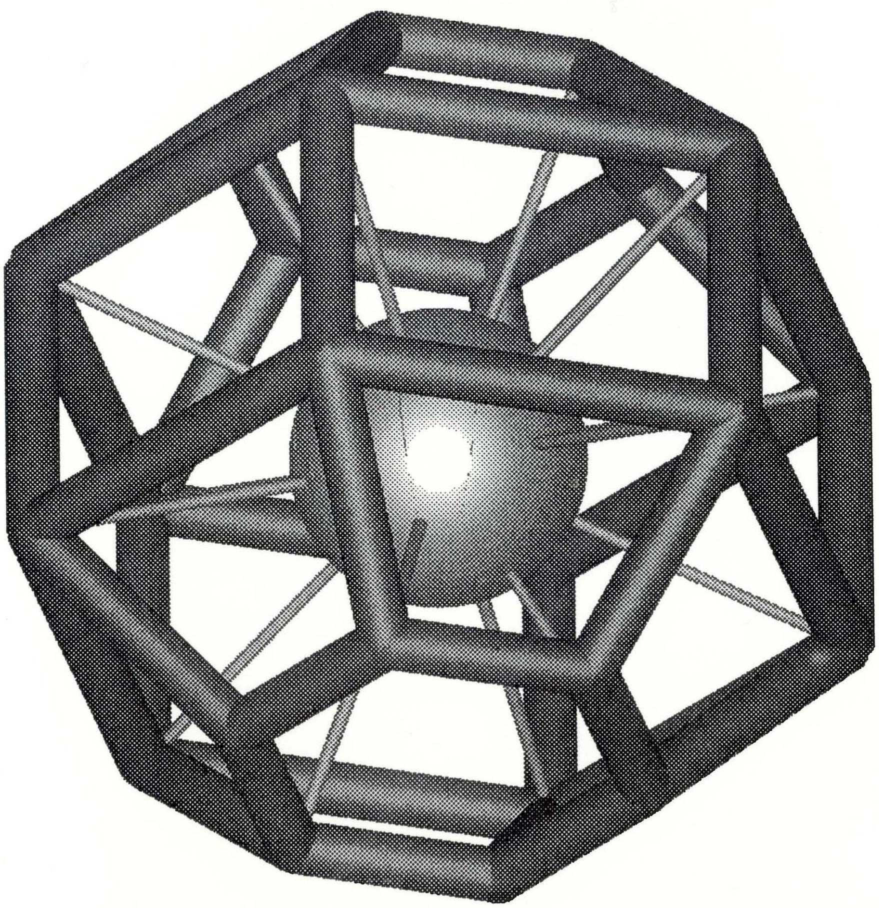
Proceedings of a Workshop on

Hierarchical Approaches to Forest Management in Public and Private Organizations

Edited by David L. Martell, L.S. Davis, and Andrés Weintraub

Petawawa National Forestry Institute • Information Report PI-X-124



Natural Resources Canada
Ressources naturelles Canada
Canadian Forest Service
Service canadien des forêts

Canada

Proceedings of a Workshop on

Hierarchical Approaches to Forest Management in Public and Private Organizations

Toronto, Canada
May 25-29, 1992

Edited by
David L. Martell,
L.S. Davis,
and Andrés Weintraub

Typesetting, Design, and Artwork
Eliza Andersen

Petawawa National Forestry Institute • Information Report PI-X-124
Canadian Forest Service

1996

Catalogue No. Fo46-11/124-1992E
ISBN 0-662-24108-8
Printed in Canada

Copies of this publication may be obtained free of charge from the following address:

Forestry Canada
Publications Distribution Centre
Petawawa National Forestry Institute
Chalk River, Ontario
K0J 1J0

Telephone: 613-589-2880

A microfiche edition of this publication may be purchased from:

Micromedia Ltd.
240 Catherine St., Suite 305
Ottawa, Ontario
K2P 2G8

Canadian Cataloguing in Publication Data

Main entry under title :

Proceedings of a workshop on hierarchical approaches to forest management in public and private organizations :
Toronto, Canada, May 25-29, 1992

(Information report ; PI-X-124)
Includes bibliographical references.
ISBN 0-662-24108-8
Cat. no. Fo46-11/124-1992E

1. Forest management -- Congresses.
2. Forests and forestry -- Congresses.
I. Martell, David Leigh, 1948-
II. Davis, L. S.
III. Weintraub, Andrés.
IV. Petawawa National Forestry Institute.
V. Title: Hierarchical approaches to forest management in public and private organizations.
VI. Series: Information report (Petawawa National Forestry Institute) ; PI-X-124.

SD118.H53 1996 634.9'2 C96-980012-6

Table of Contents

DISCLAIMER

The papers in these Proceedings are printed as submitted except for the artwork and have not been subject to editorial review by the Canadian Forest Service (CFS). Statements made by authors in this publication are not necessarily endorsed by the CFS.

Acknowledgments

The International Workshop on Hierarchical Approaches to Forest Management in Public and Private Organizations was sponsored by the Canadian Institute of Forestry and the Canadian Operational Research Society with financial support provided by the Forest Economics and Policy Analysis Project at the University of British Columbia, the Canadian Forest Service, the Land Management Planning Branch of the USDA Forest Service, the Management Sciences Working Group of the Society of American Foresters, and the Ontario Ministry of Natural Resources.

Particular thanks are due the Canadian Forest Service, which published these Proceedings, and Eliza Andersen of the Petawawa National Forestry Institute whose design and layout expertise, hard work, and patience made that possible. Wei Chang is responsible for the cover art. D. Boychuk, J.I. MacLellan, and R. Saporta, graduate students at the Faculty of Forestry at the University of Toronto, helped organize the workshop and worked diligently behind the scenes to ensure the participants were able to enjoy a stimulating working environment. Thanks are also due H. Hermansen, C.F. Hutchison, and B.M. Sakowicz, research assistants in the Fire Management Systems Laboratory at the Faculty of Forestry, and R. Saporta who assisted with manuscript preparation.

Preface

Forest management planning covers a very broad range of problems. On a time scale, operating plans stipulate what is to happen during the next few days while long range strategic plans are developed for planning horizons that span more than 100 years. On a spatial scale, decisions address areas that can range from several hectares to hundreds of thousands of hectares. From an organizational perspective, decisions are made by senior executives and crews working on the ground.

Since the late 1980's we have witnessed a growing concern about the ability of comprehensive monolithic models to satisfy the needs of planners, forest land managers and their clients. Some observers have advocated the development and use of integrated systems of small simple models that can be linked with each other. The questions of how these models should be defined, how they should be linked, and how to ensure consistency among them are obviously very challenging. We knew that practitioners had adopted a number of very pragmatic strategies for dealing with such problems and we felt that the subject presented many challenging research opportunities. With these concerns in mind, we decided the time was ripe for discussion of this important topic. We therefore organized an ad hoc discussion session that was convened at the conclusion of the Symposium on Systems Analysis in Forest Resources which was held in Charleston, South Carolina in March of 1991. We were absolutely amazed at the large number of people who stayed for the session, and the lively discussion that ensued. Afterwards, a small group met informally and decided to organize a special workshop to investigate these issues in depth. Ilan Vertinsky of the Forest Economics and Policy Analysis Project at the University of British Columbia promised seed money and a little more than a year later the Faculty of Forestry at the University of Toronto hosted an international Workshop on Hierarchical Approaches to Forest Management in Public and Private Organizations, during May 25-29, 1992.

The speakers and discussants addressed a broad range of topics including the basic principles of hierarchical planning and their practical experiences with hierarchical forestry planning systems in government and industry, and the approaches they used to deal with uncertainty and non-market benefits. We begin with *Connelly's* definition of hierarchical analysis for forest planning. *Weintraub* and *Davis* (Hierarchical Planning in Forest Resource Management: Defining the Dimensions of the Subject Area) then discuss some of the socio-economic and technical reasons why hierarchical forest management planning is growing in importance. They present a classification of forest planning hierarchies, highlight what they consider to be the more important research issues, and include a bibliography of hierarchical planning. In his accompanying commentary *Harrison* describes several metrics that might used to measure the success of hierarchical planning efforts and suggests how hierarchical planning should be applied in forest management planning.

Colberg (Hierarchical Planning in the Forest Products Industry) stresses the importance of uncertainty and presents an overview of the planning procedures used by Mead Coated Board. *Welker* and *Kollmyer* (Tactical Level Harvest Scheduling Based on Strategic Level Woodlands Planning) give a detailed discussion of the major components of the hierarchical planning system that the woodlands department of Mead used to link its strategic, tactical and operational planning systems. They stress the need to link hardware, software and people in an integrated planning system.

Jamnick and *Robak* (An Integrated Forestry Planning System) describe their hierarchical integrated planning system which enables them to use a geographic information system (GIS) to link a strata-based strategic optimization model, a heuristic harvest block design procedure and a Monte Carlo harvest timing procedure, with a detailed operational planning system. They present the results they achieved when they applied the system to a small case study area in the province of New Brunswick.

Barber, *Butler*, *Caird* and *Kirby* (Hierarchical Approach for National Forest Planning and Implementation) present a overview of a proposed new hierarchical planning framework for the USDA Forest Service's National Forest Land and Resource Management Plan. They draw upon past successes and failures and propose many valuable innovations. They stress the need for flexibility that can be achieved by establishing reserve margins for risk and uncertainty and by adopting adaptive management procedures.

Davis and *Barrett* (The North Coast Pilot Project: A Research Study on the Spatial Integration of Wildlife Habitat with Multiple Ownership Long Term Forest Planning) describe their work on a pilot project to develop and demonstrate practical ways to integrate wildlife habitat management into quantitative forest management planning systems. They describe how they combine satellite imagery, forest management planning optimization models and GIS technology to help assess the long term wildlife and timber management implications of forest management policies.

Alvarez-Gil and *Blasco* (Hierarchical Planning Systems and Public Control and Evaluation: A Methodology for the Control and Evaluation of a Spanish Public Plan) describe how the Spanish Ministry of Industry, Trade and Tourism adapted hierarchical planning procedures that have been used in manufacturing, for use in the development of a public plan for an industrial design strategy for small and medium enterprises.

Avriel and *Breiner* (Policy Analysis Models Based on Multi-Level Programming) develop a methodology for formulating and solving policy analysis problems using multi-level programming approaches. Their approach shows considerable promise for hierarchical forest management policy and planning systems in which many different players attempt to solve their problems and interact with other players above and below them in large complex hierarchical biological, social and economic systems.

Paredes (Design of a Resource Allocation Mechanism for Multiple Use Forest Planning) reviews some of the mathematical modelling techniques that have been used to develop comprehensive multiple use planning procedures for large forest land management agencies. He includes a concise summary of planning concepts, including price and quantity directed planning schemes. He then describes a comprehensive planning model for large forest land management systems, that draws upon the economic principles of multiple use forest land management. In his accompanying discussion, *Bare* points out that the proposed planning framework has many attractive features but that it is not well suited for dealing with multiple objectives and political concerns that cannot be readily expressed in economic terms.

Gunn (Hierarchical Planning Processes in Forestry: A Stochastic Programming - Decision Analytic Perspective) concentrated on the merits of hierarchical planning methods to deal with the high degree of uncertainty and long planning horizons that are characteristic of forest management planning. He points out that the use of deterministic models with a rolling planning horizon and replanning is a good heuristic procedure for dealing with forest management planning under uncertainty and that forest management planning problems usually have enormous numbers of resource possibilities that arise from the possibility of varying protection and silviculture investments over time in response to uncertain outcomes.

Mandelbaum and *Martell* (Flexibility in Forest Management Planning) describe some of the more important sources of uncertainty that complicate forest management planning and advocate the adoption of the principles of flexible manufacturing systems (FMS) to address such concerns. They describe some of the FMS flexibility measures that may be appropriate for forestry and use a simple hypothetical forest to illustrate how they might be included in forest management planning procedures.

Manley, *Papps*, *Threadgill* and *Wakelin* (Application of Hierarchical Forest Planning in New Zealand) describe some of the hierarchical aspects of the Forestry Oriented Linear Programming Interpreter (FOLPI) forest management planning system that is used in New Zealand. They describe how the hierarchical organization of the New Zealand Forestry Corporation (a state-owned enterprise) influenced the use of FOLPI to evaluate its forest plantations. They found an aggregate corporate wide model closely approximated the aggregate solution obtained by adding the objective function values estimated by using 14 district models. They also describe the variable time period approach they used to provide greater detail for the early part of the planning horizon. In his accompanying commentary *Bare* points out that the hierarchical approach does achieve computational effort reductions and identifies concerns such as spatial harvest constraints that do not appear to be addressed by FOLPI.

Leefers (Analyzing Old-Growth Designations Using Ecological and Analytical Hierarchies) describes how a hierarchical ecological classification system was used to address old growth concerns in the Huron-Manistee National Forests in Michigan. He describes the basic structure of a forest-wide FORPLAN model that was to be used to assess the opportunity cost of designating and maintaining old growth stands, and a spatial desegregation process that was being developed to associate forest level results with sub-forest areas.

Roloff and *Haufler* (Incorporating Wildlife Objectives into Forest Planning) described how they were incorporating wildlife objectives in forest management planning systems. Wildlife concerns are characterized by a need to carry out high resolution spatial analyses that include ecological classification systems. They use a ruffed grouse habitat suitability index and a GIS to assess the timber production and grouse implications of a hypothetical harvest of aspen from the Huron National Forest in Michigan.

Weintraub (Data and Decision Aggregation Processes in Forest Hierarchical Planning) addresses the need to aggregate and disaggregate information and decision linkages between different levels in hierarchical planning processes. He presents the results he and his collaborators obtained by applying aggregation procedures to several forest management planning problems. They found the aggregation procedures significantly reduced the size of the models that had to be solved and produced surprisingly small aggregation errors.

Schreier, *Thompson*, *van Kooten*, and *Vertinsky* (A Decomposed Hierarchical System for Forest Land Use Allocation Decisions with Public Participation) describe the decision support system they were developing to address local and province-wide concerns that arise from attempts to resolve forest management and land use allocation problems. The problem is decomposed into a provincial master problem and regional linear programming sub-problems and shadow prices are used to link them within an interactive solution procedure. This is an example of the type of price-guided central coordination described by *Paredes* (Design of a Resource Allocation Mechanism for Multiple Use Forest Planning). Their proposed system includes a comprehensive high resolution forest estate simulation model that is linked to a GIS to assess the spatial implications of the many attributes (e.g., timber production, fisheries, wildlife, recreation) of alternative strategies. They also discuss how they might evaluate "existence" forest values like biodiversity.

Davis and *Martell* (A Decision Support System to Help Forest Managers Evaluate Silvicultural Strategies and Tactics) describe how they used a GIS to link strategic and tactical mathematical programming models that can be used to evaluate site specific operating plans that are compatible with forest level strategic objectives. They describe how their system was tested on a 90,000 hectare forest management unit in northeastern Ontario.

Sethi, *Taksar* and *Zhang* (A Hierarchical Decomposition of Capacity and Production Decisions in Stochastic Manufacturing Systems: Summary of Results) describe some of the exciting new results that have emerged from their investigation of hierarchical stochastic manufacturing systems. They demonstrate that in hierarchical organizations, corporate long term decisions concerning investment in production capacity can sometimes be based on summary measures of the detailed stochastic behaviour exhibited at the lower levels of the organization. The papers presented at the workshop demonstrate very clearly, that forestry specialists have drawn upon and benefitted from the hierarchical production planning research and practice traditions in Operational Research. This new work by *Sethi* and his collaborators, with its emphasis on stochastic processes, will no doubt be reflected in future hierarchical forest planning systems in which uncertainty plays such a significant role.

We conclude with *Bare* (Hierarchical Forest Planning: Some General Observations) who tackled the difficult task of looking back at what transpired at the workshop and incorporating his perception of the significance of our deliberations in a hierarchical forest planning context. He also drew upon the papers that were presented and the discussion ensued and sketched out a very helpful and challenging research agenda for the future.

We were extremely pleased with the quality of the papers presented and the discussions that took place at the workshop. The participation of discussants after each paper, some of whom made their comments available for publication in these Proceedings, and the general discussions that took place helped the participants clarify many of the challenges of hierarchical planning in forestry. The workshop participants agreed to build upon the success of the Toronto workshop and that commitment has been evident in special sessions dealing with hierarchical planning in forestry that have been convened at subsequent forestry and operational research conferences. The workshop proved to be very rewarding experience and hopefully these Proceedings reflect some of the interest and excitement that was generated and enjoyed by the participants.

David Martell
University of Toronto

Larry Davis
University of California, Berkeley

Andres Weintraub
University of Chile

A Definition of Hierarchical Analysis for Forest Planning

B. Connelly

USDA Forest Service, Planning & Environmental Affairs, P.O. Box 3623, Portland, OR 97208-3623, USA

The organization of information for making decisions at different levels when the quality of the decision made at one level is dependent upon decisions or information at other levels. Levels may be defined temporally or spatially where the scope of the higher level fully encompasses the scope of the lower level.

Suggested Characteristics of Hierarchical Analysis

In considering large-scale, complex systems, where a hierarchical approach may be desirable Haimes (1982) suggests that the following characteristics be considered:

a. Explicit incorporation of multiple decision makers where appropriate
b. Explicit treatment of multiple goals and objectives
c. Handles risk uncertainty
d. Provides for a structured feedback mechanism
e. Recognizes the dynamic nature of the system

Large scale systems generally possess these characteristics. Thus analysis of such systems should be capable of addressing these characteristics.

Reference

Haimes, Y.Y. 1982. Modelling of large-scale systems in a hierarchical-multiobjective framework, *In*: Studies in the Management Sciences and Systems, Vol. 7, pp. 1-7, North Holland Publishing Company.

Hierarchical Planning in Forest Resource Management: Defining the Dimensions of the Subject Area

A. Weintraub
Department of Industrial Engineering, University of Chile, Santiago, Chile

L. Davis
Department of Forestry and Resource Management, University of California, Berkeley,, USA

Introduction

The ideas that led to organizing this workshop have been in the air for several years now. Basic transformations in social environmental concerns, in the structure of management problems, and in the tools to approach these problems have rendered conventional monolithic modeling approaches difficult, costly and of little relevance to resolving today's emerging problems.

The purposes of this paper are to highlight the motivation for hierarchical approaches which have finally led to organizing this first workshop. Specifically, we

(1) review the growing demand for hierarchical approaches
(2) propose a classification of hierarchical problems by 6 dimensions or attributes
(3) suggest some researchable questions in this subject area
(4) consider our opportunities to develop this field
(5) provide a brief bibliography of work in the hierarchical planning area.

Increasing needs

The last decade has seen increased requirements on public and private lands. These requirements have been presented in terms of commodity needs (timber, range, minerals, water), demand for recreation opportunities, and ecological protection or preservation. This latter concern relates to protecting endangered species, preservation of wildlife habitats, promoting diversity, forest health, and other ecological issues. These diverse concerns have led to significantly more complex decision problems, which go from strategic decisions such as creating habitat for the spotted owl, to detailed spatial specifications on small areas, such as adjacency requirements constraining cutting neighboring parcels in the same period. For private firms increasingly competitive global markets call for improved efficiency in management at all levels, strategic, tactical and operational, and environmental sensitivity. All this implies that we are simultaneously concerned with decisions in terms of hundreds of thousands of acres and of less than 100 acres, with horizons of many decades and also of a few years or months. We must understand and deal with technical relationships and the tradeoffs between silviculture and biodiversity, timber yields and wildlife preservation, road building and water sedimentation, social and economic issues. These relations are often obscure because of difficulties in obtaining accurate information or representing them adequately through models or concepts.

Variety of actors

As issues concerning forest management have evolved, more institutions and groups have become more intensely involved in the main decision processes relating to forest policies and management options. These include ecological groups with ever increasing constituencies, populations near forest areas, and the timber industry. This increased involvement demands we somehow integrate groups, with different, and often conflicting objectives, at different hierarchical levels into decision making processes. It will be an important challenge to reconcile these different actors and objectives into a process leading to consensual and efficient decisions. As the variety of issues grows wider and more complex, dealing with risk and uncertainty becomes increasingly more critical, which leads to even more complexity.

Improvement of technology

We have seen a dramatic change in the tools available to decision makers. Powerful personal computers at relatively low prices allow decision makers at all levels to use large and complex models. We have seen how mainframe systems such as FORPLAN are increasingly being transferred to PC's, thus becoming more available for field use. The availability of better and cheaper data, particularly from satellite imagery, portends opportunities to deal with problems at a very detailed and quantitative way. GIS systems are evolving and developing as practical tools for processing large amounts of spatial information. An example of these new possibilities is in the programming of cable logging, based on topographical information given by a combination of a GIS system and mathematical models. On a strategic level for example, GIS technologies currently help support decision analysis in relation to habitats required for the spotted owl.

Limitation of current approaches

Monolithic approaches have apparently reached a level of decreasing usefulness. For example, on a given project or timber sale in California we must jointly and simultaneously consider sustained yield within the ownership, hydrologic impacts within the watershed, economic impacts within the county, and wildlife impact over ecological provinces (Fig. 1). All except the first effect must necessarily consider multiple and/or private owners, different objectives and different decision levels; as suggested in Figure 1 we have finally reached the hierarchical, multi-criteria-multi decision maker cumulative effects problem.

Until now FORPLAN, a well known matrix generator and report writer used by the US Forest Service, has been a central tool in monolithic planning approaches. Defining detailed and sophisticated formulations using

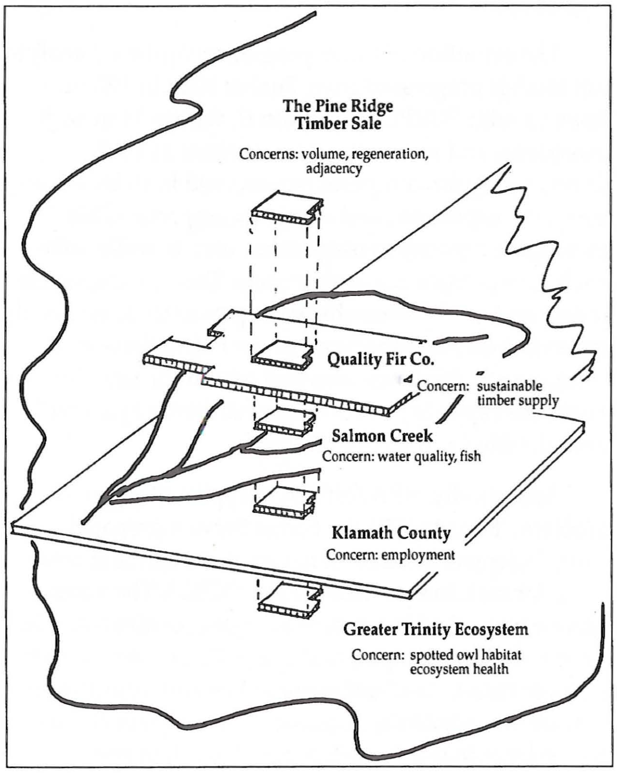


Figure 1. Dimensions of the hierarchical, multiple criteria, multiple decision maker, cumulative effects problem in the context of a timber sale evaluation.

many land types and prescription options along with coordinated allocation options quickly creates a problem size that even the biggest computers cannot handle at acceptable cost. Moreover the humans involved lose their ability to intuitively track and explain the model and its results. Second, there is often little reliable data available to quantify important biophysical responses to proposed treatments or theorized dynamic ecological behaviors. Third, analysts and modeling teams often have insufficient time, funding, training, or skills mix to develop and test appropriate models for specific national forests and to do the sensitivity analysis needed to confidently understand the model and provide some reality checks.

In many cases sustainability and preservation are the main issues in a negotiated decision process. Monolithic models cannot effectively handle this diversity. In a monolithic approach, decisions defined in models often do not correspond to actual decision making levels. Many planning problems have multiple elements or sub-problems that do not easily conform to a single format model, such as a linear program. There exist nonlinearities for many natural phenomena, and also discrete decisions created, for example, by road building, watershed protection, wildlife habitat management or other spatial considerations. In summary, monolithic approaches lack the flexibility to deal with problems which are complex, and relate to different but related levels of decision making.

Given these limitations, there have been several proposals and studies in terms of defining ways in which to deal with problems in separable forms, involving hierarchical approaches. In these studies, different strategies have been used to link planning levels. For example, top down approaches have been proposed, in which using forest wide data, approximate global level schedules for inputs and outputs are developed to best satisfy long term goals and comply with aggregate constraints. At a lower level these input/outputs are disaggregated to define alternatives with an adequate level of detail. Bottom up approaches typically use data from each planning unit to generate implementable plans. These plans can differ by their emphasis on different outputs and timing of implementation. A global model then identifies best combinations of these discrete plans to meet global objectives while satisfying global constraints. In other approaches shadow prices are used to transmit information between managerial level models. However, hierarchical approaches remain little used and a methodology to handle linkages between different decision levels to assure that the different models and decisions are consistent is not yet developed.

Co-evolution of Forest Planning Problem and Technology

Hierarchical planning is no more than another "means" to help landowners and/or society deal their "end" of effectively solving their forest planning problems. As we look ahead and work at developing our hierarchical tools, its equally important to keep a sharp eye and anticipate how the ends — the problems to be solved — will likely change in the future. In this regard it is instructive to examine how the "ends" and "means" have co-evolved over the last few decades.

Strategic planning and analysis has a history going back to at least 1900's with approaches and calculation formulas imported largely from Germany. Industrial lands and other public lands organized efforts at strategic planning in the 1940's after WWII. Industry in the South had run out of natural timber and had to start justifying substantial investments in lands and silviculture to grow future supplies. The Forest Service has provided most planning leadership and, through its research branch supplied many ideas, methods, and technology used by other public and private agencies, governments, and landowners. Planning on federal land was leisurely and rarely contested until the early 1960's, primarily because Americans could get all the forest products and recreation opportunities they wanted from more accessible public and private lands. Until the 1960s, for example, most national forests planned timber sales, but the timber remained unsold and the forests largely unroaded.

Forest planning business accelerated in the early 1960s with passage of the Multiple Use Sustained Yield Act for the U.S. Forest Service and the initiation of unit planning. The 1960s and 1970s provided us with a more environmentally aware public, Earth Day, a boom in outdoor recreation, a shift by forest industry to the national forests for a larger portion of their log supply, big computers and linear programming. Serious use and user conflict became a reality. At the same time we obtained the technology to calculate some of the tradeoffs. Today social preoccupation with the U.S. Forest Service has spilled over onto private and other public lands and has elevated to include global and multinational questions. To anticipate the future and mitigate the human burnout side effects of Toffler's Future Shock as we design and implement hierarchical planning, it is useful to track the accelerating co-evolution of planning problems and technologies experienced by the U.S. Forest Service as a mirror on the future.

Dynamics of forest service problems and planning technology

The historical evolution of the Forest Service planning problem and the available analytical tools is ably documented in Iverson and Alston (1986). Figure 2 summarizes their work and displays the co-evolution of the problem and the decision support technology over the 30 year time interval from 1960 to 1990. The flow of key Forest Service legislation, the elements of the Forest Service planning problem, the models for evaluation of land allocation and activity scheduling, models for spatial analysis, and some indication of computer power are shown.

The most important aspect of Figure 2 is the portrayal of change. The analysts, planners, and forest supervisors starting the Forest Planning process in 1975 had a different tool kit and faced a much different problem than their counterparts do in 1990. For those few who stayed in the planning/analysis business, constant changes in goals and direction, and learning to use an ever-evolving and larger menu of computers, software, and communication technology had to be accepted as a way of life.

The evolution of linear programming-based analytical models progressed from Timber Ram in 1970 to leave us with FORPLAN version II, release 14 in both mainframe and microcomputer versions in 1992. Concurrently the computer has evolved from less-than-adequate, expensive, and nearly incomprehensible mainframe capacity to ubiquitous, user-friendly, relatively inexpensive microcomputers. Today's microcomputers and workstations have the power to do nearly all the analytical planning work of the Forest Service. It seems reasonable to assume that within the next few years, the capability of computer hardware again will have doubled and its price halved.

Analytically, RPA/NFMA abruptly changed the problem. Prior to 1974 the Forest Service prepared many independent, individual resource and unit area plans for each forest. Under RPA/NFMA The Forest Service was asked to prepare a single coordinated, integrated, multiple-output, multiple-criteria plan for each national forest. Tradeoff analysis between resources or outputs was implicitly required. Resource specialists had to learn to talk to each other, share data and computers, and find analytical common ground. Managers could no longer treat plans as something to prepare in order to satisfy regulations and then reside

	1960	1965	1970	1975	1980	1985	1990	1995	2000

LEGISLATION & REGULATIONS

Primary Laws: Multiple Use Sustained Yield Act (1960) — National Environmental Policy Act of 1969 (NEPA) — Endangered Species Act (1973) — Resources Planning Act (1974)

National Forest Management Act (1976) — NFMA Regulations — Proposed Revised Regulations — ?

THE PLANNING PROBLEM

Functional Planning — Comprehensive Strategic Planning — Comprehensive site specific plans

Integration & Coordination: Consider All Outputs — Consider a range of Alternatives, Site-specific, mandated Environmental Effect Analysis — Public Involvement is Required — ?

Local vs. National: Decentralized Planning — Centralized Planning — Return to Decentralized Planning

Decision-Making: Rational, Scientific, Professional Decision Making — Team Public Administration — Public Deliberation, Political Context, Polarization — Many Actors, Many Arenas — ?

Conflicts: Surplus of Resources and Space — Between Use and Space Conflicts Begin — Intense, Complex, Multivalue Conflicts

Forest Health vs. Forest Use and Production

PLANNING TOOLS

Planning Models: Mathematical Programming: Timber RAM — MUSYC — FORPLAN 1 — ADVENT — IRPM — FORPLAN 2 — RM-FORPLAN — TEAMS SNAP SARA — ?

Binary Search Simulators: ARVOL SORAC SIMAC TREES

Spatial Analysis: Manual Map Overlay — GRID — RMGRID — WRIS — RMAP — MOSS — GRASS — ARCINFO

Computer Power

Computers: First Mainframes — Moderate Capacity Mainframes — Large Capacity Mainframes — First Microcomputers IBM PC — 286 chip — 386 chip — 486 chip

Workstations Hard Disks — Large Capacity Microcomputers — ?

DATA AND SIMULATORS TO SUPPORT EMPIRICAL ANALYSIS

Inventory: FIA inventory ground plots on private land — Timber inventories on national forests — USGS Topographic Data — SCS soil mapping — LANDSAT Vegetation Coverages

Simulators: PROGNOSIS — DFSIM — TWIGS — CACTOS — ?

Figure 2. Co-evolution of the forest service planning problem
Its data and its planning tools 1960-1990

safely on shelves. Approved plans are being interpreted as contracts by the many publics to whom the manager is ultimately accountable.

RPA/NFMA also increased the requirements for public involvement and heightened awareness of affected interests and stakeholders that the results of planning would affect their welfare. Although selecting the preferred alternative remains an administrative decision, it has become clear that if decisions are not socially and politically acceptable, they are unlikely to be implementable.

The Forest Service problem was originally defined in the progressive-scientific paradigm as a rational, efficiency-guided, single decision maker problem where a professional public administrator determined optimal resource allocation. Now the agency must operate almost as a facilitator in a public decision building paradigm to find satisfactory land allocation and prescriptions in a highly politicized, multiple-decision maker, public-deliberation arena. Affected stakeholders demand a real voice in decisions.

The million plus acres covered by each forest plan is too much space for many people because such plans cannot provide the location specific detail important to them. People want to talk about specific places and develop customized answers about what is going to happen to their favorite places over the next 50 plus years. This demands that planning be disaggregated to smaller units and that the details of plan implications be presented in maps.

The last few years (1988-1992) have seen dramatically intensifying public demand to reduce or eliminate clearcutting, to practice lower-intensity, ecologically-sensitive forestry, and to set aside much of the remaining ancient (old growth) forests on both public and private lands. This is an unprecedented manifestation of change in social values. These demands are both regional and national, transcending ownership boundaries. The accusation of overcutting and suspected long-term loss of site productivity has political currency and is prompting detailed and prescriptive sustained yield legislation. The intensity of these changes surprised and caught the forestry professionals unprepared and offers a fundamental challenge to private property rights and decision making authority of private forest owners.

In many ways, the essential task of this workshop is to peer to the right in Figure 2, and see what will be there in the 1995-2000 period and later. What problems? What new legislation? What technology? Pragmatically, any hierarchical planning technology we design today is unlikely to be operational and implemented before 1995. If we are not thoughtful, the design and technology could easily be eclipsed before the hardware is assembled, programs debugged, and manuals written. We are certain that technology and the land management problems will continue rapid development and change. Perhaps a better approach is to give some time to the "vision thing" and conceptualize general strategy, data sets, and technologies that have the flexibility to adapt most effectively and efficiently meet future needs.

A Classification of Forest Planning Hierarchies

We often speak of hierarchical planning without being precise about the planning system in question. We need a common language to talk about hierarchical planning problems, regardless of whether they are public or private, large or small in terms of scale, value at stake, or detail of content. Hierarchies can be defined in several dimensions, often a given planning situation or context will involve several of them. The most common dimensions are time and space but we need also recognize hierarchies in decision and policy making, information flow, ownership, and the quantitative and qualitative resolution and scope of forest activities and outputs considered. A given planning problem can contain some or all of these hierarchical dimensions, each at different levels of aggregation or resolution. We propose six dimensions for the classification of hierarchical planning problems.

Time Dimension

a. **very short** (weeks to months) operations scheduling, field supervision
b. **annual**, implementation, budgeting, contracts
c. **short term 3-5 years**, marketing, access, strategic plan revisions, monitoring
d. **mid term 5-20 years**, data acquisition, plan revision, technology development, monitoring,
e. **strategic, sustainable, long term 20-100 years**, sustained yield, economic forecasting, regional economic planning, land allocation and use, biodiversity, preservation
f. **ecological and forest health 100-500 years**. Site deterioration, ecosystem sustainability, biodiversity, endangered species,

Space Dimension
(contiguous planning unit size and level of aggregation)

a. stand
b. small watershed
c. ownership parcel, full ownership
d. large watershed
e. county
f. state
g. bioregion
h. nation
i. world.
j. galaxy (for the next generation of planners)

Ownership Dimension

a. single owner
b. multiple owners

Decision Making Dimension

a. laborers and project administrators (site and time specific)
b. landowners, general managers, corporations
c. local government, interest groups and regulations
d. regional commissions, interest groups and regulations
e. state and federal policy, legislature, courts, electorates.

Communication and Information Dimension

a. database structures and networks
b. protocols and priorities for using and sharing information
c. confidentiality
d. analyst client relationships

Forest Output and Activity Dimension

a. Number of different outputs and activities recognized (commodities, services, clearcut acres, seral stage acres, forest health)
b. Qualitative attributes of outputs (shape, size, composition, structure, aesthetic, suitability, etc.)

Research Questions about Hierarchical Planning

We have discussed the need to introduce hierarchical approaches to deal with complex forest problems encompassing different decision levels and dealing with multiple interest groups with different objectives. However there are many open questions which should be central topics in our discussions. We can learn from experience in the use of hierarchical approaches in other areas of decision making such as production planning in manufacturing systems.

A very critical question is how to obtain consistency between the results of decision models defined at two or more hierarchical levels. An optimal or near optimal solution at one level may not be meaningful if it is not logically or empirically consistent with results obtained at another. For example, if statements about forest harvest levels repeatedly do not match the realized harvests on the operating units. Adequate aggregation and disaggregation procedures need to be defined to create links between levels. Both information and decisions have to be involved in this process. Another important technical problem is storage, transfer, monitoring, and updating of the data characterizing hierarchical planning systems.

We need to recognize and integrate different decision makers who have different problems and objectives but are hopelessly bound together in a cumulative effect hierarchical problem. We need much better user and client friendly techniques that build credibility and communicate relevant information to these multiple decision makers. We need to demonstrate that we have recognized and reasonably dealt with important uncertainties inherent in the biological, physical, economic, and social parts of our models.

By analyzing these issues and reviewing the empirical results obtained in applications, we hope to develop robust, consistent methodologies to handle hierarchical approaches in forest planning.

Measurement of information differences between hierarchical levels

A simple example level serves to highlight a fundamental question regarding our ability to consider hierarchical planning to have a "science" component. Consider a forest being evaluated for the "best" plan at two levels of aggregation using the same goal/constraint set at each level.

<u>Level 1</u>. (whole ownership level of aggregation)

Let $\mathbf{P}^*_{1i}$ = Optimal plan choice at hierarchical level 1 for the ownership under goal/constraint set i

$\mathbf{A}^*_{1ij}$ = Amount of forest output **j** provided at level **1** by plan $\mathbf{P}^*_{1i}$

<u>Level 2</u>. (next lower level of aggregation)

Let $\mathbf{p}^*_{2ik}$ = Optimal choice at hierarchical level **2** under goal constraint set **i** for sub-unit **k**, k = 1..k

$\mathbf{a}^*_{2ijk}$ = Amount of output **j** provided by plan $\mathbf{p}^*_{2ik}$ for subunit **k**

A^*_{2ij} = Amount of forest output **j** provided at level 2 by the set of sub-unit plans $A^*_{2ij} = \Sigma_k a^*_{2ijk}$

Information difference between hierarchical levels

The quantitative amount of the difference in forest output **j** between two hierarchical levels is measured by the difference **dAj** where

$$dAj = A^*_{1ij} - A^*_{2ij}$$

The magnitude and sign of **dAj** will vary with many factors including:

1. Whether we are comparing an aggregation or disaggregation between levels.
2. The optimization approach used at levels 1 and 2. Whether continuous or integer variables, interactive procedures, multicriterion methods, subjective choice, or treatment response functions. Was the same approach used at each level? Mathematical programming or a few discrete alternatives? Simulation?
3. If discrete or integer alternatives, the number of alternatives considered at each level to find the optimal solution.
4. The number, kind and complexities of inputs, outputs, goals and constraints used to define the basic planning problem. Should the same goal and constraint sets be used at each hierarchical level?
5. The number, kind of planning dimensions used to define the hierarchical levels. How do these dimensions vary between levels.
6. Is the goal of hierarchical planning to develop methods where dAj goes to zero?

Do we have a science here?

The criterion that will ultimately determine if hierarchical planning has a science component is our ability to predict **dAj** when the problem character and the dimensions of the hierarchical structure are known. For example, consider a timber planning problem where a 1,000,000 acre West coast forest is modeled in aggregate and then in 30 some individual watershed units. If, based on theoretical and empirical research, we could reliably predict that A^*_{2ij} would be approximately 70% of A^*_{1ij} (and hence **dAj** = 30% of A^*_{1ij}), would this allow us to make a claim for scientific standing? If **dAj** is a predicable fraction of the result obtained over the whole unit, then we would have a reliable factor to adjust or discount aggregate results. This would provide a relatively low cost aggregate analysis route to estimate the practically achievable results found when the aggregate solution is disaggregated and spatially implemented.

A practical workshop product

We hope that one important product of this workshop will be a first cut listing of what we consider to be researchable questions related to hierarchical planning. This will be our collective intellectual commitment to putting some "science" in the subject, and to go beyond simply being tool builders. We need to develop general theory to organize, understand the properties of hierarchical systems and to empirically evaluate the relative efficiency and effectiveness of different strategies and approaches. To start this list, we offer the following three broad classes of research questions.

1. What is the difference in information — the numerical amount (dAj) of plan attributes through hierarchies of planning — and are these differences predictable?

If the only element defining the hierarchy is space and the only attribute of interest is timber harvest, then this question addresses measuring or predicting the well known allowable cut effect (ACE) obtained from combining planning units when there is a temporal harvest policy. When we combine planning units, the calculated harvest generally increases. Conversely when we separate the planning units, we would expect the cumulative harvest to decline. This question generalizes to consider all forms or elements of hierarchies and all important output and activity attributes tracked in planning. Specifically it is hypothesized that we can develop theory, methods and evidence to determine or estimate

a. numerical amounts of attribute differences.
b. predictability of attribute differences as a function of the hierarchical structure.
c. accuracy, precision and bias characteristics of attribute difference through different hierarchical structures and methods of analysis and aggregation.
d. relative spatial accuracy; when higher level plans are implemented, what are the probabilities of being able to correctly locate acceptable places to apply prescriptions on the ground to the planning horizon.
e. general guides to appropriate organization of goals and constraints to be modeled at each hierarchical level and suitable methods and technologies for problems analysis at each level.

2. What are the comparative efficiencies of alternative hierarchical approaches and technologies?

Some criteria are:

a. ability to provide needed attribute information
b. cost of hardware, software and data
c. real time analysis capability to support public deliberation
d. expertise needed to set up data and problem models in the system
e. expertise needed to run the systems and to understand and communicate the results.
f. portability to different ecosystems, problems, and constituencies.

3. What is the comparative effectiveness of alternative hierarchical approaches and technologies at helping resolve problems?

Some criteria are:

a. acceptability by landowners, managers, analysts, and clients or affected stakeholders.
b. credibility and trust in results from the analysis system due to clear, consistent, and intuitively validated solutions.
c. communication accuracy; the consistency, accuracy and possible bias with which numerical and qualitative information about the land systems produced by the analysis technology are transmitted and understood by clients and stakeholders.
d. perception by clients and stakeholders that they or other human beings are in control of the models and analysis technologies — is it a black box system that only technical types know and really control or is it a glass box that only does what mere mortals tell it what to do?

Important Future Issues and Opportunities

In addition to the ideas, contacts and the proceedings that we can take away from this workshop, what other opportunities are there for us? The workshop discussions at the Charlston Systems Analysis Symposium suggested that there are a lot of organizations and analysts grappling with various versions of the hierarchical planning problems. That over 60 people stayed 3 hours past the end of the conference to discuss problems and issues is good evidence that something is going on. The fact that you are here is another. Some ideas we can offer to start a discussion are:

1. The hierarchical planning subject area could easily be a regular session topic at many of our meetings.
2. We need some specific empirical applications of hierarchical approaches to help solve successfully real life problems.
3. We need to document the case applications to determine what approaches and communication strategies can gain confidence of decision makers and stakeholders in the application of hierarchical approaches.
4. Based on real data sets, conduct simulation studies to map out some of the information difference properties through different hierarchical levels.
5. Recognizing that most of us will continue to act as independent agents and scientists, there still may be ways we can collaborate to share data sets and organize and classify our applications to serve as observations in a larger collective experiment.

Bibliography of Hierarchical Planning

Part I: Forest resource management

Barber, K. 1990. Hierarchical analysis for forest planning and implementation. Land management planning staff, USDA Forest Service, San Francisco. 9p.

Bare, B. and R. Field. 1987. Evaluation of FORPLAN from an operations research perspective. In FORPLAN: An Evaluation of Forest Planning Tools, T. Hoekstra, A. Dyer, and D. LeMaster (ed.). General Technical Report RM-140, USDA Forest Service. p.133-144.

Barros, O. and A. Weintraub. 1982. Planning for a vertically integrated forest industry. Operations Research, 30(6):1168-1182.

Berk, P. and T. Bible. 1984. Solving and interpreting large-scale harvest scheduling problems by duality and decomposition. Forest Science, 30(1):173-182.

Berner, R. and J. Jordon. 1991. The role of an ecological classification system in forest plan development and implementation. In Proceedings, 1991 Symposium on Systems Analysis in Forest Resources. General Technical Report SE-74, USDA Forest Service. p. 70-80.

Brodie, J. and J. Sessions. 1991. The evolution of analytical approaches to spatial harvest scheduling. In Proceedings, 1991 Symposium on Systems Analysis in Forest Resources. General Technical Report SE-74, USDA Forest Service. p. 187-191.

Caswell, W. and A. Rao. 1974. A practical approach to the large-scale forest scheduling problem. Decision Science, 5(3):364-373.

Clements, S. P. Dallein, and M. Jamnick. 1990. An operational spatially constrained harvest scheduling model. Canadian Journal of Forest Research, 20(9):1438-1447.

Connelly, W. 1989. Area based forest planning. In Proceedings, 1989 /Symposium on Systems Analysis in Forest Resources. General Technical Report RM-161, USDA Forest Service. p.131-137.

Dallian, P. 1989. A block harvest scheduling model for spatial management planning. Masters thesis, University of New Brunswick, Fredericton, NB. 80p.

Daugherty, P. 1991. Credibility of Long-Term Forest Planning: Dynamic Inconsistency in Linear Programming Based Forest Planning. Doctoral dissertation, University of California, Berkeley. 158p.

Davis, L. 1990. An evaluation of FORPLAN and other decision support technology for the future planning needs of the U.S. Forest Service. Report to the Office of Technology Assessment, Congress of the United States. 46p.

Davis, L. and G. Liu. 1991. Integrated forest planning across multiple owners and decision makers. Forest Science, 37(1):200-226.

Dykstra, D. 1987. Evaluation of FORPLAN from an operations research perspective: discussion paper. In FORPLAN: an Evaluation of Forest Planning Tool, T. Hoekstra, A. Dyer, and D. LeMaster (ed.). General Technical Report RM-140, USDA Forest Service. p.145-146.

Eriksson, L. 1983. Column generation applied to long range forestry planning models. Report No.155, Dept. of Operational Efficiency, Swedish University of Agricultural Sciences. 38p.

Ewing, R. 1988. Integrated planning as negotiation: a California perspective on forest planning analysis requirements. In Proceedings, 1989 Symposium on Systems Analysis in Forest Resources. General Technical Report RM-161, USDA Forestry Service. p.1-5.

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

Gilbert, B. 1989. The next generation of planning analysis in the Forest Service. In Proceedings, 1989 Symposium on Systems Analysis in Forest Resources. General Technical Report RM-161, USDA Forestry Service. p.187-196.

Gunn, E. 1991. Some aspects of hierarchical production planning in forest management. In Proceedings, 1991 Symposium on Systems Analysis in Forest Resources. General Technical Report SE-74, USDA Forest Services. p.54-62.

Gunn, E. and A. Rai. 1987. Modelling decomposition for planning long-term forest harvesting in an integrated industry structure. Canadian Journal of Forest Research, 17(12):1507-1518.

Hay, D. and P. Dahl. 1984. Strategic and midterm planning of forest-to-product flows. Interfaces, 14(5):33-43.

Hoganson, H. and D. Rose. 1984. A simulation approach for optimal timber management scheduling. Forest Science, 30(1):220-238.

Hof, J. and T. Baltic. 1990. Cost effectiveness from regional optimization in the USDA Forest Service. Forest Science, 36(4):939-954.

Hof, J. and T. Baltic. 1991. A multilevel analysis of production capabilities of the national forest system. Operational Research, 39(4):543-552.

Hof, J. and J. Pickens. 1987. A pragmatic multilevel approach to large-scale renewable resource optimization: a test case. Natural Resources Modelling, 1(2):245-264.

Holling, C., G. Dantzig and C. Winkler. 1986. Determining optimal policies for ecosystems. In Systems Analysis in Forestry and Forest Industries, M. Kalli et al (ed.). TIMS Studies in the Management Sciences, 21:453-473.

Hrubes, R. G. Veiga, D. Navon, and A. Weintraub. 1987. Lowering forest planning costs through LP column aggregation: how great is the associated optimality loss? In Proceedings, 1985 Symposium on Systems Analysis in Forest Resources, P. Dress and R. Field (ed.). The Georgia Centre for Continuing Education, Athens, GA. p.20-28.

Iverson, D. and R. Alston. 1986. The genesis of FORPLAN: a historical and analytical review of Forest Service planning models. General Technical Report INT-214, USDA Forest Service. 31p.

Jamnick, M. 1990. A comparison of FORMAN and linear programming approaches to timber harvest scheduling. Canadian Journal of Forest Research, 20(9):1351-1360.

Jamnick, M., L. Davis, and J. Gilless. 1990. Influence of land classification systems on timber harvest scheduling models. Canadian Journal of Forest Research, 20(2):172-178.

Jamnick, M. and K, Walters. 1991. Harvest blocking, adjacency constraints and timber harvest volumes.

In Proceedings, 1991 Symposium on System Analysis in Forest Resources. General Technical Report SE-74, USDA Forest Service. p.255-261.

Jones, J., J. Hyde, and M. Meacham. 1986. Four analytic approaches for integrating land management and transportation planning on forest lands. Research Report INT-361, USDA Forest Service. 33p.

Jones, J., M. Meacham, A. Weintraub, and A. Magendzo. 1991. A heuristic process for solving large-scale, mixed-integer mathematical programming models for site-specific timber harvest and transportation planning. In Proceedings, 1991 Symposium on System Analysis in Forest Resources. General Technical Report SE-74, USDA Forest Service. p.192-198.

Keller, D. 1986. Spatial allocation of FORPLAN solutions. In Lessons from Using FORPLAN: proceedings of a planning and implementation workshop. Land management planning systems section, USDA Forest Service, Fort Collins, CO. p.123-129.

Kent, B., J. Hof, and L. Joyce. 1989. Experience with FORPLAN - a distillation to two proceedings from a research prospective. In Proceedings, 1989 Symposium on Systems Analysis in Forest Resources. General Technical Report RM-161, USDA Forest Service. p.203-215.

Kent, B., B. Bare, R. Field, and G. Bradley. 1991. Natural resource land management planning using large-scale linear programs - The USDA Forest Service experience with FORPLAN. Operations Research, 39(1)13-27.

Kirby, M., W. Hagar, and P. Wong. 1986. Simultaneous planning of wildland management and transportation alternatives. In Systems Analysis in Forestry and Forest Industries, M. Kallio et al (ed.). TIMS Studies in Management Sciences, 21:371-387.

Land Management Planning Systems Section, USDA Forest Service. 1992. FORPLAN Operations Guide (Release 14.1). Land Management Planning Systems Section, USDA Forest Service, Fort Collins, CO.

Laroze, A. and B. Greber. 1991. Multi-level harvest planning and log merchandising using goal-programming. In Proceedings, 1991 Symposium on Systems Analysis in Forest Resources. General Technical Report SE-74, USDA Forest Service. p.24-30.

Leefers, L. and D. Jones. 1991. Implications of shorter time horizons on forest planning analyses. In Proceedings, 1991 Symposium on Systems Analysis in Forest Resources. General Technical Report SE-74, USDA Forest Service. p.308-311.

Liittschwager, J. and T. Tcheng. 1967. Solution of a large-scale scheduling problem by linear programming decomposition. Journal of Forestry, 65(9):644-646.

Marose, R., R. Tuazon and L. Davis. 1989. Implementing an ownership-behaviour simulation of private sector timber supplies. In Proceedings, 1989 Symposium on Systems Analysis in Forest Resources. General Technical Report RM-161, USDA Forest Service. p.114-122.

Meneghin, B., M. Kirby and J. Jones. 1989. An algorithm for writing adjacency constraints efficiently in linear programming models. In Proceedings, 1989 Symposium on Systems Analysis in Forest Resources. General Technical Report RM-161, USDA Forest Service. p.46-53.

Merzenich, J. 1991. Spatial disaggregation process: distributing forest plan harvest schedules to subareas. In Proceedings, 1991 Symposium on Systems Analysis in Forest Resources. General Technical Report SE-74, USDA Forest Service. p.250-254.

Milne, B. 1987. Hierarchical landscape structure and the forest planning models: discussant's comments. In FORPLAN: and Evaluation of Forest Planning TOOL, T. Hoekstra, A. Dyer and D. LeMaster (ed.). General Technical Report RM-140, USDA Forest Service. p.128-132.

Mitchell, T. 1989. General analysis and project identification in national forest planning. In Proceedings, 1989 Symposium on Systems Analysis in Forest Resources. General Technical Report RM-161, USDA Forest Service. p.173-186.

Mitchell, T., D. Anderson and S. Mealey. 1987. A multi-stage approach to forest planning. In Proceedings, 1985 Symposium on Systems Analysis in Forest Resources, P. Dress and R. Field (ed.). The Georgia Centre for Continuing Education, Athens, GA. p.43-54.

Navon, D. 1987. Evaluation of FORPLAN from an operations research perspective: discussion paper. In FORPLAN: and Evaluation of Forest Planning TOOL, T. Hoekstra, A. Dyer and D. LeMaster (ed.). General Technical Report RM-140, USDA Forest Service. p.147-154.

Nelson, J. and J. Brodie. 1990. Comparison of a random search algorithm and mixed integer programming for solving area-based forest plans. Canadian Journal of Forest Research, 20(7):934-942.

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

Office of Technology Assessment, U.S. Congress. 1992. Forest Service Planning: Accommodating Uses, Producing Outputs, and Sustaining Ecosystems. OTA-F-505, U.S. Government Printing Office, Washington, DC. 206p.

O'Hara, A., B. Faaland and B. Bare. 1989. Spatially constrained timber harvest scheduling. Canadian Journal of Forest Research, 19(5):715-724.

Paredes, G. 1989. Design of a resource allocation mechanism for multiple use forest planning. In Proceedings, 1989 Symposium on Systems Analysis in Forest Resources. General Technical Report RM-161, USDA Forest Service. p.35-45.

Rai, K. 1984. A Decomposition Approach for a Model of Optimal Forest Management. Masters thesis, Technical University of Nova Scotia.

Reed, W. 1986. Optimal harvesting models in forest management - a survey. Natural Resources Modelling, 1(1):55-79.

Scott, J., L. Davis, F. Schurr, R. Church, P. Daugherty and P. Beck. 1991. Spreadsheet Assisted Resource Analysis (SARA) User's Manual Version 1991.1. University of California, Berkeley. 51p.

Sessions, J. and J. Sessions. 1990. Scheduling and Network Analysis Program (SNAP II), Users Guide Version 1.0 Mimeo. Oregon State University, Corvallis, OR. 73p.

Tank, W. 1989. PASS - a tool for analyzing alternative harvest schedules. In Proceedings, 1985 Symposium on Systems Analysis in Forest Resources, P. Dress and R. Field (ed.). The Georgia Centre for Continuing Education, Athens, GA. p.303-314.

Torres, J. and J. Brodie. 1990. Adjacency constraints in harvest scheduling: and aggregation heuristic. Canadian Journal of Forest Research, 20(7):978-986.

Walters, K. 1991. Spatial and Temporal Allocation of Strata-Based Timber Harvest Schedules. Masters thesis, University of New Brunswick, Fredericton, NB. 82p.

Weisz, R. 1989. Multilevel planning in a spreadsheet environment. In Proceedings, 1989 Symposium on Systems Analysis in Forest Resources. General Technical Report RM-161, USDA Forest Service. p.30-34.

Weisz, R. 1989. GIS PIP: the role of the geographic information systems in the plan implementation process. In Proceedings, 1989 Symposium on Systems Analysis in Forest Resources. General Technical Report RM-161, USDA Forest Service. p.230-234.

Weintraub, A. and A. Cholaky. 1991. A hierarchical approach to forest planning. Forest Science, 37(2):439-460.

Weintraub, A., S. Guitrat, and V. Kohn. 1986. Strategic planning in forest industries. European Journal of Operational Research, 24(1):152-162.

Weintraub, A. and D. Navon. 1976. A forest management model integrating silviculture and transportation activities. Management Science, 22(12):1299-1309.

Williams, D. 1976. Integrating Stand and Forest Models for Decision Analysis. Doctoral dissertation, University of British Columbia. 230p.

Wong, C. 1980. A Multilevel Approach to the Forest Service Planning Process. Masters thesis, Colorado State University. 79p.

<u>Part II: OR/MS & water resource management</u>

Aardal, K. and T. Larsson. 1990. A Benders decomposition based heuristic for the hierarchical production planning problem. European Journal of Operational Research, 45(1):4-14.

Axsater, S. and J. Henrick. 1984. Aggregation and disaggregation in hierarchical production planning. European Journal of Operational Research, 12:338-350.

Balas, W. and M. Karwan. 1984. Two-level linear programming. Management Science 30(8):1004-1020.

Bard, J., J. Falk. 1982. an explicit solution to the multilevel programming problem. Computers and Operations Research, 9(1):77-100.

Barra, T. 1989. Integrated Land Use and Transportation Modelling: Decision Chains and Hierarchies. Urban and Architectural Studies No.12. Cambridge University Press, Cambridge. 176p.

Bitran, G., E. Hass and A. Hax. 1981. Hierarchical production planning: a single stage system. Operations Research, 29:717-743.

Bowers, M. and J. Jarvis. 1992. A hierarchical production planning and scheduling model. Decision Science. 23(1):144-159.

Bradley, S., A. Hax and T. Magnanti. 1977. Applied Mathematical Programming. Addison - Wesley Publishing Company, Reading, MA. 716p.

Dantzig, G. 1963. Linear Programming and Extensions. Princeton University Pres, Princeton, NJ. 625p.

Dantzig,G. and P. Wolfe. 1960. Decomposition principle for linear programs. Operations Research, 8(1d):101-111.

Das, P. 1976. Hierarchical-Multiobjective Approach in the Planning and Management of Water and Related Land Resources. Doctoral dissertation, Case Western Reserve University. 323p.

Dechter, A. 1985. The Design of Hierarchical-Planning Systems by Aggregation. Doctoral dissertation, University of California, Los Angeles. 145p.

deGuia, A. 1983. Design of a Hierarchical-Production Planning and Inventory System for Consumer Products Manufacturing Network. Doctoral dissertation, University of California, Berkeley. 125p.

Dekok, A. 1990. Hierarchical production planning for consumer goods. European Journal of Operational Research, 45(1):55-69.

Dempster, M., M. Fisher, L. Jasen, [and others]. 1981. Analytical evaluation of hierarchical planning systems. Operations Research, 29(4):707-716.

Dirickx, Y. and L. Jennergren. 1979. Systems Analysis by Multilevel Methods: with Applications to Economics and Management. John Wiley & Sons, New York. 217p.

Ershler, J., G. Fontan and C. Merce. 1986. Consistency of the disaggregation process in hierarchical planning. Operations Research, 34:464-469.

Gabbay, H. 1975. A hierarchical approach to production planning. Technical Report No. 120, Operations Research Center, Massachusetts Institute of Technology.

Gelders, L. and L. Wassenhove. 1982. Hierarchical integration in production planning: theory and practice. Journal of Operations Management, 3(1):27-35.

Golovin, J. 1975. Hierarchical Integration of Planning and Control. Doctoral dissertation, Massachusetts Institute of Technology.

Graves, S. 1982. Using Lagranian techniques to solve hierarchical production planning problems. Management Science, 28:260-275.

Haimes, Y. 1976. Hierarchical-modelling for the planning and management of a total regional water resource system: joint consideration of the supply and quality of ground and surface water resources. Projection completion Report 494, Water Resource Center, Case Western Reserve University. 319p.

Haimes, Y. 1982. Modelling of large scale systems in a hierarchical-multiobjective framework. In Large Scale Systems, Y. Haimes (ed.). Studies in Management Science And Systems, 7:1-17.

Haimes, Y. et al (ed.). 1990. Hierarchical Multiobjective Analysis of Large-Scale Systems. Hemisphere Publishing Corporation, New York. 323p.

Hax, A. and H. Meal. 1975. Hierarchical integration of production planning and scheduling. In Logistics, M. Geisler (ed.). North-Holland, Amsterdam, p.53-69.

Ho, J. and E. Loute. 1983. Computational experience with advanced implementation of decomposition algorithms for linear programming. Mathematical programming, 72:283-290.

Killen, J. 1983. Mathematical Programming Methods for Geographers and Planners. St.Martin's Press, New York. 363p.

Lasdon, L. 1970. Optimization Theory for Large Systems. MacMillan, New York. 523p.

Leong, G., M. Oliff and R. Markland. 1989. Improved hierarchical production planning. Journal of Operations Management, 8(1):90-114.

Liberatore, M. and T. Miller. 1985. A hierarchical production planning system. Interfaces, 15(1):1-11.

