Operations Research in Forestry

Maarten Nieuwenhuis

Department of Forestry, University College Dublin.

Summary

The applications of Operations Research techniques in forestry and forest industries are numerous. The most widely used mathematical models are: linear programming, integer programming, goal programming, dynamic programming, network analysis, and computer simulation. The demand for improved efficiency, combined with multiple-use requirements, and the availability of computers, will result in a continuing increase of the use of Operations Research in natural resource managerial decision-making.

Introduction

Operations Research (OR) is the development and application of scientific optimization techniques for the management of organizations or systems. From early on, natural resource management has been recognized as an area extremely suitable for the implementation of OR. Five factors, which are common to most management problems in forestry, make it possible to use a wide range of OR solution procedures which have been developed to assist in managerial decision making.[14] These five factors are: a complex environment; one or more specific objectives; doubt about the best course of action; decisions constrained by limited resources; and the possibility to quantify the problems.

Each OR solution technique involves the construction of a mathematical model.[24] This is a set of mathematical statements that collectively describe the workings of an organization or system. Mathematical programming, a sub-discipline of OR, involves the use of these mathematical models to solve managerial decision making problems.[56] The specific model used in each case depends on the nature of the problem, and can be deterministic or probabilistic; analytical or numerical; linear or non-linear. This article describes a number of mathematical programming techniques and their application in forestry. It has to be emphasised that OR procedures should be used as an aid to decision making, not as a replacement of the decision maker.

IRISH FORESTRY, 1989, Vol. 46 (1): 51-58

Linear Programming (LP)

Soon after the development of the LP technique by George Dantzig during World War II, applications were developed in the area of forest management. These range from harvest scheduling[25,29] and stand management[17] to transport planning[42] and planning of production in pulp and saw mills.[55]

The name implies the use of a linear model, both in objective function and constraints. A further four conditions have to be satisfied in order to be able to use LP: proportionality, additivity, non-negativity, and continuity.[31] Without discussing these conditions any further, experience has shown that these requirements do not restrict the use of the procedure, and it has become the most widely used method of all OR techniques. The basic model consists of an objective function and a set of constraints. The objective function can be either a maximization (profits, stumpage prices, timber volumes, etc.) or a minimization (costs, earth movement, time, etc.) and expresses the alternative courses of action. The constraints express the limitations on resources, such as land, labour, machines and capital. Additional constraints can be used to include such diverse conditions as equal annual cut volumes and the restriction of machine operations on certain terrain types.

Linear programming models can be constructed at any scale or precision, because computers have made it possible to solve very large problems quickly. The most important restriction on size and complexity is the capability of the modeler to visualize the complex interactions embedded in the models.

One important aspect of LP is that it not only gives an optimal solution to the model, but at the same time a wide range of sensitivity analysis information is provided. In many cases the actual solution is of less importance than the information on the influence of changes in costs and profits and the availability of limited resources on the optimal strategy.

Integer Programming (IP)

One of the conditions on using the LP model is the continuity of the variables, which means that any positive value is allowed. In certain cases, however, it is necessary to restrict the values of all or some of the variables to positive integers. In these cases the LP technique cannot be used and special IP solution procedures have to be employed.[26]

Examples of integer variables are the number of trucks scheduled for a haulage operation, the number of fellers in a clearfell, and the number of machines available. A special type of integer variable is the 0-1 variable.[15] For instance, a stand can be scheduled for clearfell in a certain year or it may be retained. The 0-1 variable in the optimal solution will either have a value of 0 (retained) or 1 (scheduled). Similarly, a machine can be bought or not, a sawmill constructed or not, etc. Zero-one variables are also used for the inclusion of spatial and chronological restrictions in models.[34,57] For instance, a stand cannot be replanted unless it has been clearfelled, or a road has to be built before harvesting can start.[52]

Because of the complexity of the solution methods for IP models, LP techniques are often used, followed by a rounding-off of the integer variables. In some cases this can lead to satisfactory results, but often, especially in the presence of 0-1 variables, this will result in sub-optimal or meaningless solutions.

