) and MADM (Multi-Attribute Decision Models).

Multi-Objective Decision Model (MODM) — a subdivision of MCDM, MODM support the design of superior decision alternatives; methods include linear, goal, and integer programming.

Multi-Objective Programming (MOP) — programs that require the simultaneous optimization of more than one objective function. This method optimizes each separate objective function followed by an interactive search for a compromise solution that is Pareto optimal; also called Multi-Objective Linear Programming.

Network Analysis — a graphical description of a decision problem in terms of nodes and interconnected arcs enabling solutions to problems related to transportation, information systems, and project scheduling.

Non-Inferior Set Estimation (NISE) — a multi-objective programming solution algorithm that uses repeated linear programming solutions to generate an estimate of a non-inferior set.

Non-convex Decision Space — a decision space or choice not involving a decreasing rate of technical substitution, i.e., not bowed toward the origin.

Non-Dominated Solutions (see **Non-Inferior Solutions).**

Non-Inferior Solutions — solutions that are Pareto optimal; also known as globally efficient or non-dominated solutions.

Non-linear Programming — an alternative to linear programming that uses a non-linear objective function.

Objective Function — an equation that expresses mathematically the goal of a decision problem/ usually stated as a maximization of minimization problem.

Optimal Solution — a best solution, i.e., the attainment of a maximum or minimum value subject to specified constraints.

Pareto Optimal — a feasible solution such that no other possible solution is superior to it.

PARETO RACE — a type of decision support system that enables a decisionmaker to freely search the efficient frontier of a multiple objective quadratic-linear programming problem by controlling the speed and direction of motion.

Programming — a general term applied to a host of mathematical planning techniques, including linear, goal, integer, and non-linear programming.

Recursive Dynamic Programming — a solution method by which a large problem is divided into smaller problems or stages; each of the smaller problems is solved in sequence, feeding into the next higher stage.

SGIS — a decision support system that integrates a geographic information system and linear programming into a single planning system.

SHARe Model — a harvest planning model that uses spatial constraints but also allows temporal management considerations.

Shortest Path Network Flow Model — a network model by which the optimal problem solution is found by the shortest path between any pair of nodes in the network.

Simple Additive Weighting (SAW) — an MCDM method.

Simplex Method — an algebraic procedure for solving linear programming problems.

Simulated Annealing (SA) — a heuristic solution method based on simulation of the material tempering process know as annealing.

Simulation Modeling — a technique in which computers typically are used to model the operation of a complex system by abstracting, simplifying, and hence simulating the true system.

SNAP 11+ — a harvest scheduling program that uses an integer programming formulation and a heuristic solution algorithm.

STEM — a Modeling to Generate Alternatives technique for forest planning applications.

Stochastic Programming — a form of mathematical programming in which the inputs are uncertain and subject to variation; this contrasts with deterministic models in which the inputs are certain and not subject to variation.

Successive Approximation Linear Quadratic Regulator (SALQR) — a software program that has been used for optimization problems in which non-linear simulation equations are made linear in the optimization step.

Surrogate Worth Trade-Off (SWT) — a utility-based algorithm.

TABU search — a heuristic solution method that relies upon near-neighbor solutions that can be reached directly from an initial solution by a single move, i.e., adding a unit, removing a unit, or exchanging two units.

Trigger Constraints — constraints of mathematical programming problems invoked or “triggered” by predetermined conditions.

Unit Restrictive Model (URM) — refers to timber harvesting with adjacency constraints. Applied when management units are so large that the harvest of two adjacent units would necessarily violate adjacency constraints (see ARM).

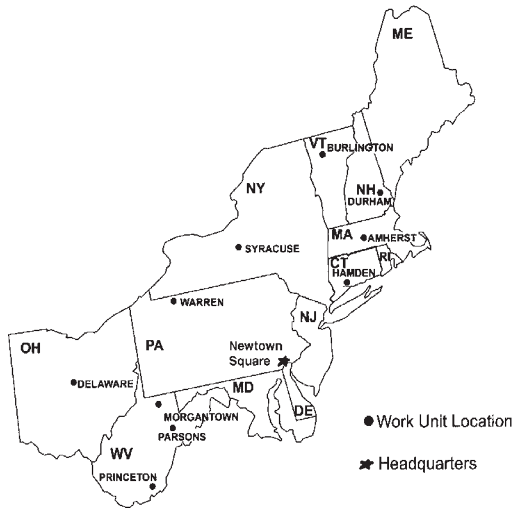
Vector — in mathematics, a [1 x n] matrix.

Weighting Methods — used to indicate the relative importance of the evaluation criteria to the decisionmaker. Examples of weighting methods are fixed point scoring, rating, ordinal ranking, graphical weighting, and paired comparisons.

de Steiguer, J. E.; Liberti, Leslie; Schuler, Albert; Hansen, Bruce. 2003. **Multi-criteria decision models for forestry and natural resources management: an annotated bibliography.** Gen. Tech. Rep. NE-307. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 32 p.

Foresters and natural resource managers must balance conflicting objectives when developing land-management plans. Conflicts may encompass economic, environmental, social, cultural, technical, and aesthetic objectives. Selecting the best combination of management uses from numerous objectives is difficult and challenging. Multi-Criteria Decision Models (MCDM) provide a systematic means for comparing tradeoffs and selecting alternatives that best satisfy the decisionmaker's objectives. In recent years, the use of MCDM in forestry and natural resources management has generated a substantial body of literature. This annotated bibliography includes 124 important references ranging from theoretical studies to real-world applications of MCDM.

Keywords: linear programming, goal programming, mathematical programming, dynamic programming, hierarchical programming, heuristics



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