Louviere, J. and H.J. Timmermans. 1990. Using hierarchical information integration to model consumer responses to possible planning actions - recreation destination choice illustration. Environment and Planning A, 22(3):291-308.

Malakooti, B. 1989. A gradient-based approach for solving hierarchical multi-criteria production planning problems. Computers & Industrial Engineering, 16(3):407-417.

Mohanty, R. and M. Krishnaswamy. 1984. An assessment of some approaches to hierarchical production planning. International Journal of Operations & Production Management, 4(1):48-60.

Mohanty, R. and R. Kulkarni. 1987. Hierarchical production planning: comparison of some heuristics. Engineering Costs & Production Economics, 11:203-214.

Murtagh, B. and M. Sauders. 1987. Large scale linearly constrained optimization. Mathematical Programming, 14(1):41-72.

Mustafa, M. 1989. An integrated hierarchical programming approach for industrial planning. Computers & Industrial Engineering, 16(4):525-534.

Nazareth, L. 1980. A management model using Dantzig-Wolfe decomposition. Management Science, 26(6):510-523.

Olenik, S. 1985. A Hierarchical Multiobjective Method for Water Resources Planning. Master thesis, Case Western Reserve University. 127p.

Saad, G. 1980. Functional and hierarchical integration of multi-plant, multi-product production plans. In Expert Systems and Intelligent Manufacturing, M. Ollif (ed.). North-Holland, New York. p.305-317.

Saad, G. 1990. Hierarchical production-planning systems - extensions and modifications. Journal of Operational Research Society, 41(7):609-624.

Saaty, T. 1980. The Analytic Hierarchy Process. McGraw-Hill, New York. 287p.

Shetty, C. and R. Taylor. 1987. Solving large-scale linear programs by aggregation. Computers and Operations Research, 14:385-393.

Tsubone, H., H. Matsuura and T. Tsutsu. 1991. Hierarchical production planning system for a 2-stage process. International Journal of Production Research, 29(4):769-785.

Vinze, A. and A. Sen. 1991. Expert assistance for the decision support process using hierarchical planning. IEEE Transactions on Systems, Man and Cybernetics, 21(2):390-401.

Vyazgin, V. 1990. Fuzzy estimates of alternatives in hierarchical planning systems. Soviet Journal of Computers and Systems Sciences, 28(2):136-141.

Weitzman, M. 1970. Iterative multi-level planning with production targets. Econometrica, 38(1):50-65.

Comments on "Hierarchical Planning in Forest Resource Management: Defining the Dimensions of the Subject Area"

Authors: A. Weintraub and L. Davis
Discussant: *T.P. Harrison*
Management Science Department, 336 Business Administration Building, Pennsylvania State University, University Park, PA 16802, USA

Weintraub and Davis, in their paper "Hierarchical Planning in Forest Resource Management: Defining the Dimensions of the Subject Area", address four key aspects of hierarchical planning (HP). They are: 1) why do hierarchical planning, 2) the history of HP, especially in forest resource management, 3) a suggested definition of HP, and 4) important issues in the use of HP. They do an excellent job of circumscribing a large and ill-defined problem.

General agreement on a crisp, comprehensive definition is a necessary prerequisite to a focused research agenda on HP. For example, depending on the context, HP can imply the use of multilevel game theoretic methods, decomposition techniques in mathematical programming, or a means to describe managerial problems at differing levels of detail. The use of HP in forest management includes pieces of each of these.

It seems that a key element in HP in forest management is the varying level of detail in the model descriptions. For example, suppose that one could analyze the entire U.S. National Forest system in one model with detail down to the stand level. Would the HP problem be "solved"? It appears unwise to characterize the HP problem in terms of a moving frame of reference, namely the ability to solve increasingly large mathematical programs. Any definition of HP should result in a categorization of problems that is invariant to improvements in solution methods.

Also, how does one characterize a successful HP effort? Some possible metrics include: 1) the ability to achieve consensus in decision making, 2) a retrospective review of outcomes that proved to be "sufficiently accurate", and 3) the means to aggregate and disaggregate various models while maintaining mathematical and managerial fidelity.

Weintraub and Davis correctly point out that hierarchical planning problems in forest management tend to be embedded in a very political environment. This aspect simply cannot be ignored. The application of any successful HP effort must include elements of group decision making processes. Research on HP must also result in methods that are "inconsistency hardened". Inconsistency exists mathematically due to aggregation and disaggregation. However, the most important facet of inconsistency occurs from the imprecise nature of preferences of the decision makers.

Due to the typically long decision horizons in forest management, risk and uncertainty are fundamental considerations. Incorporating these aspects adds great complexity to the solution methods. Yet, techniques for explicitly addressing these issues is critical.

Lastly, HP methods should scale well, and work in a nested fashion. This would permit one to look at stand level models while aggregate/disaggregating to forest level models, while aggregating/disaggregating to multi-forest models, etc.

Weintraub and Davis circumscribe many research issues in HP. Following is a complementary research agenda synthesized from their discussion: 1) inclusion of bargaining, negotiation, and multiple decision makers with multiple objectives, 2) continued development of multi-resource models for the response of the forest to various cultural impacts, and 3) methodological research on the theory of aggregation and disaggregation in mathematical models.

The HP problem in forest management is ill-defined, diverse, difficult, and rich in conflict. The ability to significantly enhance decision making in this environment will greatly determine if HP is to become a legitimate science.

Hierarchical Planning in the Forest Products Industry

R.E. Colberg

The author is owner and president of Decision Support, a management consulting firm located in Columbus, Georgia.
This paper is based on the work he did while employed by the Mead Corporation.

Abstract

Today's business strategy is often torn asunder by exogenous changes that are occurring at accelerated rates. Rather than plan for a "most likely" future, industry must now learn to plan for change itself. This paper describes the planning procedures that one US forest products firm is using to help them develop new strategic alternatives for an uncertain future.

Introduction

The US Forest Products industry is faced with new and unprecedented challenges. For years, we have enjoyed a stable business environment where the players were known, and what changes there were occurred at a predictable rate. But now, the rate of change has accelerated, making it difficult to forecast what the future may hold. Industry is squeezed by powerful and pervasive political, economic, and environmental pressures that were unknown in the past. We struggle to maintain a competitive position in global markets, while the body politic passes costly legislation regulating air and water quality, and the recycle content in our paper products. A dedicated environmental movement has successfully lobbied for more and more set-aside reserves on public lands in the west, thereby reducing the amount of timber available for industry use. In the south, there is emerging evidence that our softwood inventories are declining, with less wood available to support current capacity, or future growth.

Change is nothing new; what is new is the rapidity and unpredictable nature of the many changes that are occurring today. All of this creates a degree of uncertainty that is uncomfortable for many. Some even suggest that planning is no longer a useful business function because excessive amounts of uncertainty preclude successful implementation.

We consider this a spurious argument. Uncertainty is the engine that drives entrepreneurial success. Planning cannot eliminate, or even reduce uncertainty. We should acknowledge its existence, and then proceed to build an analytical framework that we can use to identify current risk-taking options with the greatest chance for success in an uncertain future.

The management sciences have thus far done a poor job developing this new analytical framework. Most of the papers we have read either ignore uncertainty altogether, or offer an esoteric mathematical approach that is unsuitable for large scale, real-world problems. We need something that will work; something that the individual firm can use to evaluate the likely impact of future risk and uncertainty, and develop a response that will offer a competitive edge. Hierarchical planning is an option that appears promising.

An Emerging New Analytical Approach

Last year in Charleston, we had an excellent symposium with numerous quality papers describing systems applications in forest resources management. After the formal sessions, a number of participants stayed behind to discuss their own experiences, and to offer some insight regarding hierarchical planning as a disciplined approach. The discussion took an interesting turn when a number of individuals suggested that there had to be a better way, since much of what they were doing now was not being used. These were not researchers; they were solid practitioners with careers that depend on successful implementation. Since so many expressed the same concern, there is reason to believe that the problem is widespread. Perhaps it is time for a new approach.

But if we are going to consider something new, we should also consider what it is that is wrong with the old. A good place to start might be to examine more closely the comments we heard in Charleston. We would suggest that much of the frustration expressed at that meeting results from two wide-spread misconceptions:

1) Planning is not the scheduling of future activities, but rather an attempt to determine the likely future consequences of actions we take today;
2) Planning is not static, it is a dynamic, ongoing process;

Timber harvest and forest management scheduling are classic problems that have received widespread attention. Unfortunately, many of the models that have been developed to address these issues have languished because they did not meet expectations. One reason is our penchant for large models with lengthy planning horizons, and solutions as inviolate as the ten commandments themselves.

Perhaps this results from our forestry training, and a long term outlook that is unusual in today's business world. Whatever the reason, too many analysts formulate models with structural variables representing every conceivable resource allocation or silvicultural decision for decades to come. The solution schedules timber harvest and forest management activities at prescribed intervals, and while this might have been a suitable approach in the past it's not very effective in today's dynamic business environment.

Implicit in all of this is the assumption that future events can be predicted with certainty. But we live in an uncertain world, where tomorrow is little more than a series of alternate futures with associated probabilities. Rather than a rigid schedule of future activities, we need a dynamic tool that we can use to develop current strategies with the greatest chance for success in an uncertain future. With this new approach, our emphasis is switched to the present rather than the future. Planning becomes an ongoing activity wherein we continually develop a "rolling" plan in response to our best estimates of what that uncertain future may be.

We were struggling with these issues in 1988 when Mead began looking for a better way. As a result, we developed what was then called "integrated" planning. We have since learned that this was one of industry's first hierarchical planning systems. This paper describes the system in general. A companion paper by Welker and Kollmyer will provide greater details relating to harvest scheduling applications.

The Mead Experience

Mead Coated Board is a new division, formed in January, 1988, when two former partners agreed to end a long-standing relationship. At the time, Mead acquired a paper mill, two sawmills, and a half million acres of timberlands in Alabama and Georgia. Mead has since invested more than $600 million to upgrade the old mill, and add a new machine. This is now one of the south's largest mills, with sales worldwide.

These were difficult but interesting times for those who were involved. Almost overnight, a new management team had to move in, and keep an old mill running while a new one was built. In woodlands, the task was complicated by a lack of information. We had legal descriptions, and so we knew where our newly acquired holdings were located, but there was no reliable information about timber types or volumes. We had to start from scratch, developing information and planning systems as we went along.

We began by defining the three fundamental issues that had to be addressed by any planning systems we developed:

1) How do we maximize returns from company-owned or controlled timberlands;
2) What kind of wood procurement systems are needed to meet current and projected mill requirements at minimum cost;
3) How do we manage wood products operations as an integral part of a fiber supply system for paper manufacturing?

Subsequent planning systems have all focused on these three problem areas.

Mead had prior experience developing "single use" models for specific applications. We had structured numerous sawmill simulations, and harvest scheduling models, but we had never tried to build an integrated system with these dimensions. Many of the models we had built in the past would now be combined in a single, integrated package. The individual components would fit together into one interrelated system, with these characteristics:

- *Flexible Planning Capabilities*: We were committed to planning systems that were sufficiently flexible, and broad enough in scope that they could be used to address issues at all levels in the organization -from senior management to our field foresters.
- *Three Planning Levels*: The old concept of one, all purpose model was replaced by a triad of planning systems that focused on strategic, tactical, and operating issues separately.
- *Integrated Planning Systems*: Strategic, tactical, and operating systems are all interrelated. Strategic and tactical planning provide the constraints that limit operating decisions, while operating systems process feedback that is used to modify the assumptions in our strategic and tactical models.
- *Rolling Planning Horizon*: Uncertainty increases as we move outward in time. To overcome this, our planning will focus on present decisions that have

the greatest potential for financial success in what we believe is the most likely future. The only planning that is cast in concrete is short term; one to three years at most. Short-term plans are revised at frequent intervals, often in response to better information. Rather than an inviolate schedule of future activities, this new approach is dynamic and ongoing.

The five components in Mead's Hierarchical System are shown in Figure 1. The solid arrows indicate a forward flow of data from one component to another. A similar information feedback is represented by unfilled arrows. Each component is described in greater detail in subsequent sections. We begin with a brief description of our Geographic Information System, and the key functions it performs.

Geographic Information Systems

As we began developing this whole concept, information management was a critical issue. We had to be able to store and manipulate the massive amounts of data that are needed to support a timberlands planning system. This requires use of an extensive database that can be updated frequently.

Geographic information systems offered a practical solution to a difficult problem. Using the associated data-base, we can easily store and manipulate all the required timberlands data, and the geographic coordinates we need to plot selected stands on a map. With these capabilities, We not only have the information required for scheduling timber harvest and forest management activities, but we can also prepare maps showing where selected treatment areas are located.

Thus GIS plays a dual role. The information we need to support our timberlands planning is stored in

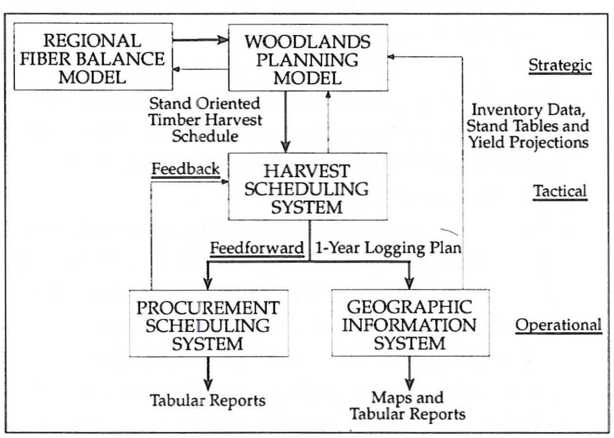


Figure 1. Hierarchical Planning Systems Mead Coated Board Woodlands Operation.

the database portion, and passed to our Woodlands Planning Model when it is needed. But the system performs a second function as well. Once we have developed a harvest schedule, this information, plus the geographic coordinates for selected stands, are passed forward to GIS where we prepare maps and tabular reports detailing next years cut from company lands. A vital information loop is closed. The results from our planning models can be output in terms that are meaningful for our field foresters. All of this is important, since these are the people who must implement the solution.

Strategic Planning

Few forest products firms cut more than a quarter of their wood requirements from their own land, relying on the open market for the remainder. Emerging trends in open-market supplies are therefore a major concern.

The first of our two strategic models is used to help us understand long term timber supply and demand relationships in our own operating area. In this model, we simulate timber supplies, and mill requirements in the three-state area surrounding our mill — Alabama, Georgia, and north Florida. We can test alternate assumptions that would effect timber growth or consumption, and measure the probable future impact on our own wood supplies. Output from this model provides the open-market constraints that we use in planning timber harvest and forest management strategies for our own lands.

Woodlands Planning is the second strategic application. Many consider this a tactical model. We see it as a strategic system because of its extended time horizon, and its frequent use as a tool to investigate manufacturing alternatives. This one model is often used to answer questions relating to added conversion capacity, or the longer-term potential for wood-products manufacturing.

The Woodlands Planning Model is used to develop timber harvest and forest management schedules for company-owned or controlled timberlands. It's also used to investigate options for improving forest productivity. A linear programming model supported by an extensive database, this is the largest system in our planning hierarchy.

Most of the data used in this model is input from GIS, and a number of smaller databases. The open-market supply constraints are provided by our Regional Fiber Balance Model. Outputs include a long-term management plan, and an extended timber harvest schedule.

These two models exhibit characteristics that are found in most strategic applications:

- An extended time horizon that may be decades in length;
- Data that is highly aggregated;
- Broad in scope, these models address fundamental issues that determine the firm's long-term survival. They are designed to answer questions at senior management levels;
- Considerable risk and uncertainty, especially in the latter planning periods.

Tactical Planning

The Woodlands Planning Model is used to develop a "stand specific" treatment and harvest schedule. But many areas that are selected for near-term harvest do not provide a suitable logging chance. They should be combined with other stands scheduled for a later date. Tactical planning is done with our Harvest Scheduling System, where we prepare revised one and five-year plans that are practical from a procurement standpoint, without overly jeopardizing our long term forest management goals.

This second linear programming model contains data for all of the stands that are in the Woodlands Planning System. The objective function values are the first period reduced costs (d_j's) from the Woodlands Planning solution. The d_j value for a stand that is selected for immediate harvest is zero. Others have non-zero d_j's that increase in value as their contribution to Mead's overall objectives diminish. Our goal is to select appropriate harvest units, while at the same time we minimize the unfavorable impact we may have on our longer-term management goals. This is accomplished in the Harvest Scheduling System where we develop a revised plan with prescribed volumes, while minimizing this new "d_j" derived objective function.

As a final step, we resolve the Woodlands Planning Model forcing this new harvest mix, and measure the difference in the two objective function values. To date, we have not observed more than a five percent difference. We consider this more than satisfactory for a "non-optimal" solution that can be easily implemented on-the-ground.

This model exhibits certain features that we often see in tactical applications:

- Moderate planning horizons, usually ranging from one to five years;
- Data is still somewhat aggregated, but more detailed than the information used in a strategic application;
- Medium scope, designed to address issues of interest to upper and mid-level woodlands managers;
- Moderate amount of risk and uncertainty.

Operations Planning

While operations planning is on the bottom rung of our hierarchical ladder, this doesn't diminish its importance. It's here where the plans developed at strategic and tactical levels are further refined for on-the-ground implemented.

The first of our two operational systems addresses wood procurement issues. Wood represents more than half the costs incurred to manufacture slush pulp. Thus reducing wood costs can have a greater impact on profit performance than almost anything we can do in the mill itself. This model contains supply and cost data for every known source of wood fiber, including our own contractors and chips from our sawmills. The goal is to minimize the "real costs" for wood delivered to the digester, unencumbered by arbitrary transfer prices or accounting mystique.

The cut from company land is a fixed amount, and this is provided as output from the Woodlands Planning Model. The remaining data is supplied by our district wood procurement managers, who update their own information at least once a year. Solutions provide a rather detailed summary of where the "least cost" volumes are located, and how much we should purchase from each source.

We have already described the dual role GIS plays in our integrated planning systems. We can only emphasize that as an operational tool, GIS provides the linkage between an abstract mathematical model, and on-the-ground implementation of solution results.

These systems also exhibit certain characteristics that identify them as operational applications. Among these are:

- A short planning horizon, usually one year or less;
- Detailed data;
- Scope limited to immediate operating issues;
- Low degree of risk or uncertainty.

Conclusions

A few comments that summarize where we are and what we have learned are perhaps appropriate. First, hierarchical planning requires a long term, ongoing commitment. The task is never done. We can always find a better way of doing things, and we are continually changing and upgrading our models and systems. Part of this is in response to changing technologies, but part is due to the insight management gains as they learn to use these systems. They soon begin challenging our ability to answer their questions in an appropriate and timely manner.

Analysts are often frustrated because their solution results are not immediately implemented. But this is not unexpected. Models are nothing more than another decision making tool. They do not make decisions; management will always reserve this right for themselves. Our success is guaranteed when we can participate as an equal in the decision-making process, using our models to help guide management in the right direction.

We don't want to leave you with the impression that we have somehow solved all of the problems. While much of what we have described is implemented, portions are still being developed. And there are still those who have little regard for what we are doing, although their numbers diminish as we proceed.

Finally, very little of what we are doing today could be accomplished without PC-based optimization tools and database capabilities. These recent technological developments have released us from a stifling mainframe environment that did little to advance our cause. Today, we routinely solve on a desktop computer models that just a few years ago we could not handle on anything other than the largest mainframe systems. And if you are considering similar applications, we recommend use of the best PC-based software available. You will need all the power and flexibility you can get for successful implementation, and subsequent use.

Tactical Level Harvest Scheduling Based on Strategic Level Woodlands Planning

J.C. Welker

Senior Business Analyst, Woodlands and Wood Products Technical Services, Mead Coated Board
1200 Brookstone Centre, Columbus, Georgia 31909, USA — (706) 576-6168

C. Kollmyer

Senior Programming Analyst, Woodlands and Wood Products Technical Services, Mead Coated Board

Abstract

Linear programming models have been used for a number of years to provide guidance and insight for strategic land management and harvest scheduling decisions on public and private lands. However, applying the results for making tactical and operational decisions has been a challenge for analysts and managers alike. This paper describes an approach used by Mead Coated Board to link strategic, tactical, and operational plans and decisions.

The strategic planning systems are used to make longterm resource allocation decisions for company-controlled lands, private lands, and wood processing facilities. The tactical level system provides five-year guidelines for managing and harvesting individual cutting units based on minimizing the impact of deviating from the strategic level plan. Operating plans are made using a Geographic Information System to interpret tactical model results.

Introduction

This workshop is partly a result of discussions held at the 1991 Symposium on Systems Analysis in Forest Resources at Charleston, South Carolina. A recurring theme was that increased use of hierarchical planning would result in better use of operations research techniques. This workshop gives us an opportunity to share our experiences and visions of the role of hierarchical planning in our respective organizations.

The implementation and use of a hierarchical planning system is an exercise in the management of three components of technical change: hardware, software, and "peopleware". This is illustrated as the sides of the triangle in Figure 1. From an operations research (OR) perspective, we have little difficulty relating to the necessity of integrating these three components. In the past, OR applications were often stymied by a lack of hardware and software. This barrier is rapidly being torn down as more powerful microcomputers and microcomputer software become available at lower prices.

We have also witnessed situations where "elegant" models are never applied due to a failure to adequately address the needs and expectations of managers and decision makers. Analysts, managers, and decision makers are working toward removing this barrier also. As these barriers are removed, we are beginning to focus on two new dimensions to the management problem:

(1) The need to use appropriate hardware, software, and peopleware at different levels of the planning and decision making hierarchy;
(2) Efficient passing of information and consensus building between hierarchical levels.

This is illustrated in Figure 1 as the series of triangles connected by forward and backward linkages between hardware, software, and planning teams.

This paper and a companion paper by Ralph Colberg explain various aspects of the planning and decision-making processes used in the Woodlands Department of Mead Coated Board. The paper by Colberg gives an overview of the planning system and its hierarchical levels. This paper is a more detailed discussion of the parts of the system used at strategic, tactical, and operational levels to manage company-controlled lands.

Planning System Environment

Instituting a planning system, like management itself, requires long-term commitment and patience at all levels of an organization. Aside from the need to acquire hardware and software, it is necessary to commit monies to such labor intensive tasks as gathering information, developing models, and analyzing results. Planning teams themselves have particular responsibilities. These include:

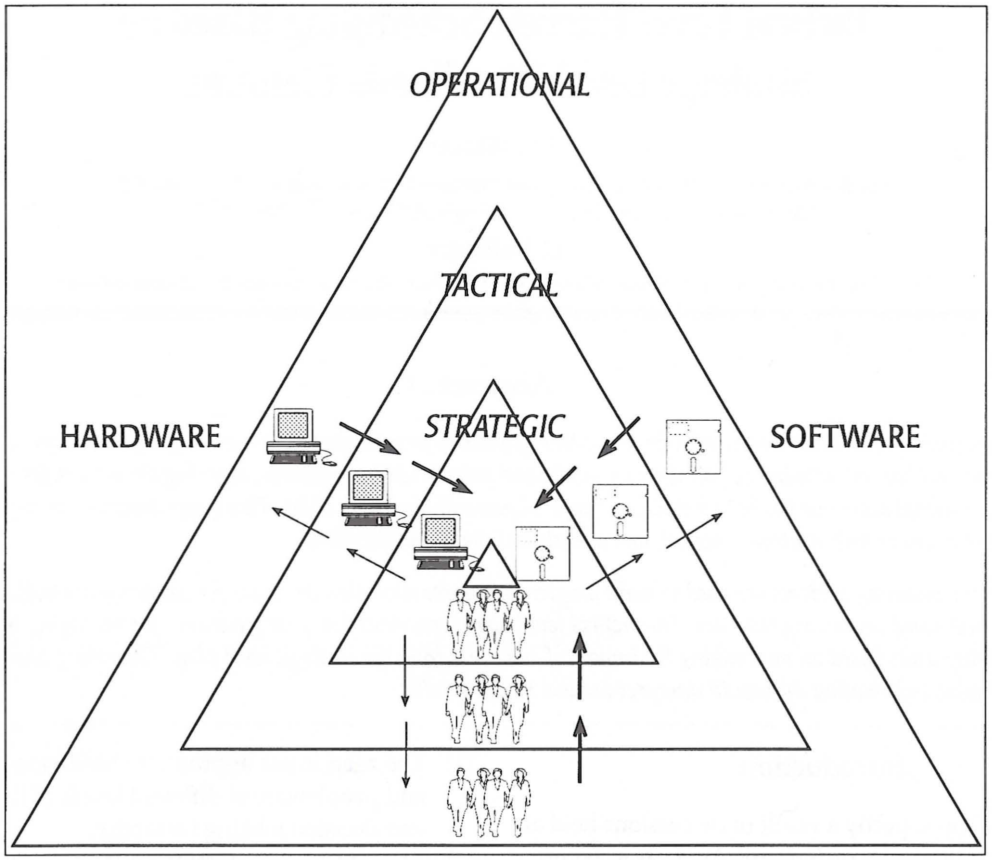


Figure 1. System types and linkages.

(1) Identifying the purposes and needs of models at the various levels of the organization;
(2) Training personnel at all levels in the appropriate use of the system and its models; and
(3) Maintaining a flexible attitude toward changing the system as new needs and purposes are recognized.

We have been fortunate at Mead Coated Board to have received such a commitment from management as we have developed the various parts of our planning system. The systems we describe in this paper have been tested and used on long-term contract lands requiring specific strategic, tactical, and operational decisions in a relatively short period of time. These decisions were needed prior to completion of data gathering on all company-controlled lands to be placed into the Geographic Information System (GIS). At the present time this task is complete and the planning system is being implemented on company-controlled lands, i.e. fee and leased lands.

In addition to management's commitment, Mead's adoption several years ago of the "continuous improvement" (CI) paradigm provides a foundation for efficient use of the hierarchical planning and decision-making system. The fundamental purpose of adopting CI methods is to provide a framework for competitively adapting to change at all levels of the organization. The four basic concepts of CI are these:

(1) Balance human and technical systems;
(2) Commitment through teamwork;
(3) Continuous improvement based on data; and
(4) Focus on the customer (internal and external).

As CI techniques and ways of thinking spread, the strategic, tactical, and operational purposes of the hierarchical planning system are clarified and reinforced.

Planning System Overview

Figure 2 shows the types and hierarchy of planning and decision making systems used with company-controlled lands. "Company-controlled lands" represent the sum of fee, long- term contract, and short-term contract lands. The systems are the same as in Figure 1 of Colberg's paper with the following exceptions:

(1) The strategic "Regional Fiber Balance Model" has been omitted;

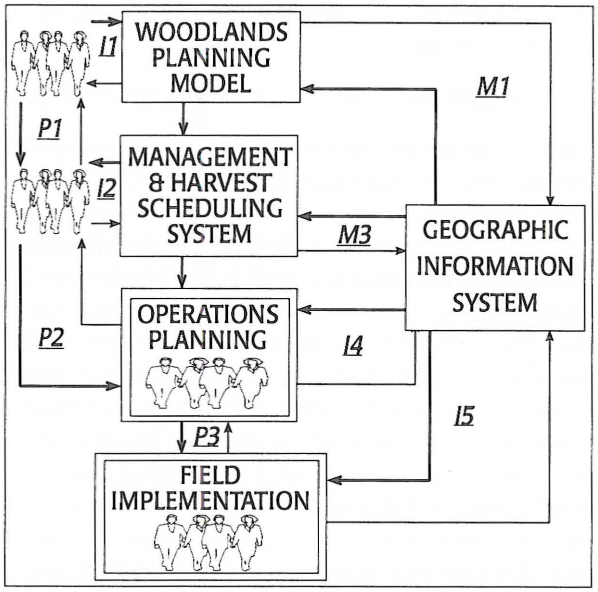


Figure 2. Planning system linkages for company-controlled lands.

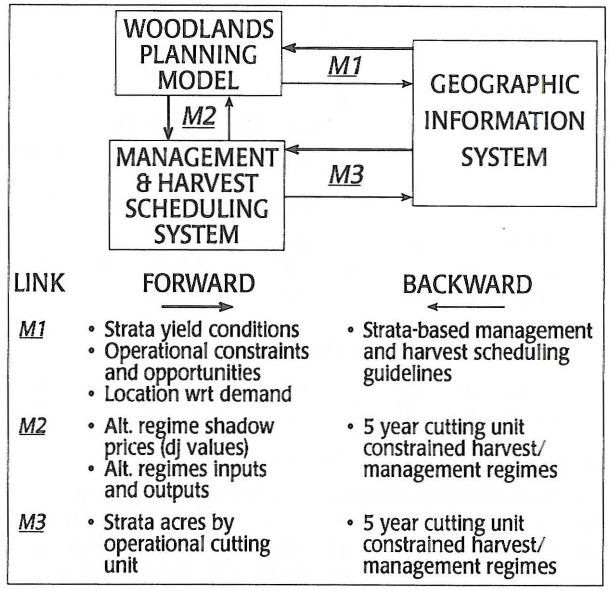


Figure 3. Software system linkages.

(2) The operational "Procurement Scheduling System" has been omitted;

(3) The "Operational Planning" and "Field Implementation" processes have been added;

There are two types of systems in the diagram: "people-based" and "software-based". A completely integrated planning system is one in which there is efficient communication of information between system types and system levels.

In our prototype application for long-term contract lands we achieved a completely integrated system. For other lands we have completed the GIS; and at the time of this writing we are working on the strategic Woodlands Planning Model linkage and application (M1). The sections which follow describe: Software Systems and linkages (Mi); People- based processes and linkages (Pi); and Software/People linkages (Ii).

Software Systems and Linkages (Mi)

The three software systems are the Geographic Information System, the Woodlands Planning Model (WPM), and the Management and Harvest Scheduling System. Colberg's paper gives a brief description of each system and its function. We will elaborate on the linkages between the systems as they are outlined in Figure 3.

GIS/woodlands planning model (M1)

The main purpose of the Geographical Information System is to provide information at the strategic, tactical, and operational levels. Each tabular data record in the GIS database represents the information for a particular "stand". A stand is defined as the smallest area which field personnel consider to be a separate management unit for making harvesting decisions. Each stand is linked to specific geographic pixel information in the graphical side of the GIS.

Some operational information recorded by field personnel is recorded at the present time only on the database side of the GIS. An example of this is certain operational information for which boundaries are more difficult to define. This is recorded as the proportion of a stand which is expected to fall within a particular management regime opportunity or constraint. Using GIS maps and on-the-ground knowledge, field personnel have recorded the proportions of acres in a stand that fall within a Streamside Management Zone (SMZ); that can be row thinned; that are recommended for maintaining or converting to pine; and that are recommended for retention for even-aged hardwood management. Figure 4 illustrates this for two compartments in the GIS. Compartment 48A in this example is made up of three stands:

Stand 1: Seeded loblolly (SL) with 863 acres;
Stand 2: Natural loblolly (NP) with 35 acres; and
Stand 3: Cove hardwood (CH) with 244 acres.

<-- GIS Field Data -->				<-- Cut. Unit/Oper. Data -->					
Std.	Field Strata	1990 Age	Total Acres	CU#	Operability Acres				WPM Yield Stratum Number
					Pine Mgt.	Hdwd Mgt.	SMZ Mgt.	Thin Feas	
					Compartment 48A				
1	SL323	14	863	53	863			432	13
2	NP223	30	35	54	35			35	24
3	CH212	36	244	54	122		122		34
					Compartment 51B				
3	NP322	30	167	24	167			167	24
4	CH323	47	47	36	28		19		36

*Woodlands Planning Model Yield Strata:

13 = Seeded loblolly, 11-15 yrs., 70 <= S150 <= 85, >600 trs/ac
24 = Natural pine, 21 to 35 yrs., S150 >= 70, BA >= 51 sq.ft./ac
34 = Cove hardwood, >= 21 yrs., Dm.Ht.>= 70, BA >= 40 sq.ft./ac
36 = Cove hardwood >= 21 yrs., Dm.Ht..> 74, BA >= 65 sq.ft./ac

Figure 4. GIS tabular data linkages to hierarchical planning models.

For Stand 1 field personnel have indicated that only 432 acres have topography permitting row thinning operations. In Stand 3 the estimate is that only 122 acres can be converted to pine and that the other 122 acres should remain in an SMZ. These designations are used as constraints in the WPM to give a more accurate representation of operational feasibilities.

In addition to operational information, each stand is assigned to a particular "yield stratum" based on the species group, stand origin and type, age class, site productivity class, and stocking class[1]. These yield strata are the initial state conditions for projecting yields for individual management regimes in the WPM. In Figure 4 there are a total of four yield strata in five stands. After aggregating stand acreage in all three ownership categories, we have about 95 yield strata in the WPM for a land base of about 500,000 acres.

A database management program is used to aggregate information so that each acreage-based decision variable in the WPM represents the number of acres in a particular yield stratum located a particular distance from Mead's wood processing facilities. The operational information is aggregated by yield/location stratum and passed to the WPM in order to set constraints on the number of acres that can be managed with a particular management regime. Once a particular model run of the WPM has been agreed upon, the strata-based cutting guidelines associated with the yield/location stratum of a particular stand are passed back to the GIS for future reference.

GIS/management & harvest scheduling system (M3)

While stands are the basic management unit in the GIS system, field personnel also indicate in the GIS what stands should be linked together as individual cutting units. The aggregation of individual stands into cutting units (CU) is illustrated in Figure 4. On the other hand field personnel have indicated that for harvesting purposes this compartment contains only two cutting units, numbers 53 and 54. Therefore, the harvest scheduling system contains a restriction that Stands 2 and 3 must be harvested together. Cutting unit (CU) designations are not written in stone but are based on best estimates by field personnel of what they would like to have considered in the development of the tactical harvesting plan. After the Management and Harvest Scheduling System is run the cutting guidelines for individual CU's are passed back to the GIS.

WPM/management & harvest scheduling system (M2)

The objective function of the WPM is to minimize the cost of delivering wood to the paper mill subject to pulp demand, sawmill capacities, and the cost of open market wood. While the model provides an optimal and generally feasible solution at the strategic level, it is not feasible at the tactical and operational levels. The purpose of the Harvesting Scheduling System is to provide harvest timing guidelines for individual cutting units over a five-year period. These guidelines are developed using a linear program where the decision variables are the individual CU's cut in a particular year of the five-year tactical planning horizon.

The objective function in this model is the minimization of the deviation from the optimal strata-based cutting guidelines given by the WPM, subject to the added limitation that stands within a cutting unit boundary are cut at the same time[2]. Each cutting unit can theoretically result in as many decision variables as their are yield/operational management regime strata in that cutting unit. After analysis we usually choose a separate decision variable for each yield stratum within a cutting unit. Also, under our operating conditions there are usually only two or three yield strata per cutting unit. The objective function coefficient is the weighted average of the shadow prices (dj's) for each yield stratum associated with the clearcut year of that decision variable.

[1]See the paper by Welker at the 1991 Systems Analysis Symposium for a complete explanation of the yield strata.

[2]There is also an option in the model to override this strict restriction and specify the number of arces in a cutting unit that do not have to be harvested simultaneously.

These decision variables and there coefficients are best illustrated with a simple example. Suppose there are three yield strata in a cutting unit: a 22-year old plantation (PL512); a 45-year old natural pine stand (NP311); and a 55- year old bottomland hardwood stand (BH311). The WPM indicated that they should be cut in three different years: 1992; 1994; and 1993 respectively. The shadow prices associated with each combination are as follows:

Yield Stratum	Acres in CU	Year Clearcut 1992	1993	1994
(dj from WPM)				
PL512	55	0	5	12
NP311	105	15	14	0
BH311	30	7	0	8
Obj. Coef.				
CU Model:		**9.39**	**9.18**	**4.74**

Therefore, the marginal cost of deviating from the WPM guideline using 1992 as the clearcut year will be $9.39 per acre in the cutting unit. Also associated with this cutting unit-based decision variable are the inputs and outputs which are also passed from the WPM.

The feedback from the Cutting Unit model to the WPM are the optimal harvest/management regimes for each cutting unit. We tested this linkage in the prototype system for long-term contract lands. The minimized cost in the objective function was increased by about 4%.

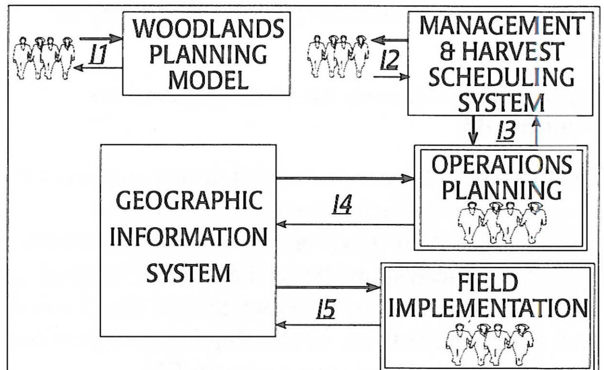
Software/People Linkages (I_i)

Efficient communication between our software systems and team members at each stage of the planning process is critical to successfully implementing an integrated planning system. These linkages are difficult to describe since they are constantly changing as planning and operation's teams gain a better understanding of how to best use the software. Some of the key elements to successfully establishing and maintaining these linkages are:

(1) Teams at all levels in the hierarchy need to **trust** that data input into the models are an accurate representation of the operating environment;
(2) Teams need to have at least a rudimentary **understanding** of what the mathematical models are doing;
(3) Model output must be presented in a **useful and verifiable format** which relates to field operations;
(4) Models must have the **flexibility** to enable teams to make timely revisions as conditions change or as decision making opportunities arise.

Following the basic tenets of continuous improvement in our management styles goes a long way towards satisfying these elements: treating individuals within the organization as internal customers; training; and giving users ownership in data input to the software.

Figure 5 illustrates the forward and backward linkages between software and people in the planning system. There are three basic types of linkages:



LINK	FORWARD →	BACKWARD ←
I1	>Macroeconomic assumptions >Operational coef. & constraints >Financial coef. & constraints	>Production benchmarks >Inventory benchmarks >Financial benchmarks
I2	>Production benchmarks >Financial benchmarks	>5-yr. financial constr. >5-yr. production constr.
I3	>Optimal and feasible cutting guidelines	>Rev. operations data
I4	>Cutting unit maps >Cutting unit tabular data	>Rev. operations data
I5	>Cutting unit maps >Cutting unit tabular data	>Revised stand data >Rev. operations data

Figure 5. Software/people linkages.

(1) Between planning teams and models (I1 & I2);
(2) Between the tactical planning model and the operational planning process (I3); and
(3) Between the GIS and operational planning and information teams (I4 & I5).

Planning team and planning models (I1 & I2)

The forward and backward linkages between the WPM and the strategic planning team are fairly straightforward; the sort of stuff that makes life interesting for persons running models! A key element to making this work with respect to the forward data linkages is to have readily available and summarized databases to empirically inform planning teams. In the absence of empirical data, the sources of model coefficients and expectations about the future are likely to be uninformed guesses made in a political environment. With respect to backward linkages, benchmarks provided by the model should be easily interpreted and provide a basis for adjusting model parameters to obtain desirable strategic outcomes. Graphical output is a useful means of communicating the various production, inventory, and financial benchmarks from the model.

At the tactical level (I2), the forward linkage is from the model to the planning team. The planning team reviews the production and financial benchmarks in the next five years. Based on their review, the cutting unit model run parameters and constraints may be altered.

Management & harvest scheduling/operations planning (I3)

The forward linkage is the harvest timing guidelines by cutting unit from the Management and Harvest Scheduling System. One way this is communicated is by a report which shows both when the WPM scheduled a stand for cutting and when the CU Model scheduled a stand for cutting. Continuing from our previous example of three stands in a particular CU:

Yield Stratum	Acres in CU	Clearcut Year WPM	Clearcut Year CU Model
PL512	55	1992	1994
NP311	105	1994	1994
BH311	30	1993	1994

At this stage the operations planning team will review this report as well as relevant GIS information (I2) and make a decision. If the team thinks that the original CU boundaries are too restrictive, they may elect to make a change at this point and feed the information back through the Harvest Scheduling System.

GIS and operations (I4 & I5)

The GIS and field observation are the sources of information used to make operational decisions. The GIS role is to provide maps and stand level volume information. This information is confirmed or revised on the basis of on site observations used to make individual cutting unit harvest and site preparation plans.

People Linkages (Pi)

The linkages which exist between teams at the various hierarchical levels represent continuing feedforward and feedbackward processes. These are summarized in Figure 6. A key task of management is to strive for a desirable outcome from these processes. A desirable outcome is characterized as one where a consensus emerges with respect to mutually consistent strategic, tactical, and operational plans for achieving corporate goals.

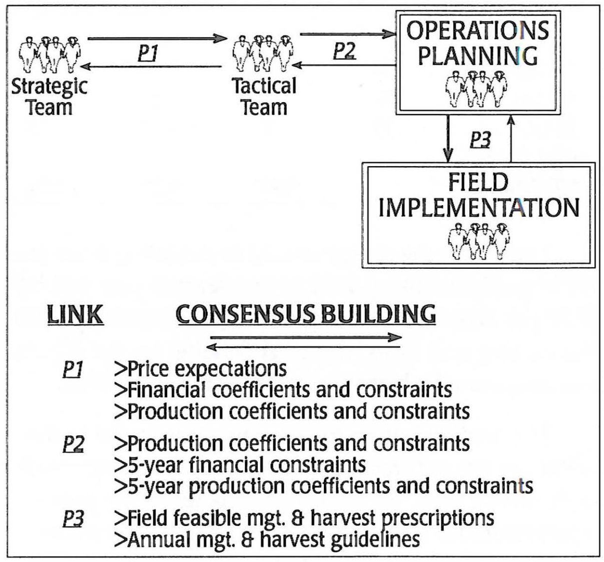


Figure 6. People linkages.

Summary

At Mead, hierarchical planning and decision making is seen as part of the Continuous Improvement paradigm we have adopted as a management philosophy. Hierarchical planning provides a framework for integrating information systems, mathematical models, and teams in order to make strategic, tactical, and operational decisions. Besides leading to better decisions, we expect that a continued commitment to hierarchical planning will improve communication within the organization and enable us to adapt to an increasingly competitive and ever-changing business environment.

An Integrated Forestry Planning System

M.S. Jamnick and E.W. Robak
Faculty of Forestry, University of New Brunswick, Fredricton, NB Canada

Abstract

A research group at the University of New Brunswick has developed an integrated forestry planning system (IFPS) to help researchers and managers generate and evaluate integrated solutions to resource and operation problems. The system has been built from existing harvest scheduling, block design, block scheduling and operational planning models linked together by common data and a geographic information system. The planning philosophy assumed by the system designers is one that emphasizes forest-wide solutions and hierarchical planning. However, once the initial "top-down"plan is created, planners are able to use an iterative process to refine and improve all plans (strategic, tactical and operational) based on knowledge gained from planning conducted at the other levels. The system is useful as both a research and a management tool.

Introduction

In most jurisdictions, forest management planning is a hierarchical process that consists of strategic, tactical and operational levels. The strategic level usually employs a strata-based timber harvest schedule with a planning horizon of 60 to 200 years. This harvest schedule is used to prepare a forest management (tactical) plan which sets forth the management objectives for a period of time, often 10 to 30 years. Operating plans which are based on the forest management plan and detail on-the-ground activities, are prepared for a one to five year period. Because the planning process is hierarchical it is essential that there is consistency between each planning level. In this paper we introduce an integrated forest management planning system that helps ensure this consistency and accelerates the development and evaluation of alternative forest management plans. A case study example, which illustrates how the system could actually be used, is also presented.

Overview of the System

The IFPS consists of four models that access or share information with a GIS database (Figure 1). This is a modular system that is designed to use any strata-based harvest scheduling model, GIS, or Monte Carlo integer programming model. Each component of the system that we have developed (CRYSTAL, BALL, OP-PLAN) uses dBase formatted files. This facilitates the transfer of data between system components and the GIS whose data files can be converted to dBase formats with relatively simple translation routines.

Recent U.S. Forest Service planning efforts have demonstrated that attempting to simultaneously solve a large integrated planning problem using a single model (FORPLAN) is not feasible because of model size and the inability of the analyst or manager to interpret and understand the solution (Barber, 1986). Thus, we take a sequential, rather than simultaneous, approach to solving the integrated forest management problem. This sequential approach is also consistent with the basic assumption that there are many alternatives available to the forest manager at each planning level and the system should allow examination and comparison of the alternatives at each level.

Currently the system is limited to timber harvesting considerations. It is our intention, however, to expand the system to include consideration of wildlife

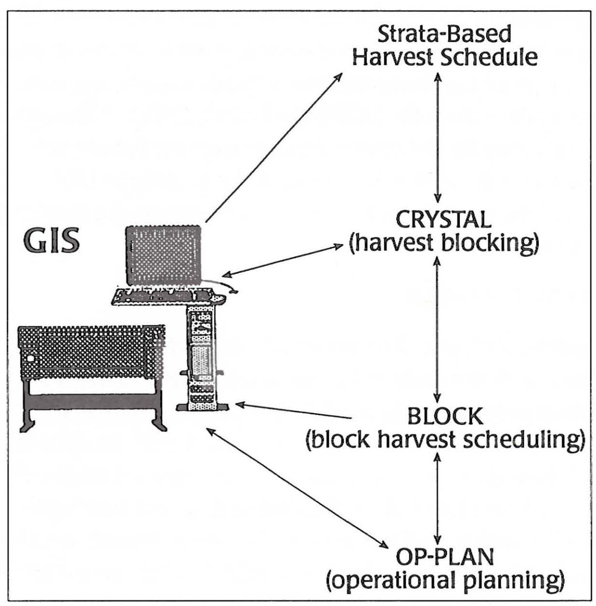


Figure 1. Overview of the integrated forest planning system.

habitat, harvesting and road construction costs, visual quality and recreation potential. Our strategy is to start with a limited prototype system that can be easily expanded in the future.

GIS Database

One of the most limiting factors in forest management planning is a lack of site specific information. Because linkages between planning levels are generally lacking, there is often inconsistency between information at each level. It is also often the case that analysts and managers are not aware of the type and amount of information that is required to plan effectively at each planning level. Thus, one important research goal is to determine what information is required at each planning level and how to best use that information. Since the GIS database largely forms the link between the strategic and operational planning levels, it is important that this database is complete, but does not contain superfluous information.

We are currently working with a GIS database supplied by the New Brunswick Department of Natural Resources. This database is rather limited and primarily contains information on vegetative attributes, streams and roads. This essentially limits our ability to consider other resources or forest outputs and it will be necessary to expand this database if the full system is to be developed. One vital piece of information that is currently missing is topography.

We have developed our prototype system using ARC/INFO Version 3.4D and CARIS (from Universal Systems Ltd.). The CARIS system runs under the UNIX operating system and consequently we have found this to be more cumbersome and difficult to integrate with the system than the DOS based ARC/INFO. Although UNIX may be the operating system of the future, we have chosen at this time to keep the prototype DOS based to simplify system design and ensure the system's usability.

Harvest Schedule

Any strata-based harvest scheduling model could be used with the system, but we have chosen to use a linear programming model. The primary reason for this decision is that we wanted to start with an optimal solution that could account for intertemporal trade-offs at the forest level. Although we realize that this "optimal" solution will not actually be implemented, we also know that this is the best we could do at the forest level without tactical or operational constraints. Thus as planning moves from strategic to tactical to operational levels, the system is able to calculate reductions in timber harvest volumes that occur at each level.

We construct a linear program that maximizes timber harvest subject to harvest flow, product mix and area constraints. This model does not include adjacency, access, or harvesting cost constraints. These tactical and operational constraints are considered during the tactical and operational planning stages. The strata-based harvest schedule that is developed at this stage is the primary input to the CRYSTAL harvest blocking model.

Crystal

Of the three planning levels, management planning is the most critical to the ultimate success or failure of the forest management effort. The purpose of a management plan is to rationalize the goals and intentions of the long-term harvest schedule with the requirements of day-to-day operations in the forest. A harvest schedule is very much an abstraction in that silvicultural activities are defined in terms of timing and the strata to be treated, but they are not defined in terms of location. A management plan is where these prescriptions begin to define on-the-ground activities. Since the management plan is the vehicle for translating the targets specified in the harvest schedule into projects that are conducted within the forest, it is doubtful that satisfactory management will result from a poorly conceived plan. Because of the innate tendency to concentrate on immediate problems, long-term management objectives are likely to be sacrificed for short-term economic gain or administrative expediency where there is no reference to a specific plan of action for the particular forest (Baskerville, 1987).

In the disaggregation of a strata-based harvest schedule, a harvest block is a contiguous parcel of forest land that is to be harvested within a specific time frame under the same (or similar) harvesting and regeneration system(s). Because silvicultural interventions are fixed in time and space by the location of harvest blocks, the harvest block is the basic unit of forest management intervention. Harvesting affects forest structure and thus has an impact on all forest outputs, timber and non-timber. The choice and timing of which stands to cut also directly affects the organization and costs of harvesting and transportation systems (Arvanitis, 1968). These choices are explicitly stated in the management plan in the form of delineated harvest blocks and an explicit schedule for harvesting them. How well the layout and harvest schedule of these blocks fits the management objectives for the forest (in terms of providing the desired mix of benefits at the desired times) directly determines how successfully the analyst has captured the essence of the forest management problem.

Timber harvest schedules are usually calculated using a strata-based model, but on-the-ground harvest activities are usually planned for harvest blocks that consist of several stands that may not all belong to the same strata. This basic difference between long-term and operational forest planning greatly complicates the implementation of forest management plans and requires some method of translating strata into harvest blocks. Manual methods of spatially and temporally allocating strata-based harvest schedules to harvest blocks have two major disadvantages.

First, the process is laborious and slow. Visual inspection must be used to detect infeasibilities that arise because of adjacency constraints. For a small number of maps covering five planning periods, visual inspection may suffice, but for large planning problems involving tens if not hundreds of map sheets, visual inspection becomes tedious and extremely time consuming. Because manual block layout is an expensive task, it is unlikely that alternative harvest block layouts are explored. Instead, it may be easier to make modifications to an existing layout to meet operational restrictions, even if the resulting block layout may yield an inferior harvest schedule.

The second drawback to the manual method of delineating harvest blocks is the lack of explicit decision criteria used to produce the block layout. Differences in block layout may vary not only with different people, but a single individual may alter his or her approach over time, particularly in the case where the individual has been working for an extended period. When the block layout is later evaluated, it may be difficult to explain why particular stands were included in, or excluded from, any one block. Conversely, an automated, systematic approach using a given set of allocation rules will always yield the same harvest block configuration.

The CRYSTAL model was designed specifically to spatially and temporally allocate the first 25 to 35 years of a strata-based solution into alternative harvest blocking patterns (Walters, 1991; Jamnick and Walters, 1991(a); Jamnick and Walters, 1991(b)). CRYSTAL is a conceptually simple model in which a stand eligible for harvest is initially chosen as a "seed". Then the neighbors of the seed are examined to determine if any of them are also eligible for harvest at this time. If so, the seed and neighboring stands are aggregated into a potential harvest block. As each eligible neighbor is added to the potential harvest block, other stands which become neighbors are examined for harvest eligibility and are added if appropriate. This process continues until no additional eligible neighbors are found or until the maximum block size is reached. After exhausting all possibilities, if the potential block exceeds the minimum block size it is assigned a block number and a harvest period which coincides with the harvest period of the seed stand, and its component stands are withdrawn from further consideration by the algorithm. If the harvest block is smaller that the minimum block size, then the stands are released and considered for later inclusion in other blocks. Finally, a new seed stand is chosen and the process of aggregation and allocation begins again. The algorithm continues until that portion of the strata-based solution that can be allocated within the constraint of the minimum block size has been allocated.

Although conceptually simple, CRYSTAL is a relatively complex model that provides numerous options to guide the harvest blocking process. CRYSTAL allows the user to develop alternative harvest blocking patterns by specifying (1) minimum and maximum harvest block sizes over the entire forest or by zones, (2) criteria for choosing seed stands, (3) the pattern of search for stands adjacent to the seed, and (4) the allowable deviation from the timing choices determined in the strata-based schedule.

Currently seed stands can be chosen by one of seven criteria: area (ascending or descending), perimeter (ascending or descending), stand identification number, stand type identifier, or allocation potential (described below). Once a seed stand has been chosen the program must select which adjacent stands will be included in the harvest block. Each stand has three attributes associated with it, one of which may be used as a selection criteria: allocation potential, stand proximity, and stand area.

The allocation potential is calculated as:

$$AP = \sum_{i=1}^{n} X_i$$

where:

AP = allocation potential

X_i = number of eligible stands contiguous to seed stand in period i

i = period of allocation

n = number of periods to be allocated

Selecting stands on the basis of increasing allocation potential will bias the solution to first allocate those stands that have few eligible neighbors.

Stand proximity is calculated as the linear distance between the centroids of a particular stand and the seed stand. By selecting nearest stands first, harvest blocks delineated by CRYSTAL will tend to be circular in shape. This may be advantageous because it will tend to reduce the ratio of perimeter to area within a harvest block. Although other factors such as terrain affect the operability of a harvest block, large perimeter to area ratios generally increase extraction costs and windthrow damage of residual trees.

If stand area is chosen as the selection criteria, CRYSTAL will select the stand with the smallest area. By building harvest blocks with the smallest stands first, the number of small stands allocated will be maximized. Since small stands tend to have low allocation potentials, the overall allocation of the harvest schedule may be increased using this criteria.

CRYSTAL selects the eligible stand with the lowest value for the chosen attribute. If a tie exists between two or more eligible stands, the program selects the stand belonging to the stand type with the largest area remaining to be allocated. Biasing the solution toward unallocated area helps to distribute the allocation across stand types and harvest periods.

CRYSTAL was designed to allocate the strata-based solution as closely as possible. Because of the spatial distribution of stands, however, it may be impossible to completely allocate a harvest schedule without violating harvest block size constraints. Therefore, deviations from the exact timing of harvest specified in the harvest schedule may be allowed in order to permit allocation of more of the harvest schedule by selecting tolerance limits that govern how much deviation in timing choices are acceptable.

A user specified tolerance value of +/-1 would allow consideration of any stands adjacent to the seed stand that are within one period of the timing choice for the seed stand. Since the intent of the program is to follow the harvest schedule as closely as possible, the program will deviate from the harvest schedule only if it is not possible to adhere to scheduled periods. This is accomplished by forcing the program to first select any adjacent stand eligible for harvest in the same period as the seed stand. There is also an option whereby the user may wish to make the selection of adjacent stands more restrictive by allowing the use of timing deviations only up to the point where the potential block reaches minimum size; therefore, only true contemporaries may be included in the harvest block.

An important feature of the CRYSTAL model is that it allows us to develop alternative harvest blocking strategies, each of which is consistent with the long-term harvest schedule. Some of these blocking patterns may better meet management objectives or be less sensitive to adjacency constraints than others (Jamnick and Walters, 1991(c)). Because adjacency is almost always a management concern, the 25 to 35 year blocking patterns created by CRYSTAL are used as input to the BALL (Block ALLocation) model.

BALL

The importance of spatial information in making forest management decisions stems in part from the need to consider spatially dependent factors such as road construction, transportation distances, and operational harvesting constraints. In addition, regulations controlling the spatial and temporal distribution of harvests must be addressed. These regulations may limit the size of harvest blocks and may impose a time delay before harvesting of adjacent areas can occur.

BALL is a Monte-Carlo integer programming model that is used to assign harvest timing choices to harvest blocks in the presence of adjacency constraints (Clements et al., 1990). The inputs to BALL are created by CRYSTAL and include a list of harvest blocks indicating adjacent blocks and the yields of each block for each period in which it is eligible to be harvested. Then given an objective (maximize volume or minimize cost are built into the model), the number of periods of adjacency delay, the maximum opening size (both adjacency delay and maximum opening size may be controlled by zone), and the number of feasible solutions to be generated, BALL will find feasible solutions that consist of the period in which each harvest block should be harvested.

Solutions are considered feasible if the following conditions are met:

(1) Meet temporal and spatial harvest flow constraints. Spatial harvest flow constraints refer to lower and upper limits per period on the volume harvested from a management unit (i.e., district, working circle, or other administrative unit). Temporal harvest flow constraints refer to the typical lower and upper volume limits per period for several product types (e.g., spruce-fir pulpwood and sawlogs).

(2) Meet temporal and spatial adjacency constraints. Spatial adjacency constraints refer to the maximum size of cut openings (e.g., 125 ha maximum). Temporal adjacency constraints refer to the time period delay between harvesting adjacent blocks. Adjacency constraints are specific to each habitat type. A habitat type, in this context, indicates the management emphasis for each harvest block; some blocks may be designated for timber production, while others are designated primarily for wildlife. Habitat types designated for wildlife usually have more stringent adjacency constraints (i.e., smaller maximum opening size and longer adjacency delays) than timber types.

Although BALL determines harvest timing choices for harvest blocks for the first 25 to 35 years of the harvest plan, it is still necessary for practical (if not regulatory) reasons to produce a five year operating plan. Such operating plans require highly detailed, site-specific analysis: production systems must be allocated to blocks, the effect of this allocation on system capacities costs must be determined, and blocking patterns and schedules must be verified to ensure that they can actually be implemented. In many ways these first five years of the plan are the most critical: it is in this time period that planned activities are closest to being implemented and tend to have the greatest impact upon forest management and financial objectives. OP-PLAN enables managers to quickly produce (and modify) operating plans and evaluate them with respect to short-term objectives and ability to be implemented.

OP-PLAN

OP-PLAN is a forest operation planning decision support system which enables managers to study the effects of area, system, work method and scheduling choices on the finances, logistics and production of an entire operation. Although originally designed to facilitate the analysis and planning of annual harvesting, wood transport, road construction and maintenance and silviculture operations, it can be used to produce multi-year operating plans (Robak, 1990). The DSS is primarily intended as an interactive simulation tool, but it can also generate the information required by an LP solver to determine optimal combinations of area, system and year for a given set of conditions.

In the IFPS being developed, OP-PLAN will be used to plan the harvest blocks created by CRYSTAL and scheduled by BALL in the first planning period. Maps and data concerning forest product estimates and operating conditions for these areas will be obtained from the GIS and other intermediate models and databases. Product demands could be generated externally, but would normally be consistent with those defined for the harvest scheduling model.

Once the forest resource data has been prepared and the OP-PLAN system has been configured for an organization, managers are required to define "default" machine types (which have unique cost and operating characteristics) for each of the four primary operating functions (harvest, trucking, roading and silviculture). In general, these machine types would be those that are available to the operation, but at any point in the planning process new or proposed machine types can be added for analysis. Where they are available, equations relating machine productivity to operating conditions can also be entered as attributes of a machine type. In every case except that of wood transportation, machine types can be grouped into "default" systems which work together for a common purpose. For example, a particular system type might include certain kinds of feller-buncher, grapple skidders, roadside delimbers and slashers which take standing trees and process them into random length logs at roadside.

After this has been accomplished, managers are able to assign "default" systems and machines to the harvest blocks being examined and have the OP-PLAN model the results. Systems can be assigned to individual areas or, to save time, to groups of areas. The effects of these choices on budgets, machine or product costs, schedules and other logistics can then be evaluated. If the default cost, usage and/or productivity factors appear incorrect for the specific situation, or if a manager wishes to test a new idea, it is possible to quickly modify the default information and view the results. Modifications to cost, usage and productivity can be carried out area by area or for an entire district at once, thereby allowing quick and efficient sensitivity analysis to be undertaken.

The results of this planning process should include:

1) the annual operating plan;
2) the equipment usage and acquisition plan;
3) annual budgets and financial analysis;
4) feedback and suggestions concerning the assumptions used and decisions taken at other levels of planning.