Goal Programming (GP)

Many decision problems in natural resource management have multiple objectives. Most public forests, for example are managed for multiple uses, such as timber production, wildlife, and outdoor recreation. A restriction of LP models is the condition that only one objective function is allowed. If the multiple objectives are in conflict with each other, one objective function cannot be formulated. In that case, GP might be the answer. GP minimizes the deviations from multiple goals, subject to constraints. This requires that both objectives and desired goal levels can be quantified, and in addition, the decision maker has to be able to rank the objectives in order of their preference. These requirements have limited the use of GP. At the same time, many applications have been developed in forest management, especially in multiple-use contexts. Examples are management of small private woodlands,[51] land use planning,[1] Christmas tree production,[22] and outdoor recreation planning.[16] The increasing demands of society on the use of forests for purposes other than timber production,[28] and the question of afforestation of large areas in sensitive landscapes make GP a technique which will become more attractive in the future.

Dynamic Programming (DP)

Certain types of decision problems involve making a sequence of interrelated decisions in such a way that overall effectiveness is maximized. Many of these problems can be solved using LP, but in some cases the resulting models are very complex and DP techniques can mean a significant simplification. No standard mathematical formulation exists that applies to all DP problems, nor is there a standard solution procedure. Because of this, DP has not been used very widely, but a few good applications have been developed in forestry. The best known model issued for the optimal crosscutting of stems.[18,43] A decision made at the butt end of the stem (e.g. to cut off a 3 or 4 metre log) is obviously going to influence the possibilities further along the stem. In cases where there are many possible assortments, the optimal crosscutting of stems can mean significantly increased profits as compared with sub-optimal solutions.[20] Other applications of DP are in the area of stand management,[5] pest management,[39] forest road location,[12] and forest fire detection.[41]

Network Analysis (NA)

The group of network analysis models consists of a large variety of techniques. The network can be a geometric network, such as a road system or a flow pattern in a saw mill, or an abstract network pertaining to the order of events or the flow of information within a project. Almost all NA problems can be solved using LP or IP techniques, but because of their relative simple structure, special procedures have been developed which solve the problems more efficiently.

The best known of the NA techniques are the transportation model and the shortest path model, which are used for the analysis of geometric networks, and the Critical Path Method (CPM) and Project Evaluation and Review Technique (PERT) which are used for project scheduling. The transportation problem is concerned with transporting goods or services from multiple supply centres to multiple demand centres in an optimal manner. Examples of situations where the transportation model can be used are: the minimization of earthwork transportation during forest road construction;[3] the transportation of timber to processing locations and the distribution of finished products to customers;[9,44,45] the movement of logging equipment from sites where harvesting has been completed to new sites; and the supply of seedlings from nurseries to planting sites.[14]

The shortest path problem deals with finding a route between two points in a network which is minimized with respect to distance, cost, time or some other appropriate quantity. Examples of the use of the shortest path model in forestry are: scheduling of logging trucks;[6] the planning of forest transportation networks;[38,47] and the analysis of forest fire behaviour.[30]

In addition to the transportation and the shortest path models, a large group of other techniques exist, such as the minimum spanning tree model, the maximum flow model, and a collection of procedures known as locational models, dealing with the optimal location of facilities in a network. Examples are: the location of a logging camp to serve a group of logging sites; the location of a garage to serve the roads within a network; and the location of a road network to serve a forest area.[37]

Both CPM and PERT deal with the scheduling of projects, where the objective is to minimize the total duration.[58] The major distinction between the two is that CPM is a deterministic model whereas PERT is probabilistic in nature. Both models are based on the fact that certain operations have to be completed before others can start. Examples of applications in forestry are planning and control of harvesting operations,[40] timber sale preparation,[11] forest road construction,[46] and sawmill modernization.[32]

Computer Simulation

Simulation is frequently described as the process of duplicating the essence of a system without attaining the reality of that system.[19] The construction of a simulation model can take three forms: physical, symbolic, and mathematical. Computer simulation deals with a mathematical model describing the system in terms of mathematical equations.