Justification for a Top-Down Approach

As demonstrated by Moore and Lockwood (1990) and Baskent (1990) it is possible to explicitly consider adjacency constraints in harvest scheduling models that rely on simulation rather than linear programming techniques. There are, however, limitations to using these approaches. Both of these models take a sequential stand level, rather than a simultaneous forest-wide approach to the harvest scheduling problem. Thus these models cannot make intertemporal tradeoffs at the forest level. Because these models simultaneously consider blocking and adjacency it is not possible to determine how much deviation (measured in reduction in timber harvest volume) from a forest wide schedule results from blocking and how much deviation results from adjacency. A further disadvantage to simultaneously considering adjacency during the harvest scheduling process is that only a single minimum and maximum block size can be considered in each run. Our system allows minimum and maximum block sizes to be specified during both the blocking and adjacency processes thereby providing greater flexibility and opportunity for development of alternatives. Furthermore, because these techniques rely on simulation they suffer from the inability to adequately constrain outputs and activities on a forest-wide basis (Hann and Brodie, 1980; Johnson and Tedder, 1983; Jamnick, 1990).

Case Study

Study Area

The study forest was four contiguous New Brunswick Forest Development Survey map sheets. Inventory and geographic information were obtained from the New Brunswick Department of Natural Resources and Energy. The forest is comprised of 3,241 stands which total 17,458 hectares of forested and non-forested lands. Following standard wood supply analysis procedures used in New Brunswick, the forest was divided into components which were primarily softwood and primarily hardwood. The harvest schedule was developed only for the 12,393 hectare softwood component. Stand types (strata) were defined based on attributes in the provincial geographic information system database and were described by seven levels of identifiers: cover type, condition class, age, management unit, soil group, silvicultural code, and management emphasis. The forest was divided into 57 stand types which ranged in size from 2 to 1921 hectares. Silvicultural prescriptions for each of the 57 stand types included clearcutting followed by natural regeneration or planting of either black spruce (*Picea mariana* Mill.) or jack pine (*Pinus banksiana* Lamb.). If the stand was naturally regenerated it was eligible to be sprayed with herbicides at age five and to have a precommercial thinning at age 15. In the case of planting, options for either light or heavy scarification were considered. Costs for all silvicultural activities (except harvesting) were considered in the problem. Yield information for each of the stand types and alternative silvicultural prescriptions required 167 yield tables for existing stand types and 42 yield tables for regenerated stand types.

Strata-Based Timber Harvest Schedule

A 70-year strata-based timber harvest schedule, consisting of 14 five-year planning periods, was developed for the forest using PC FORPLAN Version 2 (Johnson 1986). This harvest schedule maximized first period softwood timber harvest volume (excluding pine and cedar) subject to nondeclining yield, FORPLAN's "perpetual timber harvest" ending inventory constraint, an annual silvicultural budget of $75,000, and a constraint which limited jack pine plantations to 15% of the area planted. Softwood fibre was the management objective and hardwood volume merely a by-product of softwood harvests. No constraints were placed on hardwood volumes, but hardwoods were assumed to remain unharvested in any stand that contained less than 50 m^3 per hectare of hardwood volume.

The solution to this model indicated a periodic allowable softwood harvest of 123,231 m^3. The annual silvicultural budget was completely utilized in each planning period except the twelfth period. A summary of the first five planning periods of the linear programming solution is presented in Tables 1 and 2.

Allocation of the Strata-Based Solution

The first six periods of the strata-based solution were allocated to harvest blocks using CRYSTAL. Six, rather than five, periods were allocated to provide flexibility in allocating the solution in the fifth planning period. Block size was constrained to be between 15 and 75 hectares. Seed stands were selected on the basis of descending area. The search for stands adjacent to the seed stand was conducted on the basis of allocation potential and timing choice deviations were unrestricted. A total of 240 blocks were allocated over the six planning periods and 202 were allocated in the first five planning periods.

Since CRYSTAL does not consider adjacency when allocating the strata-based solution, the BALL model was used to reassign harvest timing choices to the harvest blocks. At this point we also added hardwood, cedar and pine volumes to the block yields to assist in the development of the operational plan since these volumes affect harvest costs. Blocks were assigned timing

Table 1. Forest outputs by planning period from the strata-based harvest schedule

Output (m^3 per period)	Period				
	1	2	3	4	5
Softwood gross volume	123,231	123,231	123,231	123,231	123,231
Softwood pulp volume	87,119	86,462	85,302	84,366	84,138
Softwood sawlogs	36,112	36,769	37,929	38,865	39,093
Hardwood gross volume	21,556	21,967	33,115	70,060	24,593

Table 2. Silvicultural activities by planning period from the strata-based harvest schedule

Activity (ha per period)	Period				
	1	2	3	4	5
Precommercial thinning	338	458	55	494	512
Planting jack pine	46	10	49	0	0
Planting black spruce	262	55	278	0	0
Light scarification	308	65	172	0	0
Heavy scarification	0	0	155	0	0
Herbicide application	0	802	885	956	974
Clearcutting	1,599	1,508	1,649	1,760	1,374

choices given a one period adjacency delay, a maximum block size of 125 hectares, and a periodic softwood harvest level that was constrained to be between 110,000 and 130,000 m^3. No constraints were placed on block availability (a block could be assigned to any planning period regardless of the timing choice that was assigned by CRYSTAL). Of the 100 feasible solutions generated by BALL, the best solution produced an average periodic softwood harvest of 110,920 m^3 with a first period softwood harvest of 110,087 m^3 (Table 3). Of the 39 blocks scheduled for harvest in the first planning period by BALL, CRYSTAL had assigned six, nine, four, twelve and eight to planning periods one through five respectively.

Operational Planning

The next step was to use OP-PLAN to determine an operational plan for the blocks scheduled for harvest in the first planning period. This example demonstrates very few of the capabilities of the operational planning model. To keep this example simple the only operational activity considered was harvesting, although roads, hauling costs and silviculture could have also been added to the analysis.

Five harvesting systems were specified (Table 4). The annual harvest volumes by product were determined for each of the first five years of the first planning period (Table 5). Annual harvest volumes and volumes by product were reasonably evenly distributed over the planning period. The total cost by harvest system, total harvest cost and number of blocks harvested for each year are reported in Table 6. The Fell-Skid and Val544 harvest systems were not used because their per unit harvest costs were substantially higher than the remaining three systems. At this point the operational planner has the ability to change this plan to determine if there are cheaper or better ways of accessing the scheduled harvest blocks.

Feedback Between Planning Levels

Although not demonstrated here, the final step in the analysis should consist of a complete review of the operational plan to determine its suitability to the operational and forest level planners. If incongruence or intractable problems occur then the harvest schedule, blocking process, adjacency rules or operational plan should be modified so that consistency between the plans and implementation is ensured.

Conclusions

The IFPS described in this paper should help forest managers to develop and evaluate alternative forest management and operational plans that are consistent with one another. This system still requires a lot of work, but begins to bring about a closer relationship between what is planned in the central office and what takes place on-the-ground. Our future plans call for further development of all of these tools to make them

Table 3. Outputs by planning period from the BALL model

Output	Period 1	2	3	4	5
Softwood Volume (m^3)	110,087	110,209	111,897	111,912	111,258
Hardwood Volume (m^3)	37,354	32,088	28,618	32,497	27,028
Cedar Volume (m^3)	10,515	11,232	11,043	11,381	11,286
Pine Volume (m^3)	10,340	9,895	10,945	12,313	10,559
Total Volume (m^3)	168,296	163,424	162,503	168,103	160,131
Number of Blocks Harvested	39	38	38	36	41

Table 4. Harvest systems and their components

Harvest System	Components
Fell-Skid	BJ20, TJ380, Roger, Slasher
KFF	KFF, Roger, Slasher
2-Grip	Rottne-2G, Val544-For, BJ20
Val544	Val544-Har, Val544-For
Man-Slash	Crew(TL), Slasher, Cable

Codes: BJ20 - Feller Buncher
TJ380 - Timber Jack 380 Grapple Skidder
Roger - Roger Delimber
Rottne-2G - Rottne Two-grip Harvester
Val544-Har, Val544-For - Valmet Harvester and Forwarder
Crew(TL) - Manual crew cutting tree length wood
Cable - Cable Skidder

Table 5. Annual harvest volumes for the first planning period

Output	Year 1	2	3	4	5
Softwood Volume (m^3)					
Logs	7,507	8,250	8,327	8,192	9,660
Pulp	14,412	11,594	13,366	13,599	15,177
Hardwood Volume (m^3)					
Logs	3,391	2,569	3,126	4,498	3,073
Pulp	6,807	6,582	7,269	5,332	3,791
Cedar Volume (m^3)					
Logs	693	742	821	733	865
Pulp	1,447	1,140	1,313	1,346	1,414
Pine Volume (m^3)					
Logs	1,415	1,007	1,461	1,550	1,702
Pulp	497	970	543	477	718
Total Volume (m^3)	32,774	30,286	33,106	35,730	36,400

Table 6. Annual harvest cost ($) by harvest system for the first planning period

System	Year 1	2	3	4	5
Fell-Skid	0	0	0	0	0
KFF	144,874	149,668	157,579	189,258	164,366
2-Grip	190,789	150,869	139,762	175,734	169,481
Val544	0	0	0	0	0
Man-Slash	127,280	80,654	136,504	155,729	163,221
Total Harvest Cost ($)	462,943	381,191	433,843	520,723	497,067
Number of Blocks Harvested	7	6	8	6	12

easier to use and understand as well as providing for better and more flexible harvest and allocation "rules". One example is to consider topography when allocating harvest blocks so that blocks laid out on hillsides would be oriented horizontally rather than vertically. We also plan to develop analysis procedures and models that will for explicit examination of wildlife, recreation and visual quality.

Literature Cited

Arvanitis, L.G. 1968. Formal planning to improve managerial decisions in Canada: a background report. For.Br.Can.Info.Rept. FMR-X-13, iii+33 pp.

Barber, K.H. 1986. Large FORPLAN models: an exercise in folly (why and how to reduce FORPLAN matrix size). In Proceedings of the Workshop on Lessons from Using FORPLAN. U.S.D.A. Forest Service, Land Management Planning Systems Section, Washington, D.C. Robert G. Bailey, Editor. pp 89a-89o.

Baskent, E.Z. 1990. Spatial wood supply modeling: concept and practice. Unpublished M.Sc.F. Thesis, University of New Brunswick, Fredericton. 98 pp.

Baskerville, G.L. 1987. Implementation of the Crown Lands and Forests Act - Observations and Comments on the Process. Unpublished manuscript. 57 pp.

Clements, S.E., P.L. Dallain, and M.S. Jamnick. 1990. An operational, spatially constrained harvest scheduling model. Can. J. Of For. Res. 20(9):1438-1447.

Hann, D.W., and J.D. Brodie. 1980. Even-aged management: basic managerial questions and available or potential techniques for answering them. U.S.D.A. For.Serv.Gen.Tech.Rep. INT-83. 27 pp.

Jamnick, M.S. 1990. A comparison of FORMAN and linear programming approaches to timber harvest scheduling. Can.J.For.Res. 20:1351-1360.

Jamnick, M.S., and K.R. Walters. 1991(a). Spatial and temporal allocation of strata-based harvest schedules: an algorithm. Submitted for publication to Can. J. For. Res.

Jamnick, M.S., and K.R. Walters. 1991(b). Spatial and temporal allocation of strata-based harvest schedules: results. Accepted for publication to Can. J. For. Res.

Jamnick, M.S., and K.R. Walters. 1991(c). Harvest blocking, adjacency constraints and timber harvest volumes. Presented at the 1991 Systems Analysis in Forest Resources Symposium, March 3-7, Charleston, South Carolina.

Johnson, K.N., and P.L. Tedder. 1983. Linear programming vs. binary search in periodic harvest level calculation. For. Sci. 29:569-582.

Moore, T.G.E., and C.G. Lockwood. 1990. The HSG wood supply model: description and user's manual. Info. Rept. PI-X-98, Petawawa Nat. Forestry Inst., Forestry Canada. 31 pp.

Robak, E.W. 1990. OP-PLAN on tour. Proceedings of the Subject Group 3.04 meetings of the IUFRO XIX World Congress, Montreal, August.

Walters, K.W. 1991. Spatial and temporal allocation of strata-based timber harvest schedules. Unpublished M.Sc.F. Thesis, University of New Brunswick, Fredericton. 102 pp.

Hierarchical Approach for National Forest Planning and Implementation

K.H. Barber, R.L. Butler, D.J. Caird, and M.W. Kirby
USDA Forest Service, 630 Sansome Street, San Francisco, CA 94111, USA

The Forest Service has learned a lot from its experience over the last thirteen years related to analysis in support of forest planning. The Agency's thinking has evolved considerably, its expectations have changed, and its technology has improved. A new view on how planning and analysis should be conducted is emerging. Case law related to National Forest planning, the Chief's decisions related to appeals, the new proposed planning regulations, and new technologies such as powerful, relatively inexpensive personal computers and software, Geographic Information Systems and landscape ecology, have significantly revised the agency's perspective of the planning process. This paper presents an overview of the objectives, principles, and expectations of a new proposed hierarchical analysis strategy for National Forest Land and Resource Management Plan implementation, amendment, and revision in our constantly changing environment.

Overview

The current forests planning process in general, and large linear programming models such as FORPLAN specifically, tend to overwhelm Forest Supervisors responsible for developing the National Forest Land and Resource Management Plan (L&RMP) with detailed information, yet do not provide the District Rangers responsible for implementing the L&RMP with sufficiently detailed, site specific data to develop their projects. The present system also does not allow the Regional Forester to analyze policy choices where the issue crosses forest boundaries and the decisions that need to be made on one forest are dependent on decisions made on adjacent forests. Maintaining connectivity between wildlife habitat conservation areas is an example of the type of problem that requires multi-forest/region or "mega" analysis. Intermediate levels of analysis are required to form a bridge between the Regional Guides, the Forest Plans and the individual projects and plans. This paper describes a hierarchical framework for planning and implementation that addresses the above problems. This planning Decision Support System (DSS) is based on an iterative and adaptive management and analysis process instead of traditional optimization methods and very large linear programming models.

Use of this hierarchical approach results in each level of analysis remaining consistent with the level of decision being made. It would provide only the information needed, in terms directly relevant to the decisions over which the Regional Forester, Forest Supervisor, and District Rangers have primary responsibility and control. Used in concert these different levels of analysis supplement and enhance each other's effectiveness. Hierarchical planning is a mimic of our historical decision-making process.

The proposed approach would provide for a reserve margin to account for risk and uncertainty. This reserve would also check overestimation of productive capability, a commonly found weakness in forest-wide models. The adaptive control portion of the process would provide both stability and a correction mechanism to steer activity schedules back to the desired course of action. Collectively, these concepts would allow our plans to be in place longer before significant amendments or revisions are necessary. An added benefit of this methodology is that while accuracy is desirable, is not essential, since this an adaptive, self correcting system. Long-term decisions under this approach do not depend on detailed information in future periods. Problems increase in detail, but decrease in planning horizons as we proceed down the decision-making hierarchy.

Also the analysis has been streamlined so that plans can be completed within a more satisfactory time frame (management real time) instead of our present process of constantly re-analyzing and updating the data but never finishing the plan —planning paralysis through excessive analysis. The above features give this planning process both substance and integrity. It provides the means for error detection and self-correction in the process related to both decision-making and data.

This hierarchical approach is more than a device to circumvent the difficulties the Forest Service (FS) is having with large data sets and large models developed to support the first round of the planning process. A hierarchical approach can be developed that is aware of the characteristics of each level and treats these levels according to their unique characteristics. Many features of the proposed approach were outlined and proposed in the following: (1) "Symposium on FORPLAN, An Evaluation of a Forest Planning Tool," November, 1986, (2) Forest Service Workshop, "Lessons From Using FORPLAN," 1986, (3) "Critique of Land Management Planning," 1990, prepared by Forest Service Policy Analysis Staff, and (4) "Workshop on Hierarchical Approaches to Forest Management in Public and Private Organizations," May, 1992. This approach is based on five(5) key management principles:

Commitment

Forest plan implementation should contribute positively toward the accomplishment of the plan objectives. Plan objectives such as Allowable Sale Quantity (ASQ) or new trail construction should be considered as a commitment to be accomplished with available resources and under the standards and guides. The FS policy of giving land allocations, standards and guides precedence over targets is not license to ignore target achievements or treat them as by-products or residuals. Forest targets should therefore be reasonably achievable, not speculative or merely permissive, if planning is to be more than wishing. The schedule of activities leading to the accomplishment of a forest's goals needs to be definitive enough so that accomplishment can be measured and monitored. Definitive objectives need to be assigned to lower level managers. Vague, over-generalized objectives are an invitation to unstructured, uncoordinated, and unrealized planning.

Flexibility

Flexibility must go hand in hand with commitment. Given that the implementation strategy proposed here is based on explicit and measurable targets, the on-the-ground managers will have their degrees of freedom limited. Flexibility is added into the system by the concepts of "navigational change, remedy, and insurance." The more explicitly the planning decisions are defined, the more important it is that managers periodically check on events and expectations and reschedule activities accordingly, to maintain a course toward a desired end. The traditional approach of providing flexibility through generalization of direction does not automatically revise or keep the plan viable. The manager, as navigator, must continually check his/her course and redo plans (remedy) to meet the desired goals. The process being proposed is adaptive or iterative. While targets are considered approximations, they are also definitive but re-defined and improved at all planning levels based on knowledge gained at other levels.

Flexibility is further augmented by the use of the concept of insurance. The more insurance one has, the greater the likelihood of producing implementable output schedules with FORPLAN and the greater likelihood of getting field commitment. Therefore, one must build "slack" or reserve margins into the model to allow for risk and uncertainty. The amount of slack or insurance is a matter of professional judgment since outputs usually have to be able to meet the premiums required for the insurance. Insurance is not free.

Simplicity

The DSS proposed will apply Occam's Razor (a scientific and philosophical rule devised by W. Occam) which holds that entities should not be multiplied beyond what is necessary (razor refers to the idea of shaving an argument or limiting excessive data collection and analysis). In other words, the simplest of procedures, theories, analyses, etc., should be chosen over all the competing theories that fit the known facts. Simplification (as opposed to generalization) should come from knowledge and experience, not from ideology. In the words of Albert Einstein, "Everything should be made as simple as possible — but no simpler."

Models used should be parsimonious. They should use the minimum variables necessary; however, they should get the most from the data we have. The models need to be modest also. They should not overstate their ability while remembering that the accuracy of the prediction is no better than the accuracy of the data.

Consistency-Continuity

Analysis must be done in similar units using similar techniques if the results of analysis between and within forests are going to be comparable and cumulative. Without this consistency, tiering, performance evaluation, connected actions, and cumulative effects over larger areas are not possible. While the analysis criteria used to evaluate and select between projects will be more detailed than those used in the plan, they should be consistent with the assumptions and analytical techniques used in the plan. This provides the necessary continuity between plans, schedules, and projects and gives credibility to the process. Consistency does not preclude creativity, innovation, or augmentation using new or more accurate data or analysis.

Maintaining Options

L&RMP's should not only be oriented toward preserving land use options from the perspective of wise land stewardship, as well as changing public desires or political direction. Land options are maintained when we make decisions that delay or minimize irreversible and irretrievable commitment of resources. What is desired is sequential decision-making. That is, not making a decision until it needs to be made, which is not the same as decision avoidance.

There is usually more accuracy in projecting the more traditional levels of outputs such as timber, range, and developed recreation use, than in projecting the achievement of environmental values such as biological diversity, viable populations, and aesthetics. Therefore, it makes more sense to define more common outputs as constraints and to define environmental values as objectives. This also recognizes the fact that output levels, especially the allowable sale quantity (ASQ), are politically determined within the parameters of resource capability and environmental thresholds, rather than the result of an optimization technique. The FS planning process is more of a control process than an optimizing scheme. The purpose of the planning analysis is to test the relative effects of various resource output levels, not determine which one is optimum. Therefore, minimizing or delaying irreversible commitments of resources replaces maximizing Present Net Value (PNV) as the primary objective function. Different views on what the outputs levels should be are tested by generating alternatives in which environmental effects are evaluated against outputs. However, in all cases, irreversible decisions are deferred to the last possible moment. Economic efficiency is evaluated as another output or as a secondary objective, but not ignored. Presently, the two major irreversible commitments being evaluated by plans are roadless areas and old growth.

The proposed planning approach recognizes that Forest Plans are more programmatic than specific. They are statements of intent that describe the factors that the FS will consider in making future site-specific decisions. As stated in several of the Chief's appeal decision letters, project analyses are expected to answer questions that were not answered by the L&RMP's. L&RMP's plans provide only three major categories of substantial decisions or management direction:

1. Land Allocations or Zoning (on these acres certain activities are permitted, others modified, and still others excluded).
2. Standards and Guides (conditions or constraints activities must meet within an allocation)
3. Establish production objectives and limits on resources such as timber (e.g., ASQ,suitable lands, Long Term Sustained Yield levels).

Examples of decisions generally not made by Forest Plans and deferred to project planning include:

- the choice of silvicultural method
- the selection of the specific monitoring techniques
- the disclosure of site-specific environmental effects
- the granting of oil and gas leases
- the setting of grazing allotment use
- road closure decisions
- other site specific decisions.

Forest Plans provide little insight on how, where, or when (within the 10-15 year planing period) the objectives are to be achieved. The ability to tie specific outputs to specific tracts of land is neither practical nor desirable at that level. In linear programming jargon, the plans are only a commitment to the right-hand sides. Inherent in tactical project level planning is the latitude to reschedule activities (columns) in a completely different sequence than that developed by the forest plan, provided the new schedule does not violate the land allocation nor the standards and guides. In other words, efficiency has not traditionally been the pivotal criteria. The primary tasks of project implementation are to determine where to produce the outputs specified in the plan, when, and how best to produce them. Forest-wide analyses lack the specificity to evaluate the problems of activity design, juxtaposition, fragmentation of landscape, and local cumulative effects in time and space.

Accomplishment and Consistency

Projects that implement the plans must meet the following National Forest Management Act (NFMA) requirements:

1. Projects must be consistent with the plan land allocation and standards and guides; and
2. The aggregate of (potential) project accomplishments should be able to meet and, in the case of ASQ, not exceed the output target levels defined in the plan.

In addition to these NFMA requirements, projects must satisfy National Environmental Policy Act (NEPA) requirements including the following:

1. Analysis of cumulative effects must include past, present and reasonably foreseeable actions which are likely to affect areas larger than the project area;
2. Analysis of other alternatives, including the no action or no change alternative, in which project targets implied from L&RMP'S are only provisional and other levels are examined.

Determination of Plan consistency is the easier of the NFMA requirements to show compliance with. Gauging whether activities are permitted by the allocation, and whether they meet the standards and guides, can be made on a project basis. However, Forest Plan accomplishments cannot usually be determined case-by-case at the individual project area or landscape level since the affected area usually is not large enough to satisfy forestwide objectives.

Plans generally do not assign measurable production levels to project areas; however, such targets are implied by virtue of the management direction, allocation, and a FORPLAN schedule of activities, and are implied commitments. When on-the-ground conditions do not permit projects to be designed in conformance with the schedule, or projects cannot be scheduled promptly enough to satisfy the targets, some remedy must be found. To determine if any local shortfall can be redistributed successfully — without needing a plan amendment and still meeting the second NFMA condition — is the major thrust of intermediate level analysis, called Tactical Analysis.

Tactical Analysis goes beyond a mere comparison of accomplishment against targets; it also provides a method of making adjustments so that project activities can be brought back in line to meet plan objectives, thus avoiding an amendment or at least minimizing disturbance to the plan. This is our concept of remedy.

By introducing the concept of remedy, the missing link in the NFMA requirement for monitoring and evaluation from the plan to the project level has been bridged. Now, we can characterize this requirement as follows:

- **Monitoring** is the comparison of actual production of outputs and effects of project level alternatives with the L&RMP targets or proposed production;
- **Evaluation** is the determination of the significance of observed differences between actual and promised production; and
- **Remedy** is the re-scheduling by means of an intermediate model to adjust the spatial distribution of production targets. Only when the remedy is determined to be significant would a plan need to be amended.

Variations in management prescriptions and activities, such as shifts between cutting methods, are permissible when the results are beneficial provided that standards and guidelines are unchanged and output levels are not significantly altered. The mix of activity such as the amount of clearcutting is only provisionally determined by Forest Plans. Hence, project decisions that adopt such variations would not constitute a change to the L&RMP requiring a plan amendment.

Since preferred alternatives traditionally have been heavily skewed towards projected outputs, especially timber ASQ, plan amendments must be sensitive to these outputs, as well as standards and guidelines and land allocations. Output should not always be the first objective to be forsaken when project circumstances stray from the L&RMP. Standards and guidelines above minimum requirements (MR's) should also be amendable along with targets. If outputs are not met in any given year, making up such shortfalls in the out-years should be considered at the tactical level. If the promised outputs cannot be attained through rescheduling, then we should amend and disclose. To not do so is both administratively and intellectually dishonest.

Although many will not be satisfied with all plan decisions, for the purpose of developing an implementation process that is credible, these decisions should be viewed as final. The implementation stage should not provide license to change forest planning decisions. Rather, the amendment or revision process should offer those dissatisfied with certain decisions an opportunity to change them. Project implementation should not become a "second opportunity" for specialists to add constraints that were omitted or didn't get approved in L&RMP'S. However, when a "need for change" is apparent, the process to evaluate these changes should act on them in a timely fashion.

The analysis used to evaluate and select between project alternatives will be more detailed than those of a forest plan. However, the same assumptions and analytical techniques used for the plan will apply. This continuity between plan and project levels will give credibility to the analysis process and expose problems in the plan that cannot be remedied at the project level, but must be addressed via amendment or revision.

Description of the New Analysis Approach

We are proposing an implementation strategy to support forest planning as described above. Cumulative effects, connected actions, 10-year activity scheduling, and project implementation and design all will be integrated into this process. The major emphasis in this undertaking is to (1) streamline the analysis process; (2) tier projects directly to plan activity schedules; and (3) develop project plans that are implementable. In other words, promises made are promises kept. If not, then plans should be amended or revised. This applies not only to standards and guidelines but also outputs. It is our desire to design a planning, analysis, and implementation strategy so that the overall integrity of L&RMP'S is maintained. This means we need a closed-loop system. Presently our planning is open ended with output commitments usually falling through the cracks. Closing the loop would allow our plans to be the commitment to the public that L&RMP'S were designed to provide. Although there will be circumstances when we will not be able to meet our commitments, such as limited budgets, human resource constraints, or inability to act due to temporary legal or other restraints, we do not want plan objectives and schedules to be so speculative that they have a low probability of accomplishment. However, this doesn't lessen our obligation to change our plans and disclose why we are not meeting the expectations of the plans.

This approach is consistent with National direction in that there will only be two levels of decision making: the approval of the Forest Plan and the management practices and activities to implement it. The effects of these practices, however, may be analyzed on land areas other than the forest or project when and where appropriate (i.e., landscape or bioregion). The assignment, authentication, and scheduling of targets to sub-units of the forest (part of our proposed intermediate analysis level) is not seen as decision-making, since lands are not re-allocated, overall objectives are not re-set, and standards and guidelines are not changed.

We do not intend to reintroduce "Unit" planning (planning at sub-forest level involving aggregating the results cumulatively to define the forest plan) by another name or form. Besides not creating another appeal level in the planning process, history has shown that planning on small units usually leads to "disaster by addition" and "last-man-in" syndrome. Any detail gained by more localized data is usually lost by the lack of efficiency and flexibility from the "tunnel vision" of looking at only a small area. Experience has shown that cumulative effects almost always could be analyzed at the project or forest level. Key issue areas that may include multi-project areas such as spotted owl habitat conservation areas or fire-recovery areas have been analyzed uniquely at the forest or bioregion level, so the rule still holds. Most of our shortfalls in meeting the L&RMP'S targets result from the cumulative effect of "shadow constraints and emerging issues" that were never included in our original plans, not from the shortfall caused by disaggregate output to subforest units. These constraints when applied to a project have relatively small effect on the total outputs when taken individually, but significant when considered collectively.

No single approach or model seems to meet all needs. It probably would be impossible to develop one that would. Instead, we are proposing a hierarchical approach with direct links between the levels of the planning process. Key features of this multi-level approach and its four levels are outlined below:

1. ***Policy Analysis** (Mega, bioregional, multi-forest) Level:*

This level of analysis is concerned with examination of the effects of possible policy changes related to the management of National Forests on a regional or nationwide basis. This level provides policy-makers with the probable consequences of possible changes in forest direction not analyzed by forest planning process. No NEPA decisions are made at this level. An example of this level of analysis is the study done by FS on the effects of implementing the Interagency Scientific Committee guidelines on ASQ, employment, etc. The habitat conservation areas developed by this committee cross National Forest and Regional boundaries. Many of the emerging issues such maintenance of fisheries and fur-bearer habitat are of a "mega" nature requiring analysis at the multi-forest level.

The Regions need the ability to do multi-forest analysis without having to always go back to the forest. When we do, we usually lose consistency and quality control, besides being very disruptive to the forests.

2. ***Strategic Analysis** (global/forestwide decision) Level:*

The primary function of this level of analysis is to analyze forestwide issues, concerns and opportunities, allocate lands, adopt standards and guidelines, establish production levels for output and describe environmental effects. The analysis support package created to revise the existing forestwide planning direction is a modification of the current process. Analysis areas will remain collections of homogeneous units of land (with similar output and effects for a given activity) located throughout the forest (stratum approach). These units would be further classified by key issue areas. However, no attempt would be made at this level to subdivide them into watersheds, compartments, or other subunit planning units that do not have unique management prescriptions. The forest will not stratify into units unless higher level management is willing to control and be held accountable for doing activities and producing outputs by these units.

Explicit representation of spatially continuous areas is not relevant or needed at this level of analysis. It can even be counterproductive. Linear models cannot really solve spatial problems. Placing them in the model only gives the illusion of site specific schedules.

3. ***Tactical Analysis** (scheduling) Level has the following main functions:*
   1. Spatial disaggregation of the L&RMP outputs to project level areas and testing projected targets against forest standards and guides (constraints or thresholds) calculated at the project level rather than the forest or management area.
   2. Adjusting or rescheduling the pro-rata FORPLAN solution if necessary or desirable while not violating the thresholds in any unit.
   3. A logical extension of this process is developing a 10-year rolling schedule for accomplishing the assignment of outputs to the various units. Schedules are developed in a manner that could optimize the flow of outputs while minimizing fluctuations in the workforce or any other resource consideration such as time of last entry.
   4. Analyzing connected actions and cumulative effects of a decision on a project area to an area that extends beyond the boundary of the project.
   5. Remedy or rescheduling based on new or updated data, past performance, or change in desired future condition (management direction).

This intermediate level is a feedback and adjusting process that interfaces between the 2-step decision process. When used as such, it enhances and supplements the other two levels of analysis. This analysis is a particularly important planning tool in the commonly-found situation in which forest resources are not evenly distributed, or when past practices limit activities in certain compartments or other subunits of the forest.

The following is an example of how tactical analysis works relative to disaggregating timber volume objectives in Region 5. Harvest volume goals are allocated by major forest type, timber regulation class, and non-interchangeable components (NIC's). Size class and density are not considered so long as the stands consist of merchantable timber. Timber size class and density will be considered in defining priorities for timber sale design in the operational phase that follows harvest volume goals' disaggregation to compartments or other forest subunits to meet the ASQ defined in the L&RMP.

Volume per acre used to predict volume goals by type and regulation class will come from the forest inventory associated with the plan (called "apparent" inventory). Though revised volume data from compartment examinations will not be used in this initial phase, it will be used to update the schedule in the "remedy" phase in order to maintain comparability with a forest-wide plan.

The intent of spatial dissaggregation is to determine what proportion of the compartment's timber to harvest by category. Variation from the forest mean timber volume by stratum is expected. The actual volume of harvest should approach the forest average over a number of compartments throughout the forest. If this is not the case, a plan amendment or revision is in order. The volume goal for any of the above categories is determined as a percentage of inventory harvested and applied to the total volume computed for that category based on the FORPLAN solution of the Preferred alternative.

The compartment volume goals for each type and regulation class from FORPLAN are used without modification in the design of harvest patterns for 4 to 6 decades beyond the plan period. This is done to demonstrate that dispersion and other cumulative effects can be met. It is important to note that acres treated in the future decades will be fewer relative to the present harvest due to the expected growth on the residual standing timber.

4. ***Operational Analysis** (project decision) Level:*

The entire set of operational models comprise the forest. Each model represents a contiguous area where projects are going to be planned and specific units of land are going to be assigned activities. This model would serve three major functions. First, it would authenticate and verify output targets assigned to the project area by the Tactical model. Second, it would be used to develop and analyze alternative landscape designs that meet both the objectives defined for the area and those that have emerged since the plan was approved. It would test whether a valid juxtaposition of the activity mix (over time and space) is consistent with the tenets of the plan. Spatial considerations include restrictions on cutting adjacent units, fragmentation of habitat, and vegetative-diversity patterns. Third, it would provide a basis for adjusting forest-wide constraints that were proxied at global level to represent spatial conditions. Most NEPA questions will be analyzed at this level.

Once the planned decade outputs and activities have been scheduled for each project area (i.e., compartment, subdrainage, etc.) by the tactical analysis, these objectives then become the focus for the development of alternative project designs. These are intended to move specific areas of the forest toward their Desired Future Condition (DFC) through application of appropriate management prescriptions.

The production objectives such as ASQ shown in the L&RMP's and checked by tactical analysis were determined by means of analyses that ignored spatial relationships and fragmentation between individual treatment units. While sections of most L&RMP's contain direction that pertains to juxtaposition aspects of management, those considerations are not directly accounted for in the FORPLAN analysis that determined the production levels. There can be spatial configurations of treatment units that do not permit carrying out projects to meet the implied targets and DFC for such areas. Such conflicts between on site-conditions and implied capabilities of the area are not necessarily widespread or typical, but neither are they rare as has been demonstrated in several heavy timber Regions. When they do occur, they can pose severe difficulties in meeting objectives assigned to the District Ranger, and consequently to a Forest Supervisor.

The objective of project design should be to accomplish the decade's outputs or activities within the framework of management prescriptions, allocations, standards and guides provided for in the Forest Plan, and the site-specific issues and opportunities generated by the proposals but not included in the plan. Alternative project designs are framed to highlight the differences between possible approaches to achieving the objectives of the plan (Desired Future Condition).

The "no action" alternative, as defined at this level, provides an environmental benchmark so the positive and negatives effect of implementing the "action" alternatives can be weighed objectively. Project design must also have one option that reflects the preferred alternative, one that provides the most cost-effective approach to achieving the outputs assigned by the tactical analysis and its associated schedule. This alternative can also serve as a benchmark so that the effects of other alternatives that are responses to local conditions can be weighed objectively. Other alternatives that need to be analyzed include (1) maximum volume possible up to meeting the binding constraint or threshold, (2) alternatives that respond to local issues where the volume objective may be more or less than scheduled, and (3) alternatives that show how much volume, if any, could be harvested if we went back into this unit within the plan period when less than maximum is taken in the initial entry. This data is needed for the feedback process to update and adjust both tactical and strategic analyses.

Integrated Resource Management (IRM) is initiated at this level. This integration begins during the scoping process through identifying alternatives that provide a range of possible ways to accomplish project intent and respond to local concerns not identified in the plan. If meeting local conditions requires development of alternatives that cannot meet the objectives assigned by the tactical analysis, then this is done. However, their connected actions and cumulative effects will have to be evaluated through tactical level analysis. The key is that the assigned objectives from the tactical analysis are the focus for design schemes. Alternative treatment patterns are developed that meet these objectives but emphasize or slant toward one or more environmental goal. If responding to local issues or conditions precludes meeting the objectives, then these alternatives are also evaluated. If the condition is not local but has forestwide implications, then the project level is not the appropriate place for making this decision based on the Forest Service 2-step decision process.

Within the IRM process, a hydrologist might be given a primary role in designing alternative harvest patterns; however, his/her objective would be to meet the assigned objectives by selecting units or prescriptions that would minimize watershed damage. The same function applies to the wildlife biologist or any other specialists. The benefit of this approach is that the roles of the individual ID team members are focused. None of the alternatives are incrementally developed through "chipping away" at someone else's preconceived "optimum" approach, which often puts some team members on the defensive or causes one resource (such as timber) to always be the residual. Incrementally throwing away units is not really a new or different alternative, but rather a variation of the same alternative. This IRM strategy keeps the focus of project implementation on finding ways to accomplish the objectives of the plan, not redefining its objectives. Each team member has the same common "end." Their skills are used in finding different "means" (different designs) that meet the same end (the unit's scheduled share) if this can be done within the constraints of standards and guides as defined by the plan. Hopefully, this approach will broaden the alternatives so that management can make reasonable choices.

During this analysis, distinction is made between modification of S&G's for site- or project-specific reasons and modification (amendments) which have implications beyond the specific project area. Project-specific adjustments in the application of S&G's may be entirely appropriate in a particular alternative or as a feature common to all alternatives because of the uniqueness of conditions found in the project area. This type of adjustment is called a "variance" and an amendment to the plan is usually not needed provided that the remaining units can make up the short-fall in objectives without violating their S&G's. Modification for other reasons, however, may be beyond the scope of the immediate project (i.e., in response to emerging

Forest-wide issues) and so should be handled within the Plan amendment or revision process. Normally, if the Deciding Officer determines the "need for change" of S&G's, interim guidelines will be established for use while the Plan amendment or revision process is being pursued. This interim direction should include an approximation of the effects on planned outputs or activities as resulting from implementing of the modified S&G's. Projects may go forward, after implementing the interim direction that has identified the associated changes in targets until the amendment or revision is completed.

Regardless of how alternatives for projects are developed or whether they are funded, the sum of the planned outputs or activities for the decade from all projects within the forest should add to the forest or district totals. This objective may not be met for a number of reasons, but the reasons must be accounted for properly. In other words, the ID team must show cause for not meeting its objectives.

The FORPLAN model used to develop volume objectives used weighted averages for coefficients based on forest-wide inventories. In the disaggregation process these averages are used to determine accomplishment of plan objectives. In laying out alternative treatment designs, accomplishment of Forest objectives is measured in the same data used in the forest plan. Once the volume objectives have been met based on "plan data," the actual volume based on local data is computed.

Differences between the plan averages and site-specific volume are part of the expected variance. The discrepancy does not invalidate the plan unless the shortfall cannot be compensated for by other units during the decade. The inability to match output levels within a planning decade indicates a "bias" in the original data and should be remedied by the plan amendment or revision process. The actual volume is fed back into the tactical analysis from this as well as the other projects and evaluation of "need for change" is initiated based on the cumulative volume. It is at this point in the analysis process that we switch from volume control with area check to area control with volume check on timber sale projects.

In timber sale design, harvest units (chances, parcels) are normally selected according to silvicultural priorities until the disaggregated volume objective is met. Under this scheme,volume objectives are based on forest plan yields. The acres associated with producing this volume become the "commitment" for the field in evaluating performance. Differences between actual volume, compared to apparent volume scheduled in the plan, are not evaluated at this level. Instead they are fed back up to the tactical level for analysis and evaluation

Integration

The hierarchical approach is based on a sequential and iterative process, rather than the simultaneous one for solving the integrated forest planning problem. This approach is consistent with the basic assumption that there are many alternatives available to the forest manager at each level that are consistent with higher levels. It treats planning and its associate analysis as a continuous process that is constantly changing based on new data and conditions.

Both tactical and operational planning are bound by the decisions of the forest plan and are mainly conducted by the district. Each model developed to correspond with each of the above levels would be streamlined to minimize the size of the model needed. Consistency will be maintained by using the template process derived from what is determined to be the best approaches developed within and out of region. Each level of analysis would be optimized for the purpose it was developed. This would minimize the compromises that are usually made to accommodate the building of one large model.

Hierarchical planning systems and their associated models offer potential computational advantages over monolithic mega-models of the past decade. More importantly, they also offer advantages in implementation that reflect the organization and the decentralized decision-making process of the Forest Service. It also provides a better way to deal with uncertainty that is typical of the environment.

Insurance

Explicit recognition of risk, uncertainty, error, and insurance in the analysis and decision-making is part of our strategy. Variables such as plantation success and watershed effects will be treated as probabilistic rather than deterministic outcomes. Explicit recognition that a computer derived "optimum is probably not implementable and that a revised and reduced overall production level is, will also be an integral part of this approach. A procedure for establishing a fallback position would be built into the matrix up front, rather than waiting for revisions as a result of differences between planned and site-specific discrepancies. We want to avoid having specialists attempt to build insurance into the production or constraint coefficients (tinkering). It is our belief that our approach provides a more appropriate way of utilizing 'professional judgment' or intuition.

We have introduced the concept of control (stability and steerability) and insurance into the planning process as part of a hierarchical approach to Forest planning and project level implementation. The models described above have been tested on various Forests nationwide, and the feasibility of our approach has been demonstrated. Because of the advantages of the remedy concept as the means to avoid or minimize the impact of amending the Forest Plans, the conceptual basis of hierarchical planning deserves to be reviewed for inclusion in the revision analysis guideline related to 36 CFR 219 on L&RMP implementation and their associated Forest Service manuals and handbooks.

Conclusion

Forest Plans will be implemented, budgets will be developed, and NEPA's role in formulating and evaluating production levels will occur. The pivotal issue addressed in this proposal is that accomplishment of Forest goals should approximate production commitments identified in Forest plans. When this is not possible, then the plans must be revised or amended. This approach is offered as a reasonable design to maintain an integral parallel between accomplishment of overall plan goals and actual on-site production capabilities.

The North Coast Pilot Project: A Research Study on the Spatial Integration of Wildlife Habitat with Multiple Ownership Long Term Forest Planning

L.S. Davis and R.H. Barrett

Department of Forestry and Resource Management, University of California, Berkeley USA

This study is an intensive effort to develop and demonstrate practical ways to quantify wildlife habitats for consideration in land use and timber harvest planning at a large landscape scale. It was funded by the California Legislature under the AB1580 legislation in 1989, which also created a guiding Timberland Task Force of agency, industry, environmental, and other interest group leaders, and provided for a mapping pilot study to develop and test technology for mapping wildlife habitats from satellite imagery. The central legislative goal was to develop a "coordinated base of scientific information on timberland ecosystems that permits evaluation of the habitat and biodiversity effects of alternate land use plans and mitigation measures."

The Timberland Task Force broke this overall goal down into four separate problems, each requiring separate concepts, skills and tasks. (1) *The environmental/ biological problem* was how to maintain wildlife habitats in the face of human needs for resources. (2) *Technical problems* included quantifying the dynamic and spatial relationships between vegetation and land use development to project future availabilities of wildlife. Methods are needed to monitor the status of these environmental systems. Technology is needed to communicate an enormous amount and variety of data in a form useful to policy makers and managers. (3) *A Conflict management and public deliberation problem* required we create a flow of relevant and credible information about the amount, location, duration, and severity of conflicts between human resource needs and environmental health and to help guide mitigation and land use policy. (4) Finally, it was *necessary to demonstrate solutions in the California context.*

With funding from The California Resources Agency, our interdisciplinary group was formed to work through the wildlife related problems. Through the North Coast Pilot Project, methodology was developed to deal with important technical problems. How to utilize vegetation maps derived from satellite imagery, how to integrate wildlife habitat suitability models derived from the California Wildlife Habitat Relationships System into the timber management planning process, and how to project vegetation, wildlife habitat, and habitat suitability over time and space under different land use scenarios were important technical questions. The resulting integrated system is called the California Forest Information and Analysis System (FIAS). A second pilot project is being initiated in the Sierra to consider such land use planning problems on a landscape with a checkerboard pattern of public and private ownership and to field test wildlife habitat suitability models.

To date the study has made important progress in meeting the objectives of AB1580 by first designing a coordinated data and analysis system and then demonstrating how it could work on a test area of 168,000 acres spanning 6 major ownerships in the redwood and Douglas fir forests of northern Humboldt County.

The California Forest Information and Analysis System

Important elements of this system (Figure 1) include: (1) the computer data base portion of the existing California Wildlife Habitat Relationships System (WHR), adapted to work in an ARC/INFO geographic information system environment, (2) the WHR habitat types maps provided by the mapping pilot project, (3) the U.S. Forest Service FIA and available landowner timber inventory data bases, (4) individual tree growth and yield simulators (such as CRYPTOS, CACTOS, or PROGNOSIS) used to project ecological succession "yields" of different types of land managed under different management prescriptions, (5) the SARA/ LINDO strategic planning system, used to simulate and report the stand structure, harvest, and economic results of alternative land use and timber harvest plans, policies, and mitigation measures, and (6) maps of the landowner land use plans by WHR habitat map polygons to show where specific activities will take place on the ground. All of these elements, along with many associated procedures and computer programs, are successfully installed and running in a standard PC-microcomputer environment. Although refinements and more complete documentation are needed, it is

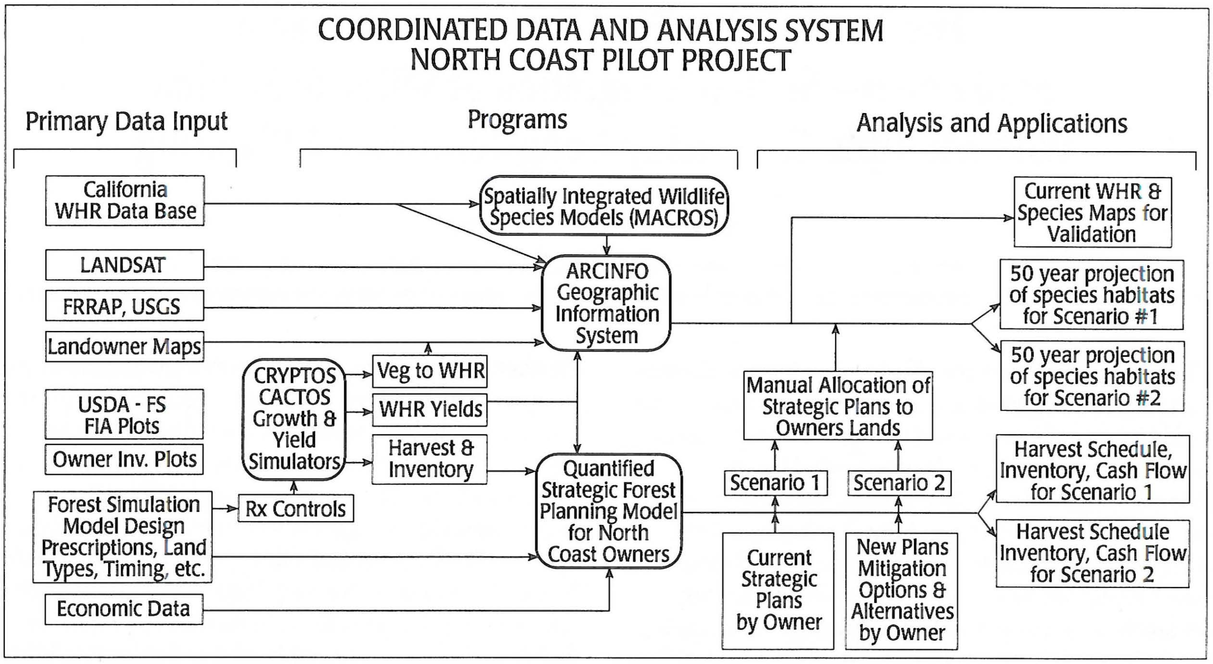


Figure 1. Flow diagram of steps required to accomplish a cumulative effects analysis with the coordinated information system.

technology that can be used today. The procedure for implementation is summarized in Table 1.

Twelve wildlife species were selected by the Timberland Task Force for detailed analysis, including the Olympic salamander (*Rhyacotriton olympicus*), tailed frog (*Ascaphus truei*), northern goshawk (*Accipiter gentilis*), mountain quail (*Oreortyx pictus*), spotted owl (*Strix occidentalis*), pileated woodpecker (*Dryocopus pileatus*), mountain chickadee (*Parus gambeli*), northern flying squirrel (*Glaucomys sabrinus*), red tree vole (*Phenacomys longicaudus*), marten (*Martes americana*), and fisher (*Martes pennanti*). For each species this project prepared a computer program (currently as an ARCINFO macro) to spatially integrate the WHR-defined habitat suitability values for feeding, reproduction, and cover with special habitat elements, such as proximity to running streams. Demonstration 50-year

Table 1. Sequential steps in modeling and analysis using the California Forest Information and Analysis System.

1. Obtain a current vegetation map from landowner or from satellite imagery using the vegetation classes defined for the California Wildlife Habitat Relationships System (WHR).
2. Use tree list inventory plots and tree growth simulation models to generate (1) ecological succession trajectories and (2) commodity yield and related trajectories associated with the application of each different land use prescription to each current vegetation type.
3. Use a linear programming, long-term forest planning model to determine the optimal 100-year land use plan for each ownership under different policy scenarios.
4. Map the resulting land use plan to the polygons of the current vegetation map using manual or semi-automated methods in a GIS environment.
5. In the GIS environment, grow the vegetation in the spatial data base according to the land use plan and the ecological succession trajectories of current vegetation to project a series of future habitat type maps under the different policy scenarios.
6. Repeat steps (3) - (5) for each landowner or landowner class and merge the projected maps to show the aggregate projections of habitat change over a defined landscape.
7. Develop spatially defined and species-specific habitat suitability models by building on the WHR system.
8. Evaluate the suitability of the projected landscapes for each modeled species and using maps, video, summary statistics, and appropriate metrics. Make appropriate summary comparisons across the different policy scenarios.
9. Summarize the habitat suitability, commodity yield, and other information in suitable formats for communication to the public and policy makers.

projections were made to show the pattern of change in suitable habitat for these species that would be expected from implementing the landowners' current management plans (Scenario 1) in the North Coast study area. The same projections were also made for a second scenario that assumed the proposed California Grand Accord Legislation had been implemented (Scenario 2). At this multi-landowner landscape scale, definite changes and differences in the amount, quality, and spatial distribution of habitat for these species are visible over time and between scenarios. The results can be presented in a variety of tables, graphs, and maps, the kind of information landowners and policy makers would find useful.

To illustrate the first and last period, Figures 2 and 3 show the spatial evaluation of projected vegetation change using the northern flying squirrel macro. Marked changes are apparent and are a clear function of different landowner policies.

The study team found that while the FIAS system functions correctly in a microcomputer environment, it is slow. The polygon-based macro's take weeks to produce the complex, dynamic map analysis of a 168,000-acre area (Table 2). Production scale analysis of spatial habitat using ARCINFO in the amount needed for California will require running part of the system on workstations or even a mainframe computer. We are currently shifting to the grid option of the workstation version (6.0) of ARCINFO for the quantitative calculation of habitat suitability, and it is an order of magnitude quicker. Moreover, considerably more sophisticated wildlife-habitat models can be developed with the grid option. While much of the system can be automated, we must emphasize that experience, expert judgment and competent technical skills will always be required to make sound interpretations of habitat and ecological consequences of long-term management and land use.

This study found that the California Wildlife Habitat Relationships System needs revision and augmentation to recognize and evaluate the kinds of habitats that will be produced by "new forestry" management prescriptions such as small group selection or uneven-age selection, cutting at low and high residual densities, or complex spatial designs of mixed prescriptions. For many wildlife species, particularly those that prefer edge, patch and linear environments, mapping of WHR habitats to a resolution of at least 5 acres is needed to adequately evaluate habitat suitability. The integrative "macros" or programs developed for each species need to be supported and maintained as a part of the California Wildlife-Habitat Relationships System.

Research Questions

This project is generating many research questions. Two important ones are:

(a) WHR Validation. Each 1990 wildlife habitat suitability map is a hypothesis about where and with what relative frequency we would expect to find that species today in the study area. Empirical data on actual frequency of occurrence can be matched against this for a validation exercise. A field test is part of the second pilot study underway in the Sierra.

(b) Tradeoff and Policy Analysis. The California Forest Information and Analysis System allows the simulation of different policies, regulations, and methods for allocation of timber harvest and other disturbance rights to landowners within a bioregion. Sensitivity studies to define the tradeoffs at different landscape scales between wildlife habitat, aesthetic values, commodity production, employment, and local economic development are needed to develop credible foundations for public deliberations about land use, mitigation policies, and development programs.

A final report on the North Coast Pilot Project will be released through the Forest and Rangeland Resource Assessment Program (FRRAP) of the California Dept. of Forestry and Fire Protection in the spring of 1993. A second pilot project is being initiated in the Central Sierra that will focus more on validation of wildlife habitat projections and on using the system to support mixed ownership and watershed level planning.

Table 2. Comparison of run times between microcomputer and workstation platforms for ARCINFO operations on coverages of 5 acre resolution

Operation	Microcomputer	Workstation
ARCGROW property (30,000 ac)	4 hr	0.5 hr
Link properties (168,000 ac)	4 hr	1 hr
One wildlife macro (168,000 ac)	25 hr	5 hr
Plot 6 maps at 1:175,000 scale	6 hr	6 hr
Plot 1 map at 1:24,000 scale	6 hr	6 hr

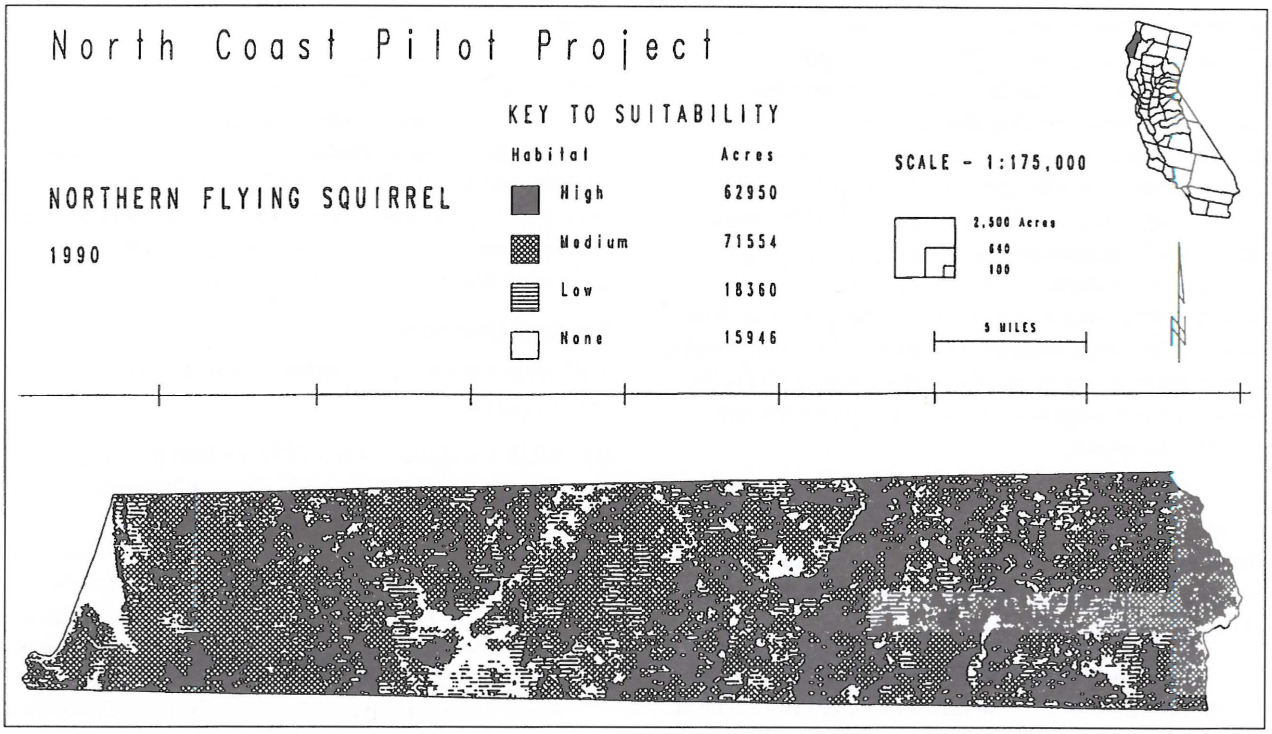


Figure 2. Habitat suitability model for Northern Flying Squirrel, 1990.

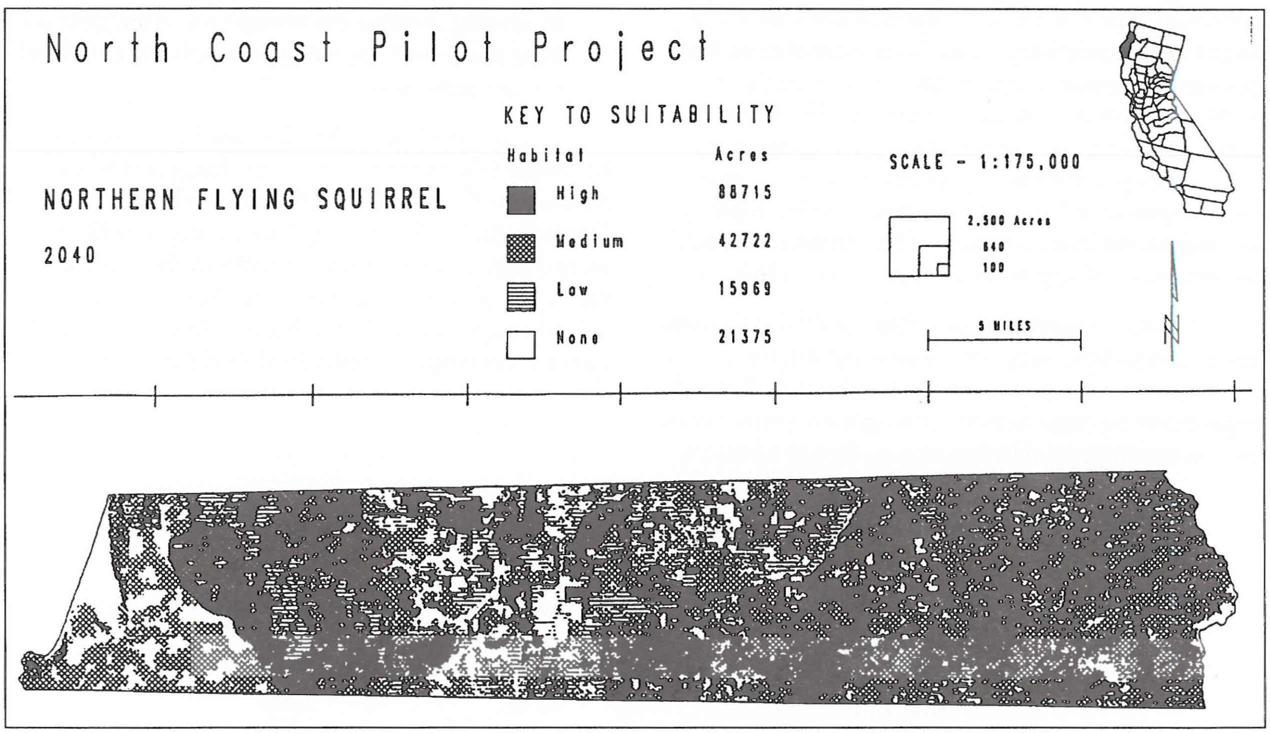


Figure 3. Habitat suitability model for Northern Flying Squirrel, 2040.

Bibliography

Airola, D. A. 1988. Guide to the California Wildlife Habitat Relationships System. California Department of Fish and Game, Sacramento, CA. 74pp.

Azuma, D. L., J. A. Baldwin, and B. R. Noon. 1990. Estimating the occupancy of spotted owl habitat areas by sampling and adjusting for bias. USDA Forest Service, Pacific Southwest Forest and Range Research Station, General Technical Report SW-124. 9 pp.

Barrett, R. H. 1983. Smoked aluminum track plots for determining furbearer distribution and abundance. California Fish and Game 69(3):188-190.

Bolsinger, C. 1980. California forests: trends, problems, and opportunities. U.S.D.A., Forest Service Bulletin PNW-89. Pacific Northwest Forest and Range Experiment Station, Portland, OR. 138pp.

Buck, S., C. Mullis, and A. Mossman. 1979. A radiotelemetry study of fishers in northwestern California. Cal-Neva Wildlife 1979:166-172.

Burger, L. W., Jr., M. R. Ryan, D. P. Jones, and A. P. Wywialowski. 1991. Radio transmitters bias estimation of movements and survival. J. Wildlife Management 55(4):693-697.

Burnham, K. P., D. R. Anderson, and J. L. Laake. 1980. Estimation of density from line transect sampling of biological populations. Wildlife Monographs 72:1-202.

Campbell, H. W., and Christman. 1982. Field techniques for herpetological community analysis. Pp. 193-200 in N.J. Scott, Jr. (ed.). Herpetological communities: a symposium of The Society for the Study of Amphibians and Reptiles and the Herpetological League, August 1977. USDI, Fish and Wildlife Service Research Report 13.

Carthaw, S. M., and E. Slater. 1991. Monitoring animal activity with automated photography. J. Wildlife Management 55(4):689-692.

Chao, A. 1988. Estimating animal abundance with capture frequency data. J. Wildlife Management 52(2):295-300.

Conner, M. C., R. F. Labisky, and D. R. Progulske. 1983. Scent-station indices as measures of population abundance for bobcats, raccoons, gray foxes, and opossums. Wildlife Society Bulletin 11(2):146-152.

Corn, P. S., and R. B. Bury. In press. Sampling terrestrial amphibians and reptiles. In A. B. Carey and L. F. Ruggiero (eds.). Monitoring techniques for wildlife in Pacific Northwest Forests. USDA Forest Service General Technical Report.

Davis, D. E. (ed.). 1982. CRC Handbook of census methods for terrestrial vertebrates. CRC Press, Boca Raton, FL. 397 pp.

Davis, L. S., F. Schurr, R. Church, J. K. Gilless, and P. J. Daugherty. 1990. The spreadsheet connection for forest planning analysis that everyone can understand and trust. Western Journal of Applied Forestry 5(3):90-93.

ESRI. 1990. Understanding GIS, the ARC/INFO method. Environmental Systems Research Institute, Redlands, CA.

Fish and Wildlife Service. 1981. Standards for the development of suitability index models. Ecological Services Manual 103. U.S.D.I., Fish and Wildlife Service, Division of Ecological Services. Government Printing Office, Washington, DC. 68pp.

FRRAP. 1988. California's forests and rangelands: growing conflict over changing land uses. Forest and Rangeland Resources Assessment Program, California Department of Forestry and Fire Protection, Sacramento, CA. 348pp.

Gillesberg, A., and A. B. Carey. 1991. Arboreal nests of Phenacomys longicaudus in Oregon. J. Mammalogy 72(4):784-787.

Guetterman, J. H., J. A. Burns, J. A. Reid, R. B. Horn, and C. C. Foster. 1991. Radio telemetry methods for studying spotted owls in the Pacific Northwest. USDA Forest Service General Technical Report PNW-GRT-272. 43 pp.

Haining, R. 1990. Spatial data analysis in the social and environmental sciences. Cambridge University Press, New York, NY. 409pp.

Kunz, T. H., and E. L. P. Anthony. 1977. On the efficiency of the Tuttle bat trap. J. Mammalogy 58(3):309-315.

Kunz, T. H., and C. E. Brook. 1975. A comparison of mist nets and ultrasonic detectors for monitoring flight activity of bats. J. Mammalogy 56(4):907-911.

Laymon, S. A., L. Overtree, G. Collins, and P. L. Williams. 1991. Final report on the distribution of marten, fisher and other carnivores in the Starvation, Tyler, Deer and Capinero Creek and White River drainages of the Sequoia National Forest: Summer 1991. Hot Springs Ranger District, California.

Linhart, S. S., and F. F. Knowlton. 1975. Determining the relative abundance of coyotes by scent station lines. Wildlife Society Bulletin 3:119-1124.

Loft, E. R., and J. G. Kie. 1988. Comparison of pellet-group and radio triangulation methods for assessing deer habitat use. J. Wildlife Management 52(3):524-527.

Mayer, K. E., and W. F. Laudenslayer, Jr. (eds.). 1988. A guide to wildlife habitats of California. California Department of Forestry and Fire Protection, Sacramento, CA. 166pp.

Morrell, T. E., R. H. Yahner, and W. L. Harkness. 1991. Factors affecting detection of great horned owls by using broadcast vocalizations. Wildlife Society Bulletin 19(4):481-488.

Moore, T. G. E., and C. G. Lockwood. 1990. The HSG wood supply model: description and user's manual. Forestry Canada, Petawawa National Forestry Institute, Information Report PI-X98. 31 pp.

Parmenter, R. R., J. A. MacMahon, and D. R. Anderson. 1989. Animal density estimation using a trapping web design: field validation experiments. Ecology 70(1):169-179.

Paton, P. W. C., C. J. Zabel, D. L. Neal, G. N. Steger, N. G. Tilghman, and B. R. Noon. 1991. Effects of radio tags on spotted owls. J. Wildlife Management 55(4):617-622.

Popper, K. R. 1962. Conjectures and refutations. Basic Books, New York, NY. 412 pp.

Ralph, C. J., and J. M. Scott (eds.). 1981. Estimating the numbers of terrestrial birds. Studies in Avian Biology 6. 630 pp.

Roughton, R. D., and M. W. Sweeny. 1982. Refinements in scent-station methodology for assessing trends in carnivore populations. J. Wildlife Management 46(2):217-229.

Schemnitz, S. D. (ed.). 1980. Wildlife management techniques manual (4th ed., rev.). The Wildlife Society, Washington, D.C. 686 pp.

Schrage, L. 1987. User's manual for linear, integer, and quadratic programming with LINDO 3/e. The Scientific Press, CA.

Seber, G. A. F. 1982. The estimation of animal abundance and related parameters (2nd ed.). Griffith, London. 654 pp.

Skalski, J. R. 1991. Using sign counts to quantify animal abundance. J. Wildlife Management 55(4):705-715.

Sinclair, A. R. E. 1991. Science and the practice of wildlife management. J. Wildlife Management 55(4):767-773.

Spellerberg, I. F. 1991. Monitoring ecological change. Cambridge University Press, New York, NY. 334pp.

U.S. Forest Service. 1979. Resources evaluation field instructions for California. USDA Pacific Northwest Forest and Range Experiment Station, Renewable Natural Resources Evaluation Research Work Unit Manual.

Verner, J. 1988. Optimizing the duration of point counts for monitoring trends in bird populations. USDA Forest Service, Research Note PSW-395. 4 pp.

Verner, J., M. L. Morrison, and C. J. Ralph (eds.). 1986. Wildlife 2000: Modeling habitat relationships of terrestrial vertebrates. University of Wisconsin Press, Madison, WI. 470pp.

Walters, C. 1986. Adaptive management of renewable resources. Macmillan Publishing Company, New York. 374 pp.

Welsh, H. H., Jr. 1987. Monitoring herpetofauna in woodland habitats of northwestern California and southwestern Oregon: a comprehensive strategy. Pp. 203-213 in T.R. Plumb and N.H. Pillsbury (eds.). Multiple-use management of California's hardwood resources. USDA Forest Service General Technical Report PSW-100.

Welsh, H. H., Jr. 1990. Relictual amphibians and old-growth forests. Conservation Biology 4(3):309-319.

Wensel, L. C., and G. S. Biging. 1987. The CACTOS system for individual-tree growth simulation in the mixed conifer forests of California. Proceedings of the IUFRO Forest Growth Modelling and Prediction Conference, Minneapolis, MN, August 24-28, 1987.

Wensel, L. C., B. Krumland, and W. J. Meerschaert. 1987. CRYPTOS User's guide: Cooperative Redwood Yield Project Timber Output Simulator. Univ.California Agricultural Experiment Station Bulletin 1924. 89 pp.

Wensel, L. C., P. J. Daugherty, and W. J. Meerschaert. 1986. CACTOS User's guide: The California Conifer Timber Output Simulator. Univ. California Agricultural Experiment Station Bulletin 1920. 91 pp.

Zeiner, D. C., W. F. Laudenslayer Jr., and K. E. Mayer (eds.). 1988. California's wildlife, Vol. I Amphibians and Reptiles, Vol. II Birds, Vol. III Mammals. California Department of Fish and Game, Sacramento, CA. 272+731+407pp.

Hierarchical Planning Systems and Public Control and Evaluation: A Methodology for the Control and Evaluation of a Spanish Public Plan

M.J. Alvarez-Gil, and D.C. Blasco

Universidad Carlos III de Madrid, c/Madrid 126, Getafe, 28903 Madrid, Spain

Abstract

This paper brings into the light the first real application in Spain of the Hierarchical Production Planning Systems Philosophy to a specific area other than manufacturing. This year, the Promotion Plan on Industrial Design (1992-1995) will begin to be implemented. This Plan will be sponsored by the Spanish Ministry of Industry, Trade and Tourism with the use of public funds to promote the incorporation of industrial design in small and medium enterprises. Prior to this implementation, the Plan needs to be studied by different experts and some important points, like objectives, goals, resources, deadlines, positive actions, etc., need to be addressed and revised. Among the main factors to be analyzed, is the way in which the Plan should be controlled and evaluated. In our paper we present a methodology for the control and evaluation of the impact of the Promotion Plan, including some recommendations about its implementation.

After considering the Plan and taking into account questions like: the scope and duration of the Plan (1992-1995), the intrinsic difficulties associated with any control and evaluation of the impact of Public Plan and Programme, the problems found when employing traditional approaches to the evaluation and control processes in previous Plans, the existing possibilities for using a "step-by-step" approach to the process, provided by the architecture of the present Plan, we have considered that the basic principles of Hierarchical Production Planning Systems can be used to develop the required methodology.

Introduction

A Public Plan is usually defined in several ways, according to the expectations of the people considered, the objectives the Plan is expected to accomplish, and so on.

There is an important conflict between the people who are going to benefit from the Plan and the rest of society. This is an old conflict: only a limited number of people will benefit from the plan while the whole society will have to bear the cost. As far as people cannot control the public resources by themselves, they cannot determine if the results of these funds are the adequate or not. However they remain interested on the way the Public Administration makes use of public money and how those resources come back to the society contributing to the nation's welfare. So far, this is the main reason for the public evaluation and control of Public Plans.

There are different approaches to this evaluation and control, most of them taking into account other techniques and criteria than those considered by businesses when evaluating and controlling the performance of their business units.

Often, the resulting measures, due to a lack of accuracy and reliability, do not bring any light into the efficiency of public plans. Sometimes this ambiguity has been pursued by the administrators, as a way to avoid public control.

We will focus on cases where ambiguity was not the intended result, and the approach to the evaluation and control process might have as a direct answer, a proper set of measures for the performance of the Plan.

Our proposal includes both a conceptual framework and a practical methodology for the evaluation and control of a Spanish Public Plan: Plan de Promoción del Diseño Industrial (Promotion Plan on Industrial Design).

The Impact Evaluation of the Plan

A Brief Description of the Suggested Methodology

The evaluation of the impact derived from the different programmes included in the plan should avoid any generic or global approach which could lead to a difficult understanding of the success and failures directly associated to that particular Programme.

Nevertheless, the results must be given in such a way that they can be compared with other parameters. So, we must look for a certain degree of homogeneity while trying to be concise and clear.

For this purpose, we will use the hierarchical approach since it is able to provide us with different information levels, relating to the aggregate needs of each evaluation stage. What we are trying to suggest is a step-by-step information analysis, according to the observed degree of specification of the description of goals, objectives and detailed measures to be taken for the accomplishment of the objectives.

The basic scheme of our model can be summarized as follows:

i. The hierarchical approach will consider four levels of analysis:

First or Strategic Level

It is devoted to the analysis of the aggregate or long term goals considered by the Plan, as well as the main objectives presented by the small and medium firms which are able to get public support by joining the Plan.

This analysis will allow us to determine whether the objectives are equivalent or not, as well as the degree of disagreement.

Only these cases of agreement will be studied on the following levels. The remaining cases will be included as part of the contrast test and will supply information to be used when planning and designing future Plans.

A scheme of this first partial evaluation can be found in Figure 1.

Second or Tactical Level

We will be able now to analyze the concordance among the medium term or semi-aggregated objectives stated in the Programmes and those requested by the firms. If they match each other we will go to the next level, otherwise we will analyze the reasons behind the disagreement and the chances to adapt the contents of the Programmes to the firms' requirements.

If there are no solutions, those are too expensive, or difficult to implement, we will include the cases as a contrast group for information purposes.

Figure 2 gives us a sample of this stage.

Third or Operational Level

Given the agreement among aggregate and semiaggregate objectives, requirements and availabilities, we will analyze whether the specific actions considered in the Plan fit the companies requirements and expectations, or not. Once again we will have to distinguish among situations in which requirements are fully satisfied and those in which there is a total or relative lack of concordance, as well as studying the reasons and the opportunities to satisfy requirements and availabilities. Therefore we will get a third contrast group, whose information will be used to evaluate the results of the Plan as well as being use for other purposes, such as improvement of future programmes and plans, or resources reassignment.

We have an illustration about that on Figure 3.

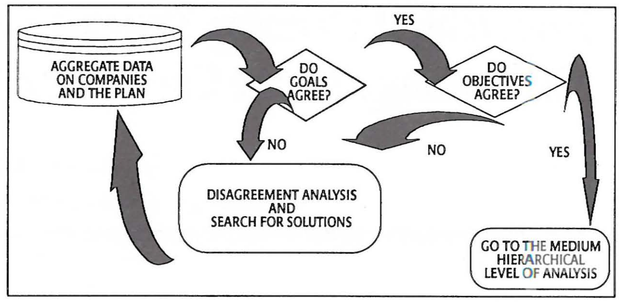


Figure 1. Initial phase: on the suitability of the plan (upper hierarchical level of analysis).

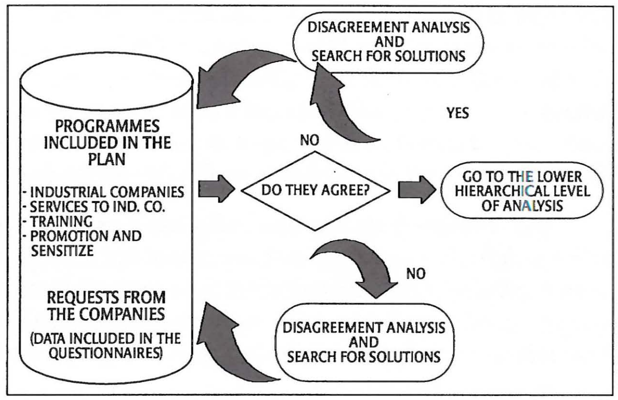


Figure 2. Second phase: on the suitability of the programmes (prior to implementation stage).

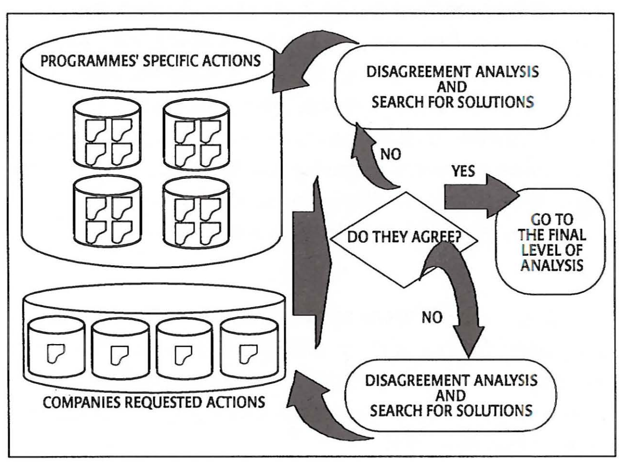


Figure 3. Third phase: on the suitability of the specific actions included in the programmes (lower hierarchical level of analysis: monitoring and control stage).

Fourth or Adaptive Level

At this level, we will proceed to evaluate and control all the results of the Plan, not only the desired, but the undesired ones as well. For this purpose we will use all information coming from involved companies, the feedback provided by the contrast groups, data obtained from our own study of the different levels of implementation, and a widescope information provided by different publications.

Figure 4 describes the complete evaluation and control process.

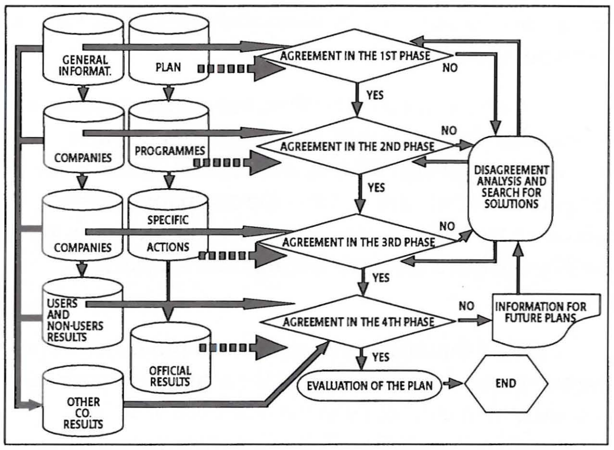


Figure 4. A schematic illustration of the integrated approach to the evaluation and control process.

All this will allow us to separate adequately the effects or impact directly associated with the implementation of the Plan from those indirectly derived or generated by external changes.

ii. Consistency must be assured among the different levels.

iii. Each level's objectives have to take into account, the restrictions from the previous level.

Information Needed and How to Use it Properly

First of all, it is necessary to determine the group of companies that are able to obtain some potential benefits from the Plan. This information would be considered at the *first level* of analysis. The information sources might came from statistics, sectorial reports, juncture reports, as well as the data collected by the Administration corresponding to previous Public Plans.

With all these data, we will proceed to characterize the initial situation in order to facilitate the isolation of the results from the implementation of the Plan.

For all these companies aiming to incorporate advanced industrial design into their processes and products but that do not have the required features or conditions, it will be useful to determine the reasons that prevent them from being beneficiaries, in order to redefine the purposes of the Plan, if needed, or to state a separation line between potential beneficiaries and non-beneficiaries. In this way we will have two categories of small and medium firms and the first contrast group.

The next step will be to identify the existing relationships between the companies' needs and the opportunities provided by the Plan. Doing this we will be able to appreciate to what extent do the firms know the General Purposes of the Plan.

After this analysis, two new groups will appear: the first one related to those companies that know the Plan and the other group formed by those that do not know the Plan or its contents. (This group will form the second contrast group)

In the *second level* of analysis, we will consider only the group of companies which do know the Plan, and we will distinguish among users and non-users. The required information will be obtained by comparing the necessities showed by each specific company and the opportunities given by the different Programmes. Whenever a necessity can't be attended, we will find a company that knows the Plan but can't make use of it. These companies will form the third contrast group.

Data on companies' requirements and supplies of resources are obtained from a compulsory questionnaire that has to be filled in by every company applying for the Plan support. (It is necessary for the proper use of our proposed methodology that questionnaires have a compulsory character). We will describe their design later.

Comparing the group of completed questionnaires and the group of accepted projects we will obtain the categories of user and non-user companies.

This will allow us to rank the existing Programmes according to their utility. We will consider that one Programme provides more utility than other whenever the number of companies that can profit by joining the Plan is bigger.

It will also be helpful when trying to characterize the unattended demands and the reasons for rejecting some particular projects. For the best use of the suggested methodology, we recommend to realize the above mentioned analysis prior to, and immediately after, the implementation of the Plan (before and during 1992). It is easy to see that after every partial evaluation we will be able to determine the existing disagreements among the contents of the Plan and the companies' wishes and expectations.

This information can be of great use when looking for a better agreement among the Public Administration and the Private Sector.

Going through the *third level*, the operational one, we have to take into account all the information proceeding from our prior analysis and evaluations. In this level we will compare the specific actions included in each programme and those requested from each small and medium firm. Companies' data are sourced through the questionnaires. These data provide a superior level of detail.

Results from this comparison will allow us to distinguish among users that are satisfied with the outputs of the Plan and those that are not satisfied. Unsatisfied small and medium firms would form the fourth contrast group. We will be able as well, to establish some differences between satisfied and unsatisfied demands and for both type, what of them were more frequent. We can also obtain a deeper degree of information when analyzing the reasons for the rejection of the requests. If more detail is needed, we might study the satisfaction degree showed by the companies concerning the received help or support.

We recommend beginning this third phase of the analysis once the Plan has been implemented and two years, at least, have passed. Since the length of the Plan is four years, we believe that two years is a valid time period, given that short term actions have been taken and medium ones are being implemented already, so the first completed and partial results are beginning to appear.

With these results, not only can we appreciate the evolution experimented by the chosen indicators, to whom we will refer later on, but to delimit the trends as well. We will be interested in both type of trends: the desired ones, which gets closer to the global objectives and goals, and the undesired trends, that are a by product of them.

On the other hand, given that there are two more years left before the completion of the time horizon, we can take advantage of this feedback and propose some corrective actions when needed, all them together with the fact that it is possible to introduce some changes in the present Plan or to postpone them for new Plans.

Data will be coming from two sources: a second questionnaire given to the user companies and widescope information proceeding from non-user companies. The questionnaire will be given to the users once those actions included in the Plan that fit the companies' request have been implemented or, at least, in the beginnings of that implementation.

If the user companies show modifications in their indicators other than those experimented by non-user companies, we will have to study them, identifying the most relevant ones and their meanings, and only then we will be able to advance some conclusions regarding those effects or impact directly derived from the plan from other motivated by environmental or external factors. More information would be obtained after comparing the results achieved by users and satisfied firms and users but unsatisfied ones.

And we can go even further, testing the manifested satisfaction degree by user and non-user small and medium enterprises. All that information comes from the private sector, that is, from the companies themselves, so we will have to know if the authorities from the Plan do have the same feelings and satisfaction degrees.

Public Administrators' opinions might differ from the companies in questions like the scope of opportunities, execution level or even the existence of actions requested by companies. Collecting information from the public authorities, we will not only have the chance to isolate potential disagreements but to contrast as well how promoters and users assess the Plan and the achieved results. An adequate use of this information will allow us to reassign resources better, to improve the course of action to take, and to reach a better understanding among administrators and beneficiaries. We also have to add what suggestions might be made on real time or in a short term period and what potential improvements due to these suggestions might be unequivocally recognized.

We are now on the best conditions for approaching the *fourth level* of analysis. We will try first to analyze the performance obtained in the accomplishment of the sub-objectives associated with the different Programmes, so it will let us get clear and concise conclusions on the adequacy to maintain the same targets on the development of new specific actions in future Programmes and Plans.

Secondly we will approach a more detailed study on the suitability and ease of implementation for the existing Programmes which might lead to the introduction of some changes and recommendations in future descriptions of the present Plan or other similar to this one. It can also be considered in new approaches which will pursue similar or even better results with fewer costs involved, whenever possible.

To conclude this level of analysis we should re-aggregate all the detailed information obtained from this "step-by-step" process. Acting in this way we will get an operative and reliable information concerning the level of achievement in the purposes of the Plan. Not only will we know better about its fulfilment but also will get useful information on the difficulties over-passed, unsurmounted handicaps and unsatisfied requests.

With all these data we will be able to find an answer for the following points:

- Was the Plan adequately designed?
- Has been the Plan adequately executed?
- Has been the control of the execution the adequate one?

These answers will take into account those answers given by the companies (included in a third question-naire) and the perceptions of the promoters.

Concerning the economic indicators on the efficiency and effectiveness of the public funds used for the financial support of the Plan, we will obtain them from the values reached by the relevant indicators, distinguishing among trends due to the Plan and those others due to global economic environment.

As a final result of our analysis we will have obtained quantitative and qualitative data. By using them we might reduce some undesired effects such as:

- lack of proper control of the Plan since there are not milestones to focus on,
- a significant proportion of the public funds can be wasted, since efficiency and effectiveness are not the relevant criteria,
- confusion between improvements generated by the economical environment and those generated by the implementation of the Plan.

When a framework which provides tools for the evaluation and control like the one we have suggested is employed, some of the following modifications might take place:

- The Promoters have to be more explicit,
- Better parameters can be used to determine when the companies achieve the optimal benefits from the Plan
- Users fully understand the objectives of the Plan
- Managers are forced to make periodic reviews of the Plan.

Data Analysis

As was mentioned before, to determine the impact of the Plan we should carefully observe and compare the changes exhibited by the different contrast groups, in order to separate those changes directly derived from the implementation of the Plan from other possible sources of change.

We will describe now how to analyze the information coming from these contrast groups. The process includes the following phases:

First phase: It is devoted to the collection of the existing information on the achieved results from the different user companies. We will consider data proceeding from the companies' relevant indicators, obtained during the implementation period and after it. This will allow us to determine if the experimented changes agree with the expectations of the companies, leading us to know:

- satisfaction degrees,
- trends in the relevant indicators,
- deviations from the expectations.

Second phase: We will collect information on the achieved results from non-user companies which do know the Plan. Again we will distinguish among obtained results and expected results. By doing this, we will obtain the same information as above, related to non-user but knowledgeable companies.

Third phase: If the information obtained is the same for the first and second observed groups, we will conclude that the effects of the Plan are not direct results but indirect ones.

Fourth phase: If there are some differences between these two groups it is possible to suggest the existence of direct impacts of the Plan, although it must be assessed as we will see later on.

Fifth phase: Non-user companies which do not know the Plan but do incorporate industrial design in their products or processes are considered. Obtained data will be grouped in the same categories as above.

Sixth phase: If the information obtained is the same for knowledgeable and non-knowledgeable companies, we will state that changes showed by the relevant indicators are due to factors other than the implementation of the Plan and associated with the global economic environmental changes.

Seventh phase: If significant differences are observed, we can suggest the existence of effects motivated by the implementation of the Plan. However, a further analysis is required in order to determine whether these significant differences remain for user and non-user companies when looking for a categorization of direct and indirect effects.

Eight phase: We will consider in this phase the existing agreements and disagreements among the companies' manifested results and those the Administration believes to be obtained.

They should agree, given that the proposed methodology includes continual evaluation and the chance to incorporate corrective measures when they were needed in order to achieve the better coincidence among companies' desires and requests and Administration' support.

Nevertheless, it is possible that in the last moment of the final evaluation step, different criteria for performance measurements are being used by both private and public organizations. If this is the case, we should know the employed criteria and the existing differences for evaluating how significant the deviations are and how much the implementation of the Plan has contributed for these deviations.

We recommend taking into account the different criteria for the purpose of their consideration in the design of future Plans.

Ninth Phase: If there is an the agreement in the previous phase, the next step will be to determine how much the a priori objectives of the Plan have been met. In this way we will be able to know:

- If the objectives have been fulfilled,
- If they have been overcome,
- If they have not been reached.

For cases in which the undesired results were relevant, the main reasons of the failure should be carefully addressed in order to take them into account for the description and contents to be included in new Plans.

Tenth phase: Previous analysis provides us with qualified information. By using it, the accuracy of our evaluation will be in no doubt, higher than the resulting from more conventional evaluations. Consequently, the line between direct and indirect effects can be more precisely delimitated, shortening the risks involved in the process, such as potential failures, biases, and so on.

On the Nature of the Required Information and Data

Our approach to the evaluation and control of the Plan has one of its main principles in facts other than the overuse of relevant information. We are more oriented to quality than quantity, being sure in the meanwhile that the better the information, the fewer errors and involved costs we will have when dealing with it. For this reason, we have grouped our information needs into the following sections:

1 Who is going to provide the information?
2 What kind of information is going to be asked for?
3 When are we going to ask for it?
4 How are we going to ask for it?
5 What is that information for?
6 When are we going to use it?
7 How are we going to use it?
8 Potential errors.

Let's consider 1,2,3,4 and 8.

1 <u>Who is going to provide the information</u>?

We will just consider those companies that applied for previous Plans similar to the present one, together with other companies that are interested in it, were not able to get any public support, as well as all those companies which are of interest for the Administration.

2 <u>What kind of information is going to be asked for</u>?

Every applying company will have to fill three questionnaires, the first when applying, the second two years later if some public support has being received, and the third at the conclusion of the Plan. Data included in these questionnaires refer to:

- General information, like name, address, activity, sales, owned capital, types of products and processes, number of employees, and so on.
- Brief description of the project to be performed, including intended objectives, financial needs, length, nature,...
- Kind of help requested and reasons for it.
- Existing industrial design.
- Intended industrial design.
- Expected and actual changes in the relevant indicators if the innovation is incorporated.

By relevant indicators we will consider:

- New products
- New processes
- Changes in personnel policies
- Changes in sales policies

- Financial opportunities
- Changes in consumers' habits
- Changes in the companies' profits.
- Changes in the Spanish corporate image.

3 When are we going to ask for the information?

Prior to implementing the Plan we will ask for the available general information proceeding from previous plans and from the contents of the Plan itself.

Concerning the information about the companies we have established four stages:

- First we will collect the data from the first questionnaire, when companies apply for public support.
- Second, two years later we will ask the user companies for the second questionnaire.
- Third, immediately after the conclusion of the Plan, by means of the third questionnaire and by the Administration archives.
- Fourth, we will look for widescope information on the remaining companies and consider the existing feedback too.

4 How are we going to ask for the information?

For widescope information we will have to adopt the existing formats. For user companies, no matter their degree of satisfaction, we will state a particular format, which will be considered when designing the questionnaires.

8 Potential errors

Although the suggested methodology is oriented to the reduction of errors and mistakes, some of them might appear like the very well known type I and type II errors. We believe that this kind of errors are quite difficult to be found when evaluating and controlling the present Plan if the instructions given by the suggested methodology are followed. Anyway, other errors can happen for reasons other than type I or type II. We mean the following cases:

- The Plan might be inadequately defined, limiting their potential impact,
- Companies might bring upon mistakes when applying for public support, forcing to its deny.
- Human errors.

Summary and Conclusions

Our conceptual framework constitutes an integrated approach to the evaluation and control of the impact of the Plan. It has its principles in the determination of the impact of the plan through the periodic revision of the different questionnaires concerning the different hierarchical levels. They contain relevant information on questions like the innovation process on industrial design, or the quantified results of that process for companies which joined the Plan and for those others not able to join it. This information also gives the opportunity to obtain relevant parameters for the measure and control of the performance of the Plan.

The results, when compared with the intended or expected ones, will provide us with the information needed to determine the nature and dimension of the impact of the plan as well as the efficiency and effectiveness of the Programmes and the specific actions included in those Programmes.

The most important advantages of the proposed methodology are:

- Information is managed in such a way that errors and mistakes are considerably reduced.
- The evaluation process can be easily automated if desired.
- Problems can be detected prior to their appearance.
- Corrective measures can be implemented on time, cost, place and the most suitable way for both companies and Public Administration.
- Feedback provided by the control and evaluation process allows a stretched tight monitoring of the implementation.
- The data base is always kept up-to-date and reliable, being of the utmost importance for improved future plans and programmes.
- This methodology provides us a better tool to separate the results and effects of the Plan from those generated by environmental changes.

As the implementation of the present Plan takes place we hope being able to clarify the following points:

1. An extended description of the methodology, which will refer to questions like information sources, test timing, required information, indicators to be used, questionnaires and so on.
2. Problems found during the revision phase and measures taken to solve them. Those measures can be essential to the improvement of new methodologies.
3. First results of our research once the Plan begins to operate, as well as difficulties found and the way in which they have been solved.

Policy Analysis Models Based on Multi-Level Programming

M. Avriel and A. Breiner

Faculty of Industrial Engineering and Management, Technion - Israel Institute of Technology, Haifa, Israel

Abstract

This paper develops a methodology for the formulation and solution of policy analysis models based on the multi-level mathematical programming approach. This approach deals with optimization problems in which the constraints include further optimization problems. Special cases and examples are considered.

1. Introduction

Multi-level programming forms a branch of mathematical programming, dealing with optimization problems whose set of constraints includes further optimization problems. In mathematical terms, multi-level programming takes the following form:

(1.1) MLP

$$\max_{x_1} f_1(x_1, \ldots, x_n)$$

subject to

(1.2) $g_1(x_1, \ldots, x_n) \leq 0$

where $(x_2, \ldots, x_n)$ satisfy

(1.3) $x_2 \mid x_1 = \text{argmax } f_2(x_1, \ldots, x_n)$

subject to

(1.4) $g_2(x_1, \ldots, x_n) \leq 0$

where $(x_3, \ldots, x_n)$ satisfy

.
.
.

(1.5) $x_n \mid x_1, \ldots, x_{n-1} = \text{argmax } f_n(x_1, \ldots, x_n)$

subject to

(1.6) $g_n(x_1, \ldots, x_n) \leq 0$

Historically, multi-level planning or programming has appeared in the literature in connection with decomposition methods for linear programming, such as the method of Dantzig and Wolfe (1960). One criticism of decomposition methods is that although the solution process can be viewed as reflecting the decision-making in multi-level organizations, in fact one is solving an optimization problem with a single objective function over a fixed feasible set. In contrast, multiobjective programming approaches, such as in Keeney and Raiffa (1976), seek to find a simultaneous compromise between often conflicting objectives, but by ignoring the hierarchical nature of the underlying problem.

The multi-level programming approach deals with modeling hierarchical decision-making systems. These systems are characterized by a hierarchy of planners, each independently controlling disjoint subsets of the overall set of decision variables. The decisions are carried out sequentially, from top to bottom. The important feature of these problems is that the objective function and feasible sets of the various decision levels depend, in part, on decisions made at other levels. For a general definition of such problems see Bard and Falk (1982), Bialas and Karwan (1982), and for a similar type of problems, called Stackelberg games, see Simaan and Cruz (1973). In general, multi-level programming problems are very difficult to solve numerically and no universal algorithm exists for their solutions. In fact, most solution procedures are applicable only to special cases of multi-level programs.

To illustrate multi-level programs, consider the following two examples:

(a) *The bi-level linear resource control problem.* This problem may be written as

(1.7) $\max_{x \geq 0} \; c_1^T x + d_1^T y$

where y solves

(1.8) $\max_{y \geq 0 \mid x} \; c_2^T x + d_2^T y$

subject to

(1.9) $A_2 x + B_2 y \leq b_2$.

In this problem, the upper level (level 1) controls x, and the lower level (level 2) controls y. Notice that the upper level objective function contains both x and y, and the feasible resource space of the lower level depends on the value of x. It is easy to show that for every non-negative (feasible) value of x, the solution of the lower level optimization problem is an ordinary linear program, whereas at the upper level it requires the maximization of a linear function over a generally non-convex set.

(b) *The bi-level linear price control problem.* This problem may be written as

$$(1.10)\quad \max_{x} \; c_1^T x + d_1^T y$$

where y solves

$$(1.11)\quad \max_{y \geq 0 \mid x} \; x^T y$$

subject to

$$(1.12)\quad B_2 y \leq b_2.$$

In this problem the upper level controls the objective function coefficients of the lower level. Notice again that for a given x the lower level solves an ordinary linear program in which the feasible set is fixed, whereas the upper level problem is more complicated.

As mentioned above, multi-level programming problems are inherently difficult to solve. Here we mention only two aspects of the difficulty. One is that for a given level of x (the variable controlled by the upper level), there may be alternate optimal solutions y at the lower level. Although each of these alternate optima yields the same value of the lower level objective function (for the given x), they can have a great impact on the upper level objective. The second, and perhaps most significant difficulty in solving the multi-level problem is that the overall problem is, in general, a non-convex and nonsmooth mathematical programming problem.

2. Policy analysis model

Policy can be defined as a set of decisions concerning the value of policy variables, reached by policy-makers to direct a system toward their goals. In the context of this work we shall usually think of socio-economic systems, although other systems may be considered as well. The level of goal achievement is determined according to the system response to the policy decisions taken. Policy analysis focuses on two interrelated subproblems: the behavioral problem — prediction of system responses to policy decisions; and the policy problem — choosing among various alternative decisions to maximize the policy-makers' goals. An important feature of the problem under study is that the policy-makers have direct control over only a small part of the system variables. The remaining policy variables describe the autonomous behavior of the other agents in the system, and no cooperation exists among the agents themselves, or between them and the policy-makers.

Mathematical models have been formulated for these two subproblems separately. For example, multi-sectoral input-output (development) models applied to the economic system enable description of the policy-makers' preferences by means of objective functions and appropriate constraints. These models are prescriptive in nature. The solution obtained from them is normative, and does not purport to predict the true response of the agents in the economic system to the selected policy alternative. Models of this type are based on the assumption that the policy-makers have direct control over all of the system variables.

On the other hand, general equilibrium models concentrate on describing the autonomous behavior of the agents in the economic system in response to a given selection of policy variables. These are descriptive models; the solution obtained from them is supposed to predict the responses of the agents in the system to the policy alternative adopted. These models do not solve the policy problem.

The multi-level programming approach permits the direct integration of these two subproblems, considering the hierarchical nature of the decision-making process. The policy problem (PP) is described at the upper level, and the behavioral problem (BP) at the lower level. An example of this approach can be found in Takayama and Simaan (1984), where the relationship between the central administration and the private sector is described by a leader-follower model, with the administration as the leader. The administration develops the socio-economic potential of the state, and thus directs the private sector — the follower — to continue the development process according to its own considerations. In time the leader-follower relationship can be gradually replaced by one of cooperation between equals, because of the maturing of the socio-economic system and changes in external conditions.

There are two more complicating factors in modeling policy analysis problems: The first is the multi-objective nature of the policy problem - that is, policy-makers have, in general, more than a single objective. Modeling multi-objective optimization problems introduces an additional level of complexity into the solution process. The second complicating factor is uncertainty, that is, the parameters of both the policy and the behavioral problems are, in general, not known with certainty at the time when decisions have to be made. Modeling the stochastic nature of the problem parameters also introduces an additional level of complexity into the solution process, such that mostly only approximate solutions can be obtained from the model.

The behavioral problem

The behavioral model of the socio-economic system to be formulated below is a fusion of input-output (development) and general equilibrium models. In particular, let us examine the suitability of the optimal solution of a development model for the solution of a general equilibrium, obtained from a system of equations representing the decentralized behavior of agents in a system characterized by a competitive market. Similar to Ginsburgh and Waelbroek (1981), consider a closed economy with no foreign trade activity. Let this economy include n producer activities, whose production levels are given by the vector x. Let the matrices A (nxn) and G (mxn) describe the technologies existing in the economy. Let the m resources at the disposal of the economy be denoted by the vector h. Given the output prices of the producer activities $P = (P_1, ..., P_n)$, the problem of the production side of the economy can be represented by the linear program:

(2.1) (PS) $\max_x \; PN^T x$

subject to

(2.2) $Gx \leq h$

(2.3) $x \geq 0$

where $(PN_1, ..., PN_n)$ represent the value added resulting from one output unit in the various technologies, that is,

(2.4) $PN = (I - A)^T P$

or

(2.5) $PN_i = P_i - \sum_{j=0}^{n} a_{ij} P_j$

If each activity represents an independent producer, the optimal solution of this problem is appropriate to the situation in a competitive market where producers compete for resources to maximize their profits. The shadow prices of the resources (the optimal dual solution of the problem) $w^* = (w^*_1, ..., w^*_m)$ will correspond to the value given to them by the market. From the duality relations of the optimal solution, the net output value will be equal to the income from the resources, that is,

$PN^T x^* = h^T w^*$

and each level of output prices P will correspond to an optimal production level x^* and resource price vector w^*.

Let the consumption side of the economy be represented by a single aggregate household whose utility, from the consumption of goods produced by the producers' activities, is a separable function of the type

(2.6) $U(z) = \sum_k U_k(z_k)$

where z_k is the quantity of product k consumed by the household. From micro-economic theory it follows that U is concave and nonincreasing, thus it can be approximated by a piecewise linear function as follows:

(2.7) $U(z) = \sum_{k=1}^{n} \sum_{s=1}^{S} g_k^s z_k^s$

(2.8) $z_k = \sum_{s=1}^{S} z_k^s \quad k = 1, ..., n$

(2.9) $\alpha_k^s \geq z_k^s \geq 0$

where g_k^s is the average marginal utility from the consumption of product k in line segment (s - 1, s), and α_k^s is the width of product k line segment (s - 1, s). The consumer problem in the economy is the maximization of the utility from product consumption under a budget constraint, and is given by the linear program:

(2.10) (PD) $\max_z U(z) = \sum_{k=1}^{n} \sum_{s=1}^{S} g_k^s z_k^s$

subject to

(2.11) $z_k = \sum_{s=1}^{S} z_k^s \quad k = 1, ..., n$

(2.12) $\alpha_k^s \geq z_k^s \geq 0$

(2.13) $P^T z \leq h^T w$.

For a given utility function U, output prices P, and resource prices w, the optimal solution of the model will provide us with the quantities required by the private consumer from the various production activities. In general equilibrium, for a given price vector for outputs and resources, producer decisions regarding quantities produced must correspond exactly to consumer decisions regarding quantities consumed. Thus, $z = (I - A)x$ will be satisfied, with producers acting to maximize their profits and consumers acting to maximize their utility. As stated above, duality of the producer problem ensures that the net output value will equal income from resources, that is

$PN^T x = ((I - A)^T x)^T P = h^T w$

The budget constraint in the optimal solution of the consumer problem is satisfied as an equality -that is, $P^T z = h^T w$. Therefore, if the price vectors are equal in both problems, then $z = (I - A)x$ — meaning that the net output produced by the producers is equal to the quantities demanded by the consumers. Accordingly, we may describe general equilibrium in the economy by solving a development model having a single aggregate consumer, by integrating the two problems described above:

$$(2.14)\ (PGE)\ \max_{x,z}\ (g^s)^T z^s$$

subject to

$$(2.15)\ (A - I)x + z \geq 0$$

$$(2.16)\ Gx \leq h$$

$$(2.17)\ Qz^s - z \geq 0$$

$$(2.18)\ \alpha_k^s \geq z_k^s \geq 0$$

This approach to the formulation of a development model, whose objective function includes consumer utility to characterize a general equilibrium, can be found in Goreux (1977), where a model for the Ivory Coast is described, and in Blitzer and Eckaus (1983), where an energy model for Mexico is presented. Kim (1984) examined linear programming development models in which the competitive equilibrium was disturbed by constraints on the shadow prices (the dual variables). By means of these constraints, it is possible to examine directly the effects of external involvement in the determination of prices in a competitive market.

Other effects also can be incorporated into the model of the behavioral level. For example, consider the modeling of taxation or subsidization of production and consumption. Let τ_x and τ_z denote the taxes (subsidies) on activities of production x, and consumption z; then the new objective function in (PGE) should be

$$(2.19)\ \max_{x,z}\ (g^s)^T z^s - (\tau_x)^T x - (\tau_z)^T z$$

The optimal solution of (PGE) will satisfy (PS) with the objective function $(PN - \tau_x)^T x$ and (PD) with the objective function $(g^s)^T z^s - (\tau_z)^T z$, for $P = P^*$ and $w = w^*$. It is thus possible to describe system responses to a variety of policy measures by means of a behavioral model of the development type, whose objective function is formulated in a manner ensuring (at least theoretically) equilibrium in a competitive system.

A few words on uncertainty: Uncertainty in the description of system responses to policy decisions may result from several factors, such as

(i) Insufficient clarity in the definition of the behavioral model;
(ii) Selection of the aggregation level for the description of various phenomena.
(iii) Reliability of the data by which the mathematical relationships in the model are estimated and expressed.
(iv) Uncertainty concerning events external to the behavioral system and outside the policy makers' control.

The immediate result of admitting uncertainty in a mathematical programming model is that the ordinary formulation of maximizing or minimizing an objective function, subject to inequality or equality constraints is no longer valid. One way of handling uncertainty in the behavioral model is by means of scenarios. Every scenario is a discrete realization of the uncertain events and the model should be reformulated in a way that considers all the scenarios, both in the objective and the constraints. Clearly, such an approach to model formulation is practical only if the number of scenarios is not too large - otherwise the model could become very difficult for efficient numerical solution. In the bi-level programming context we consider the following sequence of events including uncertainty: At the upper level the policy makers decide on a policy (set the value of the vector x), then the uncertain events are observed and, finally, at the lower level the behavioral model is solved to obtain the system response to the policy variables and the uncertain events corresponding to the realized scenario.

The policy problem

In the preceding section we discussed the use of scenarios to handle uncertainty resulting from external events outside the control of the policy makers. For each scenario an appropriate model was formulated. The model describing the policy level must, therefore, also refer to the results of implementing the policy in the various scenarios. The bi-level policy analysis model, when uncertainty is expressed by L different scenarios, can be formulated as follows:

$$(2.20)\ (BLPP)\ \max_{x} f_1\ (U_1\ (z_1), \ldots, U_L(z_L))$$

subject to

$$(2.21)\ g_{1l}(x,y_l) \leq 0 \quad l = 1, \ldots, L$$

where y_l satisfy

(2.22) $\max_{y_l \mid x} f_{2l}(x, y_l)$

subject to

(2.23) $g_{2l}(x,y_l) \le 0 \qquad l = 1, \ldots, L$

(2.24) $h_l(z_l,x,y_l) = 0 \qquad l = 1, \ldots, L$

Notice the general nature of the objective (2.20). By substituting various analytical forms for f_1, we can obtain objective functions such as the (weighted) sum of the separable utility functions, or multiple objective programming formulations. Unless we assume some simple (but still realistic) form of the various functions appearing in (BLPP) we cannot hope for solving the problem. Hence, let us assume that the functions appearing in (BLPP) are all linear, or can be approximated by linear functions. We obtain the following formulation:

(2.25) (BLLPP) $\max_{x_1, x_{2l}} c_1^T x_1 + \sum_{l=1}^{L} p_l c_{2l}^T x_{2l} + \sum_{l=1}^{L} p_l d_{1l}^T y_l$

subject to

(2.26) $A^1{}_1 x_1 + A^2{}_{1l} x_{2l} + B_{1l} y_l \le b_{1l} \qquad l = 1, \ldots, L$

where y_l satisfy for $l = 1, \ldots, L$:

(2.27) $\max_{y_1 \mid x_1, x_{2l}} d_{2l}^T y_1$

subject to

(2.28) $A_2{}^1 x_1 + A^2{}_{2l} x_{2l} + B_{2l} y_l \le b_{2l}$

Here the policy makers must reach decisions *today* concerning the policy variable vector x_1. The objective function consists of three terms: The first term represents the direct contribution of the policy variable vector x_1; The second term represents the expected contribution resulting from additional decisions x_{2l}, that the policy makers will reach in the second time-stage in light of their policy today, and in light of the realization of scenario l. The p_l are the (possibly subjective) probabilities of the scenarios, or their importance rankings; The third term stands for the expected goal achievement level that depends on the responses of the behavioral system to the policy decisions y_l in each of the scenarios. It should be noted here that the above model formulation is equivalent to the "bi-level multidivisional programming" model introduced by Bard (1983). Instead of scenarios, Bard considers divisions within an organization in the behavioral level. A possible application of such a model is for a company with a number of subsidiaries that also trade among themselves. The objectives of the subsidiaries are different from those of the parent company; control of the parent company is accomplished by setting prices for the products traded among the subsidiaries. Given these prices, the subsidiaries are autonomous with regard to the determination of their production policy. Notice that the constraints of (BLLPP) contain, at the lower level, L further linear programming problems. However, since the constraints (2.28) of the l-th scenario problem are independent of the other constraints of the other scenarios we obtain an equivalent problem:

(2.29) $(BLLPP1) \max_{x_1, x_{2l}} c_1^T x_1 + \sum_{l=1}^{L} p_l c_{2l}^T x_{2l} + \sum_{l=1}^{L} p_l d_{1l}^T y_l$

subject to

(2.30) $A_1{}^1 x_1 + A^2{}_{1l} x_{2l} + B_{1l} y_l \le b_{1l} \qquad l = 1, \ldots, L$

where y_l satisfy

(2.31) $\max_{y_l \mid x_1, x_{2l}} \sum_{l=1}^{L} d_{2l}^T y_l$

(2.32) $A^1{}_2 x_1 + A^2{}_{2l} x_{2l} + B_{2l} y_l \le b_{2l} \qquad l = 1, \ldots, L$

Problem (BLLPP1) is an ordinary linear bi-level program. As explained above, the solution of this model, despite its linearity, is very complex.

3. Solving special types of multi-level problems by linear programming

Let us look now on conditions, under which it is possible to find the optimal solution of (BLLPP1) by linear programming. Such conditions were given by Breiner (1987):

(a) If the constraints (2.30) do not include the behavioral variables y_l, that is, $B_{1l} = 0$ for $l = 1, \ldots, L$, and the coefficients of y_l in the policy level and behavioral level objective functions are positively linearly dependent -that is, there exist $\alpha_l \ge 0$, $l = 1, \ldots, L$ such that $d_{1l} = \alpha_l d_{2l}$, then the optimal solution of (BLLPP1) can be obtained by solving the following linear program:

(3.1) (BLLPP2) $\max_{x_l, x_{2l}, y_l} c_1^T x_1 + \sum_{l=1}^{L} p_l c_{2l}^T x_{2l} + \sum_{l=1}^{L} p_l d_{1l}^t y_l$

subject to

(3.2) $A_1^1 x_1 + A_{1l}^2 x_{2l} \le b_{1l} \qquad l = 1, \ldots, L$

(3.3) $A_2^1 x_1 + A_{2l}^2 x_{2l} + B_{2l} y_l \le b_{2l} \qquad l = 1, \ldots, L$

(b) If $\alpha_l = 0$ (and consequently $d_{1l} = 0$) for $l = 1, \ldots, L$ then the optimal solution for the policy variables can be obtained by solving (BLLPP2) with only (3.2) as constraints. The optimal solution for the behavioral variables in each scenario can then be obtained by solving L scenario linear programs of the form:

$$(3.4)\ (BLP_l)\ \max_{y_l} \sum_{l=1}^{L} d_{2l}^T y_l$$

subject to

$$(3.5)\ B_{2l}\, y_l \le b_{2l} - A_2^1 x_1^* - A_{2l}^2 x_{2l}^*$$

where , x^*_1, x^*_{2l} are taken from the optimal solution of (BLLPP2).

(c) If the constraints (2.30) contain both policy and behavioral variables, and the linear dependency between coefficients of the two objective functions is as stated in (a), we can solve the problem in two stages:

First we solve

$$(3.6)\ (BLLPP3)\ \max_{x_1, x_{2l}, y_l}\ c_1^T x_1 + \sum_{l=1}^{L} p_l c_{2l}^T x_{2l} + \sum_{l=1}^{L} p_l d_{1l}^T y_l$$

subject to

$$(3.7)\ A_1^1 x_1 + A_{1l}^2 x_{2l} + B_{1l}\, y_l \le b_{1l} \qquad l = 1, \ldots, L$$

$$(3.8)\ A_2^1 x_1 + A_{2l}^2 x_{2l} + B_{2l}\, y_l \le b_{2l} \qquad l = 1, \ldots, L$$

to obtain primal optimal solution $x_1^*, x_{21}^*, \ldots, x_{2L}^*, y_1^*, \ldots, y_L^*$, dual optimal solution $\pi_{11}^*, \ldots, \pi_{1L}^*$ (corresponding to (3.7)), and $\pi_{21}^*, \ldots, \pi_{2L}^*$ (corresponding to (3.8)).

In the second stage we define subsidies (or taxes) for the behavioral variables of each scenario. Let τ_l^* be vectors of subsidies defined by

$$(3.9)\ \tau_l^* = -\, B_{1l}^T(\pi_{1l}^*/p_l\,\alpha_l) \quad l = 1, \ldots, L.$$

Then we solve the following L behavioral problems, (linear programs) corresponding to the L scenarios:

$$(3.10)\ \max_{y_l \mid x_1^*, x_{2l}^*}\ d_{2l}^T y_l + \tau_l^{*T} y_l$$

subject to

$$(3.11)\ A_2^1 x_1^* + A_{2l}^2 x_{2l}^* + B_{2l} y_l \le b_{2l}$$

and obtain optimal solutions $y_l^\#$. If each of the L scenario linear programs has a unique optimal solution, then it was shown in Breiner (1987) that these $y_l^\#$ are also optimal for the original bi-level problem. If the optimal solutions are not unique, special procedures of perturbing the behavioral level objective function may be necessary.

Note that the constraints of programs (BLLPP2) and (BLLPP3) have a special staircase structure that makes these programs amenable for solution by decomposition methods, see for example Lasdon (1970).

(d) If, in addition to the conditions of case (c) above, also $\alpha_l = 0$ (and consequently $d_{1l} = 0$) for $l = 1, \ldots, L$, then we solve the problem also in two stages as follows: First we solve (BLLPP3). Let the optimal solution be denoted by $x_1^*, x_{21}^*, \ldots, x_{2L}^*$. Let $\pi_{11}^*, \ldots, \pi_{1L}^*$ be the optimal dual variables corresponding to (3.7). Define the τ_l^* by

$$(3.12)\ \tau_l^* = -\, B_{1l}^T \pi_{1l}^* \quad l = 1, \ldots, L.$$

In the second stage we solve the L behavioral problems with the modified objective function and augmented by the policy level constraints:

$$(3.13)\ \max_{y_l \mid x_1^*, x_{2l}^*}\ d_{2l}^T y_l + \tau_l^{*T} y_l$$

subject to

$$(3.14)\ A_1^1 x_1 + A_{1l}^2 x_{2l} + B_{1l}\, y_l \le b_{1l} \qquad l = 1, \ldots, L$$

$$(3.15)\ A_2^1 x_1 + A_{2l}^2 x_{2l*} + B_{2l}\, y_l \le b_{2l} \qquad l = 1, \ldots, L$$

Again, as in case (c), if the optimal solutions $y_l^\#$ are unique, they also solve the original bi-level problem.

In cases (a) to (d) described above, the optimal solution of the policy analysis model is eventually obtained by linear programming in which the policy level objective function is maximized, subject to the constraints of the policy and behavioral levels. Such a solution is, in general, an upper bound on the optimal value of the policy level objective function of the corresponding bi-level program. In cases (a) and (b), this solution is also the optimal solution of the bi-level program. In cases (c) and (d), this solution is the optimal solution of the bi-level program, provided the objective functions of the behavioral models describing the system response in the various scenarios are modified. The modification reflects policy-level involvement in the activity of the behavioral system, beyond involvement by means of the policy variables that affect the resources at the disposal of the behavioral system.

4. Examples of policy analysis problems solved by multi-level programming

Let us mention now a few applications of the multi-level programming approach for policy analysis problems that can be viewed as special cases of those problems that can be solved by linear programming, as discussed in Section 3 above:

(i) In Bisschop et al. (1982) a model of surface and ground water policies in Pakistan, called the Indus Basin Model is reported. The government of Pakistan is the policy-maker and the farmers in the Indus Basin are the policy receivers. The government decides on surface water allocations, and sets taxes (subsidies) so as to maximize welfare. The farmers, in turn react to the setting of these policy instruments by using water and choosing cropping patterns so as to maximize their own income. In the bi-level programming context, the authors of the study assume that maximizing the aggregate net farm income can be considered as a proxy for maximizing welfare, so that the both the policy and the behavioral levels share the same objective function. The two levels differ, however, in that the government wants to satisfy a set of political constraints and long-term ground water balance requirements that are outside the sphere of interest of the farmers. The Indus Basin Model can therefore be viewed as a special case of bi-level programming problems in which the policy level objective function is vacuous. Formally, we have a problem

(4.1) $A_1x + B_1y \leq b_1$

(4.2) $\max_{y \mid x, d_2^*} \; c_2^T y + d_2^T y$

(4.3) $A_2x + B_2y \leq b_2$.

Note that in this problem both x and d_2 are policy variables. The vector x contains all the variables that are not under the direct control of the farmers and that are not in d_2. For example, investments in irrigation projects and surface water allocations are some of the components of x. The vector d_2 represents a set of subsidies and taxes the government can impose on the farmers' water related activities.

In Bisschop et al. (1982) the following algorithm is suggested to solve the above bi-level program. Set $d_2 = 0$, add (4.1) to the set of behavioral level constraints, and solve the resulting linear program. Denote the optimal solution as $(x^{\#}, y^{\#})$. Let the vector $\pi^{\#}$ be the optimal dual variables corresponding to (4.1). Then, by setting $x^* = x^{\#}$, $d_2^* = -A_1^T\pi^{\#}$, the vector $y^* = y^{\#}$ solves the behavioral problem

(4.4) $\max_{y \mid x^*, d_2^*} \; c_2^T y + d^{*T}_2 y$

subject to

(4.5) $A_2x^* + B_2y \leq b2$

and also satisfies the policy level constraint (4.1). The actual solution of the above behavioral problem is necessary to ensure that the solution $y^*(x^*,d_2^*)$ is unique, i.e. the solution of (4.4) - (4.5) is the same as the $y^{\#}$ obtained by solving (4.1) - (4.3) with (4.1) added to the behavioral constraints. If $y^*(x^*,d_2^*)$ is not unique, there may be other solutions to (4.4) -(4.5) that do not satisfy (4.1). In this case a slight change in d_2^* may be necessary to "persuade" the behavioral variable to satisfy (4.1).

(ii) A policy problem with mathematical representation similar to the Indus Basin Model was formulated in Breiner (1987). This problem concerns industrial pollution control policy. In a certain geographical region there is a high concentration of industrial plants. The region experiences ecological problems. A public authority in charge of the region must determine a policy to handle pollutant emission by the plants. Assume that the activities of the plants in the region can be described by means of a process analysis linear programming model. The behavior of the system (i.e. of the plants in the region) is governed by the linear program

(4.6) $\max \sum_{i=1}^{m} \sum_{j=1}^{n(i)} v_j^i y_j^i$

subject to

(4.7) $\sum_{j=1}^{n(i)} A_j^i y_j^i \leq b^i \qquad i = 1, \ldots, m$

where y^i_j is the activity level of plant i, using technology j and v^i_j is the corresponding unit profit. The technology matrix for plant i is given by A_j^i, and the resources available to plant i are constrained by b^i. The policy makers have to solve a multiple-objective optimization problem. They aim to reduce pollution in the region by limiting the activity levels of the plants, but at the same time they must also take into account the welfare of the region, including employment level, standard of living, taxes collected from the plants, etc. The principal policy measure of the policy makers is taxation of pollutant emission by the plants. Let t^i_j denote the tax on unit activity of plant i using technology j; then the policy problem can be defined as

$$(4.8)\ \sum_{i=1}^{m}\sum_{j=1}^{n(i)} H_{pj}^{i} y_j^i \le h_p \qquad p = 1, ..., P$$

$$(4.9)\ \max \sum_{i=1}^{m}\sum_{j=1}^{n(i)} (v_j^i - t_j^i)\, y_j^i$$

subject to

$$(4.10)\ \sum_{j=1}^{n(i)} A_j^i y_j^i \le b^i \qquad i = 1, ..., m$$

where H_{pj}^i is the matrix that determines the value of goal p as a linear function of the activity levels of plant i using technology j, and h_p is the "threshold value" of policy goal p. To solve this bi-level problem we proceed as in (i) above: First (4.8) is added to the profit maximization problem of the industrial plants. Hence we solve the linear program

$$(4.11)\ \max_{y \ge 0} \sum_{i=1}^{m}\sum_{j=1}^{n(i)} v_j^i y_j^i$$

subject to

$$(4.12)\ \sum_{j=1}^{n(i)} A_j^i y_j^i \le b^i \qquad i = 1, ..., m$$

$$(4.13)\ \sum_{i=1}^{m}\sum_{j=1}^{n(i)} H_{pj}^{i} y_j^i \le h_p \qquad p = 1, ..., P$$

Then, as in (i), the value of is determined by the dual variables, and finally, the augmented behavioral problem is solved to check for the uniqueness of the optimal behavioral variables. Repeated solution of the policy problem for various threshold values of the goals generates a set of taxation rates and enables the policy makers to reach a preferred policy alternative.