The main disadvantage of simulation is that unlike other OR techniques, it does not provide optimal solutions directly. Simulation is a trial-and-error (heuristic) approach to problem solving. It is an appropriate analytical approach where it is not feasible to experiment with the actual system, or when the complexity of the system prevents the use of other analytical techniques. Infeasibility can arise because of costs, risk of disrupting the system, unavailability of the system for experimentation, or non-existence of such a system. Examples of the use of simulation in forestry include: forest machinery and systems design;[8,33,59] harvesting and transportation systems analysis[13,21,23,54]; sawmill design and layout;[4] and policy evaluation.[49]

The use of simulation has a number of additional advantages. The detailed observation of the system required to construct the model can lead to improved understanding of the system, and might even remove the need for a simulation model. Also the use of simulation is a teaching device for developing skills in analysis and decision making.

Implementation

For all of the techniques discussed above, the use of computers is essential. Small problems can be solved by hand, but the application of OR procedures to real-world problems requires large amounts of computational capacity. During the last two decades a large collection of OR routines has been developed, both for mainframe and micro computers. This includes specialized packages for natural resource management and forestry, such as Timber RAM[35] and LOGPLAN[36]. But for many applications general OR packages such as LINDO[50] and SAS/OR[10] for mainframe, and QSB[7] for micro, are more than adequate.

Recent developments involve the combination and integration of OR techniques and management information systems. For instance, a combination of network analysis and LP makes it possible to integrate road location and transport scheduling with harvest planning.[27] The integration of OR models in Geographic Information Systems makes the spatial and descriptive data bases directly available to the mathematical programming models. Research in this area focuses on forest road location[37] and harvest scheduling[2,48]

These new developments provide the decision maker in the field of forest management with the necessary tools, given the continuing demand for improved efficiency, combined with the increased implementation of multiple-use policies in natural resource management.

REFERENCES

1. BELL, E. F. 1976. Goal Programming for Land Use Planning. USDA Forest Service General Technical Report PNW-53.

2. BOSS, D. E. and CORCORAN, T. J. 1986. Local/Enterprisal Strategic Forest Planning as Assisted by Computerized Cartographic Modeling. Proceeding FAO/ECE/ILO Seminar. Oosterbeek, the Netherlands.
3. BOUGHTON, W. C. 1967. Planning and Control of Forest Roads by Linear Programming. Australian Forestry 31:111-120.
4. BRADLEY, D. E. and WINSAUER, S. A. 1978. A Brief GPSS Workbook and its Use in Solving a Sawmill Log Yard Problem. Workshop Paper, IUFRO Conference, Wageningen, the Netherlands.
5. BRODIE, J. D. and KAO, C. 1979. Optimizing Thinning in Douglas-fir with Three-Descriptor Dynamic Programming to Account for Accelerated Diameter Growth. Forest Science 25:665-672.
6. CARSON, W. W. and DYKSTRA, D. P. 1978. Programs for Road Network Planning. USDA Forest Service General Technical Report PNW-67.
7. CHANG, Y. and SULLIVAN, R.S. 1986. Quantitative Systems for Business. Prentice-Hall Inc.,Englewood Cliffs, NJ, USA.
8. CORCORAN, T. J. and SAMMIS, R. A. 1974. A GPSS Planning Model for Large Scale Strip Harvesting. Proceedings 1974 Winter Simulation Conference, Washington D. C., USA. pp221-215.
9. CORCORAN, T. J. and NIEUWENHUIS. M. A. 1985. Modeling Wood Flow under Salvage Conditions. Council on Forest Engineering Proceedings, Tahoe City, CA, USA.
10. COUNCIL, K. A. (Editor), 1983. SAS/OR User's Guide, 1983 Edition, SAS Institute Inc. USA.
11. DAVIS, S. S. 1967. An Adaptation of the Critical Path Method of Resource Allocation. Department of Natural Resources, State of Washington, USA. DNR Report 11.
12. DOUGLAS, R. and HENDERSON, B. 1987. Computer Assisted Forest Route Location. Council on Forest Engineering Proceedings, Syracuse, NY, USA. pp201-214.
13. DREMANN, A. P. TREESIM: A New Analysis Tool for Harvest System Evaluation. Council on Forest Engineering Proceedings, Tahoe City, CA, USA. pp86-89.
14. DYKSTRA, D. P. 1984. Mathmatical Programmming for Natural Resource Management. McGraw-Hill, New York, NY, USA.
15. DYKSTRA, D. P. and RIGGS, J. L. 1977. An Application of Facilities Location Theory to the Design of Forest Harvesting Areas. AIIE Transactions 9:271-277.
16. FIELD, D. B. 1973. Goal Programming for Forest Management. Forest Science 19:125-135.
17. FORNSTAD, B. F. 1971. The Linear Programming Planning System of the Swedish Forest Service. Forestry Commission Bulletin 44: Operations Research and the Managerial Economics of Forestry. pp124-130.
18. GARLAND, J., SESSIONS, J. and OLSEN, E. D. 1987. Optimal Bucking at the Stump. Council on Forest Engineering Proceedings, Syracuse, NY, USA, pp239-248.
19. GARNER, G. J. 1978. Simulation: A Decision Making Aid for Managers. Forest Engineering Research Institute of Canada Technical Report TR-30.
20. GEERTS, J. M. P. 1979. Optimal Crosscutting of Timber. Department of Forest Technique. Agricultural University, Wageningen, the Netherlands.
21. GOULET, D. V., IFF, R. H. and SIROIS, D. L. 1979. Tree-to–Mill Forest Harvesting Simulation Models: Where Are We? Forest Products Journal, Vol. 29(10):50-55.
22. HANSEN, B. G. 1977. Goal Programming: A New Tool for the Christmas Tree Industry. USDA Forest Service Research Paper NE-378.
23. HENDRICKS, G. L. 1984. STALS (Skidding, Trucking and Landing Simulation) User Manual. Tennessee Valley Authority, TN, USA.
24. HILLIER, F. S. and LIEBERMAN, G. J. 1980. Introduction to Operations Research. Holden-Day Inc., San Fransisco, CA, USA.
25. HOEFLE, H. H. 1971. Optimization of the Harvest of Small-Size Wood Through Linear Programming. Forestry Commission Bulletin 44: Operations Research and the Managerial Economics of Forestry. pp1-10.