A wide range of additional policy problems may be formulated as special cases of multi-level programming. As a result of the model formulation and solution, it is possible to generate a range of policy alternatives including three main components: present policy variable values (what to do now?), future policy variable values (what to do in each future scenario?), and values of supports (or taxes) for the activities of the behavioral system in order to ensure the satisfaction of the policy constraints as defined by the policy-makers for the various scenarios. The last two components are expressed in conformance with the scenario to be realized in the future. In practice, the policy-makers can carry out the present optimal policy alternative, as obtained from the model, wait for the realization of a scenario, and then possibly reconsider the policy problem, change preferences, reevaluate the likelihood of realization for possible scenarios, etc. In any case, they are not committed to any specific future actions, since in most cases it is possible to change the course of action in the future.

Acknowledgements

This study was partially supported by the Fund for the Advancement of Research at the Technion and by the Bloomfield Fund.

References

Bard, J.F. (1983). "Coordination of a Multidivisional Organization through Two Levels of Management," OMEGA 11, 457-468.

Bard, J.F., and Falk, J.R. (1982). "An Explicit Solution to the Multi-Level Programming Problem," Computers and Operations Research 9, 77-100.

Bialas, W.F., and Karwan, M.H. (1982). "On Two-Level Optimization," IEEE Trans. Automatic Control, AC-26, 211-214.

Bisschop, J., Candler, W., Duloy, J.H., and O'Mara, G.T. (1982). "The Indus Basin Model: A Special Application of Two-Level Linear Programming," in Mathematical Programming Study 20, 30-38.

Blitzer, C.R., and Eckaus, R.S. (1983). "Energy-Economic Interactions in Mexico: A Multiperiod General Equilibrium Model," Report MIT-EL 83-017WP.

Breiner, A. (1987). "A Policy Analysis Model Based on Multi-Level Programming," D.Sc. Thesis, Technion - Israel Institute of Technology.

Dantzig, G.B., and Wolfe, P. (1960). "Decomposition Principle for Linear Programs," Operations Research 8, 101-111.

Ginsburgh, Y., and Waelbroek, J. (1981). Activity Analysis and General Equilibrium Modelling, North Holland, Amsterdam.

Goreux, L.M. (1977). Interdependence in Planning: Multilevel Programming Studies of the Ivory Coast, Johns Hopkins University Press, Baltimore.

Keeney, R.L., and Raiffa, H. (1976). Decisions with Multiple Objectives: Preferences and Value Trade-Offs, John Wiley & Sons, New York.

Kim, S. (1984). "Economic Planning with Institutional Price Constraints for a Decentralized Economy, Mathematical Programming, 29, 100-112.

Lasdon, L. (1970). Optimization Theory for Large Systems, Macmillan, New York.

Simaan, M., and Cruz, J.B. (1973). "On the Stackelberg Strategy in Nonzero-Sum Games," Journal of Optimization Theory and Applications, 11, 533-555.

Takayama, T., and Simaan, M. (1984). "Multi-Level Interaction of Government and Private Sectors in Economic Development," in Dynamic Modeling and Control of National Economies, Pau, L.T. and Basar, T., eds., Pergamon Press, 135-141.

Design of a Resource Allocation Mechanism for Multiple Use Forest Planning

G.L. Paredes V.

Institute of Forest Management, Universidad Austral, P.O. Box 853, Valdivia, Chile.

Abstract

Forest planning is discussed, particularly the features that make it a complex problem requiring hierarchical solution approaches. Some fundamental planning concepts are recalled and new developments based on decentralized planning procedures are described, providing a basis for comprehensive planning methods.

A hierarchical, regional or corporate, planning approach is presented, describing the economics of local and central decision making processes. The method is currently under development and iteration routines are being evaluated.

Introduction

During the last decades, the planning process in forest institutions has been "enhanced" by an increasing availability of sophisticated models and computational algorithms, along with more computing power. Nevertheless, this supply of models and equipment has not translated into a qualitative improvement of actual planning processes and many basic economic issues remain unanswered. At the same time, many forest-based corporations are still hesitant to adopt the new improvements.

The planning process of forest resource utilization is, by itself, a complex subject. A forest is, at the same time, production unit, asset, and storage for nonconsumed commodities. Furthermore, recent societal concerns have translated into new laws and regulations that rule the use and production of, not only the traditional market commodities, but other services now valuable to society. For large private holdings, the new economic restrictions on their operations and a competitive environment require a careful decision process that considers simultaneously transportation, protection, financial and silvicultural activities along with the traditional harvest scheduling decisions. As a result, forest planning in either public or private agencies has typically become a large-scale and complex decision problem.

The above situation is evident in public agencies where timber, recreation, wildlife, water and other nonmarket commodities have to be accounted for in the planning process. In large private corporations the nonmarket concerns are often replaced by other pseudo-commodities such as requirements on cash flows, market share, financial ratios, and other "externalities". The analogies are in many cases straightforward, so the concepts discussed in this paper, although related to planning in a public agency, can easily be extended to private firms.

In response to this scenario, the forest economics research community has dedicated much of its effort to the development of modeling techniques and computational procedures that allow it to partially address some of the issues raised by the forest planning complexity. This research community has not yet developed an appropriate and generalized framework for its successful implementation. Where multiple-use forest planning and economic efficiency are institutionally requested, the modeling approaches currently undertaken have either raised problem complexity to levels beyond comprehension of the managers, the public and even the modelers themselves; or simplified it to levels where it no longer allows for efficient allocation decisions.

In general, the current scenario of forest planning can be characterized as follows:

- a frequent separation of stand and forest level analyses, thus resulting in a misunderstanding of many policy issues, such as the below cost timber sales (BCTS), the allowable cut effect (ACE), and the selection among different management regimes.
- The economic information provided by the mathematical programming techniques utilized is almost invariably neglected or retrieved only for computational purposes. This has been an absent topic in the literature related to valuation of nonmarket commodities and to accounting procedures in forest management.
- Reported modeling approaches attempt to include, at the same level, decision variables and parameters

that result in large and uncomprehensive models. Furthermore, these models are often based on a single mathematical programming technique without exploiting the advantages of specialized methods.

- The development of resource allocation mechanisms for forest management has, in general, been divorced from real management requirements in hierarchical decision processes. Therefore, incentive mechanisms for managerial efficiency have been difficult to establish.

With the scenario just described, the overall purpose of this paper is to demonstrate that duality information embedded in mathematical programming methods can resolve many of the forest policy issues that the practice of industrial and multiple-use forest management have raised.

This paper analyzes the features of forest planning that make necessary its hierarchical decomposition and describes a proposed approach in this direction. The approach uses current developments in economic planning and management theory that need to be incorporated into the design of a resource allocation mechanism in order to overcome failures of the current planning experience. Finally, it describes a design for a hierarchical planning mechanism that overcomes some of the shortcomings of current approaches bridging corporate and forest level analyses.

Planning for Multiple Use of Forest Lands

The performance of a forest planning process has been traditionally viewed as dependent on, or conditioned by, the analytical model utilized. In describing analytical requirements for multiple-use forest planning Teeguarden (1987) points out that some of the "generic characteristics of the ideal analytical model ... [are] the following key structural capabilities" (p.20) : (1) simultaneous multi-resource land allocation, activity scheduling, and prescription selection analysis; (2) analysis of both spatial and temporal allocation problems, including the effect of policy constraints; (3) establishment and analysis of vertical linkages between forest, regional and national levels; (4) establishment and analysis of horizontal linkages to other national forests and the private sector in a region; (5) economic efficiency analysis; (6) economic and social impact analysis.

With all these requirements, in addition to others, multiple- use forest planning becomes a large-scale and complex task. Simultaneous consideration of spatial and temporal relationships, externalities of timber production and vegetation manipulation, and production of non-market goods and services raises the complexity level beyond the limits of any single technique. Forestry literature reveals that the approach generally utilized to deal with these aspects has been to break down the problem in the sense that one requirement is addressed at a time. Then, the modeling technique is enlarged to account for that aspect, and finally its mathematical properties are studied in order to derive a numerical procedure that overcomes the computational burden of the previous enlargement.

The subsections below discuss some of the modeling efforts reported in forestry literature along the lines of the main dimensions of forest planning.

The Time Dimension

Modeling efforts have been largely dominated by their focus on the dynamic nature of forest systems production. Issues such as forest regulation, long run sustained yield, and non-declining flow of timber are important and traditional concepts inherited from nineteenth century forestry in Europe. Foresters have to deal with them in forest modeling and planning processes. A survey by Reed (1986) presents many of the relevant approaches to account for the time dimension of forest planning. When the initial state of the forest does not present the equilibrium conditions for maximum sustained yield, binary search, the maximum principle, and linear programming have demonstrated their suitability to deal with the dynamic aspects of large scale forest planning.

Well known examples of linear dynamic models for forest planning are the works by Navon (1971), Johnson and Scheurman (1977), and a modeling scheme recently proposed by Reed and Errico (1986). The incorporation of time in forest resource allocation has an explosive effect on problem size. Without aggregation of time periods, problems soon become intractable within a linear programming approach as the number of stands or time period increases. However, their linear formulation presents a well-defined staircase structure suggesting the use of decomposition techniques. The works by Liittschwager and Tcheng (1967), Caswell and Rao (1974), Williams (1976), Nazareth (1980), Ericksson (1983), Berck and Bible (1984), and Hoganson and Rose (1984) are some of the efforts along the lines of the Dantzig and Wolfe technique, to overcome the computational burden of large-scale harvest scheduling problems. Their focus has been on the computational aspects of using this technique when forest planning is enhanced with respect to the time dimension.

The Space Dimension

Forest modeling efforts were enhanced in the early 70's when it was realized that, to solve for the best use of forest land, not only a dynamic problem had to be solved for, but also a spatial location one in order to obtain meaningful and implementable land use decisions.

With the work by Kirby (1973) global network analysis for all projects with shared access became a promising modeling approach for meaningful forest planning. However, the interest later tended to dissipate when researchers and practitioners realized that no algorithm with polynomially bounded execution time could be found to solve the concave programming problem resulting from MIP models. The approach is therefore used in small size, short-run, planning problems. Weintraub and Navon (1976), and Fowler and Nautiyal (1986), among others, have also contributed to integrated models with mixed-integer programming formulations.

Although through MIP models it becomes possible to deal with many of the issues that affect the ultimate viability of land-use plans, its use has been rather restricted, when compared to LP-based models, because of the computational burden.

Recently, more elaborate heuristics by authors such as J. Sessions have been implemented to handle fixed cost in network representations of forest planning problems. Even though these methods do not guarantee optimality, they have been shown to provide solutions within 10% deviations from true optimal solutions with the advantage of significantly reducing computational requirements.

Linkage to Other Institutional Levels and Agencies

The solution methods outlined above all have a common ingredient: their developers have attempted to solve as much as they can while using a single optimization technique. This is well exemplified through the description of IRPM as a "multicommodity, multiperiod, fixed-charge, capacitated network with mutually exclusive road capacities" (Kirby et al., 1986).

Furthermore, forest planning has been viewed as a single- level exercise as if every aspect of the decision process could be adequately addressed through a unique model. The results are formulations that tax either planning staff comprehension or computing capabilities. It is also now becoming clear that an undesired by-product of a single-level approach has been its inability to model the linkage to other agencies and to other decision making levels within the institution.

In light of the problems of practical forest planning, the idea of partitioning the planning process has recently grown up among forest managers. Hierarchical, or multi-level planning, is claimed as a necessary approach by Dykstra (1987), who distinguishes strategic planning at the regional-national level, tactical planning at the forest level, and operational planning at the district level. Coordinated planning with other agencies is also suggested by, among others, Binkley (1987). Also Beuter (1985) has argued in favor of implementing decentralized management of land units in a "business-like" fashion.

Few contributions are found in forest literature on analytical models to address either decentralization or inter and intra-institutional linkages. The economic ideas embedded in the decomposition method of Dantzig and Wolfe provided a solid analytical framework to managerial decentralization and give a protocol of messages to be implemented in hierarchically dependent management units to achieve optimal allocation decisions (Baumol and Fabian, 1964). However, of the works utilizing the method, only Williams (1976) seems to capture the idea of the Dantzig and Wolfe routine and provides an interesting, but sketchy, description of decomposition as applied to an idealized hierarchical decision process in a public forest agency.

One of the attempts to overcome the lack of coordination between regional and forest levels was developed by Hof and Pickens (1987). They propose a two-level model where the upper level solves an integer programming problem with discrete activities, each representing the choice of management plans developed by the local planning units. These local management plans are generated as revenue maximizing solutions to linear programming models of production at the corresponding unit, under different local level budget constraints and different relative price vectors. These "output/cost" alternatives become zero-one variables in the higher level model, which "would select alternatives so as to maximize some objective function" (p. 246).

This model is conceived as a non-iterative process that would allow to overcome the absence of planning processes at the local level.

Hof and Pickens' proposal would generate a large upper-level integer problem. To "overcome" the combinatorial complexity of these large integer programs they suggest using some rounding procedure to determine the set of plans to implement. The problems associated with this procedure are well known in mathematical programming literature, and it can be easily shown that it may render either infeasible solutions or suboptimal choices.

Navon and Weintraub (1986) also suggest a heuristic to elaborate supply alternatives for "a few neighborhoods" in the decision or policy space of the wildland enterprise. The procedure involves only one iteration between central authority and unit managers. These submit only one set of discrete proposals, covering all scenarios, to the center. Then, they are returned back a message describing their production plan.

In this procedure, if the constraints in the global integer program are not the same as the master constraints in the global linear program, then the procedure can not guarantee optimality since the units prepare their plan proposals as "small" deviations from the partial plans. The global integer program may not cover a wide enough range of alternatives as to allow for smooth substitutions.

In terms of message exchanges, the procedure requires massive data transmitted between the center and the units, and forces the center to solve two large-scale problems.

Weintraub et al. (1986) formulate a "two-stage hierarchical" model to consider major investment decisions along with timber management in a forest firm. A strategic mixed-integer programming model solves for those discrete investments options and for aggregated timber management regimes, hauling and plant operations. Tactical decisions are obtained by solving a continuous allocation model with disaggregated data.

Their modeling approach attempts to reduce computer time requirements of large integer strategic decision models. It has been experimentally applied in the U.S. Forest Service (Hrubes et al., 1987). The procedure follows, in general, a rather mechanistic aggregation of variables without mapping the decision making processes at each level of the institution.

Partitioning of the forest planning problem has been also attempted in the planning practice of public institutions. Mitchell et al. (1987) describe a procedure that sequentially solves: (1) a one-period "steady state" model to address spatial management issues; (2) a "harvest scheduling" model to analyze the dynamic characteristics of the timber harvest flow; and (3) a "final model" where activities are input according to selections made in the previous steps and modifications by operations personnel. The implementation of this procedure allows a heuristic reduction in the number of activities to be considered in the final planning model. The planning process is still centralized at the forest level, however it allows for certain involvement of the lower decision making level. In general, this procedure represents one of the many attempts that can be found in the practice of forest planning in order to break down the problem to actual comprehension levels.

As observed from the examples above, the driving concern in their development has been the search for computationally feasible methods for a large-scale problem. The limitations arise when including, at the same resolution level, decision variables and parameters that correspond to different types of management participation. Reliance on a single mathematical programming method, without exploiting the advantages of specialized techniques, also characterizes most of the reported planning procedures.

This mindset has been pervasive in forest planning, and is well reflected throughout the experience of the U.S. Forest Service. The experience in industrial forest entreprises has not been different.

As illustrated in the previous paragraphs, the recent practice of forest economics and planning has been confounded by a number of policy issues and societal concerns on the management of forest lands. Mathematical programming and computers have often been viewed as salvation devices and currently many stake their hope on even more computing power or faster techniques. Instead, it is proposed here that the practice of forest planning could first recast some of the recent developments in management and economic theory. The next section describes some of them.

Digression on Planning Concepts

The concepts below relate to the problem of planning for an economic system, where the entity may be a public agency or a large private corporation. Managerial problems in complex organizations have captured the attention of economists, computer scientists and cyberneticians in light of the decisive relationship between information flows and organization's behavior and economic performance. The availability of computing and communication equipment, the robustness of economic theory and developments in mathematical programming techniques have created new managerial potential to cope with a continuously changing environment. Not surprisingly, management sciences have demonstrated important results during the last two decades.

Planning has been a much misunderstood activity. Planning is usually seen as being the activity carried out by professionals, called planners, whose output is a document, the plan, and this is then submitted to the competent authority to be accepted or rejected (Beer, 1979). That this is the typical view of planning is demonstrated by observing that actual planning processes are typically undertaken at distant time intervals by professionals and experts in collecting, processing and summarizing massive data.

It has been demonstrated the existence of a cognitive gap between the common belief in planning and what planning actually is. By analogy to living organisms Beer (1979) has illustrated that planning can not be studied in isolation from the corresponding organization. Planning "needs to be seen as a continuous managerial process of decision, whereby allocations of investment are made now, so that the future may be different" (p. 336).

Therefore, as time goes on and more information becomes available, "it is madness to implement a plan at some date later than when it was conceived". A planning system that does not relate to a continuous process is nonsensical. Decisions taken yesterday are, very probably and ostentatiously, wrong today. It is actually observed an "endless flux of the planning process, undertaken by managers [not planners], and constantly aborted by their own decisions. [This is] the reality of management, the rest is illusion" (Beer 1979, p. 338).

Planning needs also to be defined with respect to measures of achievement of the corresponding institution, i.e., with respect to its short- and long-term viability. Plans are then based on some of three measures of achievement: (1) what is *actually* being done with the existing resources and constraints, (2) what *could be* done with the existing resources and constraints, and (3) what *ought* to be done by enhancing resources and relaxing constraints. The notion of *programming* or tactical planning deals with current operations accepting current targets. *Strategic* planning sets new capability objectives and tries to achieve them. *Normative* planning targets the latent potential of the organization.

These notions of planning are usually confused with the planning forms occurring at different hierarchical levels of the organization. For example, in a forest public agency it would be said that tactical planning is the one undertaken at the district or sub-forest level; strategic planning at the forest level and normative planning at a multiforest level. This approach would be too restrictive in the sense of precluding a district manager from setting his own strategy to remove constraints and to enhance its resource base. On the other hand, it would neglect that tactical planning actually occurs at the multi-forest level, where the periodic budget process is a typical example. In practice, it is observed that the three types of planning are, somehow, undertaken concurrently at each hierarchical level. In this way planning becomes a continuous process, and it corresponds to the "control structure" that Kantorovich (1976) identifies as being of critical importance for successful application of mathematical programming in resource allocation. The requirement for planning to be a continuous process, capable of real-time responses to a continuously changing environment, necessarily imposes some constraints on the type of resource allocation model to be used. It restricts its size, forcing it to represent only what is strictly and absolutely relevant for the corresponding level. But this size restriction is netted out by the other requirement: it has to be recursive, i.e., the planning decisions are taken at all recursion levels of the institution. Centralized planning and its associated large-size models, where all recursion levels are included, are thus precluded.

The above concepts provide a solid framework for the main task in forest planning: the design of resource allocation mechanisms as developed from economic theory.

The selection of a plan of action for an economic organization involves the solution of a large constrained maximization problem. It corresponds to the concept of strategic planning discussed above and it represents the model that "glues" (Beer, 1979, Chapter 13) the activities of the organization during the short-term. As illustrated by Hurwicz (1973) the problem is not a trivial one. First, the computation of the maximizing values of the variables requires the availability and selection of a well-defined mathematical programming method or procedure that satisfies both the parameter data available, and the functional relationships among resources, commodities and preference values. Secondly, computing and analysis capabilities require managers to parcel out the computing procedures so the problem can be solved and appropriately comprehended. By parceling out, information transfers are minimized and divisional managers become involved in the planning process by handling the information on their own production possibilities.

Because of the limiting computing capabilities and the high dimensionality of actual planning processes, it also becomes unavoidable that the solution of a large constrained optimization problem is an iterative process.

The last decades of economic analysis have broken out of the limitations imposed by its traditional acceptance of the institutional status quo. Since the works by

Lange (1936) a new approach to economic analysis regards the structure of a economic system also as an unknown in the problem of finding a system that would be superior to the existing one (Hurwicz, 1971; Kantorovich, 1976).

Hurwicz (1973) defines the *function* of a resource allocation mechanism as "guiding the economic agents (producers, consumers, bankers and others) in decisions that determine the flow of resources" (p.16). It specifies the rules according to which, given his information, a participant sends messages to others. These are called *response rules*. An important condition is that the mechanism should guide economic agents to decide on activities that are both individually feasible and collectively compatible.

A second condition is that a resource allocation mechanism should operate whichever is the over-riding criteria: production efficiency of Koopmans and Kantorovich, or Pareto's optimality, or maximization of Samuelson-Arrow social welfare function. These may be defined independently of the mechanism.

The *environment* in which the mechanism shall operate is defined by taking together the individual endowments of economic agents, and their technology and preferences. These are those constraints and conditions that can not be modified by the designer and the users of the allocation mechanism.

Participants set an exchange of messages between them. The dimensionality of the message space depends on the number of types of information transmitted: activity proposals, resource flow proposals, prices, production costs, preferences, technology, or resource endowments are all potentially used in the message exchange. The totality of messages permitted under a mechanism constitute its *language* (Hurwicz, 1973). For large-scale allocations, language dimensionality is one of the main concerns since it translates into interpretation and computation requirements, and into data transmission errors.

Transition from dialogue to decisions and actions are regulated by the *outcome rules*. The resource allocation mechanism is then fully specified by its language, the response rules and the outcome rules.

An over-riding concern in the design of allocation mechanisms refers to its Pareto-satisfactoriness. A process is said to produce Pareto-satisfactory allocations if these are unbiased, single-valued, and represent an optimal equilibrium state for some setting of the distributional parameters.

A second concern is its informational aspects: dimensionality of the message space, informational efficiency, and information processing expenses.

The decentralized characteristics of the competitive process make it superior to alternative resource allocation mechanisms (Mount and Reiter, 1974). This process satisfies the privacy requirements (messages transmitted by an agent depend only on its technology and messages received earlier; the contents of a message concerns only proposed actions of the sender), and the anonymity requirement (i.e., agents need not know the source of received messages). By minimizing information transfers and processing, the competitive process reduces to a minimum the costs, delays and possibility of errors.

Unfortunately the competitive process proves to be Pareto- optimal only when operating in a classical environment, i.e. where externalities are not present, public goods are not involved, and convexity can be guaranteed (Koopmans, 1951). This fact raises the question of whether informationally decentralized procedures can be designed for different environments.

Further properties of an allocation process have been discussed in the works by Marshak (1959), Hurwicz (1973), Aoki (1971), Kornai (1967), Heal (1971) and Weitzmann (1974), among others. The most important additional feature to account for, in assessing an allocation routine, are its asymptotic efficiency, its feasibility and its provision for incentives. Asymptotic efficiency refers to monotonicity and convergence, taken together. Since implementation of an iterative process will typically consider only a finite number of iterations, it will be desirable to have a high rate of "early convergence" to an optimal allocation. Feasibility matters for the same reason above: stopping the iterative process after a finite number of steps should yield a feasible allocation.

The problem of incentives refers to the healthy and implicit assumption that participants have an interest to act in the same direction as the plan objective. As stated by Kantorovich (1976) "the problem is to make profitable (for the local decision making organs) the decisions which are profitable for the system, and to check the validity of the activities..." (p. 205). The problem therefore involves the construction of "a system of information, accounting economic indices and stimuli which permit the local decision making organs to evaluate the advantages of their decisions from the point of view of the whole economy" (p. 205). This clearly has an effect on plan implementation.

Literature on economic theory has made the distinction between price-guided and quantity guided planning procedures. Through duality theory they can be shown to be mathematically equivalent, however the distinction remains necessary since the informational requirements are different, and they present different properties under different environments.

Price-guided Routines

The typical price-guided planning routine was first described by Lange (1936) to demonstrate that a centrally planned or socialist economy could emulate a Walrasian tatonnement thus reaching a Pareto-efficient allocation, as in a competitive market environment. Discussed and formalized later by Arrow and Hurwicz (1960), Lange's model conceives a central planning board (hereafter the center) acting as an auctioneer quoting prices for each commodity. The firms behave as buyers and sellers successively adjusting their demands and supplies in response to the announced prices. Under certain conditions (to be discussed later) the process reaches equilibrium and commodities are traded accordingly at the prices and quantities specified at the equilibrium.

In large-scale optimization, a decentralized procedure would involve the firms' managers each solving their profit maximization problems given their production technology and a set of shadow prices for each commodity.

The central planning authority solves the economies problem by successively adjusting its estimates on the shadow prices.

The gradient process of Arrow and Hurwicz provides a method for successively adjusting the center's estimates on the shadow prices that solve the economies problem. Given an initial set of values for the variable vectors are adjusted according to the following rules:

- demand for final consumption is adjusted at a rate proportional to the net marginal contribution to the objective function.
- the scale of operations is obviously adjusted in the direction of higher profits,
- the shadow prices for commodities are adjusted proportionately to the negative of the difference between supply and demand.

As observed, the process is attractive since it requires a minimum of information transfers: at each iteration, the center transmits a vector of prices and the firms return back their respective demands and supplies of commodities. By imitating a Walrasian tatonnement as in a competitive market, the process is informationally efficient, preserves information privacy and anonymity.

However, the process is based upon assumptions on the objective and production functions that can sometimes be restrictive. Concavity of the production functions implies the requirement for constant or decreasing returns to scale, and constant or decreasing marginal rates of substitution over all output/input relationships. Concavity of the objective function requires that the set of outputs (those at least as satisfactory as a given bundle) should be a convex set.

Even though these assumptions may appear rather restrictive, it is important to note that one of the main reasons for non-convexities is the presence of high fixed costs that remain constant over a wide output range so they usually affect the long-run production set. At the planning level considered here (strategic) and according to the definitions early in this section, decisions on major investment items (capital equipment, developments, or research programs) are assumed as given by normative planning. Although this reasoning is not valid for set-up costs, since these are directly determined by the choice among discrete production alternatives (Heal, 1973, p. 148) they can be assumed away in strategic planning of public wildlands, where allocations are typically variations on intensity levels for existing production alternatives.

A major drawback, however, of this procedure is that at any step other than at the optimum, plans need not be feasible, i.e. supply need not equal demand. The procedure, although it is very efficient in its informational aspects, does not guarantee a feasible allocation unless the procedure has converged to the optimum.

Another interesting price-guided mechanism has been proposed by Malinvaud (1972). Inspired by the decomposition algorithm of Dantzig and Wolfe (1960), the Malinvaud process bears no resemblance to the market tatonnement process. The center sequentially learns more about the production set of each firm by gathering data. The accumulated information enables it to construct successively more accurate approximations to the firms' production sets.

In this process the assumptions are less rigorous than in the Lange-Arrow-Hurwicz process: the production sets need only to be convex, not strictly convex. Constant returns to scale are therefore not ruled out. With respect to information decentralization, the Malinvaud procedure does not satisfy the anonymity requirement since at a typical step the center receives a production program from each firm. The procedure also requires the center to "memorize" by recalling, at any step, all previous relevant responses of the firms. The center is also required to solve a constrained maximization problem in order to find the associated shadow prices that are utilized by the firms in the next step.

With respect to convergence efficiency and feasibility, the Malinvaud process is superior to the former. It converges asymptotically to the optimum and, furthermore, allocations at any intermediate step are feasible.

Quantity-guided Routines

The observation that many actual planning procedures operate by setting quantitative targets to the units, and the fact that they seem to perform satisfactorily, motivates economists to attempt a generalization of quantity-guided procedures (Kornai and Liptak, 1965; Heal, 1969, 1971; Weitzmann, 1970; among others). Heal (1969) discusses a planning routine where the structure of the messages has been inverted: the center sends out quantitative targets and receives marginal productivities, these are then used to compute marginal social values and to re-allocate resources among the firms according to their productivity.

The procedure starts with the central planning board proposing an initial feasible allocation of resource inputs to every firm i. Thereafter the following steps are iteratively performed:

Step 1 Each firm informs two pieces of information describing, respectively, the new output allocation and the rates of product transformation for the given inputs.

Step 2 The center computes global production and the marginal social values of resources allocated to each firm.

Step 3 The center changes the previous resource allocation increasing input to those firms with higher marginal social values. The center communicates these new allocations and the procedure returns to step 1.

As demonstrated by Heal (1969) the process has the following characteristics:

(a) Every re-allocation satisfies the necessary conditions for optimality. Furthermore if the initial allocation is not a local minima, none of the subsequent re-allocations will be local minima.

(b) The allocations sequence causes the objective function to increase monotonically.

(c) For a feasible initial allocation the subsequent allocations are always feasible.

The procedure is simple to implement. The firms are required to evaluate the marginal productivity of their resources and to assess their output given the allocation command of the center. The central planning authority has to evaluate the marginal social value of each resource and to solve a system of linear equations in order to obtain the necessary resource re-allocations.

The validity of the procedure, with regard to its convergence, optimality, and feasibility characteristics, is independent of any assumptions on the concavity of the objective function or on the convexity of the production sets. Moreover, the center is not required to exercise memory, as is required in the Malinvaud routine.

The price and quantity-guided mechanisms described above are just a few of those proposed for large-scale resource allocation. They, however represent the two extremes on which variations have been developed to overcome the limitations of either one.

These procedures, with their advantages and shortcomings, demonstrate that the topic of resource allocation mechanisms design has invaded research practice in the economic field. Current allocation procedures are no longer viewed as one of the "givens", thus new frontiers, questions and tools become apparent. The common denominator of these approaches is that mathematical programming techniques are now viewed according to their economic and managerial usefulness, not only on their mathematical tidiness. Furthermore, the motivational issues have also provided a strong argument in favor of informationally decentralized iterative procedures, so that local managers are incorporated into the decision making process.

A Strategic Allocation Model for a Forest Region or Corporation

The concepts and procedures presented above are now used to develop a resource allocation mechanism that appropriately addresses the policy and managerial issues raised by the practice of multiple-use forest planning.

The need for a hierarchy of control in large-scale systems has been recognized and illustrated a number of times and from different conceptual standpoints.

In multiple-use land management the need for this hierarchical approach seems to be unquestioned because of the technical, ecological and economic characteristics of the forest ecosystem production process.

On one hand, the complexity of the problem to solve is such that it is necessary to break it down, then solve each segment in a hierarchical way. On the other hand, we often have a requirement to address problems the way they are analyzed and solved within the organization's hierarchy.

The relevant questions are: how to define the levels of control within an organization; how many are necessary, and how are they linked. A proposition for spatial hierarchies - nation, region, forest, district- would be necessarily restrictive if a single planning horizon were attached to each level. Temporal hierarchy must also be defined at each level; at a national level, for example, budget allocations are conducted on a yearly basis, while another decision making process allocates long-term research and development projects.

Multi-level, multi-type decompositions of large-scale systems, formalized since the early 70's in systems engineering (Haimes, 1982), result in multifarious sub-systems that can be identified as being potentially viable or economically efficient (Beer, 1979).

The following description of a forest resource allocation process focuses on a short-run regional or corporate economy. Short-run is here understood as the period of time where major investments relevant to a regional or corporate level are assumed as given. Normally a period of five years is considered appropriate.

Inherent in the design of a resource allocation process is the problem of representing society's (or owner's) preferences among alternative states of the economy, so that the problem can be stated as finding the most preferred feasible state. Usually societal preferences for public forest management are vaguely presented with expressions as "maximum social benefit" or "maximum net public benefit" without explicitly mentioning, but relying upon, some measures of economic efficiency and equity. For private forest corporations the most preferred state is defined by terms such as "economic viability", or "maximum shareholders benefit".

For a meaningful construction of an objective function representing societal, or shareholders, preferences it is necessary to rely on the concept of tradeoffs between variables. The evaluation of these is greatly simplified if the objective function can be assumed to be additively separable, i.e. it can be represented in the form:

$$U(y) = \sum_{g=1}^{G} U(y_g) \qquad (4.1)$$

where U(y) is the total utility function and $U(y_g)$ is the separable utility of consuming the group of variables represented by $\mathbf{y}_g$.

At a corporate or regional level it is possible to assume that this assumption holds in multiple-use planning. The commodity bundle can be separated into groups of homogeneous commodities. This is facilitated if (i) variables are made explicit in the input/output decision space, and (ii) constraints, if any, on variables should be explicit. The effect of these conditions is to avoid hidden pre-allocations of resources, and the construction of variables with embedded, not recognizable and not available, constraints.

Paredes and Brodie (1988) demonstrate that when these conditions are met the objective function for the multiple-use forest model can be additively separated into different commodity groups:

$$U(\mathbf{y}) = U(\mathbf{y}_m) + U(\mathbf{y}_n) \qquad (4.2)$$

where $\mathbf{y}_m$ and $\mathbf{y}_n$ are, respectively, the vectors of market and nonmarket commodities. Since output levels for nonmarket goods are usually modeled as right-hand side allocations,

$$U(\mathbf{y}_n) = \boldsymbol{\mu}_n \cdot \mathbf{y}_n \qquad (4.3)$$

where μ_n is the vector of shadow prices associated with an allocation of $\mathbf{y}_n$.

Additionally, this modeling approach for a separable objective function satisfies the requirements for a homogeneous scaling among the groups of variables. It is known, from duality theory, that shadow prices in a general linear programming context, are expressed in the same measure units as the primal objective function, i.e.

$$\boldsymbol{\mu}_n = \delta U(\bullet)/\delta \mathbf{y} \qquad (4.4)$$

implies that the measure units of $\mu_n \cdot \mathbf{y}_n$ are consistent with those of $U(\mathbf{y}_m)$.

By expressing all valuation units in the allocation problem in terms of $U(\mathbf{y}_m)$, the units of measure for these become the numeraire of the process. Since a close approximation to social welfare is desired, the numeraire has to be chosen accordingly. The ideas presented in the previous section suggest that a desirable property would be a resemblance of the process in a competitive market.

At the same time it is convenient to recall here that one of the requisites forest managers and economists are recently requiring from an allocation mechanism, refers to its capability to account for cumulative effects across production units on a regional basis (Teeguarden, 1987).

Both requirements are implicitly satisfied by Samuelson's "net social payoff" concept to solve for multimarket equilibrium. Even though Samuelson (1952) did not imply any social welfare significance to the net social payoff magnitudes, it has been later demonstrated by Willig (1976) that the use of consumer's surplus magnitudes provides a good approximation to the appropriate welfare measures.

The use of net social payoff as the numeraire in the objective function at the regional level provides an interesting and, more important, implementable measure of social welfare to drive the allocation process.

Required elements for a net social payoff function are an inverse form of demand functions for each demand center in the region. These functions are econometrically or technically derived having the general form:

$$\mathbf{P}_c = \mathrm{D}_c(\mathbf{y}_c) \qquad (4.5)$$

where $\mathbf{P}_c$ is the per unit price paid at demand center c for commodity quantities traded at that location, $\mathbf{y}_c$.

The supply functions are provided either by parametric programming for those production units "controlled" by the process, as illustrated by Paredes and Brodie (1988) in a forest-level context, or by behavior simulation or econometric analysis for those units beyond the institutional limits. Typically a supply function will have the form:

$$\mathbf{P}_p = \mathrm{S}_p(\mathbf{y}_p) \qquad (4.6)$$

where $\mathbf{P}_p$ is the per-unit marginal cost of producing the set of commodities, at levels specified by $\mathbf{y}_p$, at the production unit p.

Commodity flows are modeled through specific variables y_{pc} describing the bundle of commodities flowing from production center p to market location c. The associated transportation costs are generally assumed linear and described through the coefficients t_{pc}.

The objective function then takes the form:

$$\max U = \sum_c \int_0^{u_c} D_c(\tau)\, d\tau_c = \sum_p \int_0^{w_p} S \qquad (4.7)$$

subject to

$$u_c \leq \sum_p y_{pc} \quad \text{for all c} \qquad (4.8)$$

$$w_p \geq \sum_c y_{pc} \quad \text{for all p} \qquad (4.9)$$

where equation 4.8 bounds the total amount demanded at the c-th market location, and equation 4.9 bounds the amount of commodity supplied at the production unit p. The τ's are dummy integration variables. Equation 4.7 accounts to the net social payoff as the consumers' surplus less producers' surplus and transportation costs.

An objective function formulated in this way, at a regional or corporate level, addresses a topic often neglected in forest planning models, accounting transportation costs as endogenous variables. This can provide an alternative to current timber valuation methods based on a stumpage concept. While the flat stumpage approach may be appropriate for small owners, it is necessarily restrictive in a forest/regional context where the definitive impact of the main cost item (hauling) is dependent on market location.

Similar functional forms for the objective have been previously used in forestry planning by Greber and Wisdom (1985), although they focus on interactions in roundwood markets only, and transportation costs are not endogenous to the model. A closer form has been utilized by Fowler and Nautiyal (1986) for land allocation to agricultural, timber, mining, urban and recreational uses.

The construction of an objective function which, at the regional (or corporate) level, approximates society's (or shareholders') preferences on economic welfare states, provides a solid base to decompose the planning procedure to lower hierarchical levels. This achieves Kantorovich's "system of information, accounting and economic indexes and stimuli" mechanisms which makes local managers to select socially (or corporate) optimal actions.

Production levels and flows are technically constrained by the system of equations relating outputs and inputs for each local production unit. The following equations describe, respectively, those constraints:

$$\mathbf{w}_p - \sum_p \mathbf{T}_p(\mathbf{x}_p) = \mathbf{0} \quad \text{for all p} \qquad (4.10)$$

$$\sum_p \mathbf{x}_p \leq \mathbf{b} \qquad (4.11)$$

where $\mathbf{T}_p(\mathbf{x}_p)$ is the production function at unit p that describes the technological relationships between inputs, $\mathbf{x}_p$, and outputs, $\mathbf{w}_p$. In a strict sense, equation 4.10 is redundant since the relevant information on output levels is already embedded in the objective function's term for the producer's surplus. Equation

4.10 is included here only for completeness when illustrating, later, the operational aspects of the model.

b represents the vector of initial resource endowments of the regional economy. It describes both the resource base of each production unit (land base and vegetation cover, for example) that can not be changed within the planning period, and the resources (public and private) available to the regional economy which will be consumed by the local units.

As described above, the model still does not provide an explicit treatment for production/consumption of those commodities that can not be treated with information provided by actual markets. The presence of externalities, the production impacts on public goods, and the effect of economies/diseconomies of scale are some of the "cumulative effects", as usually identified in recent forestry literature, that need to be explicitly accounted for.

These constraints are represented, generically, by the form

$$\sum_{p} g_p(w_p, x_p) \geq h \qquad (4.12)$$

where the function g(•) describes the technical relationships, linear or nonlinear, between market commodities/resources and the nonmarket ones. The vector **h** describes the levels requested for nonmarket commodities. The convention that goods are desirable is followed here.

It needs however be recalled that the **h**'s are still regarded as decision variables. The regional planning authority determines their optimal values trying to emulate a Lindahl equilibrium for public goods. This will be discussed later.

The problem is therefore to maximize (4.7) subject to equations (4.8) to (4.12) and the usual nonnegativity constraints of the arguments **x** and **w**.

A "one-pass" solution of the planning problem presented would be a formidable task. Each local unit would need to transfer to the center the information described by the $T_p(\bullet)$ and $g_p(\bullet)$ functions. Even if the model solves for short-run allocation and it has unlimited computing facility, the problems of transferring local expertise would render the "one-pass" approach impractical. Decentralization now comes to the rescue.

To understand the economics of the procedure, a characterization of optimality conditions is presented.

Simplifying notation let

$$R_c = \int_0^{u_c} D_c(\tau_c)d\tau_c, \qquad (4.13)$$

$$R_p = \int_0^{w_p} S_p(\tau_p)d\tau_p, \text{ and} \qquad (4.14)$$

Then the Lagrangian function associated with the problem can be written:

$$\begin{aligned} L = \sum_c R_c - \sum_p R_p - \sum_{pc} t_{pc} y_{pc} & \\ + \sum_c s_c[\sum_p y_{pc} - u_c] & \\ + \sum_p m_p[w_p - \sum_c y_{pc}] & \qquad (4.15) \\ + \pi [b - \sum_p x_p] & \\ + \theta [\sum_p g_p(w,x) - h] & \end{aligned}$$

where σ, μ, π, and θ are dual multipliers.

The Kuhn-Tucker conditions for optimality explain the economic rationale of the allocation process. At the demand centers, the total level of traded commodity, $\mathbf{u}_c$, satisfies the following conditions:

$$\begin{aligned} & \mathbf{u}_c \geq 0 \\ & \mathbf{m}_c - \sigma_c \leq 0 \\ & \mathbf{u}_c[\mathbf{m}_c - \sigma_c] = 0, \text{ for all c} \qquad (4.16) \end{aligned}$$

where $\mathbf{m}_c$ is the total consumers' willingness to pay for a consumption level $\mathbf{u}_c$ at demand center c, and σ_c is the imputed value of the commodity delivered at the demand center. These are usually called regional consumer equilibrium conditions and state that, for positive levels of consumption, the price paid at the market equals the imputed cost of producing the commodity and transporting it to market at c.

Transportation decisions, from production unit p to market c, satisfy:

$$\begin{aligned} & y_{pc} \geq 0 \\ & -t_{pc} + \sigma_c - \mu_p \leq 0 \\ & y_{pc}[-t_{pc} + \sigma_c - \mu_p] = 0, \text{ for all p, c} \qquad (4.17) \end{aligned}$$

These conditions regulate the flow of commodities across the region. They state that a commodity is hauled, $y_{pc} \geq 0$, if its transport cost, t_{pc}, does not exceed the price differential between its imputed values at production unit, μ_p, and at demand location, σ_c. These conditions are usually referred to as locational price equilibrium conditions.

The optimal production level at unit p, w_p is determined with the following conditions:

$$w_p \geq 0$$

$$-m_p + \mu_p + \theta \bullet \delta g_p(\bullet)/\delta w_p \leq 0$$

$$w_p[-m_p + \mu_p + \theta \bullet \delta g_p(\bullet)/\delta w_p] = 0, \text{ for all p} \quad (4.18)$$

where m_p is the marginal cost of the commodity at the production unit p, where m_p is evaluated with the technological constraint in equation 4.10. These are called the supplier's equilibrium conditions and state that a commodity is produced ($w_p > 0$) up to the level where its imputed value, m_p, equals the market value of the output, μ_p, at p, plus the value of its marginal impact in the production of non-market outputs, $\theta \bullet \delta g_p(\bullet)/\delta w_p$.

The optimal use of resources, x_p, is specified by:

$$x_p \geq 0$$

$$\mu_p \bullet \delta T_p(x_p)/\delta x_p + \theta \bullet \delta g_p(\bullet)/\delta x_p - \pi \leq 0$$

$$x_p[\mu_p \bullet \delta T_p(x_p)/\delta x_p + \theta \bullet \delta g_p(\bullet)/\delta x_p - \pi] = 0, \text{ for all p} \quad (4.19)$$

where π is the marginal value of production factors. These conditions state that resources are consumed up to the level where the marginal value of the resource is completely allocated among its marginal value impacts on the production of market, $\mu_p \bullet \delta T_p(x_p)/\delta x_p$, and non-market commodities, $\theta \bullet \delta g_p(\bullet)/\delta x_p$.

The following are the market prices equilibrium conditions. They regulate commodities and resources valuations to avoid excess demand or excess supply possibilities.

$$\sigma_c \geq 0, \sum_p y_{pc} - u_c \geq 0$$

$$\sigma_c[\sum_p y_{pc} - u_c] = 0, \text{ for all c} \quad (4.20)$$

$$\mu_p \geq 0, w_p - \sum_c y_{pc} \geq 0$$

$$\mu_p[w_p - \sum_c y_{pc}] = 0, \text{ for all p} \quad (4.21)$$

$$\pi \geq 0, \mathbf{b} - \sum_p x_p \geq 0$$

$$\pi[\mathbf{b} - \sum_p x_p] = 0, \quad (4.22)$$

$$\theta \geq 0, \sum_p g_p(w,x) - \mathbf{h} \geq 0$$

$$\theta[\sum_p g_p(w,x) - \mathbf{h}] = 0 \quad (4.23)$$

The conditions in 4.20 and 4.21 determine, respectively, the consumers' and producers' behavior when facing positive prices and excess supply or demand for their commodities.

Conditions specified in 4.22 determine the pricing rules for resources consumed in production. Conditions in 4.23 guide the units' decisions on expansion of the production level of non- market outputs according to the price offered by the center.

A local manager would seek to allocate his inputs, x_p, so as to maximize his total profits from market commodities, at prices μ_p, and those nonmarket commodities that the center regulates, at prices θ. Local managers solve the problem:

$$\underset{\{x_p, w_p\}}{\text{maximize}} \quad \mu_p w_p + \theta \bullet g_p(w_p, x_p) \quad (4.24)$$

subject to

$$w_p - \mathbf{T}_p(x_p) = 0 \quad (4.25)$$

$$x_p \leq b_p \quad (4.26)$$

$$x_p, w_p \geq 0$$

given μ_p, θ, and b_p

The corresponding Lagrangian to this problem is:

$$\mathbf{L}_p = \mu_p w_p + \theta \bullet g_p(w_p, x_p) - \phi_p \bullet [w_p - \mathbf{T}_p(x_p)] + \pi_p \bullet [b_p - x_p] \quad (4.27)$$

Conditions for an optimum to the local manager problem are given by:

$$w_p \geq 0, \ \mu_p + \theta \bullet g_p(w_p, x_p) - \phi_p \leq 0$$

$$w_p[\mu_p + \theta \bullet g_p(w_p, x_p) - \phi_p] = 0 \quad (4.28)$$

$$x_p \geq 0, \theta \bullet \delta g_p(\bullet)/\delta x_p + \phi_p \bullet \delta T_p(x_p)/\delta x_p - \pi \leq 0$$

$$x_p[\theta \bullet \delta g_p(\bullet)/\delta x_p + \phi_p \bullet \delta T_p(x_p)/\delta x_p - \pi] = 0 \quad (4.29)$$

According to the definitions given in the regional problem formulation ϕ_p is exactly equal to $\mathbf{m}_p$. Thus the optimality conditions for a local manager, in equations 4.28 and 4.29, are equivalent to those in 4.18 and 4.19 for the global regional problem.

This clearly shows that if the center have available the correct values for μ_p, for all p, and those for θ, then it could provide that information to the local managers and they would allocate resources and production in a socially optimal way. Alternatively, the center could set quotas on input or outputs for each firm following the ideas of Heal's quantity-guided procedure.

The regional or corporate manager's problem, after the firms have provided information on their output levels for market commodities, w_p, and their resources usage, x_p, can be stated as:

$$\max U = \sum_c R_c - \sum_c t_{pc} y_{pc} - m_p w_p - \pi \bullet [\sum_p x_p] + \theta \bullet [\sum_p g_p(w_p, x_p)] \quad (4.30)$$

subject to

$$u_c \leq \sum_p y_{pc}, \text{ for all c} \quad (4.31)$$

$$w_p \geq \sum_c y_{pc}, \text{ for all p} \quad (4.32)$$

where equation 4.30 describes the center allocating consumption of the private commodities to maximize the difference between consumers surplus, $\Sigma_c R_c$, plus the social value of the nonmarket commodities, $\theta \bullet [\Sigma_p g_p(w_p, x_p)]$, and the costs of transportation from production to consumption centers, $\Sigma_c t_{pc} y_{pc}$, plus production costs, $m_p w_p$, and the costs of resources utilized, $\pi \bullet [\Sigma_p x_p]$.

With optimality conditions given by:

$$y_{pc} \geq 0, -t_{pc} - \sigma_c + \mu_p \leq 0$$

$$y_{pc}[-t_{pc} - \sigma_c + \mu_p] = 0 \quad (4.33)$$

$$u_c \geq 0, m_c - \sigma_c \leq 0$$

$$u_c[m_c - \sigma_c] = 0 \quad (4.34)$$

which are equivalent to those given in 4.16 and 4.17 for the global problem.

As observed, the multiple-use forest planning problem for a regional (or corporate) economy is decomposable into decisions corresponding to a regional planning bureau and those associated with local unit managers. The language of the solution mechanism can incorporate either price or quota messages, or both. By letting each local manager adjust their input and output levels under his control according to the price messages received from the center the problem is solved as in the Lange-Arrow-Hurwicz routine described in the previous section. In this case the center would adjust its price messages proportionally to the excess demands at the commodities and resources markets. Such a routine is informationally efficient and results in Pareto-efficient allocations. However, a drawback in applying it is that the size of the problem would require to terminate the process after a finite number of iterations, possibly without ever reaching a feasible allocation.

Alternatively the problem can be solved with a price-guided routine where the center adjusts production quotas or resource consumption among local units according to their social marginal cost or to their value marginal product, respectively, as in Heal (1969). It can also be solved with a mixed price-quantity procedure as the one described by Heal (1971). These methods would guarantee a sequence of feasible solutions with a monotonically increasing value of the objective function.

The selection of an iterative procedure to solve for the corporate problem goes beyond the relevant scope of this analysis, even though it is being experimented in a forest corporation. The approach to planning process adopted here views it as a continuous decision making process that detects and evaluates environmental variations and, if necessary, adjusts actual operations to achieve the new equilibrium state. Therefore, each time the model is solved only a few iterations become necessary to reach the new optimum. This is the property called homeostasis that characterizes optimally designed systems (Arrow and Hurwicz, 1960; Beer, 1972). A huge planning effort undertaken periodically every five or ten years, as currently done in many forest institutions, is no longer necessary. The institutions need a permanently actualized model of the planning problem.

Nevertheless, computational efficiency considerations are still important for the set-up stage of such a planning procedure, particularly when current output levels and market values are distant from the equilibrium values.

The selection of an iteration routine for the planning model just presented must also consider explicitly the particular characteristics of the resources and the nonmarket commodities represented in **b** and **h**, respectively.

Some of the resources in **b** are inherent to each local unit, such as the land base or the capacity of the internal transportation infrastructure. The corporate authority would benefit from the knowledge of the associated social value of these resources, as reported by π_b, to allocate the regional budget on, for example, virtual expansions of the land base through coordination with state and private lands, or construction of transportation facilities.

Other elements in **b** describe regional or corporate resources that are allocated among competing units. The annual budget is the typical example. Budget allocations are easily handled by the central authority through a quota mechanism where budgets are adjusted according to its relative social marginal productivity in each local unit. Thus each unit is required to inform its budget requirement as well as the marginal productivity of this input.

Further, some resources in **b** have the characteristics of public goods, from a local manager standpoint. The corporate manager supplies the commodity up to the level where its marginal social cost equals the sum, over all local units, of its marginal productivity effect on the market goods, $\delta T(\bullet)/\delta b$, times the marginal social value, μ_p, of the firm's output. In other words, the social value of an increment in supply of the public commodity equals the sum, over all firms, of its opportunity values if these are evaluated at shadow prices. This is clearly the case of budget allocations to fire prevention and protection systems, pest control, and research and development programs. At equilibrium for these commodities it is observed that the amount of the good demanded from each unit equals the amount supplied and, simultaneously, the marginal cost of supplying it equals the sum **b**, over firms, of its marginal value.

For the nonmarket commodities accounted for in **h** the corporate manager does not have available an exact estimate of the society's (shareholders') willingness-to-pay curve, but only a crude estimate for the range of such values. Many of these commodities are typically public goods in the classical sense: protection of endangered species, ecosystem preservation, habitat diversity. In these cases the corporate manager should price commodities such that the accumulated reactions of all firms result in an output level with opportunity cost equal to the total society's willingness-to-pay. Here the role of the center is to achieve, through a pricing mechanism, an output level that is politically acceptable to society.

At any instant the local units allocate their resources and scheduled their outputs mix and levels such that they maximize revenues. If the prices, set by the center for the nonmarket commodities, are socially correct, then the firms will automatically allocate at the optimum for the whole economy.

Discussion

The last three sections have illustrated, respectively, the current approaches to forest planning and their shortcomings, the recent developments in the theory of economic analysis and management, and a design of a resource allocation model for multiple-use forest planning at the regional level.

The current situation in forest planning has been often characterized as rather confusing. National societies all over the world claim for multiple-use management of the forest resource, yet forest economists and planning specialists fail to provide a unified framework and the tools for the public and private agencies to conceal such a managerial concept with the requirements of economic efficiency.

Resolution of the conflicts raised by competing uses of the forest land require the design of resource allocation mechanisms that provide managers and interest groups with a tidy and consistent picture of the values associated to each allocation option. As a public manager once stated with respect to legislation and economics: "We need more one-armed economists who won't be able to say, 'but, on the other hand'..." (cited by Miles, 1986, p46).

The developments in economic analysis (Hurwicz, 1972) and the findings of managerial cybernetics (Beer, 1972, 1979) during the last decades provide the tools required to address the complex issues of multiple-use forest management that past and current reliance on both orthodox planning concepts and generic mathematical programming tools have failed to solve.

The computing power recently made available to the planning bureaucracy has translated into modeling approaches that, through a single-level large-scale mathematical model, attempt to solve for all possible decisions at once. The inappropriateness of such an approach has been clearly revealed through both its lack of responsiveness to managerial requirements at each decision level of the management hierarchy, and its failure to address key policy issues of forest planning.

The last section has illustrated that a hierarchical decision model, together with the concept of planning as a continuous process, permits one to reduce model size at each decision level and to incorporate explicitly those forest policy issues otherwise ignored.

The notion of "net public benefit" is provided with a concrete and measurable indicator, the net social payoff. Also decision on nonmarket, public commodities are made on the basis of the same numeraire.

By partitioning the allocation problem among hierarchical decision levels local managers are provided with a pricing mechanism that permits them to allocate resources under classical rules of economic efficiency.

Furthermore, the center is also provided with the tools to evaluate and control the managerial performance of local managers.

A further advantage of the model discussed is that decisions on the key issues, related to consumption or production of nonmarket and public commodities, are left to the corporate planning authority where both the capability to handle econometric estimates and the comprehensiveness of public issues are expected to be higher. Centralized decision on these issues releases local managers from the pressure of interest groups and diminishes the need for subjective allocations.

One of the key aspects of the planning procedure presented here is the iteration routine. This is currently being experimented, for a private corporation, in a search that looks for feasible solutions at any stage, quick convergence and minimum information transfers between corporate and local levels

Literature Cited

Aoki, M. 1971. An investment planning process for an economy with increasing returns. Rev. of Econ. Studies 38:273-280.

Arrow, K.J. and L. Hurwicz. 1960. Decentralization and computation in resource allocation. pp. 34-104. In Essays in Economics and Econometrics, R. W. Pfouts, Ed. The U of North Carolina Press, Chapel Hill.

Beer, S. 1972. Brain of the Firm. Allen Lane.

Beer, S. 1979. The Heart of the Enterprise. Wiley, Oxford. 582 p.

Berck, P. and T. BIBLE. 1984. Solving and interpreting large-scale harvest scheduling problems by duality and decomposition. Forest Sci 30:173-182.

Beuter, J.H. 1985. Federal timber sales. Congressional Research Service, 85-96 ENR, Washington DC. 140 p.

Binkley, C. S. 1987. The cost and benefits of a forest planning model: Discussant's comments. pp. 100-104. In FORPLAN and evaluation of a forest planning tool. USDA Forest Service Gen Tech Rep RM-140.

Caswell, W. M. and A. Rao. 1974. A practical approach to the large-scale forest scheduling problem, Decision Sci 5:364- 373.

Dykstra, D. P. 1987. Evaluation of FORPLAN from an operations research perspective: Discussant's comments. pp. 145-146. In FORPLAN and evaluation of a forest planning tool. USDA Forest Service Gen Tech Rep RM-140.

Ericksson, L. O. 1983. Column generation applied to long range forestry planning models. Swedish Univ of Agricultural Sciences. Dpt. of Operational Efficiency. Rep N. 115, 38 p.

Fowler, K. S. and J. C. Nautiyal. 1986. A model for land use planning. TIMS Studies in the Management Sciences 21:257-267.

Greber, B. and H. Wisdom. 1985. A timber market model for analyzing product interdependencies. Forest Sci 31:164-179.

Haimes, Y. Y. 1982. Modeling of large scale systems in a hierarchical-multiobjective framework. Studies in Management Science and Systems 7:1-17.

Heal, G. M. 1969. Planning without prices. Rev. of Econ. Studies 36:346-362.

Heal, G. M. 1971. Planning, prices and increasing returns. Rev of Econ Studies 38:281-294.

Heal, G. M. 1973. The Theory of Economic Planning. North Holland-Elsevier. 409 p.

Hof, J. G. and J. B. Pickens. 1987. A pragmatic multilevel approach to large-scale renewable resource optimization: A test case. Natural Res Modeling 1:245-264.

Hoganson, H.M. and D.W. Rose. 1984. A simulation approach for optimal timber management scheduling. Forest Sci 30:220-238.

Hrubes, R. J., D. I. Navon, G. Veiga and A. Weintraub. 1987. Lowering forest planning costs through LP column aggregation: How great is the associated opportunity loss? pp. 20-28. In The 1985 Symposium on System Analysis in Forest Resources. P. Dress and R. Field, Eds. Georgia Center Cont. Ed., Athens.

Hurwicz, L. 1973. The design of mechanisms for resource allocation. Am Ec Rev 63(2):1-30.

Johnson, K.N. and H.L. Scheurman. 1977. Techniques for prescribing optimal timber harvest and investment under different objectives: Discussion and synthesis. Forest Sci Monograph 18. 31 p.

Kantorovich, L. V. 1976. Mathematics in economics: Achievements, difficulties, perspectives. Mathematical Programming 11:204-211.

Kirby, M. W. 1973. An example of optimal planning for forest roads and projects. In: Planning and Decisionmaking as Applied to Forest harvesting. J. O'Leary (Ed). Forest Res Lab, Oregon State University. 75-83.

Kirby, M.W., P. Wong, W.A. Hager and M.E. Huddleston. 1986. Guide to the Integrated Resource Planning Model. USDA Forest Serv. Berkeley CA. 212 p.

Koopmans, T.C.(ed). 1951. Activity analysis of production and allocation. Cowles Commission Monograph No.13. John Wiley & Sons, NY. 404 p.

Kornai, J. 1967. Mathematical programming of long-term plans in Hungary. pp. 211-231. In Activity Analysis in the Theory of Growth and Planning, E. Malinvaud and M. O. Bacharach, Ed. St. Martin's Press.

Kornai, J. and T. Liptak. 1965. Two-level planning. Econometrica 33:141-168.

Lange, O. On the Economic Theory of Socialism. Rev. of Econ. Studies. 4:53-71, 123-142.

Lee, S. M. and B. H. Rho. 1979. The modified Kornai-Liptak decomposition algorithm. Comp. and Ops Res 6:39-45.

Liittschwager, J. M. and T. H. Tcheng. 1967. Solution of a large-scale scheduling problem by linear programming decomposition. J of Forestry 65:644-646.

Malinvaud, E. 1967. Decentralized procedures for planning. In Activity Analysis in the Theory of Growth and Planning, E. Malinvaud and M. O. Bacharach, Ed. St. Martin's Press.

Marschak, T. 1959. Centralization and decentralization in economic organizations. Econometrica 27:399-430.

Miles, J. 1986. The shifting political environment. College of Forestry, Oregon State University. The 1986 Starker Lectures. pp.39-49.

Mitchell, T. R., D. Anderson and S. P. Mealey. 1987. A multistage approach to forest planning. In The 1985 Symposium on System Analysis in Forest Resources. P. Dress and R. Field, Eds. Georgia Center Cont. Ed., Athens.

Mount, F. and S. Reiter, 1974. The Informational size of the message spaces. J. Econ. Theory 8:161-192.

Navon, D.I. 1971. Timber RAM: a long range planning method for commercial timber lands under multiple use management. USDA Forest Serv. Res. Pap. PSW-70, 22 p.

Navon, D. and A. Weintraub. 1986. Operational model of supply for wildland enterprises. TIMS Studies in the Management Sciences 21:353-370.

Nazareth, L. 1980. A land management model using Dantzig- Wolfe decomposition. Management Sci 26:510-523.

Paredes, G. and J. D. Brodie. 1988. Activity analysis in forest planning. Forest Science 34:3-18

Reed, W. 1986. Optimal harvesting models in forest management - A survey. Natural Res. Modeling 1(1):55-79.

Reed, W. and D. Errico. 1986. A new look at whole-forest modeling. Natural Resources Modelling.

Samuelson, P. 1952. Spatial price equilibrium and linear programming. Am Ec Review 42:283-303.

Teeguarden, D. E. 1987. The Committee of Scientists perspective on the Analytical requirements for forest planning. In FORPLAN and evaluation of a forest planning tool. USDA Forest Service Gen Tech Rep RM-140.

Weintraub, A. and D. Navon. 1976. A forest management planning model integrating silvicultural and transportation activities. Management Sci. 22:1299-1309.

Weintraub, A.,S. Guitart and V. Kohn. 1986. Strategic planning in forest industries. European J. of Op. Res. 24:152- 162.

Weitzman, M. 1970. Iterative multi-level planning with production targets. Econometrica 38:50-65.

Williams, D.H. 1976. Integrating stand and forest models for decision analysis. Unpubl PhD diss, Univ British Columbia. 230 p.

Willig, R. D. 1976. Consumer's surplus without apology. Am Ec Review 66:589-597.

Comments on "Design of a Resource Allocation Mechanism for Multiple Use Forest Planning"

Author: Gonzalo Paredes

Discussant: B. Bruce Bare

This excellent paper describes a theoretical, two-level, deterministic, hierarchical, iterative resource allocation framework based on duality information that can be used for coordinating economically-based multiple use planning. The model is proposed for use by those organizations where economic efficiency is the objective of management. Both market and non-market outputs are included in the theoretical model structure.

The paper begins with a brief criticism of current multiple use planning efforts. These are identified as: (1) lack of use of economic information provided by the mathematical model, (2) lack of linkage between stand-level and forest-level analyses, (3) development of single, large-scale models that fail to exploit the special structure of the planning environment, and (4) failure to recognize the hierarchical nature of the decision process. Following this, the paper reviews the essential characteristics of multiple use planning and how economic theory proposes to address such problems. The last section of the paper presents a framework for utilizing this theory in a forest planning context.

Multiple use planning is seen as a complex and large-scale task which must simultaneously consider spatial and temporal relationships; externalities of timber production and vegetation manipulation; production of non-market goods; and linkages with various administrative levels of the organization. The general approach to this problem has been to break it down into a series of smaller modelling projects. A brief review of how the time and space dimensions have been treated is presented. It is pointed out that most all approaches have used a single optimization technique and have viewed planning as a single-level exercise. Only recently has the idea of partitioning the planning process been recognized. And, few examples of such an approach can be found in the literature. Those that are reviewed are non-iterative in nature and involve coordination between a two-level hierarchy. The driving concern in the approaches presented has been to search for a computationally feasible method to solve the large-scale problem. And, reliance has been placed on a single mathematical programming method with a single objective function.

The author advocates that planning be viewed as a continuous and recursive process. This, therefore, dictates that planning models be arranged in a hierarchy such that each model only include factors absolutely necessary for planning at each level of the organization.

The author reviews two economic theories useful for forest planning: (1) price-guided and (2) quantity-guided procedures. While mathematically equivalent, informational requirements differ. Both approaches result in mathematical programming models which seek to maximize a utility function subject to non-linear constraints. In either case, the model is solved by decomposition into a two-level set of linked submodels. Price-guided procedures assume a central authority quoting prices for an initial allocation of each output. These prices are then acted upon by the firms at the second level of the hierarchy who independently adjust their outputs in return. Output levels with their accompanying shadow prices feedback to the central authority where prices are again adjusted and another iteration of the planning loop begins. Under a very strict set of assumptions, this process reaches an efficient equilibrium. A draw back is that until the final iteration, no feasible allocation may be available. Quantity-guided procedures have the central authority set initial feasible resource input targets for each firm. Based upon each firm's input/output productivity, certain outputs are produced, and marginal rates of physical productivity are linked back to the central authority. There, marginal rates of social value are used to re-allocate input resources to the firms for a another iteration. One advantage of the quantity-guided approach is that a feasible allocation is available whenever the iterative process is terminated. Other advantages and disadvantages of both general approaches are discussed.

A theoretical prototype multiple use planning framework is next described. The model is sufficiently general to permit either price or quantity-guided allocation schemes. It envisions a regional authority at one level and a series of independent local managers at the second level operating over a five year planning horizon. No algorithm is suggested for solving this large-scale resource allocation problem, nor are any numerical results presented. The paper closes with a discussion of the pros and cons of the proposed framework. One of the advantages cited is that decisions related to non-market goods are treated only at the regional level, thus freeing local managers from making subjective allocations.

With reference to the five features listed earlier in my general comments, it appears that the proposed framework possesses some, but not all, of the desired characteristics. The framework recognizes multiple decision makers, but assumes that their goals and objectives can be expressed in a single utility function. Thus, the explicit treatment of multiple objectives is not achieved in this approach. The framework does a good job of addressing the need for a dynamic and recursive planning system. Planning is viewed (at least conceptually) as a continuous process and a formal set of feedback procedures are built into the structure of the framework. Missing from the proposed approach is any recognition of risk and uncertainty. It must also be pointed out that by relying entirely on economic efficiency as the guiding resource allocation criterion, distributional and/or politically motivated concerns may arise. And, it is doubtful if the proposed framework is capable of being responsive to such concerns.

Hierarchical Planning Processes in Forestry: A Stochastic Programming - Decision Analytic Perspective

E.A. Gunn

Department of Industrial Engineering, Technical University of Nova Scotia

Abstract

This paper considers forest management planning as a hierarchical process with attention paid to tactical level models such as FORPLAN. The paper examines how the forest planner should understand the model outputs in light of the uncertainties in growth and the potential for destruction by insects, disease and/or fire. By looking at the problem as a stochastic programming problem, it seems clear that issues of data accuracy are less important than the planning process used. Some computational experiments illustrate this observation. We close by discussing a structure for a family of tactical models.

Introduction

The concept of hierarchical production planning emerged in the mid 1970's in recognition of the fact the complexity of large organizations and the uncertainty of the planning environment necessitated a multi-level approach to problem solving. Such an approach was designed to address explicitly the hierarchy of management decisions that characterize large organizations. This approach was also designed with an explicit recognition that much of the problem data is uncertain and that only for near term problems was the data accurate enough to justify its use in detailed planning. Since then an extensive literature on hierarchical planning has developed. A bibliography by Bukh (1991) lists 183 papers or other documents related to hierarchical planning published between 1974 and 1981. The year 1974 can be seen as the beginning of hierarchical planning since the seminal papers of Hax and Meal and Jaikumar date from this time. Interestingly, none of the papers cited by Bukh deal with forest management.

Recently, hierarchical planning has seen important application in forest management. To date it seems that much of the work on hierarchical planning in forestry has focussed on the use of a family of models as a means of avoiding the computational effort of a single large model. The main concern seems to be whether or not the hierarchical approach is "accurate" in the sense that the solution achieved through the hierarchical family is the same, either in policy or in objective value, as the solution achieved from a single large model. The recent paper by Weintraub and Cholacky (1991), which presents an important example of the hierarchical structuring of a forest management problem, focusses to a large extent on this question of accuracy. This viewpoint on hierarchical planning is similar to the concerns found in the literature on aggregation and dissaggregation.

We would like to emphasize a different aspect of hierarchical planning in this paper. We want to focus on the decision process itself. From the point of view of aggregation/dissaggregation, there is a large complex model to be solved, a model so large that it cannot be solved directly, but rather requires the decomposition embodied in the hierarchical approach. Our viewpoint is different. The forest management problem, at almost any level of aggregation and time scale, is fundamentally uncertain. Some of this uncertainty is uncertainty in growth and yield. This can be due to a fundamental lack of data on land capability, stocking, dbh and height growth, species distribution and many other factors. It can also be due to the influence of disease, insects, weather, airborne pollution, wind storms and/or fire to name but a few. Additionally there is price uncertainty as well as uncertainty in the technology of the wood using sector to consider. In the face of this uncertainty, it is inconceivable that any plan can actually be implemented in its entirety over the planning horizon for which the plan was developed.

Gordon Baskerville has remarked that "forest management is a control problem, not an optimization problem". Just as a governor on a lawn mower adapts to the load it encounters, forest management policy should be formulated with fairly explicit plans to adapt the policy as uncertain events occur. This is not to say that there should be no optimization. In fact we shall argue that hierarchical planning provides the right concept for optimal control of the forest system if the hierarchical planning system is implemented properly. Control of a system depends on observation of the current state of the system and correction of the control process. Thus, control of a system depends on the flow of information, particularly the feedback loops built into this information flow. We shall argue that one key element for the design of a hierarchical planning system is attention to the information flow and feedback in this system.

In Gunn (1991), the four main aspects which characterize hierarchical planning were given as i) the use of separate models for each hierarchical level, ii) the rolling planning horizon implementation of model solutions, iii) the recognition of uncertainty and iv) the mirroring of corporate organizational structure. In what follows, we will try to examine how these notions apply in forest management models.

A Hierarchy of Forest Planning

In a hierarchical approach to forest management, we try to address three issues. The first is the identification of appropriate levels and the decision problems that need to be addressed at each level. The second is discussion of the aggregation at each level and the information feedforward/feedback. The third will be the treatment of uncertainty. This last issue will be our main concern here.

For the purposes of this paper we will focus on the tactical level. There are three reasons for this. Firstly we shall argue that the major modelling efforts, embodied in such packages as FORPLAN, TimberRAM etc. have been aimed at tactical planning. Secondly, tactical models are often used at the strategic decision level as simulation devices. Thirdly, the operational level tends to be highly specialized to the local environment so that the types of models appropriate at this level are not completely clear.

Before turning our attention to the tactical models, it is perhaps worthwhile to indicate how these problems fall within the Anthony's strategic, tactical and operational framework. Briefly these can be defined as:

i) *Strategic Decisions*: Defining the role and nature of the enterprise and the resources that the enterprise will have available to it.
ii) *Tactical Planning*: Making the most effective use of the resources available to the enterprise
iii) *Operational Control*: Detailed scheduling of weekly and shift level activities to make the system function.

Strategic Level

If we adopt as our framework a firm that owns its own land outright or holds it under long term lease, then the strategic decisions include how much land to operate for forestry purposes and the production capacity of the various segments of the enterprise. The latter would include the number, type and capacity of sawmills, pulpmills, and facilities requiring wood fiber. Other strategic decisions might include investments in harvesting systems, transport systems, and processing machinery and the decision to sign long term contracts. At a governmental level, the design of the regulatory environment is also strategic.

Strategic decisions are not always made purely on "economic" terms. In many cases they involve an expression of will on how the enterprise wishes to define itself. Interestingly, the Swedish approach to forest involves just such a strategic approach (see Hägglund). Few models have evolved that directly address strategic problems of forestry. In general we see evidence of tactical models being used to simulate the effects of strategic alternatives.

Tactical Level

Forestry presents an interesting case in that some of the tactical problems are of such long term that they almost beg to be treated as a strategic. For example, we have the harvest scheduling problem addressed by the linear programming packages such as FORPLAN, MUSYC, and TimberRAM. In spite of its very long time horizon, the nature of the problem appears to be tactical; namely how to schedule harvesting and silvicultural activities for an existing land base over time.

Tactical problems in industrial forestry have at least three aspects. The first is guaranteeing the long term supply to the wood consuming industry while maximizing expected profits. This supply problem requires an attention to not only the gross timber harvest at any point in time but its division into appropriate timber classes (softwood and hardwood;veneer logs, sawlogs, pulpwood). The second involves stand level harvesting issues. These involve developing a plan for harvesting and silviculture treatments specific to the site capabilities and species of the various stands in a district or some smaller management region. Issues, such as adjacency and/or road building, may also need to be considered. The third is the problem of annual wood logistics. At this stage growth is not an issue. The problem is to decide where to harvest and on the allocation of the harvested timber types to mills so as to maximize profit (gross revenues minus harvesting transportation and other procurement costs). Issues of available work force and machinery as well as mill production schedules, seasonality in markets and management of finished product inventory may well enter here. The outcome of the annual aggregate plan is usually an annual or longer term budget.

Much of the current usage of FORPLAN and other such packages have been for tactical problems with significant constraints not mentioned above. These have included stringent definitions of sustainability as well as specific concerns as to wildlife habitat and preservation of ecological niches. It is important to recognize that these constraints constitute strategic decisions of the forest enterprise or of the larger society within which the enterprise exists. Tactical level models do not have normative capability for these strategic decisions. Tactical level models do provide the ability to evaluate (simulate) the consequences of these decisions in terms of the tactical level objectives.

Operational Level

Within forestry, operational decisions typically constitute the weekly and shorter term decisions that are required to implement the first period of the current tactical plan. These include project management and scheduling decisions such as scheduling cutting crews and machines to stands,maintenance scheduling, truck allocation and scheduling, mill production schedules and specification of wood mix, sawing optimization and others. The primary goals are feasibility and cost minimization. Note that the operational planning does play a role in the tactical plans in that failure to find a feasible operational plan within the tactical constraints must feed back to modify the tactical plan .

Modelling for Tactical Planning

Tactical models for forest management have, for some time now, been formulated as linear programming models. Before this discussion let us outline a somewhat abstract version of these LP problems:

$$\textit{Maximize:} \quad \sum_{t=1,T} e^{-rt} \sum_{z=1,Z} R_{zt}(x_z, h_z)$$

Subject to :

$$x_z = G_z(h_z), \qquad z = 1,Z \qquad (1)$$

$$(x_z, h_z) \in \mathbf{F}_z, \qquad z = 1,Z \qquad (2)$$

$$\sum_{z=1,Z} \mathbf{H}_{zt}(x_z, h_z) \in \mathbf{H}_t \qquad t = 1,T \qquad (3)$$

where :

- T is the time horizon, the number of time periods.
- Z is the number of management zones .
- h_z is a vector of decision variables indicating harvest policy on zone z. Usually h_z will have dimensions depending on the number of time periods and age classes.
- x_z is a vector of state variables of timber amounts over time on zone z. Usually x_z will have dimensions depending on the number of time periods and age classes.
- $R_{zt}(x_z,h_z)$ is a function giving expected revenue in period t, zone z for the decision process h_z and the state process x_z
- $G_z(h_z)$ is a function relating the state process for zone z to the choice of the harvest process h_z
- $H_{zt}(h_z)$ is a function giving the wood volumes from zone z generated in period t by using harvest policy h_z
- $\mathbf{F}_z$ is the set of feasible harvest, state processes for zone z
- $\mathbf{H}_t$ is the set of feasible timber harvest volumes for period t

This structure portrays the forest harvest scheduling problem as involving harvest decisions over a number of independent management zones z=1,Z. The objective is to maximize discounted net present value of revenues with the only linkage being the Harvest Constraints (3). Without this linkage, then the solution to this model would correspond to "Faustmann-like" harvest policies on each zone.

There are a number of questions that are often raised with regard to these models. We argue that much of the confusion is a result of not considering the particular tactical planning role. These questions include i) model type, ii) stand vs. region based models, iii) time horizon and time divisions, iv) flow constraints and v) attitude to uncertainty.

Model Type

This refers to the modelling of the growth and harvest process on each zone (equations 2,3 above) Two dominant models, Model I and Model II, of the growth/harvest process have emerged. These were first discussed by Johnson and Scheurman (1977). Model I consists of enumerating a number of possible schedules for a given land unit with the decision variables consisting of an assignment (or partial assignment) of the land unit to the harvest schedule. Model II consists of specifying a network of possibilities where each arc corresponds to the assignment of the land unit to a particular treatment/harvest strategy only until the next regeneration process. Although equivalent flexibility in harvest schedules can be represented with a much smaller number of decision variables using a Model II representation, Model II requires a more extensive constraint structure than the equivalent Model I. A third model, which we will refer to as Model III, has been developed simultaneously by Garcia (1984), Reed and Errico (1986) and Gunn and Rai (see Rai, 1984) and is similiar in intent to Model II formulations.

Stand Based versus Region Based Models

The question here is what do we mean by the "zones" in our LP model. Jamnick et al. (1990) have recently explored the accuracy of stand based versus region based models. For stand based models, the forest is represented on a stand basis. A stand is usually thought of as a unit of land with a homogenous mix of species, age class and homogenous growing conditions (soil, drainage, etc.). Stands are the natural unit for forest treatments since it only possible to forecast response with a knowledge of the stand composition and site capability. On the other hand, it requires an enormous number of stands to represent the landholdings of any large scale forest enterprise.

Another option is to aggregate landholdings on the basis of such factors as geography, ownership, covertype and site type and try to predict the growth and silviculture response of this aggregate. Jamnick et al. have shown that this may well underestimate the performance achievable with a stand based model. However, for overall enterprise planning, even a region based representation leads to large models.

Time Horizon and Time Divisions

The proper choice of the time horizon T and time divisions t must be addressed. Long horizons are required to ensure long term feasibility of the wood supply and to properly take into account future costs imposed by current decisions. Small time divisions are useful to properly account for growth and the overall wood supply dynamics. However, long time horizons and small time divisions imply enormous models. Compromises inevitably have to be made.

Flow Constraints

In Ware and Clutter (1971), it was made clear that without some type of harvest flow constraints(3), the harvest becomes extremely erratic and incompatible with the normal operation of a wood processing industry. Two types of constraints are often used. One is even flow where the requirement is that the harvest volume in period t should be equal to (within a tolerance of) the harvest in period t-1. A second type is non-declining yield where the constraints (3) require that the harvest in year t is greater than in year t-1. Both of these have the difficulty that harvest is itself a multidimensional quantity. There are issues of commodity classes of the timber produced, for example veneer logs, sawlogs, pulpwood. Also, it is not clear how best to measure harvest (volume, area harvested, revenue).

Both the even flow and non-declining yield constraints have little meaning in terms of the operation of an enterprise. Second, they are known to produce unstable and paradoxical effects when implemented in a rolling planning framework (see Daugherty and Pickens et.al.) Barros and Weintraub (1982) and Gunn and Rai(1987) have discussed situations where there are issues of substitution and complementary production. Sawlogs can be substituted for pulpwood. Also, sawlogs, when processed, result in chips which can serve as inputs to the pulpmill. In both of these papers, we see the use of capacity based constraints as flow constraints. The Gunn and Rai formulation of this model is reproduced in Appendix 1 to illustrate this type of modelling.

Uncertainty

The LP models do not explicitly account for uncertainty. There are however a number of implicit ways of doing so. Discount rates higher that nominal interest can be used (see Bussey, 1980). Many modellers will downgrade growth estimates as a hedge against events such as fire or budworm. In other industries, notably the electric power industry, one often sees the use of a reserve margin on system demand used as a mechanism for dealing with uncertainty. However, unless the harvest flow constraints are similar to the capacity based constraints of Gunn and Rai (1987) and Barros and Weintraub (1982), reserve margins on system demand constraints are not possible.

A point that we will focus on in this paper is that using the model in a rolling horizon framework amounts to taking advantage of the recourse possibilities to uncertain events.

Hierarchical Planning and Uncertainty

The key modelling framework for the tactical models in the forest management planning hierarchy are linear programming models. This raises a question since linear programming models assume that all the data is known with certainty.

Forestry planning problems are fundamentally uncertain. The growth and yield tables cannot be known precisely. Events such as fire, insect infestation, disease, or wind throw are fundamental uncertainties that occur over the planning horizon of most forest management models. Economic factors such as price inflation (deflation) and exchange rate uncertainties compound the problem.

There has been a considerable body of work in the area of forest management under uncertainty beginning with the work of Lembersky and Johnson (1975). However, this work has focussed exclusively on the single stand management problem. The solution methodology has been that of dynamic programming.

If we look at the model (1)-(3) and apply the decision framework that we find in dynamic programming, then the problem that results can be written, again abstractly, as:

$$Max \left\{ R_0(x_0,h_0) + e^{-r} E\xi\, G_1(x_1);\, h_0 \in \mathbf{H}(x_0) \right\} \quad (4)$$

where :

$$x_{t+1} = \gamma\,(x_t, h_t, \xi_t(x_t)) \quad (5)$$

$$G_t(x_t) = \text{Max}\,\{\, R_t(x_t, h_t) + e^{-r}\, E_\xi G_{t+1}(x_{t+1});\; h_t \in \mathbf{H}(x_t) \,\} \quad (6)$$

and:

$G(x_t)$	- is the dynamic optimal value function for starting period t in state x_t
x_t	- state of the forest enterprise at the beginning of period t
ht	- management or harvest action in period t
$\xi_t(x_t)$	- stochastic process conditional on x_t
r	- discount rate
$R_t(x_t,h_t)$	- return in period t if we begin in state x_t and follow management action h_t
$H(x_t)$	- the set of feasible management actions given the forest state x_t.
$\gamma(x_t,h_t,x_t)$	- a function giving the end of period forest state given the initial state x_t, the management action ht and the realization x_t from the stochastic process

The decision framework of (4)-(6) above is that of stochastic programming with recourse. This problem statement is that of taking a decision today that maximizes the expected net present value of all future returns. Note that the possibility of disaster is not excluded in the above model. That is, it is possible, given a sequence of decisions h_0, ... h_{t-1} and outcomes $\xi_0(x_0)$ ...$\xi_{t-1}(x_{t-1})$, that we come to a point where the function $R_t(x_t, h_t) = -\infty$ for all $h_t \in \mathbf{H}(x_t)$ or where $\mathbf{H}(x_t)$ is empty. This corresponds to there being no feasible way to supply the industry needs in period t. In that case $G_t(x_t) = -\infty$. Note finally that there is no particular requirement that T be finite. However it is well known that, depending on the discount rate r, we can approximate the optimal decision h_0^* by using only a finite number of time periods.

It is important to note the decision and information structure of the problem. First the only decision that one takes with certainty is the current decision h_0. All future decisions h_t depend on the the state variable x_t which in turn depends on the conditional random process ξ. Second, the essential feature of the problem is recourse. One does not take the decision h_t at time 0, but only at time t with full knowledge as to the state x_t and the ability to exploit the action space $\mathbf{H}(x_t)$ to optimize current returns and expected future returns.

If we rewrite the usual harvest scheduling linear programming problem (1)-(3) using a similar notation to (4)-(6), the problem can be written:

$$\text{Maximize } G_0 \quad (7)$$

Subject to:

$$\begin{aligned} G_0 &= R_0(x_0, h_0) + e^{-r} G_1 \\ G_t &= R_t(x_t, h_t) + e^{-r} G_{t+1} \qquad t = 1, T-1 \qquad (8) \\ G_T &= R_T(x_T, h_T) \end{aligned}$$

$$\begin{aligned} x_1 &= \gamma\,(x_1, h_1, \bar{\xi}_1) \\ x_{t+1} &= \gamma\,(x_t, h_t, \bar{\xi}_t) \qquad t = 1, T-2 \qquad (9) \\ x_T &= \gamma(x_{T-1}, h_{T-1}, \bar{\xi}_{T-1}) \end{aligned}$$

$$\begin{aligned} h_0 &\in \mathbf{H}(x_0) \\ h_t &\in \mathbf{H}(x_t) \qquad t = 1, T \qquad (10) \end{aligned}$$

The notation corresponds to (4-6), with the assumption that $R_t(x_t, h_t)$ and $\gamma(x_t, h_t, \bar{\xi}_t)$ are linear functions and the sets $\mathbf{H}(x_t)$ are described by linear constraints. The $\bar{\xi}_t$ is the "average value" of the process ξ. Note that, in general, it is not clear what this "average" means since the actual process ξ_t is conditional upon x_t.

Note the differences between problem (7)-(10) compared to (4)-(6) First the decision structure is different. The decisions h_0, ..., h_T are taken at t=0 once for all time. Furthermore these decisions h_t are taken not with perfect knowledge of a state x_t, but with respect to some "average" state that results from the "averaged process". There is no possibility of recourse if the outcome of the stochastic process is either below or above the "average". Note also that there is little sense to the notion of implementing this "average optimal" decision since the average process is never experienced.

If stochastic programming is the correct decision framework, where does this leave us. Direct solution using dynamic programming of the model (4)-(6) is obviously impossible for problems involving the number of stands required to represent a typical tactical model. Another approach is that of stochastic linear programming. Gassman (1989) has illustrated an application of these ideas to examine the effect of fire. The problem with this approach is that its computational requirements grow dramatically with the number of possible realizations from the stochastic process. In any realistic tactical model there will be a many possible realizations for each stand and when one considers all the stands simultaneously this means that there will be an enormous number of possible realizations in the joint process. This tends to mean that only highly simplified situations can be modelled.

However, Dempster et al. have reported that a hierarchical planning process is actually a good heuristic for solving stochastic programming problems. That is we solve the linear programming model with deterministic data but implement the model in a rolling planning horizon framework. By a rolling horizon, we mean that only the first period solution is implemented and all parameters of the model are updated and the optimal solution re-calculated before proceeding to the next period. By doing this we make possible recourse to unplanned events. There are two questions about this approach that need to be answered. First, can we verify that the hierarchical approach is likely to perform well in this forest management environment? Second, are there things that we can do to the LP model to make it more suitable for the underlying stochastic programming problem?

Feasibility for the Stochastic Problem

It will be useful to turn our attention to what it means to have a feasible solution to the stochastic programming problem (4) -(5). First note that the decision space involves only $\{ h_0 \in \mathbf{H}(x_0) \}$. The decision variables do not involve h_t or x_t for $t \geq 1$. However, it is wise not to regard $\mathbf{H}(x_0)$ as the feasible region. Suppose we think of the stochastic process as coming from a discrete probability distribution. Then we can think of the term $E_\xi G_1(x_1)$ as:

$$E_\xi G_1(x_1) = \sum_{k=1}^{K} p(\xi=\xi^k) G_1(x_1(h_0),\xi^k) \qquad (11)$$

where the notation $G_1(x_1(h_0,\xi^k))$ indicates the optimal expected value over all future periods if decision h_0 is taken and the realization ξ^k occurs. Note that ξ^k should be thought of as an entire sequence $\xi x^k_1, \ldots \xi^k_T$ of stochastic events which make up this single realization. Then we can define:

$$F^k_0(x_0) = [h_0 \in \boldsymbol{H}(x_0): G_1(x_1(h_0,\xi^k)) > -\infty] \qquad (12)$$

That is $F^k_0(x_0)$ is the set of first stage harvest decisions that result in feasible outcomes if the stochastic process actually takes on the kth realization. Put another way, each possible realization of the stochastic process over time induces constraints on the first stage problem to ensure feasibility for future stages. The actual feasible region for problem (4)-(7) can then be written as:

$$h_0 \in \mathbf{H}(x_0) \cap \mathbf{F}_0^1(x_0) \cap \ldots \cap \mathbf{F}_0^K(x_0) \qquad (13)$$

Again it is worth considering the difference between the stochastic programming problem and the usual deterministic LP. In this latter case there is only one such induced constraint on the first stage decision. That is

$$h_0 \in \mathbf{H}(x_0) \cap \mathbf{F}^*(x_0)$$

where $F^*(x_0)$ is the set of first stage decisions that are feasible for future stages of the "average process".

Optimality for the Stochastic Problem

The next question we want to examine is that of optimality for the stochastic problem. One can consider a number of possible "solutions". If we let h_0^k denote the solution of the kth deterministic problem corresponding to perfect knowledge of the realization ξ^k of the stochastic process. Then $h_0^k \in \mathbf{H}(x_0) \cap F_0^k(x_0)$. Denote by G^k_0 the optimal value corresponding to h_0^k. If we let

$$\bar{G}_0 = \sum_{k=1}^{K} p(\xi=\xi^k) G_0^k \qquad (14)$$

then $\bar{G}_0$ is the expected value of the first stage decision problem if we have perfect information as to which realization of the stochastic process is to occur. Obviously $\bar{G}_0$ provides an upper bound on the optimal value for the stochastic problem. However, $\bar{G}_0$ is not attainable since it requires both perfect knowledge of every realization of the process and the ability to make a different first stage decision for each realization.

If we allow ourselves to make only one decision as is required in a realistic decision problem, one concept might be the average of the individual first stage decisions h_0^k. That is our first stage decision would be the expected first stage h_0^{Exp}, given by:

$$h_0^{Exp} = \sum_{k=1}^{K} p(\xi = \xi^k)\, h_0^k \qquad (15)$$

In this case the expected optimal value would be

$$G_0^{Exp} = \sum_{k=1}^{K} p(\xi=\xi^k)[R_0(x_0,h_0^{Exp}) + e^{-r}G_1(x_1(h_0^{Exp},\xi^k))] \qquad (16)$$

The difference $\bar{G}_0$ and G_0^{Exp} might serve as an indication of the optimality of h_0^{Exp}. Note however, that, in general it, is not necessarily true that h_0^{Exp} would be feasible. This is because it is only necessary that $h_0^k \in \mathbf{F}^k_0(x_0)$. Thus it is not necessarily true that h^k or h^{Exp} will be in the intersection set (13). Even if h_0^{Exp} is feasible, there is no reason to believe that it is optimal.

Hierarchical Planning for the Stochastic Problem

Even the solution concept h_0^{Exp} is not available to us in a typical forest management situation. As indicated before, the deterministic problem is often so large that it is difficult to solve and there are so many events that can happen that it is unrealistic to think of solving for the individual h_0^k. What we typically do is solve for first stage solution h_0^{Avg} of the deterministic problem. It is this solution that we attempt to implement in the current period. if we let G_0^{Avg} be the expected value of this solution, we have

$$G_0^{Avg} = \sum_{k=1}^{K} p(\xi=\xi^k)[R_0(x_0,h_0^{Avg}) + e^{-r} G_1(x_1(h_0^{Avg},\xi^k))] \qquad (17)$$

Note that G^{Avg} is not itself well since the notation $G_1(x_1(h_0^{Avg},x^k))$ implies "optimal decision making in all future stages. However, we will content ourselves with this imprecision for the moment. The natural questions that arise when we examine hierarchical planning in this framework are two. First is h_0^{Avg} feasible. Second how close is G_0^{Avg} to the optimal solution to the stochastic program.

The answer to these questions depends to a large extent on our design and implementation of the hierarchical planning process. Let us deal with feasibility first. The decision h_0^{Avg} is in fact feasible to the deterministic initial period constraints and also for the induced constraints caused by the later periods given that the stochastic process takes on "average values". Can it fail to be feasible for the true stochastic problem?

Our answer is that it should be feasible if the hierarchical process is designed properly. If we carry out the replanning often enough, then it is difficult to see how implementing one period of a hierarchical plan is likely to cause future infeasibility of wood supply. For example if we replan on an annual basis and if we are considering a reasonably large number of stands in our tactical model, it is difficult to conceive of practical circumstances (insect, fire, hurricane?) that would make it impossible to meet overall wood requirements in future periods because of the actions that we have taken in the first period. Forestry is characterized by an enormous number of recourse possibilities which include planting, increased silviculture or increased protection that make it possible to recover from adverse outcomes in one year. As long as we use reasonably short replanning intervals, plans based on average data should be feasible in the sense that we can take recourse to whatever outcomes occur.

A possible exception to this could occur if the "average plan" corresponding to the decision h_0^{Avg} implied extremely tight wood supplies for certain sectors of the industry in future years (sawlogs, veneer logs for example) In this case an unfavourable outcome in the short term could in fact make it impossible to supply those sectors which have extremely tight supply requirements. This effect however can be eliminated by not allowing such situations in the first place. One way of doing this is to increase the wood requirements for such sensitive industry sectors by adding a small "reserve margin" to the demand in future years. If the "average plan" can meet this reserve margin demand, then it is probable that it can be met in whatever realization of the stochastic process occurs. If the "average plan" cannot meet the reserve margin demand, this points out that the current industry capacity is not compatible in a robust sense with the capacity of the forest to supply wood products and this necessitates a change in the strategic plan.

Now let us turn our attention to optimality. As indicated above, for certain highly simplified stochastic programming problems, Dempster et al. have demonstrated that hierarchical planning is in fact approximately optimal in the sense that as the systems become larger, the hierarchical plan, implemented in the rolling planning horizon we have been discussing, gives an objective function value which approaches that of the true stochastic optimal. We expect a similiar phenomenon here. Obviously, if we have only a single stand, it is easy to conceive of situations where the optimal deterministic solution is different from the optimal stochastic solution. Martell (1980) demonstrated such a phenomenon in the case of rotation decisions in the face of increased fire probability with stand age. However, just as the coefficient of variation of a sum of n random variables decreases with n, we would expect that the need to explicitly consider variability in the tactical models would decrease as we consider more regions or recourse opportunities in our models.

Some Computational Tests of the Stochastic Problem

We have designed a series of computational experiments to test some of the ideas discussed in this paper. We have used a model similiar to that described in appendix 1. We have generated the growth process corresponding to the hsp_{ijt}, hsl_{ijt}, hhp_{ijt}, hhl_{ijt} for each "zone" from a Markov process. The model shown in Appendix 1 is based on the assumption that all land not harvested advances to the next age class in the next period.

We will report on the computational experiments in some detail in a subsequent paper. For now, we illustrate some of our results in Table 1. This gives computational results on 15 randomly generated scenarios. The scenarios were generated with both growth rates and the possibility of disaster being random variables.

The first column, labeled PI, is computed as if perfect information were available on the entire scenario in advance. The second column MPI, is computed by fixing the first stage harvest decision vector at the mean of the decisions used for each of the scenarios in the PI case and then re-solving the linear program to optimally choose the recourse decisions. This resulted in the column labeled MPI. We also computed the "average data" for the problem and solved this linear program. It had an objective function value of $320.24 M. The first stage harvest decisions for this problem were fixed and the 15 scenarios solved again. This gives the column labeled MAD. Note that there are only small differences between the expected objective value with perfect information (average of PI) and the expected objective function value using the optimal first stage fixed decision or the optimal objective function using "deterministic average" data. Although hardly definitive, this illustrates the point that we have been trying to make, namely, that the average data gives first stage decisions that perform approximately optimally if recourse opportunities are preserved.

Table 1. A Computational Illustration of Objective Function Variation ($'000,000)

PI	MPI	MAD
328.80	326.83	327.67
321.00	306.07	311.15
327.43	323.67	325.12
323.84	320.11	321.89
314.85	305.35	304.86
329.19	321.55	322.62
325.29	321.53	323.61
320.43	316.83	316.00
327.80	325.89	327.63
330.53	322.16	321.19
320.77	317.18	319.27
319.78	311.07	309.68
326.60	322.41	323.60
330.54	325.88	329.22
324.81	319.96	321.87
Average results		
324.78	319.10	320.39
Average Data		
320.24		

Structuring a Family of Tactical Models

Here we look at an an example of structuring a family of tactical models. Our perspective in what follows is that of a large, integrated forest company. However, the perspective could be extended to that of a province or state planning the management of its forest industry. Much of this same structure was discussed in the earlier paper Gunn (1991). A conclusion that follows from the analysis to this point is that the design of the hierarchical structure should attempt to produce a robust, clearly understandable solution that accomplishes the goals that we set for ourselves. It is our contention that the accuracy of the hierarchical decomposition is less important.

It seems necessary to identify three types of tactical level problems which we refer to as long range tactical, medium term tactical and annual aggregate planning. Although each of these models are tactical, each deals with such different issues it is difficult to see how we can accommodate these within a single model and still understand the results. Moreover such a model would be so cumbersome and require such extensive data collection as to violate the principles of a hierarchical approach.

Long Range Tactical

The long range problem is that of ensuring long term wood supply while maximizing forest net revenues. The problem here is to ensure that the various types of timber requirements (veneer logs , sawlogs, pulpwood) can be satisfied in an economical manner from the total landholdings of the enterprise. Landholdings are differentiated by management district (geographical zone), forest cover and possibly by ownership distinctions. In the situations that we have in mind, sustainability of harvest is in terms of the long term ability to supply industry requirements, although there will be a need to consider other issues such as workforce stability within each district. A typical company that we are familiar with has about a million acres of land managed as 8 districts and distinguishes their holdings by 3 cover types and 3 ownerships. Thus we would need about 72 zones to represent the land base.

Trying to represent the landholdings on a stand basis for such a large amount of land would be prohibitive. Thus it would appear that the model should be region based. Since the objective is long term revenue maximization and the ability to meet the industry specific wood requirements this would argue for the use of capacity based harvest requirements in contrast to ideas such as non-declining yield. Since the models are not stand specific, most of the arguments for Model I formulations would not apply. This would argue for use of Model II or III. In order to make the model more robust under the uncertainty, two ideas can be helpful. The first would be the use of fairly high discount rates to guarantee the economic viability of the plan and the second would to increase the wood demand in the key wood using sectors by a small reserve margin so as to ensure both long and medium term feasibility.

One issue that we might want to deal with is transportation of wood to the various mills. However, it seems unwise to deal with this in detail at this stage. What might prove useful is to include a cost for each zone which would approximate transportation costs to some reasonable mill destination without worrying in detail about the actual mill assignment at this level.

What should be implemented from this long term model? The main thing that the model is telling us is how much of the various types of wood products should be produced from each zone in the first period so as to be compatible with planned industry capacity both in the short and long term.

Medium Term Tactical

The long range tactical models can, based on highly aggregate forest information and uncertain information on price, market, growth and technology, develop an optimal plan in terms of forest harvesting by zone that is long term feasible for industry capacity. However, since it is not stand specific, it is not possible to interpret this solution on terms of stand treatments. The medium term problem is to decide on these stand level decisions for the stands within a zone.

Clearly this model should be stand based. Because the upper level model gives a rough idea of harvest and silviculture policy, it may be reasonable to use a Model I based formulation because of the flexibility it allows. This model does not need to be as long term as that discussed above since issues of long term feasibility have been dealt with there. However, it would seem wise to use shorter periods to facilitate implementation. Harvest flow constraints can be simplified to requiring that the volume of each type of wood produced correspond to that calculated in the long term model for each model period.

Short Term Tactical

The output of the medium term plan will give a harvest and treatment plan for each stand. However, this plan is still not detailed enough for annual planning. We need to be able to specify for the coming year (perhaps broken down to smaller time periods) which stands to cut and how to allocate the wood products to the mills operated by the enterprise and/or its customers so as to maximize its profits. Constraints, such as available workforce and machinery, enter into the model as do mill prices, harvest costs, and transportation costs. These models may be single period models or multi period models covering up to five or more years with quarterly or monthly periods. The key distinction is that it is not necessary to account for growth in these models. These are quite standard LP models. A single period model of this type was described by Gunn (1975)

Overall Structure

Given the above considerations, the outcome is a structure somewhat like that shown in Figure 1. This figure indicates the goal and nature of each tactical level, the replanning interval and information linkage to the lower level problem in the hierarchy.

There are two points to note about this structure. First, it is oriented to implementation with each model leading to an immediate decision. For example the long term tactical decision is how much to plan to cut from each zone over the next 10 years. The medium term decision is the amount of harvest and silviculture treatment on each stand of the zone in the next 5 years. The short term decision is how much to harvest from each stand in the zone over the next year and how to market the resulting timber . The operational decisions include where to send the cutting crews next week. The second point to note is that long term decisions do not depend on detailed information in periods far from the current decision point. Problems increase in detail but decrease in planning horizon as we proceed down the decision hierarchy.

Conclusion

Hierarchical planning systems have had a strong impact on the planning process of manufacturing and other industries. They offer potential computational advantages but, more importantly, they also offer advantages in implementation in that a well structured hierarchical system reflects the organization and decision processes of the enterprise.

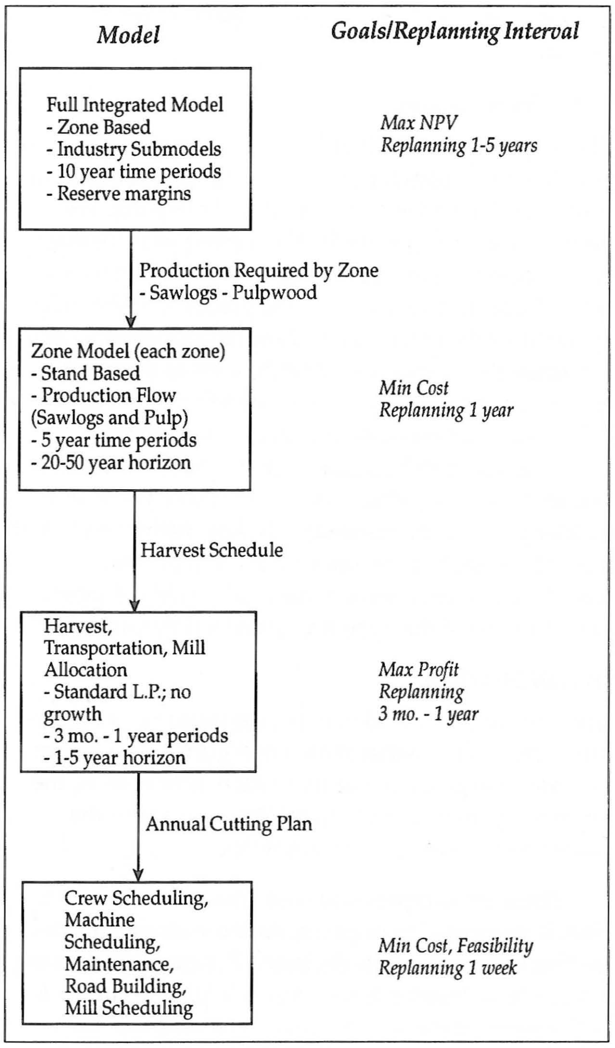


Figure 1. Outline of Example Hierarchical Structures.

An important issue in hierarchical systems is their ability to deal with the uncertainty that is typical of the real environment. Previous research indicates that hierarchical planning systems are well suited to deal with these issues but research remains to verify these issues and to discover the most effective means of structuring the decision process to cope with this uncertainty.

Acknowledgments

This work was partially supported by Grant A1365 from the Natural Sciences and Engineering Research Council of Canada.

Literature Cited

Barros, O.; Weintraub, A. 1982. Planning for a vertically integrated forest industry. Operations Research. 30: 1168-1183.

Bradley, S.; Hax, A.; Magnanti, T. 1977, Applied mathematical programming. Reading, MA. Macmillan. 716 pp.

Bukh, N.D. A bibliography of hierarchical production planning techniques, methodology and applications (1974-1991). Working paper. Institute of Management. University of Aarhus, Aarhus C, Denmark.

Bussey, L.E. 1980. The economic analysis of industrial projects. Englewood Cliffs, NJ. Prentice-Hall. 491 pp.

Daugherty, P.J. Dynamic inconsistency in forest planning. Paper presented at Symposium in Systems Analysis in Forest Resources, Charleston, South Carolina, March 3-7, 1991. (not published in proceedings)

Dempster, M.A.H.; Fisher, M.L.; Jansen, L.; Lageweg, B.J.; Lenstra J.K.; Rinooy Kan, A.H.G. 1981. Analytical evaluation of hierarchical planning systems. Operations Research 29(4) :707-716.

Faustmann, M. 1849. Berechnung des werthes, welchen walboden sowie noch nicht haubare holzbestande fur die waldwirtschaft besitzen. Allg. Forst und Jagd Zeitung 25: 441-445.

Garcia, O. 1984. FOLPI, a forestry-oriented linear programming interpreter, In: Nagumo, H. et. al. (Ed.) , Proceedings IUFRO Symposium on Forest Management Planning and Managerial Economics. University of Tokyo. pp 293-305.

Gassman, H.I. 1989. Optimal harvest of a forest in the presence of uncertainty. Can. Journal of Forest Research 19: 1267-1270.

Gunn, E.A. 1975. An application of linear programming to the planning of woodlands operations. Canadian Operational Research Society 1975 Annual Conference. Waterloo, Ontario. (unpublished, available from author).

Gunn, E. A. 1988. Perspectives on rotation:An examination of various modelling approaches to forest rotation planning. In: Charles A., and White, G., eds., Proceedings, conference on resource modelling and analysis, Resource Modelling Association, Sept. 29-Oct 1, Halifax, N.S. pp. 191-198.

Gunn, E.A.; Rai, A.K. 1987. Modelling and decomposition for planning long term forest harvesting in an integrated industry structure. Can. Journal of Forest Research, 17: 1507-1518.

Gunn, E. A.; Rutherford, P.J. 1990. Integration of annual and operational planning in a coal mining enterprise, Proceedings of the APCOM Symposium. Berlin.

Hägglund, B. 1990. Sustained yield forest management: the view from Sweden. Forestry Chronicle (February) 29-31.

Hax, A.; Candea, D. 1984. Production and inventory management. Englewood Cliffs, NJ. Prentice Hall. 513 pp.

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

Jamnick, M. S.; Davis, L.S.; Gilless, J.K. 1990. Influence of land classification systems on timber harvest scheduling models. Can. Journal of Forest Research 20:172-178.

Johnson, K. N. 1986. FORPLAN version 2: an overview. Land Management Planning Systems Section. USDA Forest Service, Washington, DC.

Johnson, K. N.; Scheurman, H.L. 1977. Techniques for prescribing optimal timber harvest and investment under different objectives - discussion and synthesis. Forest Science Monograph 18.

Lembersky, M. R.; Johnson, K.N.; Optimal policies for managed stands: an infinite horizon markov decision process approach. Forest Science 21(2): 109-122.

Luss, H. 1982. Operations research and capacity planning problems: a survey. Operations Research 30(5): 907-947.

Martell, D.L. The optimal rotation of a flamable forest stand. Can. J. For. Res. 10, 20-34, 1980.

Navon, D. I. 1971. Timber RAM, a long range planning method for commercial timberlands under multiple use management. USDA Forest Service Res. Paper PSW-70, Pacific Southwest Forest and Range Exp. Station, Berkeley, California.

Pickens, J.B., B. Kent, and P.G. Ashton. The declining even flow effect and the process of national forest planning. Forest Science, 36(3), 665-679.

Rai, A.K. A decomposition approach for a model of forest management. M.A. Sc. thesis. Department of Industrial Engineering. Technical University of Nova Scotia, 1984.

Reed, W.J.; Errico, D. 1986. Optimal harvest scheduling at the forest level in the presence of the risk of fire. Can. Journal of Forest Research.

Rockafellar, R.T.; Wets, R. J. 1987. Scenarios and policy aggregation in optimization under uncertainty. IIASA Working Paper WP-87-119. Laxenburg, Austria. International Institute for Applied Systems Analysis.

Silver, E.; R. Petersen, R. 1985. Decision systems for inventory management and production planning (2nd Ed.). New York. Wiley. 722 pp.

Tait, D. 1987. The good fairy problem: one more look at the optimum rotation age for a forest stand. Forestry Chronicle. 63(4):260-263.

Wagner, H.M. 1975. Principles of operations research (2nd ed.). Englewood Cliffs, NJ. Prentice Hall. 1038 pp.

Ware, G. O.; Clutter, J.L. 1971. A mathematical programming system for the management of industrial forests. Forest Science. 17: 428-445.

Vertinsky, I.; D. Kira, D.; V. Kanetkar, V. 1989. A study of production decisions under extreme uncertainty in the wood products industry, FEPA WP. 122, Forest Econ. and Policy Analysis Research Unit, Univ. of B.C., Vancouver.

Vollmann, T.E.; Berry, W.L.; Whybark, D.C. 1984. Manufacturing planning and control systems. Homewood, IL. Richard D. Irwin Inc. 744 pp.

APPENDIX I - Formulation of an integrated model

This model is based on the Model III land management constraints. The wood demand sector is highly simplified with one pulpmill, one sawmill with a chipper, one sawmill with no chipping capability and with one "other demand" sector which we refer to as firewood. These "mills" are best thought of as aggregate representations of the demand in the relevant sectors. This particular aggregation is only one example; others may be appropriate in particular circumstances. This aggregation does however capture the features of substitutability (sawlogs for pulpwood) and of dependent demand (pulpwood on chips). For a more detailed discussion see Gunn and Rai (1987).

Variables

X_{ijt}	hectares of land of harvest zone i in age class j at end of period t.
C_{ijt}	hectares of land of harvest zone i in age class j regeneration harvested during period t.
SL^k_t, HL^k_t	volume (m^3) of softwood (SL) and hardwood (HL) sawlogs allocated to use k in period t. Use k=1 corresponds to sawmills with a chipper; use k=2 corresponds to sawmills without a chipper; use k=3 corresponds to pulpmills.
SP_t, HP_t	volume (m^3) of softwood and hardwood pulpwood allocated to pulpmill in period t.
SL_t, HL_t	volume (m^3) of softwood and hardwood pulpwood allocated to firewood (non-pulpmill or sawlog) demand in period t.
SC_t, HC_t	volume (m^3) of softwood and hardwood chips produced at sawmill and allocated to pulpmill in period t.

Constraints

Land Management Constraints for Harvest Zone i

$X_{ijt} = X_{i(j-1)(t-1)} - C_{ijt}$ j=1,J-1;t=1,T

$X_{iJt} = X_{i(J-1)(t-1)} + X_{iJ(t-1)} - C_{iJt}$ t=1,T

$X_{i0t} = \sum_{j=1,J} c_{ijt}$ t=1,T

Data: J - number of age classes
T - number of Time periods
$X_{i,j,0}$ - hectares in age class j at period 0 (initial)

Mass Balance Constraints for Each Period t

$$\sum_{i=1,I}\sum_{j=1,J}(hsp_{ijt}C_{ijt} + tsp_{ijt}X_{ijt}) = SP_t + SF_t$$

$$\sum_{i=1,I}\sum_{j=1,J}(hsl_{ijt}C_{ijt} + tsl_{ijt}X_{ijt}) = SL^1_t + SL^2_t + S$$

$$\sum_{i=1,I}\sum_{j=1,J}(hhp_{ijt}C_{ijt} + thp_{ijt}X_{ijt}) = HP_t + HP_t$$

$$\sum_{i=1,I}\sum_{j=1,J}(hhl_{ijt}C_{ijt} + thl_{ijt}X_{ijt}) = HL^1_t + HL^2_t + S$$

Data:

i) hsp_{ijt}, hsl_{ijt}, hhp_{ijt}, hhl_{ijt} - volume (m^3) of softwood pulpwood, softwood logs, hardwood pulpwood, hardwood logs, respectively produced by regeneration harvesting one hectare of harvest zone i, age class j in period t.

ii) tsp_{ijt}, tsl_{ijt}, thp_{ijt}, thl_{ijt} - volume (m^3) of softwood pulpwood, softwood logs, hardwood pulpwood, hardwood logs, respectively produced by thinning and other activities on one hectare of harvest zone i, age class j which does not undergo regeneration harvesting in period t.

Allocation Constraints for Consuming Sectors in Period t

i) Sawmill Demand
$minsl^1_t \leq SL^1_t \leq maxsl^1_t$
$minhl^1_t \leq HL^1_t \leq maxhl^1_t$
$minsl^2_t \leq SL^2_t \leq maxsl^2_t$
$minhl^2_t \leq HL^2_t \leq maxhl^2_t$

ii) Chip Production
$SC_t = \alpha SL^1_t \qquad HC_t = \alpha HL^1_t$

iii) Pulpmill Demand
$minsp_t \leq \beta_1 SP_t + \beta_2 SL^3_t + SC_t \leq maxsp_t$
$minhp_t \leq \beta_3 HP_t + \beta_4 HL^3_t + HC_t \leq maxhp_t$

iv) Firewood Demand
$minsf_t \leq SF_t \leq maxsf_t$
$minhf_t \leq HF_t \leq maxhf_t$

Data:

$minxx_t$, $maxxx_t$: Minimum and maximum demand for sector *xx* in period t. The sectors *xx* correspond to softwood and hardwood at sawmills 1 and 2 (sl^1, sl^2, hl^1, sl^2), softwood and hardwood at pulpmills (sp, hp) and softwood and hardwood firewood (sf,hf). Note pulpmill demand is in m^3 of chips.

a volume of chips per unit volume of sawlogs.

$\beta_1, \beta_2, \beta_3, \beta_4$: volume of chips produced per unit volume of softwood pulpwood, softwood sawlogs, hardwood pulpwood and hardwood sawlogs respectively.

Objective Function

$$\begin{aligned} \textit{Maximize} \quad & \sum_{t=1,T} \varnothing_t \, [psl'_t(SL^1_t + SL^2_t) + psl''_t SL^3_t \\ & + psc_t SC_t + psp_t SP_t \\ & + psf_t SF_t + phl'_t(HL^1_t + HL^2_t) \\ & + phl''_t HL^3_t + phc_t HC_t \\ & + php_t HP_t + phf_t HF_t] \end{aligned}$$

Data:

$\varnothing_t$ discount factor for period t
psl'_t, phl'_t price for softwood, hardwood sawlogs ($\$/m^3$) delivered to sawmills in period t.
psl''_t, phl''_t price for softwood, hardwood sawlogs ($\$/m^3$) delivered to pulpmill in period t.
psc_t, phc_t price for softwood, hardwood chips ($\$/m^3$) delivered to pulpmill in period t.
psp_t, php_t price for softwood, hardwood pulpwood ($\$/m^3$) delivered to pulpmill in period t.
psf_t, phf_t price for softwood, hardwood firewood ($\$/m^3$) in period t.

Flexibility in Forest Management Planning

M. Mandelbaum

Department of Computer Science and Mathematics, Atkinson College, York University, North York, Ontario, Canada, M3J 1P3

D.L. Martell

Faculty of Forestry, University of Toronto, Toronto, Ontario, Canada, M5S 3B3

Abstract

This paper is concerned with incorporating flexibility into forest management planning. We explore the nature of change and uncertainty that complicate long term planning in forestry and we investigate the measurement and use of flexibility to deal with such issues. We then use a simple hypothetical forestry planning problem to illustrate potential applications of flexibility measures to forest management.

Introduction

Foresters frequently deal with planning problems that entail great uncertainty, and planning horizons that extend over several hundred years. The very long planning horizons and the fact that societal values associated with forests vary over time make it extremely difficult for forest managers to imagine how future generations might value forest environments and specify objective functions that will represent future preferences adequately. In addition, forest managers must deal with the diverse views of many different stakeholders such as politicians, civil servants, the forest industry, environmental groups, and aboriginal peoples.

In principle, it is possible to encode uncertainty and formally incorporate it into stochastic forest management planning models. Although some such models have been developed, planning procedures that explicitly account for uncertainty have not yet had a significant impact on the practice of forestry.

If a forest manager is confident that a particular course of action is the best one to follow, he or she could commit himself or herself to it fully. But, due to uncertainty, the program of decisions which seem to be optimal if conditions remain as expected, may not turn out to be the best or even feasible when conditions change. Therefore, he or she will want to be flexible, either able to take appropriate action if future changes make it necessary or desirable, or able to choose an action now that will retain its desirability even under change.

This paper is concerned with incorporating flexibility into forest management. We will explore change and uncertainty that complicate forest management, the type of decisions that need to be made, and how one can measure and achieve flexibility. We will then present an illustrative example of the use of some flexibility measures in forest management planning.

The Need for Flexibility in Forest Management Planning

Forest planners must deal with change and uncertainty that vary with respect to the magnitude of their impact over time and space. The major sources of change and uncertainty in forestry can be grouped into a number of categories, some of which follow.

Natural causes, such as fires, insect or disease, can significantly reduce timber supplies in a given area.

Demand for forestry products could change in the future so that totally different types of trees may be needed. For example, consumer preferences for paper can shift over time, and the demand for some types of paper (e.g., computer paper) can shift in response to technological change.

Process Technology can cause major changes in the way forests are managed. For example, changes in the way products are made could render certain species of trees useless and increase the demand for other species in the future.

Climate or weather changes can have significant impacts. Local year to year changes in weather can increase or decrease growth and the amount of timber available for cutting. For example, drought can retard the growth or significantly influence the area burned by forest fires. But climate change like global warming is even more significant than short term variations in local weather. Tree species that currently thrive at a particular location may not survive there under the influence of the new climate. For example, black spruce is most suitable for parts of the boreal forest region of Canada, but under global warming it may not grow well in the southern portions of that region in the future.

Government policy can radically alter forest management by the manner in which it reflects changing social and economic trade-offs. Government needs to balance many diverse concerns such as employment, recreation, parks, wildlife, nature reserves, environmental pollution, and aboriginal land claims. Government legislation requiring large amounts of recycled fibre content in newsprint will have a dramatic effect on demand for virgin newsprint. Government action can cause major shifts in land use. For example, it can put major environmental concerns ahead of forest industry concerns and deny cutting rights in some areas. Government policy changes depend on the relative concerns and voices of the general population and various interest groups.

Given the extreme uncertainty associated with forestry, it is not surprising some observers have stressed the need for flexibility in forest management. Brumelle et al. (1989) developed a conceptual framework for dealing with both structured and unstructured forest management problems. They pointed out that many forest management planning problems are what Mason and Mitroff (1973) call unstructured problems because uncertainty makes it difficult to determine the eventual impact of many forest management practices and predict how societal preferences for forest values will change over time. They suggested that Holling's (1978) concept of resilience be explicitly incorporated into forest management planning processes. Krebs (1985) describes resilience as "a measure of the ability of a system to persist in the presence of perturbations". The resilience concept is based on an assumption that complex ecosystems systems are not and need not be stable, but rather they are dynamic systems that change over time in response to perturbations like fire and insects. Holling suggested we focus on system survival rather than stability.

Going even further, Brumelle et al. (1989) described several indicators that could be used to incorporate resilience into forest management systems. Their resilience factors included species diversity and structural flexibility. They used the term structural flexibility to refer to the physical and managerial infrastructure of forest users. Hunter (1990) stressed the need to include biological diversity from a landscape ecology perspective, into forest wildlife management.

Pollard (1991) discussed the potential implications of climate change on forestry and said "What we can advocate with confidence is flexibility". He stressed the need for flexibility both in the forest and in the industries that use forest products. Burton et al. (1992) pointed out that "Uncertainty exists with regard to climate change and future socioeconomic values. It is therefore prudent to maximize flexibility by promoting a wide array of species and potential products". They suggested the "Value of biodiversity to foresters and other land managers is analogous to the value of diversification within regional economies."

Foresters can take many actions to increase forest flexibility. They can develop "flexible trees" with characteristics that allow them to be used for many purposes, or "flexible forests" that can be used for many different purposes. They can use tending techniques like thinning, fertilization, and protection, to alter stand development so as to better respond to future changes in the demand for forest products. They can develop strategies that can be implemented sequentially and leave options open for the future and enable them to respond effectively to change. They should ensure that to the greatest extent possible, they do not implement irrevocable strategies.

The forest management planning process itself should be geared to flexibility. It should include forecasting, planning, deciding, action or implementation, and controlling functions. Deliberate searching for new actions must be part of the plan since increasing the number of actions at our disposal increases flexibility.