26. HOF, J. G. and PICKENS, J. B. 1986. A Multilevel Optimization System for Large-Scale Renewable Resource Planning. USDA Forest Service General Technical Report RM-130.
27. JONES, J., G. HYDE, J. F. C. and MEACHAM, M. L. 1986. Four Analytical Approaches for Integrating Land Management and Transportation Planning on Forest Lands. USDA Forest Service Research Paper INT-361.
28. KIRBY, M. W., HAGEN, W. A. and WONG, P. 1986. Simultaneous Planning of Wildland Management and Transportation Alternatives. Studies in the Management Sciences, Vol. 21: System Analysis in Forestry and Forest Industries. pp371-387.
29. KOGER, J. L. and WEBSTER, D. B. 1984. LOST: Logging Optimization Selection Technique. USDA Forest Service Research Paper SO-203.
30. KOURTZ, P. H. and O'REGAN, W. G. 1971. A Model for a Small Forest Fire. . . To Simulate Burned and Burning Areas for Use in a Detection Model. Forest Science 17:163-169.
31. MAKOWER, M. S. 1965. Introduction to Mathematical Programming. Proceedings Mathematical Models in Forest Management, University of Edinburgh, Scotland. pp2-6.
32. MATER, M. H. 1967. PERT – A New Technique for Reducing Sawmill Modernisation Costs. Forest Industries 94(7):36-39.
33. MURPHY, G. 1983. Effect of Method Changes on Cable Logging Production. New Zealand Forest Service FRI Bulletin No. 35.
34. NAUTIYAL, J. C., NGO, H. S. and THADANEY, H. K. 1975. Land Use Model for Planning: A Practical Application of Mixed Integer Programming. Canadian Journal of Operations Research and Information Processing 13(1):19-35.
35. NAVON, D. I. 1971. Timber RAM: A Long-Range Planning Method for Commercial Timberlands under Multiple-Use Management. USDA Forest Service Research Paper PSW-70.
36. NEWNHAM, R. M. 1975 LOGPLAN – A Model for Planning Logging Operations. Forest Management Institute Information Report FMR-X-77. Canadian Forest Service.
37. NIEUWENHUIS, M. A. 1986. Development of a Forest Road Location Procedure as an Integral part of a Map Based Information System. Ph. D. Thesis, University of Maine, USA.
38. NIEUWENHUIS, M. A. 1987. The Use of a Geographic Information System in Computer-Assisted Forest Road Network Analysis. Council on Forest Engineering Proceedings, Syracuse, NY, USA, pp177-184.
39. NORTON, G. A. and HOLLING, C. S. 1976. Pest Management. Pergamon Press. Oxford.
40. NOVOTNY, M. 1971. Application of Mathematical Methods in Operational Planning of Logging Operations. Forestry Commission Bulletin 44: Operational Research and the Managerial Economics of Forestry. pp95-103.
41. O'REGAN, W. G., KOURTZ, P. H. and NOZAKI, S. 1975. Patrol Route Planning for an Airbourne Infared Forest Fire Detection System. Forest Science 21:382-389.
42. PHILLIPS, W. W., CORCORAN, T. J. and BRANN, T. B. 1986. A Database System for Wood Harvest and Transportation Planning. TIMS Studies in the Management Sciences 21:389-402.
43. PNEVMATICOS, S. M. and MANN, S. H. 1972. Dynamic Programming in Tree Bucking. Forest Products Journal 22(2):26-30.
44. PULKKI, R. E. 1984. Rationalization of Wood Delivery by Road, Railway and Water in South-Eastern Finland. COFE/IUFRO Proceedings, University of Maine, USA. pp201-210.
45. PULKKI, R. E. 1984. A Spatial Data Base Heuristic Programming System for Aiding Decision-Making in Long-Distance Transport of Wood. Suomen Metsatieteelinen Seura.
46. RAMSING, K. D. 1966. How the Critical Path Method Can Assist Road Construction. Forest Industries 93(12):66-69.
47. REINDERS, M. P. and WIJNGAARD, P. J. M. 1984. The Optimization of a Forest

Road Network – A New Model for Both Flat and Broken Ground. Department of Forest Technique, Agricultural University, the Netherlands.
48. REISINGER, T. W. and DAVIS, C. J. 1985. Using Geographic Information Systems to Determine Operable Areas – A Trafficability Approach. Council on Forest Engineering Proceedings, Tahoe City, Ca, USA. pp35-40.
49. ROGERS, J. J., PROSSER, J. M. and GARETT, L. D. 1982. ECOSIM: A Prototype System for Estimating Multiresource Output under Alternative Forest Management Regimes. Proceedings 17th IUFRO World Congress, Subject Group 3:04:01, Kyoto, Japan. pp122-127.
50. SCHRAGE, L. E. 1982. User's Manual for LINDO. The Scientific Press, University of Chicago, IL, USA.
51. SCHULER, A. T., WEBSTER, H. H. and MEADOWS, J. C. 1977. Goal Programming in Forest Management. Journal of Forestry 75:320-324.
52. SCHUSTER, E. G. and JONES, J. G. 1985. Below-Cost Timber Sales; Analysis of a Forest Policy Issue. USDA Forest Service General Technical Report INT-183.
53. SESSIONS, J. 1987. Network Analysis Using Microcomputers for Logging Planning. Oregon State University, OR, USA.
54. SINNER, H. U. 1973. Simulating Skyline Yarding in Thinning Young Forests. Proceedings IUFRO Working Parties S3:04:01 and S4:03:01, Freiburg, West Germany.
55. WALKER, H. D. 1986. Economic Wood Supply Analysis Using Linear Programming. Proceedings CARIS Workshop, Lakehead University, Canada. pp24-44.
56. WARDLE, P. A. (Editor). 1971. Operational Research and the Managerial Economics of Forestry. Forestry Commission Bulletin 44, London, UK.
57. WEINTRAUB, A and NAVAN, D. 1976. A Forest Management Planning Model Integrating Silvicultural and Transportation Activities. Management Science 22:1299-1309.
58. WIEST, J. D. and LEVY, F. K. 1969. A Management Guide to CPM/PERT. Prentice-Hall Inc., Englewood Cliffs, NJ, USA.
59. WINSAUER, S. A. and BRADLEY, D. P. 1982. A Program and Documentation for Simulation of a Rubber-Tired Feller/Buncher. USDA Forest Service Research Paper NC-212.