Thompson and Vertinsky (1991) illustrated how the Brumelle et al. (1989) framework can be used to assess silvicultural investment policies. They dealt only with the diversity aspect of resilience and applied it to a British Columbia silvicultural planning model developed by Phelps et al. (1990). They used the Shannon - Wiener information index that ecologists often use to measure diversity. They defined one diversity index based on forest age classes and a second index based on species. They used those diversity indices and several traditional measures (e.g., harvest volume and net present value) to evaluate silvicultural options for several scenarios in a simulated forest. They did not describe how one could combine the different measures but it is clear, that in principle, multicriteria methods could be used for that purpose.

This paper will illustrate how such techniques can be incorporated into forest management planning systems and provide a basis for developing methods for handling flexibility in forest management. We will use some of the principles of flexible manufacturing systems that have been developed by production planners and others, to combine selected aspects of the biological diversity of the forest with land use activities to create land use flexibility measures. It is in many respects, similar to the conceptual framework that Brumelle et al. (1989) developed to incorporate resilience into forest management planning. We believe land use flexibility indices based on biological and economic factors can be used to help ensure the system will be flexible enough to sustain the ecological and socioeconomic integrity of forests and facilitate the development and implementation of what are commonly referred to as sustainable development strategies.

A Selective Review of the Flexibility Literature

Flexibility is a very appealing concept which appears to be applicable to a wide variety of disciplines, and many authors have attempted to understand flexibility. A body of knowledge has developed in economics, planning, decision sciences and flexible manufacturing systems, that is designed to incorporate flexibility into decision making. Ways of evaluating and measuring flexibility are being devised and methods for using them are being developed. Many authors have discussed the qualitative aspects of flexibility or referred to it casually as an interesting or useful concept. Fewer authors have been able to quantify flexibility or have treated it precisely. In this section, we review some of the publications in which authors have attempted something more than a casual reference to the concept, or have treated it quantitatively. For the purposes of this paper we will organize the discussion more or less by discipline.

Economics

Economists studying the theory of the firm were among the first groups to look at flexibility. An early discussion of flexibility is typified by Stigler (1939). The economists defined the flexibility of a plant as the flatness of the average cost curve, arguing that the flatter the cost curve the better a plant could respond to changes in the price of the products being manufactured. Marschak and Nelson (1962) clarified the quantitative basis of these economic decisions by using a two period sequential decision model to study the phenomenon. In their model, an initial decision, the plant type choice, is taken in the first period, while the output of the plant is chosen in the second period after the plant type has been determined.

Others economists were interested in the economic concept of liquidity and related it to flexibility. For example, Jones and Ostroy (1975) set up a sequential decision problem and defined flexibility as the ability to switch from a first period decision to a second period decision at a low cost. The switch was accomplished by having an asset with high liquidity.

Within the theory of consumer choice researchers talked about the flexibility of consumer choices. For example, Koopmans (1964) believed that we need flexibility to allow for changing consumer preferences in the future. He provided several elementary logical axioms based on mathematically defined sets of alternative choices, to exemplify flexibility.

Planning and Investment

Planners attempted to use flexibility as one of the criteria in a multiple criterion decision problem (for example see Friend and Jessop 1969). The work by the Coventry et al. (1971) study team was a practical attempt to incorporate quantitative measures or tests of flexibility into regional planning.

Around the same time, Gupta and Rosenhead (1968) and Rosenhead et al. (1972) proposed a robustness (flexibility) measure that depends on the size of the "remaining" action set after an initial decision is taken. The set of "remaining" actions that is used in the measure contains only those actions that according to their present loss function are satisficing and, according to the authors' hypothesis, this would give these actions a high enough chance of being good actions in the future. Their measure then is a ratio of the set size of those actions "remaining" after an initial action is taken to the overall set size before an initial action is taken.

Arrow and Fisher (1974) treated the idea of irreversibility (inflexibility) of certain actions in applications that destroyed the environment such as building a dam or other land developments. They constructed and compared two small sequential mathematical decision models, M1 that gave the decision without full information and M2 that gave the decision with completely known information. They showed that if M1 implied irreversible solution then so did M2, but if M2 gave a reversible solution it did not imply that M1 would also give a reversible solution.

Decision Methodology

Ashby (1960) introduced the notion of "requisite variety" relating to flexibility. The measure he adopted is the logarithm of the number of action possibilities open to each decision maker. He pointed out that in a pursuit the pursuer must have greater variety of movement than the evader in order to catch it. Merkhofer (1977) studied a sequential decision problem of taking all the action now versus delaying choice. He defined flexibility as related to the delay or postponement of a decision. He calculated the maximum expected loss value of delaying choice as the difference in the losses between taking action now or delaying until the most comprehensive information is obtained. Pye(1978) put forward a flexibility measure based on entropy within a mathematically defined sequential decision making setting.

Mandelbaum (1978) is a comprehensive review and analysis of flexibility. He set up a formal sequential decision making structure which he used as a background for cataloguing an extensive literature. He studied the evaluation of flexibility and pointed out that if we had a "perfect" model then no separate flexibility evaluation would be required. To evaluate flexibility we would need to know the effectiveness with which the system coped with each kind of contingency and the likelihood that flexibility would be needed. He also dealt with decision theoretic models to study flexibility, especially the need for multiple criterion objective functions.

Mandelbaum and Buzacott (1990) extended Mandelbaum's (1978) work. They presented a scenario with a two dimensional criterion function with flexibility as one of the criteria can naturally be anticipated when the decision maker is uncertain about the future. They also showed conditions under which the number of future options might be an appropriate measure of flexibility.

Manufacturing

The latest group of researchers to become intensely interested in flexibility are those in manufacturing and production, mainly those who are studying and implementing flexible manufacturing systems (FMS). An extensive literature has evolved in an attempt to develop methods to be used in designing and choosing FMS's. One direction this research has taken is to explore qualitatively the types of flexibility that an FMS should or could have. This approach was typified by Brown et al. (1984). They defined terms like product, machine, routing, and volume flexibility for different areas that required flexibility. They also tried to indicate how flexibility might be achieved.

Other researchers have tried to measure flexibility. This is typified by papers like Brill and Mandelbaum (1989), Mandelbaum and Brill (1990), and Yau (1989). Yau (1989) defined flexibility as a measure of entropy of the possibilities. Brill and Mandelbaum (1989) on the other hand, defined machine and machine group flexibility. Their measure considers a set of tasks to be performed, a set of effectiveness measures of how well a machine can do each particular task, and a set of weights over the task set. The measure of machine flexibility is essentially the sum of the weighted effectiveness measures over the task set of interest and thus are analogous to probabilities in a sample space.

An Illustrative Example

In this example we will adapt measures of flexibility that come from the manufacturing literature (Mandelbaum and Brill 1989). In doing so, we will use a simple hypothetical forest to illustrate our ideas. Assume we are dealing with a 100,000 ha forest that is covered with a single species of tree, and the forest contains many stands that differ with respect to their age and area. Thus, we will treat a forest stand (which can be used, in concert with other resources, to produce goods valued by society) as being analogous to a machine in a factory, and we will treat a forest management unit or a forest like a group of machines or a factory.

In our example, all the forest stands are being managed under one of three silvicultural regimes.

Regime 1 - Old Growth Forest: These stands have not been significantly influenced by human activities. Natural processes (e.g., fire, insects, and disease) have not been altered by people, and the stands have largely been preserved in their natural states. These stands would be considered by many to be "old growth" forests. They can be used for a variety of "low impact" activities that might range from virtually no access to light recreational use. If they were to be harvested they would effectively vanish for the foreseeable future.

Regime 2 - Basic Silviculture: This land is used for a variety of light or moderate recreational activities and industrial forestry practices that involve basic silviculture. Stands that are harvested are allowed to regenerate naturally with little intervention in natural regeneration and growth processes. Natural processes like fire, insects, and disease are modified to reduce their impact on recreational and industrial activities.

Regime 3 - Intensive Silviculture: This is forested land that is subject to heavy recreational use and intensive silviculture that includes site treatment, artificial regeneration, and tending after harvests. Forest protection practices are directed towards reducing losses caused by fire, insects, and disease.

Strategic Flexibility

One aspect of flexibility is the extent to which the land that comprises the forest can be shifted between silvicultural regimes during the planning horizon. From a manufacturing perspective, it is analogous to the extent to which it is possible to install a new production line in an existing factory, or change "the business" of a corporate entity. We therefore define the strategic flexibility of a particular forest as a function of the number of silvicultural regimes that can be activated in the future given the current status of the forest. Regime 2 land can be converted to regime 3 land and vice versa over the course of a 200 year planning horizon. However, as Reed (1990) points out, once you alter the old growth regime 1 stands, they are gone, and you have eliminated some options for the future.

The simplest measure of strategic flexibility (Strategic Flexibility Index 1 or SF_1) is the fraction of regimes that can be present in the future given the current forest structure. Table 1 illustrates how SF_1 varies as the forest structure varies, where a forest structure is a vector of the number of hectares under the three regimes. Given this definition of strategic flexibility, forests 1 and 2, which allow the possibility of 3 silvicultural regimes in the future, are more flexible than forests 3 through 6 which allow only 2 possible regimes.

SF_1 is very much an aggregate index that has very little resolution. It produces the same values for forests 1 and 2 which subjectively differ considerably with respect to their flexibility. A more refined strategic index (SF_2) might include area weighting factors. One alternate approach to finding the flexibility of a forest might be to define a weighting factor α_k for each regime k (the fraction of the area of the forest that is being managed according to silvicultural regime k) and multiply it by NR_k (the number of regimes that can be applied to that land in the future) and divide the result by N, the total number of regimes in the set of regimes being considered for the forest, and then to sum over all regimes k to get the flexibility measure. In mathematical terms,

$$SF_2 = \sum_k \alpha_k NR_k / N$$

where α_k is the fraction of the area of the forest that is regime k land, and $0 \le \alpha_k \le 1$, and

NR_k is number of regimes that can be implemented in the future, on land that is currently being managed by regime k, and

N is the total number of regimes in the set of regimes being considered for the forest.

The resulting indices are shown in the last column of Table 1. Note that these indices are between 0 which represents no flexibility (if none of the candidate set of regimes can be implemented in the forest in the future) and 1 which denotes complete flexibility (if all of the candidate sets of regimes can be used).

One could extend the weighting factor by using the value of each regime to weight areas, analogous to what Brill and Mandelbaum (1989) did with task weights when computing machine flexibility. But, if we have no knowledge of which regime is more important than another in the future, these values could all be left equal.

Tactical or Land Use Flexibility

We now define tactical or land use flexibility index from a land use perspective. Tactical flexibility is a measure of the number of different kinds of land use activities that can be carried out in the forest at any particular time. From a manufacturing perspective it is a measure of the extent to which the forest "factory" can "manufacture" different products or perform different tasks at time t. It is a socioeconomic analogue of biological diversity.

Before we proceed it is important to clarify what we mean by land use. We define a parcel of land as a specific forest stand or a set of stands that may or may not be contiguous. We define two types of land use

Table 1. Future regimes as a measure of strategic flexibility

Forest	Area of Regime 1 (10^3 ha)	Area of Regime 2 (10^3 ha)	Area of Regime 3 (10^3 ha)	Number of regimes possible in the future	SF1	SF2
1	100	0	0	3	1	1
2	20	20	60	3	1	.73
3	0	20	80	2	.67	.67
4	0	10	90	2	.67	.67
5	0	1	99	2	.67	.67
6	0	0	100	2	.67	.67

activities; basic and compound. A basic activity is a single type of land use, for example fishing or hiking. A compound activity is a combination of one or more basic activities that can be carried out simultaneously on the same parcel of land, for example, hiking and fishing. Since the value that people derive from participating in land use activities is determined in part by the presence or absence of other people who use the same parcel of land, we will use compound activities to measure land use flexibility.

We let $a_1, a_2, ..., a_m$ denote the basic land use activities, and $A_1, A_2,.. A_n$ their associated compound activities. For example, Table 2 illustrates how two basic activities, canoeing and logging transportation, can be used to define 3 compound activities. Note that each basic activity is also a compound activity.

Suppose our hypothetical forest contains regime 1, 2, and 3 land which contains forest stands that are classified with respect to the age of their trees. The land use possibilities for a parcel of land is the set of compound activities that can take place on that parcel. It may be possible to allocate a parcel of land to one of many possible compound activities. Table 3 describes the land use possibilities for a hypothetical forest using the compound activities in Table 2 above. Table 3 reflects the fact that it may be possible to use a particular parcel of land for compound activities that entail using some parcels of land for more than 1 basic activity simultaneously. The land use possibility indicator variable for a compound activity A_j and a parcel of land is set equal to 1 if and only if activity j can take place on that parcel of land, and it is set equal to 0 otherwise.

The simplest tactical flexibility index (TF_1) is the fraction of the total number of different land use activities you can carry out in the forest at time t, given the structure of the forest at that time. The TF_1 of the forest in Table 3 is 1.

TF_1 does not account for the amount of land that can be used for each land use activity. We can deal with area by weighting the number of uses by area as follows. We begin by defining the flexibility of land parcel i, f_i, as the fraction of compound activities that can be carried out on parcel i.

$$TF_2 = \sum_i \beta_i f_i$$

where $ß_i$ is the area of land parcel i expressed as a fraction of the total area of the forest, and

f_i is the land use flexibility of parcel i

Table 2. Basic and compound activities

COMPOUND ACTIVITIES (A_j)	BASIC ACTIVITIES (a_h) Canoeing a_1	Transportation a_2
A_1 Canoeing	yes	no
A_2 Transportation	no	yes
A_3 Canoeing & Transportation	yes	yes

Table 3. Possible land use by cover type at a particular point in time for the example forest

Regime index k	Age index a	Area of Parcel i (10^3ha)	Compound activity land use indicator: Canoe (A_1)	Transporation (A_2)	Canoe & Transportation (A_3)	Flexibility of Parcel i (f_i)
1	>200	28	1	0	0	1/3
2	20	7	0	1	0	1/3
2	40	8	0	1	0	1/3
2	60	9	1	1	0	2/3
2	80	3	1	1	0	2/3
2	100	4	1	1	0	2/3
3	20	5	0	1	0	1/3
3	40	4	0	1	0	1/3
3	60	25	1	1	1	1
3	80	2	1	1	1	1
3	100	5	1	1	1	1
Total		100				0.63

TF_2 equals 0.63 for the hypothetical forest described in Table 3. Note that the TF_1 and TF_2 flexibility measures, in this case, can range from 0 (no flexibility) to 1 (complete flexibility).

Further extensions are possible. We could add a relative weight w_j for each activity A_j that reflects the relative importance of each activity A_j, where $0 \leq w_j \leq 1$. We could also define an index e_{ij} as the effectiveness of land parcel i for activity j where $0 \leq e_{ij} \leq 1$. Thus the flexibility of a parcel of land would be

$$f_i = \sum_j w_j e_{ij}$$

In our examples above we have assumed that $e_{ij} = 0$ or 1, or that these effectiveness measures are the land use possibility indicator variables for each activity and parcel of land, and assumed that all the w_j are equal to 1 divided by the total number of activities under consideration.

There are those that might argue that the weighting for future use of activities cannot be determined and in that case they can assume that all the weights are equal. Also one might argue that to define effectiveness measures for the future might also be presumptuous and they can then set them to be either 0 or 1 signifying ability to do that activity on the parcel of land or not respectively.

Incorporating Flexibility in Forest Management Planning Models

Having defined a tactical flexibility index, we will now explore how it can be incorporated into forest management planning procedures. As we indicated above, Thompson and Vertinsky (1991) advocated the use of biological diversity indices as well as economic measures, to evaluate forest management policies. One simple way of merging the various system performance measures is to develop a multiattribute utility function that weights the different measures. One could for example, combine Thompson and Vertinsky's (1991) present net worth and diversity indices to form a single objective function.

The resilience of a system is the probability that it will survive. However, there is no clear relationship between diversity and the other factors described by Brumelle et al. (1989) and resilience. Many people believe that more biological diversity is better from a biological standpoint, and similarly, more flexibility is better from a socioeconomic standpoint. That suggests the use of an objective function that includes economic, biological diversity and socioeconomic land use flexibility factors. That is

z = F (present net worth, biodiversity indices, flexibility indices)

One problem with that approach is that if we use the Shannon - Wiener diversity index, the resulting objective function will be a nonlinear function of the state of the forest. That would transform a linear forest management planning model into a nonlinear optimization model with a nonlinear objective function and perhaps one or more nonlinear biodiversity constraints. Since our land use flexibility index is a linear function of the structure of the forest it could readily be combined with present net worth in linear optimization model. We will therefore initially restrict our attention to model that has only economic and land use flexibility components.

The simplest approach would be to use standard mathematical programming planning models like FORPLAN or variants of it to formulate and solve land use allocations so as to maximize present net worth. One could then tally the tactical flexibility of the solution at different points in time.

A more comprehensive approach would be to explicitly incorporate weighted flexibility indices into the objective function and/or the constraints. One approach might be as follows.

Let $x_{k,a,t}$ be the area of the parcel of land that is under regime k and a years old at time t

Let $e_{k,a,j}$ = 1 if you can perform compound activity j on type k land that is age a
= 0 otherwise

Let $\beta_{k,a}(t)$ be the fraction of the forest area for the parcel of land that is under regime k and a years old at time t.

Then $\beta_{k,a}(t) = x_{k,a,t} / \sum_k \sum_a x_{k,a,t}$

Let w_j be 1 divided by the total number of activities under consideration

$$f_{k,a}(t) = \sum_j w_j e_{k,a,j}$$

Let TF(t) be the tactical flexibility of the forest at time t

Then $TF(t) = \sum_k \sum_a \beta_{k,a}(t) f_{k,a}(t)$

Since TF(t) is a linear function of the land management planning decision variables $x_{k,a,j}$, it could readily be incorporated into the objective function or constraints of a traditional forest management planning model. We are currently developing such a model and will use it to explore how economic and land use flexibility factors can be traded off against each other in attempts to evaluate sustainable development policies.

Discussion

Note that our index as it is currently designed, does not address spatial issues. Just as spatial considerations can be important in traditional timber harvest scheduling models, it will ultimately be necessary to expand our model to embrace spatial diversity and flexibility explicitly. Hunter (1990) deals with many spatial considerations problems in his discussion of forest wildlife management.

Also, flexibility with respect to a given set of land uses tasks does not take account of the fact that new land uses might emerge in the future. Perhaps biodiversity as measured by a weighted function of the Shannon - Wiener index might address that issue.

References

Arrow, K. J., and Fisher, A. C. (1974). Environmental Preservation Uncertainty and Irreversibility. Quarterly Journal of Economics, 88, 312-319.

Ashby W.R. (1960). Design For a Brain. (2nd ed.) London, England: Science Paperbacks.

Brill P.H., and Mandelbaum M. (1989). On Measures of Flexibility in Manufacturing Systems. International Journal of Production Research, 27(5), 747-756.

Brill P.H., and Mandelbaum M. (1990). Measurement of Adaptivity and Flexibility in Production Systems. European Journal of Operational Research, 48.

Brown J., Dubois D., Rathmill K., Sethi S.P., and Stecke K.W. (1984). Types of Flexibility and Classification of Flexible Manufacturing Systems. WP 367, Graduate School of Business Administration, University of Michigan.

Brumelle S.L., Stanbury W.T., Thompson W.A., Vertinsky I.B., and Wehrung D.A. (1990). A framework for the analysis of risks in forest management and silvicultural investments. Forest Ecology and Management 35: 279-299.

Burton, P.J., A.C. Balisky, L.P. Coward, S.G. Cumming, and D.D. Kneeshaw. (1992). The value of managing for biodiversity. The Forestry Chronicle 68(2): 225-237.

Coventry City Council. (1971). Coventry, Solihull, Warwickshire Sub-regional Planning Study. England: Solihull County Borough Council and Warwickshire County Council.

Friend, J. K., & Jessop W.N. (1969). Local Government and Strategic Choice. London: Tavistock Publishing.

Gupta, S. K., and Rosenhead J. (1968). Robustness in Sequential Investment Decisions. Management Science, 15, B18-B29.

Holling C.S. (1978). Edited by Holling C.S. (editor.), Adaptive Environmental Assessment and Management. Toronto, Ontario. J. Wiley and Sons.

Hunter Jr., M.L. (1990). Wildlife, forests, and forestry principals of managing forests for biological diversity. Prentice Hall, Englewood Cliffs, NJ. 370 pp.

Jones, R. A., and Ostroy J.M. (1975). Liquidity as Flexibility. Toronto, Canada.

Koopmans, T. C. (1964). On Flexibility of Future Preferences. in M. W. Shelly, and Bryan G.L. (eds.), Human Judgements and Optimality. (pp. 243-254). New York, New York: J. Wiley and Sons Inc.

Krebs, C.J. (1985). Ecology: the experimental analysis of distribution of distribution and abundance, Third Edition. Harper and Row, Publishers, New York. 800 pp.

Mandelbaum M., and Brill P.H. (1989). Examples of Measurement of Flexibility and adaptivity in Manufacturing Systems. Journal of the Operational Research Society, 40(6), 603-609.

Mandelbaum, M. (1978). Flexibility in Decision Making: An Exploration and Unification. Doctoral dissertation, University of Toronto, Toronto, Ontario, Canada.

Mandelbaum, M., and Buzacott J. (1990). Flexibility and Decision Making. European Journal of Operational Research, 44(1), 17-27.

Marschak, T., and Nelson R.R. (1962). Flexibility Uncertainty and Economic Theory. Metroeconomica, 14, 42-59.

Merkhofer, M. W. (1977). The Value of Information Given Decision Flexibility. Management Science, 23, 716-728.

Mason, R.O., and I.I. Mitroff. (1973). A program for research on management information systems. Management Science 19(5): 475-487.

Phelps, S.E., Thompson, W.A., Webb T.M., McNamee P.J., Tait, D., Walters C.J. (1990). British Columbia silviculture planning model: Structure and Design. Unpublished report to B.C. Ministry of Forests.

Pollard D.F.W. (1991). Forestry in British Columbia: Planning for Future Climate Today. The Forestry Chronicle 67(4), 336-341.

Pye, R. (1978). A Formal Decision-Theoretic Approach to Flexibility and Robustness. Journal of the Operational Research Society, 29, 215-227.

Reed, W.J. (1990). The decision to conserve or harvest old growth forests. Working Paper 142. Forest Economics and Policy Analysis Research Unit. University of British Columbia. 21 pp.

Rosenhead, J., Elton M., and Gupta S.K. (1972). Robustness and Optimality as Criteria for Strategic Decisions.Operations Research Quarterly, 23, 413-431.

Stigler, G. (1939). Production and Distribution in the Short Run. The Journal of Political Economy, 47, 305-327.

Thompson, W.A., and I. Vertinsky. (1991). Evaluation of silvicultural investments under uncertainty using simulation. Working Paper 161. Forest Economics and Policy Analysis Research Unit. University of British Columbia. 21 pp.

Yau D.D. (1989). Material and Information Flows in Flexible Manufacturing Systems. Material Flow, 2, 143-149.

Application of Hierarchical Forest Planning in New Zealand

B. Manley, S. Papps, J. Threadgill and S. Wakelin
Forest Research Institute, Private Bag 3020, Rotorua, New Zealand

Abstract

Hierarchical forest planning has been an issue in New Zealand in terms of (i) the level at which the estate is modelled and (ii) the time horizon over which planning is carried out. This paper reports recent experience in New Zealand using the FOLPI forest estate modelling system. Applications include a single-model approach using selective aggregation to provide variable resolution and a linked-model approach with separate models. Proposals for the future include adoption of the variable resolution approach with the development of a hierarchical structure within a large single model.

1. Introduction

Garcia (1984) developed the FOLPI (Forestry Oriented Linear Programming Interpreter) forest estate modelling system for forest planning. In 1984 the FOLPI prototype was handed over to the authors of this paper to implement. Since then FOLPI has been used in a wide range of forestry applications and the modelling system has evolved in response to experience gained.

At this workshop a working definition for hierarchical approaches to forest planning has been given as "The organization of information for making decisions at different levels when the quality of the decisions made at one level is dependent upon decisions or information from another level. Levels may be defined temporally or spatially where the scope of the higher level fully encompasses the scope of the lower level".

By this definition many of the FOLPI applications have involved hierarchical planning – both in terms of the level at which the forest estate is modelled and the time horizon over which planning is carried out. The hierarchy arises from the nature of New Zealand forestry organizations and the range of planning decisions they have to make. For example, the State-owned plantations (which, until recent sales, made up about half of the New Zealand plantation estate) were managed using a multiple-tier organizational structure (see Goulding, 1984).

This paper reports on applications of the FOLPI system in New Zealand. Background to the modelling system is given in Section 2. Applications involving spatial and temporal hierarchies are reviewed in Sections 3 and 4 respectively. The impact of recent software and hardware developments is described in Section 5. Finally, the trend towards a variable resolution model with the development of a hierarchical structure within a large single model is discussed.

2. Background

Croptype Concept

An underlying concept of New Zealand forest management planning is that of the croptype which was adopted to link stands and forests. A croptype is an aggregation of forest stands which may differ in age and time of harvest, but are regarded as uniform with respect to future silviculture, yield prediction and the associated streams of inputs and outputs. For forest planning purposes, stands are aggregated into croptypes with each croptype consisting of a table of areas by age for stands with a common yield table.

Aggregation of stands is generally done on the basis of species, silvicultural treatment, site productivity, and logging characteristics (e.g., terrain). For strategic planning purposes a forest estate will generally be aggregated into 20–60 different croptypes. The number of stands aggregated into one age-class of a croptype can vary depending on the estate being modelled. Table 1 shows the distribution of the number of stands aggregated into each croptype/age-class cell for two forests typical of the range of forests modelled – a small forest of 16,000 ha and a large estate of 170,000 ha. Distributions are similar apart from the distribution for the large forest having a longer tail. Most of the cells representing large numbers of stands are for younger ages. For both forests about half the croptype/age-class cells represent only 1 or 2 stands.

Aggregation of stands into croptypes causes loss of detail. Rather than being able to model management activity by individual stand, the management unit becomes the age-class of a croptype. The assumption that all stands in a croptype have a common yield table causes additional loss of detail. There is also a danger of bias if the yield table represents an aggregation of many stands. For example, if a crop type includes older more

Table 1. Distribution of the number of stands represented by each crop type/age-class cell

Stands per crop type/age-class cell	Forest	
	A	B
	(%)	
1	32	31
2	18	18
3	13	11
4	18	8
5	4	6
6	6	5
7	6	3
8	2	3
9	1	2
10		1
11 - 20		8
21 - 30		2
31 - 40		1
41 - 97		1
Average number of stands per crop type/age-class cell	3	5.2
Area (ha)	16,000	170,000
Number of croptypes	7	42

productive stands with younger less-productive stands the croptype average yield table may cause forest harvest levels to be underpredicted initially and subsequently overpredicted.

On the other hand, use of croptypes reduces the planning problem to a tractable size and enhances comprehension of both the problem and the results. The concept has facilitated forest planning in New Zealand and is flexible enough to accommodate a range of situations. For example, at one extreme each stand might be in a unique croptype whereas at the other extreme all stands in a forest might be assigned to the same croptype.

FOLPI Formulation

Within the FOLPI linear programming (LP) formulation there are two types of constraints: (1) user constraints specified in the forestry problem formulation, and (2) structural constraints that ensure conservation of area. The structural constraints are automatically generated by the system.

Within the structural constraints there are three types of decision variables:

1. y_{tij} - the area cut in period "t", croptype "i", age-class "j".
2. r_{tik} - the area of croptype "i" replanted following harvest in period "t" into croptype "k".
3. z_{ijk} - the area of croptype "i", age-class "j" transferred at the start of the planning horizon into croptype "k".

$$\sum_j y_{tij} = \sum_k r_{tik} \qquad t = 1, \ldots, T \quad i = 1, \ldots, I \qquad (1)$$

$$\sum_k r_{tki} = \sum_{s=t+1}^{T+1} y_{s,i,s-t} \qquad t = 1, \ldots, T \quad i = 1, \ldots, I \qquad (2)$$

$$a_{ij} + \sum_k z_{kji} - \sum_k z_{ijk} = \sum_{s-1}^{T+1} y_{s,i,j+s-1} \qquad i = 1, \ldots, I \quad j = 1, \ldots, J \qquad (3)$$

where "A_{ij}" is the initial area in crop "i" and age-class "j", "I" is the number of croptypes, "J" is the oldest initial age-class, and "T" is the number of planning periods.

Garcia (1984) represented the flow of areas in the system as a network (see Fig. 1). In this network the "y" cut variables are represented by the arcs, the "r" replanting variables by the flows along the bottom and the "z" transfer variables by the flows along the left-hand-side. The structural constraints ensure the conservation of flow at each of the three kinds of nodes in Fig. 1:

1. the area cut in each period from each croptype must equal the area replanted in that period from that croptype to all other croptypes;
2. the area planted into a croptype in any period must be subsequently cut;
3. the area initially in each age-class of each croptype, plus the area transferred in, less the area transferred out, must equal the area subsequently cut.

The LP formulation is similar to a Model II (Johnson and Scheurman 1977) formulation. Garcia (1990) in his revised classification of forest LP models classed the formulation as Model B – essentially a

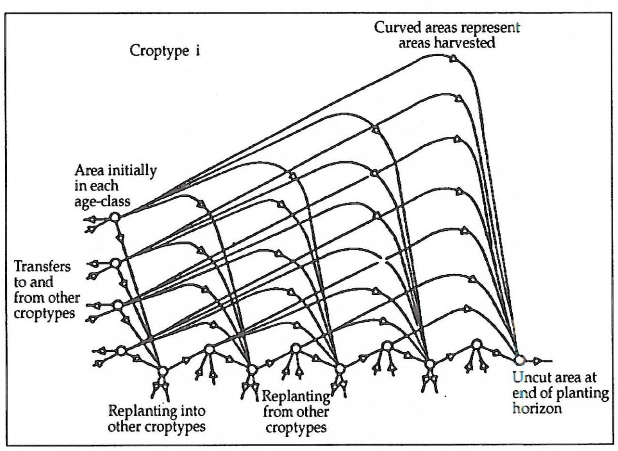


Figure 1. Network representation of the flow of areas in the FOLPI system (after Fig. 4 of Garcia 1984).

Johnson and Scheurman Model II except for the addition of transfers and replanting across croptypes.

The FOLPI system (illustrated in Fig. 2):

1. checks the syntax of the forestry problem specified by the user;
2. translates the forestry problem into an LP problem by building a matrix in MPS-format (Mathematical Programming System Format);
3. solves the LP problem using a third-party LP package;
4. interprets the optimal solution from the LP package back into terms of the original forestry problem;
5. produces summaries of results.

Auxiliary systems have been developed:

- for data manipulation and aggregation;
- to automate the generation of large parts of the objective function and user constraints section of a FOLPI problem specification;
- to directly convert FOLPI output into worksheet format. Considerable analysis is carried out using spreadsheet packages on personal computers. For example, the implications of different assumptions about borrowing and taxation, in the context of forest valuation, have been considered in this way.

Need for Aggregation

The appropriate level of aggregation depends on the situation being modelled. Often there is a trade-off between the level of detail required and the desired solution time. The availability of memory and hard disc resources are also potential limitations to problem size.

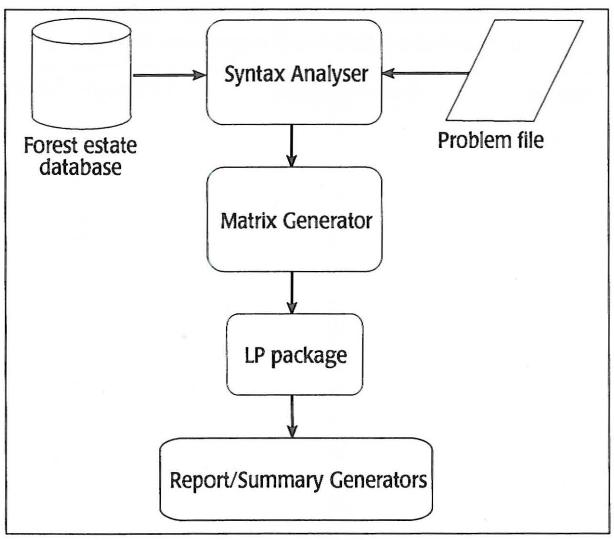


Figure 2. Flow chart of the FOLPI system.

In our FOLPI applications we have been concerned with aggregation decisions relating to:

(a) age-class width and period length
(b) planning horizon (i.e., number of planning periods)
(c) number of croptypes
(d) permissible clearfell age range.

Generally speaking, the problem size in FOLPI varies with the product of the number of croptypes, the number of planning periods and the number of potential clearfell ages. Table 2 indicates how solution time varies with these factors for some example problems.

For most early applications an age-class width and period length of 2 years was used. This provided sufficient detail for long-term applications (in the New Zealand context where target rotation lengths for radiata pine are typically around 30 years) with problem size and hence computer time substantially reduced compared to using a 1-year age-class width and period length. Computer software and hardware developments over the last 3 years have been such that the "appropriate" level of aggregation (reflecting the desired level of detail/desired solution time compromise) has moved substantially towards less aggregation. These impacts will be discussed later. Suffice to say here that in current applications use of a 1-year age-class width/period length is the norm.

Table 2. Impact of problems size factors on solution time

	Relative solution time
(a) Age-class width and period length (Constant 60 year planning horizon)	
1 year	83
2	10
3	3
4	1.5
5	1
(b) Planning horizon (Constant 2 year age-class width)	
40 years	1
70	2.5
100	4
130	6
(c) Number of croptypes	
10 croptypes	1
20	3
40	8

3. Estate Level Hierarchy

The hierarchy that we have modelled can be represented as:

- corporate
- district
- forest
- croptype
- stand

3.1 Stand vs Forest optimum

In one application (Manley and Wakelin 1990) we compared the optimum silvicultural strategy for individual stands with that for different forests. We used a stand evaluation package (STANDPAK, Whiteside 1990) to rank silvicultural regimes on an individual stand basis. The best silvicultural regime for a stand did not necessarily translate into the best strategy for a forest when wood supply commitments were included. The best silvicultural strategy at the forest level depended both on the initial age-class distribution and on the demand placed on the quantity and quality of forest out-turn.

3.2 District vs Corporate level

In 1987 the NZ Forestry Corporation Ltd (a State-owned enterprise) succeeded the NZ Forest Service in the management of 537,000 ha of State-owned plantations together with a further 56,000 hectares of State-owned forest on leased land.The creation of this new organization, responsible for the management of almost half of New Zealand's plantation area, raised some important issues:

- What management strategy (new planting, silviculture, harvesting, replanting) should the NZ Forestry Corporation adopt? There was an increasing emphasis on financial considerations with the focus on profitability and cash-flow. The Forestry Corporation needed to develop a management strategy to reflect the changing environment.
- What was the value of the State plantation forests? The Government wanted the NZ Forestry Corporation to operate commercially, free from day-to-day political control, with the goal of being a successful business. Hence it needed to value the assets transferred to the corporation. A forest asset valuation was required for normal accounting purposes and performance monitoring.

How we used FOLPI to help address these issues is detailed elsewhere (Manley and Threadgill 1991). What is relevant here is the hierarchical nature of the NZ Forestry Corporation and how this influenced the modelling process.

The Forestry Corporation's 100 forests throughout New Zealand were managed in 14 districts. As part of the valuation process we built an estate model for each district. Each model had around 40 croptypes. We ran a sequence of between 3 and 8 models for each district to enable alternative management strategies to be evaluated.

We then developed a single corporate model which had a total of 55 croptypes. The 40-odd croptypes in each district model were aggregated into 3 to 5 croptypes for the corporate level model. The rationale behind this model was two-fold:

- The 14 district models had been developed independently with no account taken of actual or potential interactions between districts. In particular there was concern that the sum of the forecast wood harvest from the 14 district models was unrealistic. Therefore an upper-limit was placed on annual national wood harvest in the corporate model.
- The Forestry Corporation was still attempting to reach agreement with the Government on forest values. The two parties disagreed on key valuation assumptions. It was decided that, for sensitivity analysis purposes, it was better to run a single aggregate model rather than 14 district models.

An initial corporate model was run which attempted to mimic the assumptions made in each district model. Table 3 compares the forest value for each district from (a) the original district model and (b) the corporate model. The differences in value between the two approaches are the result of model aggregation.

Table 3. Comparison of forest value for each district from a district model and a corporate model

District	District model	Corporate model
1	334	330
2	144	140
3	28	31
4	30	30
5	73	71
6	43	48
7	86	92
8	37	38
9	26	22
10	76	87
11	7	7
12	19	18
13	9	10
14	88	94
	1000*	1018

*For reasons of confidentiality all values have been scaled so that District model total equals 1000.

Consequently values from the corporate model can be above or below those estimated in the district models depending on how aggregation of croptype yield tables has affected the timing of future forest harvests in each district.

Although the values for some of the smaller districts vary by up to 20%, total estate value is within 2%. Consequently, the corporate model was used for detailed sensitivity analysis.

4. Time Level Hierarchy

Much of our recent work has been concerned with integrating short-term (1 to 5 year) harvest plans with long-term tactical and strategic plans. Increasingly, there is a need for greater detail about the short-term to be incorporated into forest estate models. However, it is important that long-term consequences are also considered to ensure coherency between short-term and long-term planning. Broadly speaking, two approaches have been followed: (1) a single model approach using selective aggregation to provide less detail for the long-term; (2) a hierarchical approach with separate long-term and short-term models with linkages between the two.

Single model approach

(1) *Stand detail for the first rotation*

The aggregation of stands into croptypes can cause loss of detail as each age-class of a croptype can represent a number of stands. In practice, this loss of detail is often not great. The nature of LP is such that all area in a croptype/age-class cell is often assigned the same treatment anyway. Of greater concern is the fact that all stands in a croptype are assigned the same yield table. While this aggregation is at a generally acceptable level for long-term planning, more detail is often required for the short-term.

We have been experimenting using an initial forest description in terms of stands and maintaining this level of detail for the first rotation. On clearfelling, stands are regenerated into croptypes. The effect of maintaining this stand-level detail on problem size depends on the average number of stands in each croptype/age-class cell.

For example, Table 4 compares the problem size and solution time for two long-term (50-year) models used to represent a 16,000 ha forest: (1) a model in which detail about the 222 stands in the forest was maintained for the first rotation. On clearfelling, stands were replanted into one of seven croptypes; (2) a model in which stands were initially aggregated into these seven croptypes.

Table 4. Impact of maintaining stand level detail for the first rotation

Model	Rows	Columns	Non Zeros	Relative solution time
222 stands	3554	6846	24318	7.8
7 croptypes	567	2000	8620	1

With forests containing several hundred stands it is clearly possible to maintain stand level detail for at least the first rotation. Difficulties arise when forests have several thousand stands as is the case in larger New Zealand forests.

(2) *Variable planning period length*

In the original FOLPI formulation the planning period length (and the age-class width) had to be constant throughout the planning horizon. We have adapted FOLPI to allow the period length to increase during the planning horizon (Papps and Manley 1992). Suppose that initially the period width is set equal to α years. The new version of FOLPI permits the period length to change to any multiple of α at any specified time during the planning horizon.

Conceptually the revised formulation can be represented by Fig. 3. The problem formulation creates a seam between period (p-1) and period p where the period length (and age-class width) changes. A new set of nodes is created at this seam. Standing forest area that exists in period (p-1) is aggregated and reassigned to age classes corresponding to the new age-class width. This is done by introducing linking variables Vij which represent the area in croptype i in age-class j

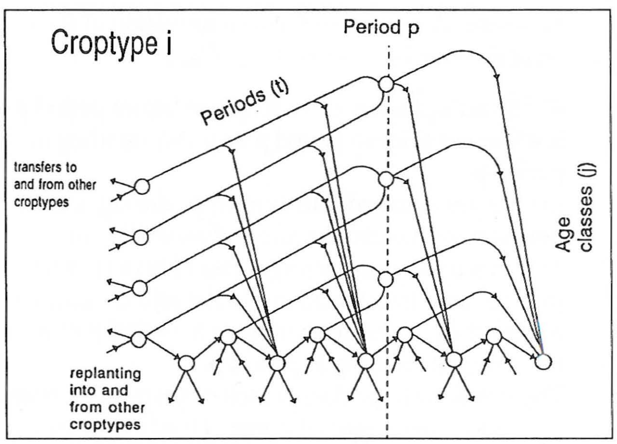


Figure 3. Network representation of the flow of areas in the Variable Planning Period Length version of FOLPI.

(expressed in terms of the original age-class width) at the start of period p (or the end of period p-1).

The formulation of the structural constraints then becomes:

(1) No change from original formulation.

(2) (i) for $t < p$:

$$\sum_k r_{tki} = \sum_{s=t+1}^{p-1} y_{s,i,s-t} + V_{i,p-t}$$

for t=1, ..., p-1 and i=1, ..., I

(ii) for $t \geq p$:

$$\sum_k r_{tki} = \sum_{s=t+1}^{T+1} y_{s,i,s-t}$$

for t=p, ...,T and i=1, ...,I

(3) $$A_{ij} + \sum_k z_{kji} - \sum_k z_{ijk} = \sum_{s=1}^{p-1} y_{s,i,j+s-1} + V_{i,j+p-1}$$

for i=1, ...,I and j=1, ..., J

In addition a further constraint set is required to provide the linkage across the seam:

(4) $$\sum_{k=nj-n+1}^{nj} V_{ik} = \sum_{s=p}^{T+1} y_{s,i,j+s-p} ;$$

for i=1, ..., I and j=1, ...J

So if n = 2 then the left hand side becomes:

$$V_{i,2j-1} + V_{i,2j}$$

and if n = 3 the left hand side becomes:

$$V_{i,3j-2} + V_{i,3j-1} + V_{i,3j}$$

This formulation ensures the conservation of flow at each of the four kinds of nodes in Fig. 3:

2. (i) The area planted into a croptype before period p is either cut prior to period p or is still standing at period p.
(ii) The area planted into a croptype during or after period p must equal the area subsequently cut.
3. The area initially in each age class of each croptype plus the area transferred in less the area transferred out must equal the area cut prior to period p plus the area still standing at period p.
4. The area in each age class of each croptype at the start of period p must equal the area subsequently cut.

Table 5 shows the results of running a sequence of models for each of three different forest estates where:

(1) The period length (and age-class width) stayed constant at one year.
(2) The period length changed from one year to two years in year 11 (year 21 for Model 2).
(3) The period length stayed constant at two years.

The variable length models have more constraints (and sometimes more variables) than even the constant one-year model. However, there are fewer non-zero elements and solution times are lower, particularly for the larger Model 3.

Hierarchy of models

Developing a hierarchy of linked models is an alternative to developing a single model covering both the short- and long-term. Subsequently, we have developed a "short and fat" version of FOLPI capable of scheduling the harvest of 2000 stands over 5 periods.

In one application, a 70 year model with 42 croptypes was run for a 170,000 ha resource to determine the long-term sustainable yield. The results from this model were used in setting up a five year harvest scheduling model with 1146 stands. The size of the two models is given in Table 6.

The linkage between long-term and short-term models can take a number of forms:

(i) The output from the long-term model specifies the area to be cut by croptype and age-class in each year. These cuts can be imposed as constraints in the short-term model. The short-term model is then restricted to selecting which stands in the specified croptype age-class are cut in each year e.g., the long-term model specifies that 95 ha is to be cut from croptype RADMIN, age 32 in 1993. The short-term model determines which of the 15 stands in the appropriate croptype age-class are cut in 1993 to make up this 95 ha.
(ii) The short-term model is constrained to cut the same total area from each croptype in each year as is cut in the long-term model. No restriction is placed on the age-class from which the cut is taken, e.g., the long-term model specifies that 250 ha is to be cut from croptype RADMIN in 1993. The short-term model determines which of the 150 stands in that croptype are cut in 1993 to make up this 250 ha.
(iii) The short-term model is constrained to cut the same total volume from each species in each year as is cut in the long-term model. Candidate stands selected for inclusion in the short-term

Table 5. Effect of variable planning period length model on problem size and solution time

Planning period length (and age class width)	Objective function	Constraints	Variables	Non-zeros	Relative solution time
Model 1					
One year	2,187,480	435	1,191	5,237	6.2
Length changes	2,249,169	800	1,547	3,398	3.5
Two year	2,475,144	237	491	2,070	1
Model 2					
One year	637,899	481	1,534	6,966	4.3
Length changes	642,577	842	1,702	3,771	2.4
Two year	649,360	250	537	2,255	1
Model 3					
One year	320,920,366	5,246	30,496	93,683	8.0
Length changes	322,322,890	5,651	15,772	44,662	2.2
Two year	320,551,762	2,796	10,579	32,061	1

Table 6. Example of size of models used in hierarchical planning

Model	Constraints	Variables	Non-zeros
Long-term (70 years)	3,874	15,975	115,978
Short-term (5 years)	7,164	12,562	32,561

model are those stands in croptype age-classes cut in the first 5 years of the long-term model, i.e., the long-term model determines the total harvest volumes and the croptype age classes that the volume can be cut from but does not constrain the year in which each croptype is cut.

(iv) Again the long-term model determines the total annual cut for the short-term model. However, candidate stands are selected independently of the long-term model using age as the main criterion.

Options (iii) and (iv) are used by two large forestry organizations in New Zealand. Both approaches allow the short-term model to reselect amongst the candidate stands. These options provide a relatively loose linkage between the long-term and short-term models. The long-term model provides the allowable cut for the short-term model. Candidate stands are selected for inclusion in the short-term model either on the basis of the long-term model or simply on age. The short-term model then schedules the harvest from these candidate stands.

The advantage of having flexibility in the short-term model is that it allows stands to be selected on the basis of their unique yield characteristics rather than on a croptype average yield table. Although the long-term model provides what in some sense can be regarded as a global optimum, it is in fact the optimal solution to an aggregate model which like all models is an abstraction of reality. Allowing the short-term model flexibility in the selection of stands for harvest ensures that best use is made of the more detailed information incorporated in that model. Results must then be fed back into the long-term model and the system rerun iteratively to ensure coherency.

5. Impact of Software and Hardware Development

Software and hardware developments since 1984 have been dramatic and have had a major impact on both the size of model that we have physically been able to solve and the actual solution time. The practical effect is that we are now building larger more detailed models.

In 1984 we were using MINOS (Murtagh and Saunders 1985) to solve FOLPI problems on a VAX 11/780. In 1986 we started using SCICONIC initially on the VAX 11/780, subsequently on a microVAX II and finally on a microVAX 3500.

The SCICONIC package has a routine (PRESOLVE) which eliminates redundant rows and associated columns before solving the reduced LP problem. It was noticeable that the PRESOLVE routine would often eliminate over half of the rows generated by the original FOLPI matrix generator. The fact that the original matrix generator was inefficient did not create difficulties for most FOLPI problems when SCICONIC was used because of the built-in PRESOLVE routine. However, because SCICONIC had a limit of 32,000 rows and columns (combined) it meant that some large problems with single-year period length and age-class width could not be solved and had to be aggregated.

It also presented a restriction on the development of a personal computer (PC) version of FOLPI because:

- the LP matrix generated was often too large for the then available PC LP packages;
- these PC LP packages did not have the equivalent of the SCICONIC PRESOLVE routine (the now available C–WHIZ package does in fact have a similar routine). The PC packages would therefore have to solve the larger original problem taking considerable extra time to do so.

In the original matrix generator only a partial check was done for redundancies. In 1989 a revised matrix generator was developed with comprehensive checks to determine relevant variables. The net result was a more efficient matrix generator.

Table 7 compares the matrix generated by the original matrix generator with the matrix generated after the revision for nine test problems. The revised matrix generator produces a matrix with 36 to 72% of the rows, 29 to 83% of the columns and 30 to 89% of the non-zero elements. These improvements (together with the development of DOS extenders allowing full use of available memory) meant that a PC version of FOLPI was viable. Subsequently such a version was developed in order to make the system more portable.

We have tested a number of LP solvers over the last two years and have been impressed by recent developments. Table 8 compares the solution time of 22 different FOLPI problems for four different PC LP packages:

- SCICONIC V2.13 (1992) from SD-Scicon UK, Milton Keynes, England.
- LINDO/386.V5.01 (27 July 1991) from Lindo Systems, Chicago.
- XA V6.00/386 (1991) from Sunset Software, San Marino, California.
- C-WHIZ V1.2 (2 December 1991) from Ketron Management Science, Arlington.

Times are total times on a 486/33 Mhz PC including loading the matrix, solving, and saving the solution. Also included are the times for the same problems using SCICONIC V1.48 on a microVAX 3500. This is not a valid comparison in the sense that both hardware and software are different. However, it is included to give an indication of how dramatically solution times have reduced in our own computing environment. In fact, much of our work was done on a microVAX II which was about 3 times slower than the MicroVAX 3500. Elapsed times for both microVAXs were of course often substantially greater because of the shared facilities.

Other PC LP packages that we previously evaluated were:

- XPRESS MP from Dash Associates, Blisworth, England.
- LPS 867 from Applied Automated Engineering Corp, Pennington, New Jersey.

At the time of this earlier testing (1990) XPRESS MP was an average factor of 1.8 (range 0.9 to 3.9) greater than the then current version of XA. LPS 867 was an average factor of 6.8 (range 2.1 to 26.2) greater than XA.

6. Discussion

Our approaches to hierarchical planning can be categorized as:

(i) a single model approach in which major advances have been:
  - the development of a more efficient matrix generator to allow larger more detailed models to be solved;

Table 7. Comparison of problems generated by original and revised matrix generators

		Matrix generator					
		Original			Revised		
		Rows	Columns	Non-zeros	Rows	Columns	Non-zeros
1	TESTXCRA	543	1,819	7,536	273	780	3,320
2	WAIRCRASH	2,807	10,182	39,965	1,006	2,932	12,106
4	CANTCRASH	2,944	9,512	37,647	1,695	5,028	20,780
6	NEFDNORTH	1,413	10,265	44,977	973	6,393	28,735
7	BOPCRASH	2,324	14,967	65,901	1,637	9,176	42,224
12	GNELBASE	4,701	17,352	78,109	3,377	14,400	69,292
14	KANGATT	2,240	8,865	34,678	1,071	3,936	16,393
15	CORP55	5,632	22,851	96,098	3,186	12,134	62,085
16	OTCRASH	3,607	14,017	59,045	2,270	8,507	36,371

Table 8. Comparison of solution times for different LP solvers

		Rows	Columns	Non-zeros	MicroVAX 3500 SCICONIC	SCICONIC	LINDO	XA	C-WHIZ
					Solution time (minutes)				
						486/33 PC			
1	TESTXCRA	273	780	3,320	1.0	0.4	0.6	0.4	0.2
2	WAIRCRASH	1,006	2,932	12,106	4.7	1.7	7.0	2.8	0.9
3	WAIRSCALE	1,006	2,932	12,106	5.0	1.8	5.8	2.8	1.1
4	CANTCRASH	1,695	5,028	20,780	11.9	3.5	14.3	5.6	1.3
5	PESTCRASH	2,153	12,921	59,487	33.2	11.3	35.3	12.7	3.5
6	NEFTNORTH	973	6,393	28,735	48.2	8.5	18.3	10.8	3.0
7	BOPCRASH	1,637	9,176	42,244	131.3	23.6	41.1	29.5	8.4
8	NORMALCR	771	2,479	18,399	28.1	8.8	D	5.4	6.8
9	NORMALXA	734	2,243	17,784	2.4	1.0	D	10.1	0.8
10	NOMEM80	749	2,674	18,664	14.7	4.0	D	5.0	5.8
11	AGNOG1	544	5,455	16,424	1.8	1.1	1.8	2.0	0.6
12	GNELBASE	3,377	14,400	69,292	101.7	27.5	153.9	21.4	5.2
13	KANGW30	4,241	5,567	35,280	33.2	9.7	32.7	16.7	4.1
14	KANGATT	1,071	3,936	16,383	8.8	3.0	7.6	3.2	1.0
15	CORP55	3,186	12,134	62,085	74.4	23.0	73.3	24.7	5.6
16	OTCRASH	2,270	8,507	36,371	24.5	8.4	24.8	10.1	2.6
17	NZFPUSER	1,124	4,231	17,632	11.3	4.3	20.7	7.0	1.8
18	WIND1510	4,241	5,567	35,280	29.8	10.9	33.0	16.9	4.6
19	TURREGEN	4,604	13,420	61,519	283.7	48.3	958.1	185.0	20.3
20	BOPREALI	2,471	7,645	67,596	27.1	9.6	168.2	10.2	2.1
21	SILVRES	4,583	16,156	94,766	606.6	134.8	476.4	116.1	38.0
22	BOP91	3,874	15,975	115,978	374.3	89.6	1342.8	61.0	30.0
	Average*				84.4	19.8	179.8	25.4	6.7
	Average relative to C-WHIZ				12.6	2.9	25.4	3.8	1.0

D = Degenerate problem – did not solve.
* LINDO comparisons based only on 19 problems that solved.

- the selective aggregation of croptypes and a variable planning period length version of FOLPI which together result in models with greater detail for the short-term and less detail for the long-term.

(ii) a multiple model approach with separate but linked models for the long-term and short-term.

The single model approach that we have implemented can best be described as a variable resolution approach. It is possible to develop models that provide detail for the short-term yet which also incorporate long-term consequences. While the need to reduce computational burden has been a factor in adopting the variable resolution approach, the ultimate rationale is the underlying hierarchical nature of the planning decisions facing New Zealand forestry companies.

Whether the variable resolution approach to modelling meets the definition for hierarchical planning given in the Introduction is debatable, if irrelevant in a practical sense. Decision-makers are faced with two conditional problems (among others):

- What is the best long-term management strategy for the company subject to meeting short-term operational constraints?
- What is the best short-term operational plan subject to the company's long-term management strategy?

The classical hierarchical approach is to solve each of these problems separately with models of different resolution linked by decomposition or heuristic techniques. In comparison, the variable resolution approach incorporates both problems within a single model with variable spatial and temporal resolution. Such an approach involves larger models but overcomes the practical difficulties in linking separate models. In the current New Zealand forestry environment, where there are limited spatial constraints imposed on harvesting, such an approach is feasible.

Computer software and hardware developments have been discussed in this paper. This is because their impact is such, and the changes are so great and continuing, that they will continue to influence the nature of forest planning. The fact that a problem that took over 30 CPU hours (38 elapsed hours) to solve 4 years ago on a microVAX II can now be solved in 38 minutes on a 486 PC is significant. Certainly much more powerful mainframes than a microVAX II existed 4 years ago. What is significant is the price/performance ratio of modern PCs and the total control the user has over when a problem is run and how much it costs. These determine the size of the problem that it is practical and economic to build and solve.

One organization using the "short fat" version of FOLPI has enquired about the possibility of the short-term model being extended to incorporate the long-term. We can envisage that future modelling will include:

- stand level detail for stands (or logging units) which have had a pre-harvest inventory and which will make up the bulk of the harvest for the next 3-5 years. Each stand's yield table will be based on the individual stand inventory results.
- "stratum" level detail for stands aged say 15 to 25 which have had a less intensive mid-rotation inventory. The stands in each inventory stratum would be represented by a croptype, i.e., each croptype would have area in only one age-class. Again the yield table would be based on inventory results.
- croptype level detail for young stands with generic croptypes used to represent this component of the estate.

Such a model could have 1-year period lengths for the first 10 years with a subsequent aggregation into 2 year periods. It is conceivable that the model could include 1000 stands, 100 strata and 20 croptypes. Given hardware and software developments the solution of such problems will be practical.

The emphasis will shift to data generation and handling procedures which automatically generate yield tables and other data inputs for each croptype. An efficient matrix generator will be required to cope with restrictions of available memory.

The focus of the proposed variable resolution approach is the ongoing development of a hierarchy within a single model.

7. References

Garcia, O. 1984: FOLPI, a forestry-oriented linear programming interpreter. Pp. 293-305 in Nagumo, H. et al. (Ed.) Proceedings of the IUFRO Symposium on Forest Management Planning and Managerial Economics, University of Tokyo.

Garcia, O. 1990: Linear programming and related approaches in forest planning. New Zealand Journal of Forestry Science 20(3): 307-31.

Goulding, C. 1984: Yield regulation and management planning in a decentralized organization. In Nagumo, H. et al. (Ed.) Proceedings of the IUFRO Symposium on Forest Management Planning and Managerial Economics, University of Tokyo.

Johnson, K.N., and Scheurman, H.L. 1977: Techniques for prescribing optimal timber harvest and investment under different objectives – discussion and synthesis. Forest Science Monograph 18.

Manley, B.R., and Threadgill, J.A. 1991: LP used for valuation and planning of New Zealand forests. Interfaces 21: 66-79.

Manley, B.R., and Wakelin, S.J. 1990: Impact of volume supply constraints on the choice of silvicultural regime. Pp. 275-285 in James R.N., Tarlton G.L. (Ed.) "New Approaches to Spacing and Thinning in Plantation Forestry". Proceedings of IUFRO Symposium. Ministry of Forestry, FRI Bulletin No. 151.

Murtagh, B.A., and Saunders, M.A. 1985: MINOS 5.0 User's Guide. Stanford University, Systems Optimization Laboratory, Technical Report, SOL 83-20.

Papps, S.R., and Manley, B.R. 1992: Integrating short-term planning with long-term forest estate modelling using FOLPI. Pp. 188–198 in Wood, G., Turner, B. (Ed.) Proceedings of IUFRO Conference "Integrating Forest Information Over Space and Time", Australian National University, Canberra.

Whiteside, I.D. 1990: STANDPAK modelling system for radiata pine. Pp. 106-11 in James R.N., Tarlton G.L. (Ed.) "New Approaches to Spacing and Thinning in Plantation Forestry". Proceedings of IUFRO Symposium. Ministry of Forestry, FRI Bulletin No. 151.

Comments on "Application of Hierarchical Forest Planning in New Zealand"

Authors: B. Manley, S. Papps, J. Threadgill, and S. Wakelin
Discussant: B. Bruce Bare

This excellent paper presents the empirical results of a series of case studies run on New Zealand's forest plantations. The paper is organized into five sections which deal with: (1) a description of the recent evolution of the organization, a definition of the forest classification system, an introduction to the FOLPI modelling system, and the computational justification for aggregating data into age class by croptype strata, (2) a discussion of a five-tiered approach to spatial classification, (3) a description of several temporal hierarchy schemes including: (a) a single model with variable levels of data aggregation and (b) a loosely-linked hierarchical system of short and long-term models, (4) the modelling and computational impacts of PC-based software developments over the past ten years, and (5) a concluding discussion section. Overall, the paper is well organized, well presented, and enjoyable to read.

The applications of the forest planning system discussed in the paper are based on the FOLPI linear programming model. They involve a single objective function and decision maker but make no allowances for the incorporation of risk and uncertainty. However, the applications do exhibit feedback between the levels of the modelling hierarchy and operate within a dynamic planning environment. The primary motivation behind the adoption of a hierarchical approach is to reduce the computational burden. And, using this criterion it appears quite successful.

The hierarchical approach discussed in the paper uses a "short and fat" version of FOLPI. Four alternative schemes of constraining the 1 - 5 year short-term LP model based on the harvest calculations of the 30-80 year long-term LP model are proposed. The linkage between these two-levels is quite loose and apparently only involves the addition of constraints into the short-term model. The results of the short-term calculations are fed back to the long-term model in order to investigate the impact on long-run concerns.

There is no mention of spatial constraints on the harvesting of adjacent stands; road location and construction are not considered; and wildlife habitat and riparian zone impacts are ignored. Perhaps these are not important concerns in the forest system being studied.

Analyzing Old-Growth Designations Using Ecological and Analytical Hierarchies

L. A. Leefers

Associate Professor, Department of Forestry, Michigan State University, 126 Natural Resources Building, East Lansing, MI 48824-1222, USA, (517) 355-0097

Abstract

The Huron-Manistee National Forests are in the process of identifying approximately 70,000 hectares of candidate old growth as part of an appeals settlement agreement. Efforts to pursue hierarchical planning through Opportunity Area analyses have been greatly improved due to development of an ecologically based old-growth design. This design relies, in part, on the Forests' hierarchical, ecological classification system (ECS). The final design will be evaluated in terms of how well various ECS-vegetative type combinations are represented. Hierarchical planning on the Forests has evolved since their Land and Resource Management Plan was approved in 1986. Early efforts were somewhat disjoint because overriding management issues were difficult to address on an area-by-area basis. With the development of an old-growth design, the Forests in cooperation with Michigan State University are examining the opportunity costs of their proposed allocation. A forestwide FORPLAN model with linkages to the Spatial Disaggregation Process software is being developed.

Introduction

National forests in the USDA Forest Service's Eastern Region (R9) have recently completed their forestwide plans. A major outcome of these strategic planning efforts is the allocation of land to specific management prescriptions. These prescriptions focus on producing resource outputs, providing opportunities for recreation-related activities, and attaining desired forest conditions. Current forest plans address issues and concerns usually identified in the late 1970's and early 1980's. As a result, analyses and needed quantitative models (e.g., FORPLAN) were often designed to address problems that have declined in importance, rather than emerging issues.

A major issue that has evolved in the past few years relates to biological diversity and in some cases more specifically to old-growth designations, particularly in the Pacific Northwest. This issue is also highlighted in the Eastern Region by an appeal settlement of the Huron-Manistee National Forests' (HMNF) Plan (HMNF, 1988). In resolving this appeal, the HMNF which is located in northern Michigan agreed to designate approximately 70,000 hectares for old-growth development during the first 10-year planning period. Overall, the Forests cover 388,250 hectares with 37,369 identified vegetative stands.

The HMNF, like other forests, must now update their strategic plan with new standards and guidelines and by superimposing new allocations (or designations) over those presented in the HMNF's final environmental impact statement. From an analytical standpoint, the concern centers on the implications of new allocation choices and management direction within the context of earlier decisions.

Specifically, the HMNF Management Team is interested in assessing the opportunity costs (in terms of net timber returns) and harvesting implications of old-growth allocations. Two allocation schemes will be examined. The first, developed by the Forests' Old Growth Team, utilizes an ecological design which capitalizes on semiprimitive nonmotorized areas and river corridors to form a network of areas of varying sizes across the HMNF. The second scheme uses larger areas or "mega-sites" as the design basis.

Though analysis results are not yet available, a review of past planning activities on the Forests highlights the linkages between initial forest plan allocations and plan implementation processes in the Eastern Region. These efforts accentuate the need for stronger linkages between the strategic and tactical/operational levels of forest planning. Moreover, for ongoing analyses, they provide a basis for examining the applicability of newer hierarchical planning approaches such as the Spatial Disaggregation Process (Merzenich, 1991).

Evolution of Forests' Planning Efforts

Recent forest planning efforts (i.e., post-National Forest Management Act) can be characterized as a learning process in which management policies, personnel and planning tools are changing. To gain insight into the process on an Eastern Region forest, this section reviews (1) initial forest plan allocation, scheduling and modeling, (2) early plan implementation efforts, and (3) the effects of an appeals settlement on these processes.

Initial Forest Plan Allocation, Scheduling and Modeling

The HMNF's Land and Resource Management Plan (hereafter called the Plan) and Final Environmental Impact Statement were approved on July 16, 1986. Cost efficient land allocation and resource scheduling were analyzed using FORPLAN (HMNF, 1986, p. B-23). The model was designed to address management problems associated with the HMNF's timber resources, recreation resources, wildlife and fish resources, road system, and special areas. Forest-based data used in the analysis were gathered mostly in 1982, approximately 10 years ago.

Five levels of identifiers were used in FORPLAN to address the problems; often these were combinations of strata that could have been separated into additional level identifiers. The first level identified forest (i.e., Huron or Manistee), timber suitability, and land type association (LTA) groups. The second level identified recreation opportunity spectrum (ROS) classes and contiguous areas that had potential for allocation to semiprimitive ROS management prescriptions. The third level identified relatively contiguous special areas (e.g., Kirtland's Warbler Management Areas, Pere Marquette National Scenic River, etc.) and general forest lands that were geographically dispersed. The fourth and fifth levels identified vegetative groups, site classes, vegetative age groups, and even- and uneven-aged management options.

Management constraints were developed for nondeclining and long-term sustained-yield of timber, ending timber inventory, minimum management requirements, resource demand, and vegetative management. In addition, selected contiguous areas were limited to desired management prescriptions (e.g., prescriptions emphasizing semiprimitive recreation management). In essence, FORPLAN was used to simulate the effects of management with many of the strategic allocation decisions made by the HMNF's Management Team and public input.

From a "new" allocation standpoint, ten contiguous areas were allocated to semiprimitive nonmotorized and motorized recreation with additional areas allocated to white-tailed deer and ruffed grouse management, respectively. Much of the remaining area was slated for management similar to that which had occurred historically, albeit with more specific management standards and guidelines.

Timber harvests and other resource outputs were scheduled and expected to increase over time. In effect, most individuals and groups were getting a larger piece of the HMNF pie than they had previously. This was possible due to the large timber base (i.e., 357,060 hectares tentatively suitable for timber production) relative to the final selection of approximately 210 thousand hectares for timber management. Though there were several appeals, the Forests proceeded with Plan implementation. The perception that the HMNF had a considerable amount of slack in its timber base provided latitude in addressing these appeals.

Early Forest Plan Implementation Efforts

The Eastern Region published broad integrated resource management guidelines for implementing forest plans just before the Plan was approved(USDA-FS Eastern Region, 1985). Six steps are included in this approach:

(1) Opportunities — This requires identifying subforest areas for best implementing the Plan. These areas are closely related to Management Areas identified in the Plan, but often reflect modification agreed upon by the HMNF's Management Team. The resulting areas are called Opportunity Areas (OAs); there are 102 OAs on the HMNF.
(2) Analysis — Though specific analysis guidelines were not developed, Ranger District personnel were charged with identifying projects that would ensure an integrated approach to forest management, including the spatial arrangement of desired future forest conditions on OAs.
(3) Schedule — This step includes scheduling and budgeting projects to best meet Forest Plan direction. The timeframe is the first decade of the planning horizon.
(4) Design — This involves site-specific design and appropriate National Environmental Policy Act (NEPA) analysis.
(5) Execute — At this step, projects are completed according to design.
(6) Protect and Manage — This step relates to continuing stewardship of forest resources. It is followed by monitoring.

In short, this approach relies on personnel to implement plans with monitoring as a major tool for ensuring compliance and eventual (in)feasibility. There were earlier efforts in 1984 to disaggregate FORPLAN solutions to subforest areas, but the approach proved too cumbersome. And a process-based implementation approach was favored over a computerized approach.

The HMNF began implementation in 1986 by requiring each of seven Ranger Districts to complete an OA document during 1987. Completion of all OA documents was scheduled over a multi-year period ending in 1995. High priority was given to OAs which would likely be most restricted in terms of vegetative management (e.g., semiprimitive nonmotorized areas). Projects in other areas are still pursued using the NEPA process, however. For example, timber sales needed to create habitat for ruffed grouse are proposed even though the OA in which they occur has not been analyzed completely. The strength of this approach is in reliance on District personnel and public input to create implementable projects.

However, a major shortcoming of this approach became evident quickly. Each OA Team had to deal with a number of issues that were linked with broader areas. For example, several hundred thousand forested acres were identified as "not appropriate for timber management". Locating these lands on an OA-by-OA basis without consistent direction would likely miss the target. There were also concerns over whether too little or too much timber was being scheduled for harvest in areas. Firmer direction soon came as the result of an appeals settlement agreement (HMNF, 1988).

The Appeals Settlement and Its Effects

Among other issues, the settlement agreement provided a mechanism for withdrawing appeals by environmental and commodity-oriented groups. As part of the settlement, the HMNF agreed to designate approximately 70,000 hectares for "old growth" during the first 10-year planning period. This facet of the agreement favored groups interested in protecting species requiring old growth and interior habitats. There are, of course, few tracts in Michigan that can be considered old growth at the present time. Thus, designating specific areas that can be restored to old growth is an important task.

Krejcarek (n.d) noted that the ongoing OA analysis procedure "... did not accommodate spatial continuity needs for delineating 'old-growth emphasis areas' across OA and Ranger District boundaries." To address the "old-growth" issue on the HMNF, an Old Growth Team was formed in 1989. This technical advisory group consists of university, forest products industry, environmental, Forest Service Research, and HMNF representatives. The Team's objectives include:

(1) designing a landscape for old growth which ensures biological [diversity] and economic efficiency which enables assessment of cumulative effects at various geographic scales,
(2) formulating local definitions and categories for old growth forests,
(3) devising appropriate management and restoration practices by old growth definition and category, and
(4) developing methods for implementing these practices and their effects (Cleland, 1990).

A key element in the HMNF's old-growth design is their ecological classification system (ECS). The ECS provides an important framework for hierarchical planning (Brenner and Jordan, 1991). As noted by these authors, landtype associations or LTAs were used to help identify management areas in the first round of planning. LTAs are mapped ecological units which are often differentiated in terms of landforms, natural vegetative communities, and soil associations. In the HMNF's original FORPLAN model, for example, LTAs were aggregated into three classes: sand plains and low sandy hills, rolling plains and morainal hills, and low, wet areas. LTAs are at the mid-level of the ECS hierarchy with multi-state provinces at one extreme and sites less than an acre in size at the other (Brenner and Jordan, 1991).

A balance of old-growth forest types across LTAs is desired to ensure a full variety of landscape ecosystems. The HMNF is currently using eight LTAs for planning purposes. The LTAs play a dual role of assisting in the HMNF's old-growth design (including evaluation) and in providing a basis for the opportunity cost analysis.

The most recent summary of old-growth designations by LTA are as follows:

Landtype Association	HMNF (%)	Old-growth (%)
Sandy outwash plains	45.4	37.3
Dry sandy hills (ice contact)	21.5	15.0
Morainal hills	13.5	9.9
Wet sand plains	5.4	6.8
Wetland associations	10.6	27.7
Clayey hills and plains	0.9	0.7
Loamy ground moraines and outwash	2.3	1.4
Active and stable dunes	0.3	1.3

The three largest LTAs are not proportionately represented in the current design because semiprimitive areas (including several new areas designated in the settlement) were used as initial core areas with riparian and wetland associations as linkages.

The design's spatial heterogeneity is based, in part, on Harris' (1984, p.135) proposed log-normal size-frequency distribution. As reiterated by Hunter (1990, p.87), this allows for a few large areas and numerous smaller areas. This design then mimics the area distribution of many natural phenomena (e.g., wildfires, riverine systems, etc.). Hunter concedes, however, that this is "...based on informed speculation."

An alternative using a "mega-site" design approach is being developed. This design will likely concentrate more on dry sandy hills, morainal hills, and clayey hills and plains where long-lived forest types dominate. A breakdown including vegetative types by LTA will be used for comparing the current and "mega-site" designs.

In modeling, the eight LTAs will be used to the extent practicable given their utility in differentiating timber management costs, silvicultural prescriptions, and yields (Leefers et al., 1987). In reviewing yield data used in the Plan, several questions regarding yields of existing versus regenerated stands surfaced. Of greatest concern are considerable volume increases associated with regenerated types that are extensively managed. If these yield increases are unfounded, the long-term sustained-yield or timber management acres could change significantly.

Timber yields for different forest types in the Plan were based on site index. While this is useful in some analyses, growth and yield data for this analysis are based on tree lists from ECS sample plots. These plots provided the basis for developing the ECS's ecological landtype phases (ELTPs) which will be used in operational or project-level planning on the HMNF. ELTP's provide finer detail than LTAs in the ECS hierarchy. Yield estimates for these plots are currently being reviewed.

The old-growth design has had a strong effect on the OA planning efforts. OA discussions have evolved from brief presentations of future targets, to residual or "what's left" old-growth designations, and now to clear identification of the role a particular OA plays in a cohesive design. This has considerably reduced the time needed for analysis and allows for fine-tuning of the design. Clearly, this has been a hierarchical planning effort that has relied on ECS data and an old-growth design to improve the acceptance and ecological feasibility of Plan implementation. To date, over 71,630 hectares of candidate old growth have been identified; only a few thousand hectares have old growth attributes. Candidate old growth stands have not yet been legally designated through the NEPA process.

Several other Old Growth Team efforts bear on the analysis, too. The first is the definition of old growth for the HMNF. Plan definitions highlighted the stand age. Newer definitions are specific to LTAs and include timber type and desired characteristics for canopy layers (e.g., age, basal area, trees per acre, etc.), understory and ground cover, decadent trees, dead trees, and disturbance. Development of these definitions is coordinated with other Lake States forests to provide consistency and to avoid future problems (for example, see Wilderness Society, 1988, p. A-1).

The other related effort by the Old Growth Team is development of standards and guidelines for "restoring" stands to old-growth conditions. In some instances, harvesting may be required, and the Team has drafted direction for these practices. They provide the basis for old-growth prescriptions in FORPLAN.

Effects of old-growth allocations in terms of opportunity costs and on allowable sale quantities are unclear at this juncture. This has evolved due to questionable yield data for regenerated timber stands and to development of an old-growth design that does not correspond directly to acres "not appropriate for timber management." Thus, a new forestwide analysis is needed that accounts for old-growth allocations and related standards and guidelines.

New Forestwide Model

A new forestwide FORPLAN model is being developed to assess the opportunity costs associated with two old-growth designs. The HMNF will be stratified initially using Forest (Huron or Manistee), forest types, age, LTAs, size-class density, and old growth status. This will provide a means for incorporating management constraints used in the Plan while clearly identifying the old-growth areas. Old-growth will be modelled as single analysis areas for the Huron and Manistee National Forests.

Currently, three parallel efforts are underway. First, Corporate Database System information on all forest stands has been transferred in ASCII format to Michigan State University. The data have been reviewed by the author and numerous corrections have been made by District personnel.

In addition, tree lists and "initial condition" timber yields are being estimated for approximately 220 ECS stands. These are being compared with existing and regenerated yields used in the Plan. This comparison will provide an indication of potential differences between Plan and forthcoming results. It also highlights the utility of having ECS data available. After comparisons are made, growth and yield data based on aggregations of these stand tree lists will be developed for FORPLAN analyzes.

Finally, timber cost and return data are being collected. The stumpage price data will be combined with time series data used in developing the Plan analysis. Then real price trends will be examined along with average prices. Cost data will be gathered for timber management costs only. Recreation and other non-timber values and costs are excluded from this analysis, though HMNF may add them at a later date. "Shadow prices" for other resource constraints will be calculated. Thus, effects of management constraints for minimum habitat requirements will be assessed.

When these activities are completed three FORPLAN alternatives will be examined. The first will maximize present net value subject to existing Plan constraints. This will provide old growth without any specific design. The second will superimpose the ECS-based old-growth design over this problem. The difference between objective function values will give a measure of the opportunity cost (Jones et al., 1978; Teeguarden, 1981). The third alternative will combine "mega-site" allocations with constraints used in the first, and opportunity costs will be calculated. Additional analyzes will examine the marginal cost of expanding the old-growth acreage. For all cases, the forest-type composition of harvests and representativeness of old-growth designations will be compared.

Approved OA prescriptions must be included in the analysis through the use of constraints where needed. However, without a forestwide linkage to the OAs, feasibility is uncertain. As an initial screening for feasibility, the Spatial Disaggregation Process (SDP) will be tested for disaggregating FORPLAN results to OAs (Merzenich, 1991). Preliminary efforts with this software are presented in the next section.

Linkages with SDP Software

SDP provides a means for disaggregating forestwide analysis results to subforest areas. To accomplish this task, forestwide results must be transferred to database software, aggregated on a subarea basis, and displayed in map form (Merzenich, 1991). SDP encompasses database management, map display, and harvest redistribution algorithms. Thus, the nature of the problem being addressed may affect the extent to which elements of this system are used.

For the HMNF, only preliminary SDP models have been developed. SDP uses a computerized map, so rigid map boundaries must be selected. Of course, multiple maps could be developed but this may defeat the notion of "quick" analysis. For the HMNF, OAs are mapped separately for each Forest. Outputs from the FORPLAN model can be reported by Forest providing a convenient link. Alternatively, forestwide results could be prorated.

A very useful and expanding feature of the map display is the ability to present attributes of areas. For meetings and visual analysis, users can display features such as percent of old growth, ROS, vegetative information, and so on. These data must be developed in the database, but can then be quickly viewed. For example, this could be used to highlight areas whose current type composition is most or least like the desired future conditions for areas. Thus, opportunities could be seen and later pursued with more detailed analyzes.

To utilize the timber harvest redistribution algorithms, thresholds or upper limits must be placed on subareas (e.g., OAs). Examples could be related to available harvest area given forest types, ages, and standards and guidelines on clearcut sizes. Current algorithms are fairly simplistic in that they redistribute based on average volumes per subforest area. In some areas, this may create problems (e.g., when volumes by age, type and site differ considerably) while in others it may be a good approximation. For eastern national forests which have been developing OA analyzes, it may be useful to include lower limits to reflect decisions that have been made. These would complement the thresholds or upper limits.

The most powerful analytical element of the system is the database software. Here, FORPLAN solutions can be linked to individual stands. That is, the greatest detail exists in this element. For many purposes, this may be an overwhelming amount of information. Then, the more aggregated visual display may be more helpful. In addition, ties between thresholds and FORPLAN constraints could be developed in an iterative process to help ensure that FORPLAN results are implementable.

As noted above, it is premature to judge the utility of the SDP framework in analyzing proposed harvests on the HMNF. It shows great promise, and designers are developing additional features that will increase its flexibility. Without question, some means is needed for examining forestwide analysis results on a subforest level.

Conclusions

This paper has described the evolution of post-NFMA forest planning on the Huron-Manistee National Forests. The focus has been on changes in issues (principally concern for old growth) and the effects of the changes on hierarchical planning on the HMNF.

People, rather than models, have played the major role in implementing the Forests' Plan. Information is developed, and decisions are made. However, analytical models can help clarify relationships that cannot be addressed on an area-by-area basis. FORPLAN, SDP and other models can assist in these efforts.

Three hierarchical elements have been described. The first is the unifying role of the old-growth design on Opportunity Area analyzes. The second is the use of the ECS in evaluating the design and in differentiating management options. The last is the effort to link FORPLAN solutions to Opportunity Areas.

If initial land allocations are already made, analysis can address more specific questions such as "What is the opportunity cost of designating land for old growth?" Less time is needed for developing the allocation choices. This should be encouraging to national forests preparing to revise their original plans. It should also provide more opportunities to develop plans from the bottom up since fewer strategic choices are needed. However, difficult decisions must still be made. As Bolgliano (1989, p. 48) astutely concluded, "[r]egrowing eastern old-growth raises the same basic questions managers out West are struggling with: How much is enough, and where should it be?"

Further, Crow (1990, p. 50) noted that: "[a]lthough we know very little about old-growth forests, we do know that old growth is different than young growth and that these differences enhance biological diversity if old growth is a component of the regional landscape." Assessing opportunity costs provides us with a little more knowledge about old-growth allocations.

Acknowledgments

Several individuals have helped and continue to assist me in this project. Thomas Crow, from the USDA-Forest Service's North Central Forest Experiment Station, has funded this project, and Michael Vasievich has provided administrative support. David Cleland, originally on the HMNF, has made significant contributions in the development of the ECS and the old-growth design. Don Krejcarek has coordinated this project on the HMNF with over a dozen people. James Merzenich and William Connelly, from the Forest Service's Pacific Northwest Region provided SDP assistance and insights. Many others deserve recognition as well. As with all studies of this type, final responsibilities for completeness rest with the author.

References Cited

Bolgiano, C. (1989). "A Case for Eastern Old-Growth", American Forests, May/June: 26-29, 31, 48.

Brenner, R.N. and Jordan, J.K. (1991). "The Role of an Ecological Classification System in Forest Plan Development and Implementation", *in* M.A. Buford (compiler), Proceedings of the 1991 Symposium on Systems Analysis in Forest Resources, USDA Forest Service, Southeastern Forest Experiment Station Gen. Tech. Rep. SE-74, pp. 70-80.

Cleland, D.T. (1990). "Old Growth Team Report", memorandum to Steve Kelley, Forest Supervisor, Huron-Manistee National Forests, Cadillac, Michigan, 4 p.

Crow, T.R. (1990). "Old Growth and Biological Diversity: A Basis for Sustainable Forestry", Chapter 6 in The Faculty of Forestry and the School of Continuing Studies (compilers and editors), Proceedings from the Conference on Old Growth Forests, Canadian Scholars Press, Inc., Toronto, Ontario, pp. 49-62.

Harris, L.D. (1984). The Fragmented Forest, The University of Chicago Press, Chicago, Illinois, 211 p.

Hunter, M.L., Jr. (1990). Wildlife, Forests, and Forestry: Principles for Managing Forests for Biological Diversity, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 370 p.

Huron-Manistee National Forests (1986). Final Environmental Impact Statement, Land and Resource Management Plan, Cadillac, Michigan.

Huron-Manistee National Forests (1988). "Final Statement of Agreement for Appeals 1730, 1731, and 1735" signed on August 11, Cadillac, Michigan, 47 p.

Jones, J.G., Beardsley, W.G., Countryman, D.W., and Schweitzer, D.L. (1978). "Estimating Economic Costs of Allocating Land to Wilderness", Forest Science 24(3): 410-422.

Krejcarek, D. (No date). "Huron-Manistee National Forests Old-Growth Initiative", unnumbered mimeograph, Huron-Manistee National Forests, Cadillac, Michigan, 5 p.

Leefers, L.A., Cleland, D.T., and Hart, J.B. (1987). "Ecological Classification System: Information and Economics", *in* R.L. Hay, F.W. Woods, and H. DeSalm (editors), Proceedings of the Central Hardwoods Conference VI, pp. 195-204.

Merzenich, J.P. (1991). "Spatial Disaggregation Process: Distributing Forest Plan Harvest

Schedules to Subareas", *in* M.A. Buford (compiler), Proceedings of the1991 Symposium on Systems Analysis in Forest Resources, USDA Forest Service, Southeastern Forest Experiment Station Gen. Tech. Rep. SE-74, pp. 250-254.

Teeguarden, D.E. (1981). "A Method for Designing Cost-effective Wilderness Allocation Alternatives", Forest Science 27(3):551-566.

The Wilderness Society (1988). End of the Ancient Forests: A Special Report on National Forest Management Plans in the Pacific Northwest, Global Printing, Inc., Alexandria, Virginia, 57 p.

USDA Forest Service, Eastern Region (1985). Working Together for Multiple Use, Integrated Resource Management, U.S. Government Printing Office, Washington, D.C., 26 p.

Incorporating Wildlife Objectives into Forest Planning

G.J. Roloff and J.B. Haufler
Michigan State University, Department of Fisheries and Wildlife, East Lansing, MI, USA

Abstract

The ability of contemporary forest plans to fulfill multiple-use objectives of all natural resource managers depends on the development of systematic approaches that adequately project timber outputs, allow for coordinated recreational planning, and allow for the spatial and temporal analysis of habitat conditions for a diverse assemblage of wildlife species. These factors can be addressed in forest plans by integrating forest stand inventories, ecological classification systems (ECS), and wildlife habitat models through the use of geographic information systems. We demonstrate this approach by simulating the removal of approximately 35,000 cords of aspen (Populus spp.) from 4500 ha in the northern lower peninsula of Michigan. The effects of the harvest were assessed in terms of timber output, the proximity of cuts to roads, the effects on ruffed grouse (Bonasa umbellus) habitat, and short- and long-term changes in the vegetation composition and physiognomy.

Introduction

Contemporary forest planning must meet multiple use objectives to satisfy diverse interest groups and to fulfill the various goals of natural resource professionals. In the past, forest planning has attempted to meet multiple-use objectives through a generalized, quantitative approach. This approach usually assessed total acreages of selected forest types and projected outputs of cords or board feet of timber, total number of recreation user days, and wildlife responses as activity days of consumptive or non-consumptive use. Management goals varying depending on the forest, the organization, and the user constituency, and thus, goals are defined and assessed in a variety of ways. Few of the planning approaches have considered the actual spatial arrangement of vegetation cover types, nor have successional changes of more than one harvest rotation in length been included. These considerations are critical components in the forest planning process for successful multiple-use management.

Most wildlife biologists are skeptical of forest plans that do not incorporate the spatial arrangement of vegetation types and long-term changes in vegetation composition and structure. Research has demonstrated that many wildlife populations respond differently to changes in these landscape components. Forest plans that exclude these considerations leave much room for variation in potential responses by wildlife populations.

The ability to integrate effective wildlife habitat management into forest plans will rely on developing systematic approaches that will allow for the projection of timber outputs, coordinated recreation planning, and for the spatial analysis of current and future wildlife habitat conditions. Methods are needed that will classify landscape components into discrete units linked by their ecological relationships. Also, the method needs to be flexible, allowing spatial analyses at a variety of landscape resolutions in addition to assessing the effectiveness of multiple-use management over varying time scales.

The Proposed Approach

The approach we are developing uses an ecological classification system (ECS) and a forest cover type map to provide a planning base map. These coverages have been digitized into a geographic information system (GIS) for data and map storage and retrieval, display purposes, spatial analyses, and temporal modeling. Timber output models and wildlife habitat models are also incorporated to predict forest outputs.

Ecological classification systems have recently provided a means of classifying landscapes based on their ecological relationships. The underlying assumption of an ECS is that the forms and functions of forest communities will express the interactions of climate, landform, soils, and biota over time within similar ecological units (Rowe 1991). An ECS has been developed for use in Michigan that allows for the mapping of ecological units that will develop into forest stands with similar vegetative features and successional pathways. Thus, by using the ECS in a forest planning context, the delineated boundaries have a greater ecological significance as opposed to delineating stand boundaries on the basis of dominant overstory vegetation alone.

The early applications of the ECS were to obtain relatively rapid, inexpensive inventories for broad level planning purposes (Russell and Jordan 1991). As the forest planning process responded to federal legislation mandating multiple use management, it became apparent that forest plan implementation required a more detailed level of land and ecosystem classification (Russell and Jordan 1991). The ecological land type phase (ELTP) was subsequently incorporated into the forest planning process. The ELTP provides the most detailed, site specific level of the ECS that is normally mapped on an operational basis. The approach we are proposing operates on the ELTP level.

The ECS is useful for describing ecosystem dynamics and estimating the biotic potentials of various sites. The information regarding future plant communities and successional trends is important to the forest planner because issues such as habitat fragmentation, old growth, and biodiversity need to be addressed. Additionally, by recognizing the potential to enhance or degrade specific forest sites, silvicultural applications best suited for each site can be applied (Fox 1991).

The ECS does not replace timber or other vegetation inventory systems. The corporate database system (CDS), with forest stand-based data, compliments the ECS. The CDS delineates existing forest vegetation on the basis of dominant overstory vegetation and also classifies stands based on size class and stocking density levels. By combining the two classification systems, resource maps are created that can describe the existing vegetation, predict ecological processes (e.g., successional pathways, disturbance regimes), and estimate the environmental effects of individual forest planning projects.

Preliminary results from the research we are conducting indicate that the ECS is an effective tool for increasing the accuracy of quantified vegetation attributes (e.g., basal area, canopy cover). Our data suggest that the sample variance of different vegetation attributes decreases when the sampling scheme incorporates ELTP's. This trend implies that the ECS is an effective tool for increasing the accuracy of quantitative estimates of forest outputs. Thus, use of the ECS is one tool for forest planning that we have incorporated that not only helps plan for temporal changes but also can increase planning accuracy.

The approach we are developing also uses habitat suitability index models (U.S. Fish and Wildlife Service 1981) to quantify wildlife habitat quality. Ecological theories that support the concept of wildlife-habitat relationships include habitat space and selection (the "niche" concept), island biogeography, territoriality, and carrying capacity (Balda et al. 1983, Flather and Hoekstra 1985). The underlying assumption of habitat models is that the intensity of habitat use represents habitat suitability (Best and Stauffer 1986). Assumptions and concerns of wildlife habitat modeling have been discussed (Farmer et al. 1982, Cole and Smith 1983, Van Horne 1983), but the basic approach has received considerable support. Although the most accurate assessment of wildlife density and habitat quality relationships is dependent upon an understanding of the demography of the wildlife population and the factors that influence survival and reproduction (Van Horne 1983), until databases provide this information, the most feasible means of assessing wildlife potentials of an area is via habitat measurements. We believe that if model output is conscientiously analyzed, habitat modeling can be a valuable planning tool and represents the most pragmatic approach available today.

Wildlife habitat suitability models can be applied to a multitude of landscape resolutions and can be used to assess wildlife responses to forest planning activities. Habitat suitability is linked to the individual habitat variables with linear relationships, and the estimates of habitat suitability for each variable are combined into a meaningful index using a variety of weighting and averaging procedures (Laymon and Barrett 1986). By incorporating the ELTP classification into the assessment of the habitat variables, the variance of the habitat suitability index can be reduced. Incorporating ELTP's into the habitat models also permits resource planners to estimate the future suitability of wildlife habitat.

Finally, we are using a GIS to integrate the ECS, CDS, and wildlife habitat models. The value of GIS for display and transmission of forest inventory results is now widely recognized in the forestry community (Sheffield and Royer 1990). In addition to providing analysis capabilities at a variety of landscape resolutions, the GIS also provides a means of spatially analyzing the arrangements of forest stands. The spatial analysis capabilities of the GIS can assist forest planners in addressing a variety of issues including habitat fragmentation, corridors, and the strategic locations of silvicultural treatments. The spatial effects of silvicultural treatments and/or arrangements on different wildlife species can also be addressed. The GIS also provides a tool that can generate information on any forest outputs for which quantitative information is available on a forest stand or forest type basis.

As will be demonstrated in the following example, the approach to forest planning that we are proposing would function at all levels of hierarchial forest planning. The effects of specific projects can be quantified and documented. The tactical planning of facilities, roads, and costs of various planning alternatives can be addressed by this approach. Additionally, forest outputs (e.g., cords of timber) can be evaluated for a variety of management scenarios. The adaptability of the GIS allows for a strategic evaluation of a regional and dynamic landscape. Also, planned activities can be assessed as to how they fit into regional goals or priorities in terms of the multiple use objectives.

An Example: Aspen Cutting on the Huron National Forest

As an example of how the proposed approach would operate, we chose to simulate the harvest of aspen (*Populus* spp.) on 4500 ha of the Huron National Forest, Michigan. Specifically, we simulated the removal of approximately 35,000 cords of pole-timber aspen (both bigtooth (*P. grandidentata*) and trembling (*P. tremuloides*)) via clearcutting. Cuts were interspersed, however, stands within 700 m of a primary road were not cut for aesthetic reasons. The objectives of the harvest were to meet the timber output goals while minimizing the area subjected to clearcutting. Under this management scenario, the stand (or parts of stands) that contained the largest volumes of aspen were cut. The harvest was analyzed as to timber output, the proximity to primary roads, the effects on ruffed grouse (*Bonasa umbellus*) habitat, and the short- and long-term changes in vegetation that would occur on the disturbed sites.

Pole-timber aspen stands (721 ha) were delineated from the Forest Service's stand inventory database by using the GIS (Fig. 1). The corresponding ECS coverage was overlaid, and the ELTP's of each aspen stand were incorporated into the assessment of basal area (Fig. 1). By incorporating the ECS, each aspen stand could potentially contain numerous ecological units of differing basal areas and corresponding ELTP's (Fig. 1).

The numbering scheme of the ECS for our geographic region ranged from 200 to 282, with the numbers generally increasing with increases in site fertility or moisture availability. From the forest stand/ECS database, it was determined that the mean basal areas for bigtooth aspen stands on ELTP's in the 230's and 220's were the highest, followed by stands of trembling aspen on ELTP's in the 220's. These ELTP's differ primarily in soil capabilities, with the 230's being more fertile sites than the 220's. Cutting priority was thus established based on forest stand/ELTP relationships.

The GIS was used to select the stands from the forest stand/ECS database that satisfied the cutting objectives and limitations and to display the spatial arrangements of the cuts (Fig. 1). Cuts were an average

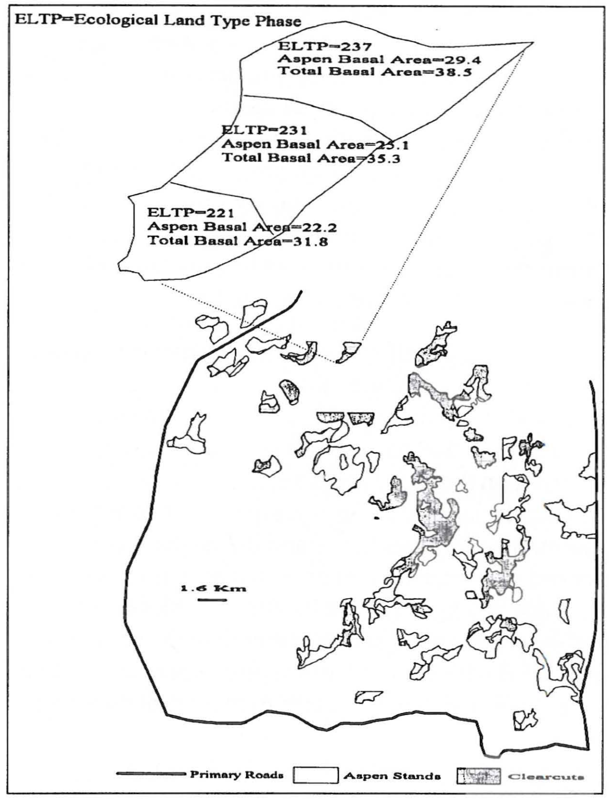


Figure 1. Pole-size aspen delineated from Forest Service's stand inventory database. Spatial arrangement of proposed clearcuts. No cuts were within 700 m of a primary road. Enlargement: Individual aspen stand showing the influence of ELTP on the assessment of basal area.

of 1880 m from primary roads. It was estimated that this harvest would yield 34,990 cords of pole-timber aspen.

The effect of the timber harvest on ruffed grouse was assessed by comparing habitat suitability indices for pre-harvest and post-harvest conditions. The index used was on a 0.00 to 1.00 scale; with 0.00 representing the poorest quality habitat and 1.00 representing the highest quality habitat. Although we chose to evaluate the effects of the harvest on grouse, any number of wildlife species could be used if habitat models exist and the databases contain the necessary variables. Habitat suitability indices for grouse were obtained by applying data from the forest stand/ECS database to the habitat model developed for grouse in Michigan (Hammill and Moran 1986). Mean values for sapling and shrub densities, sapling and shrub heights, and conifer branch heights were used to compute the indices. The habitat model also required a quantitative assessment of the interspersion of suitable fall/spring cover and winter food sources (Hammill and Moran 1986).

Habitat suitability indices can be computed at a variety of landscape resolutions using area weighting procedures. For example, the pre-harvest suitability of grouse habitat was assessed at the individual stand level at the township section level (Fig. 2), and for the entire area. Figure 2 also demonstrates the use of the GIS to quantify the interspersion of grouse habitat. For example, if a suitable winter food source for grouse was within the 100 m buffer surrounding the "suitable cover", the interspersion index was 1.00.

To assess the effects of the timber harvest on ruffed grouse habitat suitability, the harvested stands were projected approximately 10-15 years into the future. It was assumed that natural regeneration of aspen occurred on the harvested sites, and post-harvest sapling stocking densities corresponded to pre-harvest pole-timber densities (i.e., stand delineated as densely stocked pole-timber were projected as densely stocked saplings). By inserting the habitat variables of the post-harvest sapling stands rather than the variables associated with the pre-harvest pole-timber stands into the grouse model, a quantitative estimate of the effects of the harvest on the habitat suitability for grouse could be calculated.

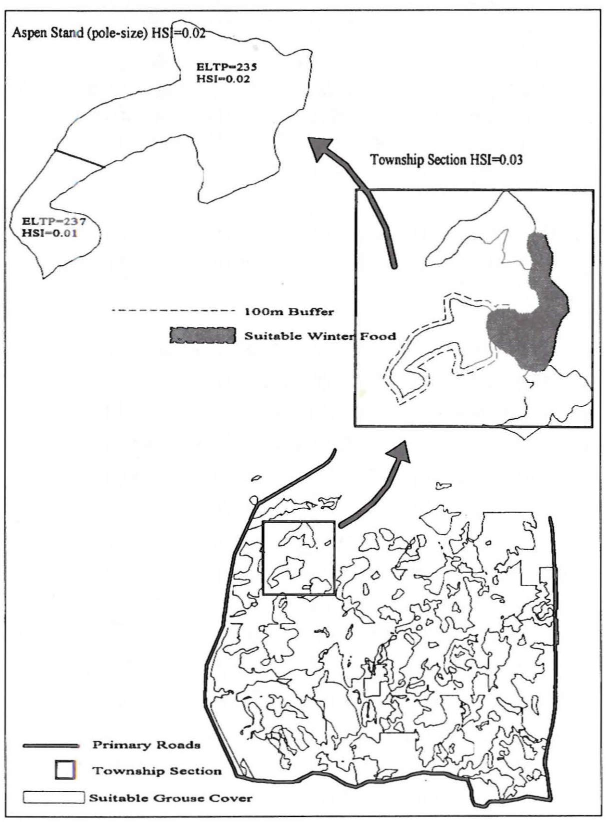


Figure 2. Forest stands delineated as suitable for ruffed grouse cover. Enlargements: The technique used (buffering) to quantify the interspersion index for grouse. Mean habitat suitability indices (HSI's) for a township section, forest stand, and ecological unit (ELTP).

The suitability of the entire study area prior to the harvest was 0.02. Following the removal of approximately 35,000 cords of pole-timber aspen, the habitat suitability index for the area 10-15 years from the present was 0.04. Without the timber harvest, grouse habitat quality on the entire area would be projected to decrease in 10-15 years to 0.00. Thus, the timber harvest appeared to maintain the quality of the grouse habitat. Without the timber harvest the suitability of the grouse habitat would be reduced, primarily due to decreases in sapling densities and low interspersion indices. The changes in habitat suitability indices for the entire area are subtle, however, when the changes in habitat suitability are analyzed at a smaller landscape resolution, the effects are more pronounced. For example, the habitat suitability index for the individual stand delineated in figure 3 was 0.02. When the same stand is harvested and regenerates to saplings, the habitat suitability increases to 0.15.

Habitat suitability values for other wildlife species on the area at the present time were 0.57 for black-throated green warbler (*Dendroica virens*), 0.14 for gray squirrel (*Sciurus carolinensis*), 0.01 for eastern bluebird (*Sialia sialis*), and 0.01 for pileated woodpecker (*Dryocopus pileatus*).

The future vegetation cover types of the harvested stands can be predicted from the ECS. Natural regeneration of aspen will initially dominate the harvested stands, and the aspen cover type will prevail for approximately 50-70 years, corresponding to the pathological rotation of aspen in Michigan (Zavitkovski et al. 1976). As the stands continue to mature without catastrophic disturbance, the aspen should lose dominance to red maple (*Acer rubrum*), mixed oak (*Quercus* spp.), or other tolerant tree species as predicted by the corresponding ELTP's. In addition to shifts in overstory composition, understory and ground layer vegetative physiognomy and composition of stands will diverge as time progresses. The divergence partially depends upon the underlying ELTP's. Other factors that may cause a divergence include disturbance and short-term climatic fluctuations.

As the stands on ELTP's in the 220's progress to maturity, the vegetative composition of the understory is predicted to consist of red maple (177 stems/0.04 ha), witch hazel ((*Hamamelis virginiana*)(48 stems/0.04 ha), and beaked hazel (*Corylus cornuta*). Oak species will be poorly represented. The ground flora will consist of low coverages of maple-leaf viburnum (*Viburnum acerifolia*) and bracken fern (*Pteridium aquilinium*), red maple, juneberry (*Amelanchier* spp.), and sedges (*Carex* spp.).

The understory and ground layer of stands on ELTP's in the 230's will have a different vegetative physiognomy and composition. Understory species will be predominantly red maple (67 stems/0.04 ha) and witch hazel (196 stems/0.04 ha). The dominants of the ground layer will include high coverages of maple-leaf viburnum, sarsaparilla (*Aralia nudicaulis*), starflower (*Trientalis borealis*), lily-of-the-valley (*Maianthemum canadense*), large-leaf aster (*Aster macrophyllus*), and squaw root (*Conopholis americana*).

Conclusions

The technology is presently available to incorporate the proposed approach into forest planning. Ecological classification systems may need to be modified and mapped in certain areas, but the framework for their implementation and use is available. Implementation of the proposed approach will require a commitment and prioritization of resources. Truly effective multiple-use forest plans need to recognize the importance of incorporating adequate spatial and temporal components. Only by recognizing the importance of such approaches can forest planners expect to obtain the support and endorsement of all natural resource managers.

Acknowledgments

The U.S.D.A. Forest Service and the Michigan Agricultural Experiment Station are acknowledged for their financial support of aspects of this research.

References

Balda, R. P., W. S. Gaud, and J. D. Brawn. (1983). "Predictive models for snag nesting birds". Pages 216-222 *in* J. W. Davis, G. A. Goodwin, R. A. Ockenfels, tech. coords. Snag Habitat Management: Proceedings of a Symposium. United States Department of Agriculture, Forest Service General Technical Report RM-99.

Best, L. B., and D. F. Stauffer. (1986). "Factors confounding the evaluation of bird-habitat relationships". Pages 209-216 *in* J. Verner, M. L. Morrison, and C. J. Ralph, eds. Wildlife 2000. University of Wisconsin Press, Madison, Wisconsin, U.S.A.

Cole, C. A., and R. L. Smith. (1983). "Habitat suitability indices for monitoring wildlife populations", Transactions of the North American Wildlife and Natural Resources Conference, Vol. 48.

Farmer, A. H., M. J. Armbruster, J. W. Terrell, and R.L. Schroeder. (1982). "Habitat models for land use planning: assumptions and strategies for development", Transactions of the North American Wildlife and Natural Resources Conference, Vol. 47.

Flather, C. H., and T. W. Hoekstra. (1985). "Evaluating population-habitat models using ecological theory", Wildlife Society Bulletin, Vol. 13.

Fox, T. R. (1991). "The role of ecological land classification systems in the silvicultural decision process". Pages 96-101 *in* D. L. Mengel and D. T. Tew, eds. Ecological Land Classification: Applications to Identify the Productive Potential of Southern Forests. United States Department of Agriculture, Forest Service General Technical Report SE-68.

Hammill, J. H., and R. J. Moran. (1986). "A habitat model for ruffed grouse in Michigan". Pages 15-18 *in* J. Verner, M. L. Morrison, and C. J. Ralph, eds. Wildlife 2000. University of Wisconsin Press, Madison, Wisconsin, U.S.A.

Laymon, S. A., and R. H. Barrett. (1986). "Developing and testing habitat-capability models: pitfalls and recommendations". Pages 87-91 *in* J. Verner, M. L. Morrison, and C. J. Ralph, eds. Wildlife 2000. University of Wisconsin Press, Madison, Wisconsin, U.S.A.

Rowe, J. S. (1991). "Forests as landscape ecosystems; implications for their regionalization and classification". Pages 3-8 *in* D. L. Mengel and D. T. Tew, eds. Ecological Land Classification: Applications to Identify the Productive Potential of Southern Forests. United States Department of Agriculture, Forest Service General Technical Report SE-68.

Russell, W. E., and J. K. Jordan. (1991). "Ecological classification system for classifying land capability in midwestern and northeastern U.S. national forests". Pages 18-24 *in* D. L. Mengel and D. T. Tew, eds. Ecological Land Classification: Applications to Identify the Productive Potential of Southern Forests. United States Department of Agriculture, Forest Service General Technical Report SE-68.

Sheffield, R. M., and L. A. Royer. (1990). "GIS - a broad scale inventory perspective", Forestry on the Frontier, Proceedings of the 1989 Society of American Foresters National Convention, Spokane, Washington, U.S.A.

United States Fish and Wildlife Service. (1981). Standards for the Development of Habitat

Suitability Index Models. United States Fish and Wildlife Service, Release Number 1-81, 103 ESM.

Van Horne, B. (1983). "Density as a misleading indicator of habitat quality", Journal of Wildlife Management, Vol. 47.

Zavitkovski, J., J. G. Isebrands, and D. H. Dawson. (1976). "Productivity and utilization of short-rotation *Populus* in the Lake States". Pages 392-401 *in* B. A. Thielges and S. B. Land, Jr., eds. Proceedings, Symposium on Eastern Cottonwood and Related Species, Louisiana State University, Baton Rouge.

Data and Decision Aggregation Processes in Forest Hierarchical Planning

A. Weintraub

Department of Industrial Engineering, University of Chile, Chile.

Abstract

We analyze several forest management problems related to cases in the US Forest Service and pine plantations belonging to vertically integrated forestry firms in Southern Chile. We present several problems at different managerial levels, such as land use allocation, road building, stand management: problems that are viewed as separate ones but linked. We discuss, for different cases how the linkage was developed between different decision levels so as to obtain solutions that are consistent and close to optimality. The basic approaches are based on different forms of aggregation and disaggregation of data, relations and decisions, for linking problems of different managerial levels.

Introduction

When using a hierarchical approach to deal with forest management, decisions can be analyzed in separate, manageable levels. A difficult problem with this approach is to adequately link decision processes in different levels, as the decisions are obviously interelated. The basic links are flow of information as decisions move up to a strategic level, and flows of directives as decisions move down, to tactical and operational levels.

In order to handle this, aggregation and disaggregation processes must be defined. We will consider cases related to forests belonging to the US Forest Service and also in the context of vertically integrated Chilean forest firms, whose timber comes from pine plantations.

In this paper we analyze different approaches we have used successfully to obtain consistency between planning levels.

a) LP aggregation, where the dimensions of large scale LP planning models are reduced through taking convex combinations of columns. A typical application is the use of models where variables represent management alternatives.
b) Modal aggregation, similar in spirit to LP aggregation and simpler, where representative columns are chosen to reduce the dimensions of the LP.
c) A priori aggregation which is a more rigourous way of carrying out modal aggregation. In this case, the original data is aggregated by creating representative stands using cluster analysis and management alternatives are generated for those.
d) Proxy variables. This corresponds to the case where decision variables at detailed level cannot be easily aggregated for consideration in higher level models. Such is the case of road building decisions, which are of combinatorial nature. In this case, for the aggregate, higher level model, proxy relationships are defined.
e) Simulation. In this case, the results obtained at lower decision levels are used as inputs for higher level models.

LP Aggregation

This application is carried out for large scale LP models, where decision variables are as continuous. This is the typical case when variables define silvicultural or management alternatives as in a Model I formulation (Johnson and Scheurman, 1977). The LP aggregation approach was first proposed by Zipkin, 1979 and is based on replacing a set of similar columns by a convex combination of them.

In this form very large scale LP models can be reduced significantly in size, reducing computational effort and eliminating detailed options of analysis which are not required at higher levels of decision.

Let X_j, $j \in J$ be the set of variables to be aggregated into one variable Y. Then

$$Y = \sum_{j \in J} \alpha_j X_j \qquad (1)$$

$$\sum_{j \in J} \alpha_j = 1$$

Note that, the new column generated is a convex combination of the original ones,

$$A = \sum_{j \in J} \alpha_j A_j$$

The aggregate LP problem is solved yielding both a bound on the error in the objective value due to the aggregation process, and an automatic feasible solution to the original LP problem, which is obtained using relation (1)

In Weintraub et al. 1986 this procedure was used for data corresponding to pine plantations in Chile. Solving the aggregate LP rather than the original LP problem led to a 75% reduction in CPU time, with a 7.7% bound on the error in objective value. In this case, choosing the set of columns to aggregate was done by observation. Columns were considered similar basically if they belonged to similar stands, harvesting was carried out in the same period and yields, even though belonging to different stands were similar (within 10% - 15%).

In order to improve the quality of the aggregation process we used a more rigorous approach to group similar columns, based on cluster analysis (Saez, 1991, Weintraub et al. 1992). The grouping method is based on defining a distance measure, which allows to define the similarity among columns and an algorithm, which determines the sequence in which the columns are analyzed.

After several tests, we found the best definition of distance was given as follows.

Let a column vector be defined as $A_j = [c_j, a_{1j}, a_{2j}.....a_{mj}]^T$. Then the distance between two columns A_j and A_k is given as:

$d(A_j, A_k) = 1 - \cos(A_j, A_k)$

Note that if $A_j = A_k$, then $d(A_j, A_k) = 0$

After testing several options, the algorithm chosen to classify each column was as follows.

0. Take column j = 1. It forms the nucleous of cluster number 1.
   Take j = j + 1.
   Define a measure ϵ of acceptable distance. That is, if $d(A_j, A_k) \leq \epsilon$, then columns j and k belong to the same cluster.
1. Take column j. Compare A_j with the nucleous of all clusters already defined. If there exist clusters whose nucleous has a distance to A_j within ϵ, go to 2. Otherwise go to 3.
2. Choose the cluster with the nucleous closest to A_j. Incorporate A_j into that cluster.
   Take j = j + 1, go to 1.
3. If no cluster exists close enough to column j, it defines the nucleous of a new cluster. Take j=j+1, go to 1.

We note that this clustering method is relatively fast and simple to implement.

This approach was tested on several problems defined using data representative of pine plantations in Southern Chile.

The results were extremely satisfactory. A typical problem with 60 stands and 1349 columns was reduced through the clustering based aggregation to an LP with 479 columns. The upper bound of the error in objective value due to the aggregation procedure was less then 1% in three different formulations of the problem. Similar results were obtained in other problems, with up to 90 stands and 1800 variables.

As a contrast, the same problem was aggregated using the more intuitive approach described above based on grouping similar columns. This led to an aggregate LP with 418 columns (of very similar size to the LP aggregate using cluster analysis). In this case, the bound on the error was between 3% and 9% in the three problems, with an average of about 7%. This indicates a dramatic improvement in the quality of the aggregation process when cluster analysis was used.

Modal Aggregation

This corresponds to a very simple and fast to implement aggregation approach. One way of implementing it is the following (Hrubes et al. 1985). Group sets of stands which are similar in relevant characteristics, such as geographical location, age, into macro-stands. For each macro-stand, choose representative management alternatives. These can be defined by considering a representative stand which assumes the average characteristics of the original stands.

The shortcomings of this approach is that there is no guarantee that the solution obtained at the aggregate level can then be disaggregated into a feasible solution for the original problem.

In Hrubes et al. 1985, this approach was tested using data sets of the US Forest Service. Model I and Model II FORPLAN formulations (Johnson and Scheurman, 1977) where defined. The original LP problems had relatively large matrices (10.000 -45.000 columns and 600 - 2000 rows). Reductions in the dimensions of the problem and computational effort for the aggregate problem ranged from 30% to 65%, while the error in the objective value induced by the aggregation was below 3%. Note however, that small levels of infeasibility occurred.

A Priori Aggregation

When using LP aggregation procedures, which we could call a-posteriori aggregation, a full blown LP matrix has to be developed and then reduced through aggregation. This implies all relevant data has to be gathered and processed. In a process we can call a priori aggregation, the idea is to aggregate relatively similar stands.

This is in the same spirit as modal aggregation, but carried out in this case in a more rigorous way, using cluster analysis. The process is described in more detail in Saez 1991 and Weintraub et al. 1992. The idea is to define a set of basic land and tree characteristics which are used to determine timber growth yields and other relevant inputs or outputs.

In our case, for pine plantations in Southern Chile, there were five basic characteristics, to consider for each stand:

C_1: tree age, C_2: site quality, C_3: distance to plant, C_4: density and C_5: number of hectares.

Given a set of stands, we wish to form sets of relatively similar stands, or macro-stands. We need to define three processes to define the macro-stands.

1) A distance measure, to determine the similarity of stands.
2) An algorithm to assign stands into macro-stands, based on the distance measure.
3) A procedure to determine the values of the five basic characteristics defined above for the macro-stand.

This clustering problem is much smaller than that defined in the a posteriori aggregation. The number of original elements is given the stands (less than 100 in our example) rather than management alternatives and we have only 5 coefficients of comparison for each element. Given this smaller size, we can afford to use more elaborate clustering techniques.

1) Distance measure
   We used a measure of disimilarity defined by Gower, (Hartigan, 1975) which corresponds to the weighted average of the differences of each coefficient between two elements or stands. In this form, G_{jk}, the disimilarity measure between elements j and k is given as:
   (we do not include number of hectares in the disimilarity measure).

$$G_{jk} = \sum_{i=1}^{4} W_i V_{ijk} / \sum_{i=1}^{4} W_i \qquad (2)$$

   W_i is the weight assigned to characteristic i in the comparisons, and $V_{ijk} = | V_{ij} - V_{ik} | / R_i$. Here V_{ij} is the numerical value of characteristic i in element j and R_i is an average value taken by characteristic i among all elements. Thus V_{ijk} measures the relative difference in the values of a characteristic between two elements or stands.

   The weighting parameters W_i are determined through testing. Given then a partition of all stands into macro-stands the total distance or measure of disimilarity is given by

$$\delta = \sum_{k \in K} \sum_{ij \in S_k} G_{ij}$$

   where K is the set of macro-stands and S_k are the stands in macro-stand k.

2) Classification Algorithm.
   Given the distance measure defined above, we used a k-means type algorithm, (Hartigan, 1975). This algorithm is based on partitions to form clusters. We start with an initial partition. We used the leader type algorithm defined in the a-posteriori aggregation to find a good initial solution. Based on this solution, the algorithm looks, in a given sequence, for changes of elements from one set to another to improve the quality of the solution. When no improvement can be obtained in the distance function, the algorithm stops.

3) The basic characteristics of each macro-stand (tree age, site quality, etc) are determined as weighted averages of the values for each stand. The weights are proportional to the areas of each stand in the macro-stand. For the number of hectares, we naturally just consider the summation of hectares of each stand.

   The process then proceeds by generating management alternatives for each macro-stand, based on the representative characteristics defined above. Note the reduction in the amount of data required and in the size of the new LP model. We used the same problems as in the a-posteriori aggregation. In order to evaluate the quality of the solutions obtained in the a-priori aggregate LP, we compared the solutions of 3 problems a) the original LP b) the aggregate LP c) the disaggregated LP. The latter one corresponds to taking the solution in the aggregate LP and disaggregating those values into production levels at stand level to find a feasible solution for the original problem.

In a typical case, a 90 stand problem was reduced to 28 macro-stands. The error due to the aggregation process in the objective value and total timber production was below 1.5%.

We note that in a-priori aggregation, there is a significantly reduced need of generating data. In addition in the a-priori aggregation the computational effort required in the aggregation process is significantly smaller than for the a-posteriori aggregation. In both cases the computational effort required in the aggregation process is significant and the process should be designed carefully to minimize the amount of computer effort required.

Proxy Variables

In some cases if we want to model some management activities in detail, we have to introduce non-continuous variables or relations. Typical cases are road building decisions or spatial constraints such as non intervening adjacent units. These involve the definition of integer decisions. While describing these decisions accurately is necessary at operational or tactical level, it is not possible to carry out such detailed planning at global or forest wide level. But integer variables cannot be aggregated as we have seen for the case of continuous variables. A proxy relation was proposed in Weintraub and Cholaky, 1991, for the case of road building variables. At lower or zone level, roads were described in detail through a mixed integer model. At forest wide level road building decisions were introduced through a proxy relation which linked budgets for road building to areas which could be accessed. This proxy relation was based on defining road building plans for the whole forest which indicated a sequence and timing for all road building projects. At global level, an aggregate problem was solved. The results obtained in terms of total inputs and outputs for each zone including road building budgets, were used for the zone level models as goals to be achieved. In order to obtain consistency between the two levels, two iterations were required to calibrate the aggregations carried out and in particular to improve the definition of road building plans. This could be done based on the road building decisions given by each mixed integer model at zone level.

Results on a small, representative test case led to high consistency between the two levels of decision, which indicates that this is a viable approach for hierarchical planning.

Simulation

In this case there is no direct linking between different levels of decision. Results at one level are used as references or guidelines for higher or lower levels of decision. Such was the case in two systems that have been implemented for the timber industry in Chile (Weintraub et al 1991).

The first system was related to daily scheduling of truck operations. The system is based on a simulation model which emulates the minute by minute movements of all trucks during the day. Within the model, a set of heuristic decisions assigns each truck to its new task after unloading. The model is run daily and has as inputs the volumes of timber of different types that must be carried from origins in the forest to different destinations (plants, sawmills, port) and truck fleet characteristics. The main outputs are the daily truck requirements and the schedule for each truck to be used.

But the simulation model can also be used as a support to define future fleet requirements. This can be done by running a simulation with typical of daily data supply and demand for a future situation.

The second system involves decisions in terms of which stands to harvest, choice of bucking patterns and machinery and truck fleet to be used. A mixed integer LP model is the basis for this harvesting problem. We note the relations between the two systems. Information from the daily truck scheduling system is used as input for the harvesting model, to determine transportation costs and fleet requirements relative to volume of timber hauled. On the other hand, the daily truck scheduling system uses as inputs, the supply of timber at origins and the demands of different products at destinations. This information is basically provided by the harvesting system, which schedules timber harvest operations and how contracts are to be fulfilled.

Up to this point, no work done has been done to develop a more rigorous linkage between these two decision levels.

Conclusion

We have shown several management problems through a hierarchical approach. Some correspond to real applications while others are basically methodological proposals.

As a positive conclusion, we have seen that in all cases a hierarchical approach is both needed (a monolitic approach would be impossible to implement or nonsensical) and viable. In all cases we have found at least a reasonable consistency between decisions at different levels. In some cases the errors due to the aggregation - disaggregation procedures were surprisingly low, as in the case of a priori aggregation, which may be a promising way of dealing with large scale planning problems.

As a drawback we must note that the approaches proposed were ad hoc, devised for each specific problem and there has not been much experience in terms of actual applications or in developing robust methodologies for linking different decision levels.

References

Hrubes, R, Navon, D., Vega, G., Weintraub, A., 1985 "Lowering Forest Planning Costs Through LP Column Aggregation: How great is the Associated Optimality Loss: Proceedings of the 1985 Symposium on Systems Analysis in Forest Resources. Athens, Georgía pp. 20-28.

Johnson and Scheurman, H.L., 1977. Techniques for Prescribing Optimal Timber Harvest and Investment under Different Objectives: Discussion and Synthesis. Forest Science. Monogr.18. Soc. Am.For., Bethesda, MD.

Hartigan 1975. Clustering Algorithms. John Wiley & Sons.

Weintraub, A., Saez, G. and M. Yadlin, 1992. "Aggregation Procedures in Forest Management Planning Using Cluster Analysis". To be submitted for publication.

Saez, G., 1991. "Tecnicas de Clasificación para Agregación de Problemas de Planificación Forestal. Engineering Thesis, University of Chile.

Weintraub, A., Morales, A., Serón, J., Epstein, R., "Managing Operations in Pine Forest Industries" Proceedings of the 1991 Symposium on Systems Analysis in Forest Resources Charleston, SC., March 1991.

Weintraub, A, and A. Cholacky 1991. "A Hierarchical Approach to Forest Planning". Forest Science, Vol. 37, N°2. pp. 439-460.

Zipkin, P. 1980. "Bounds on the Effect of Aggregating Variables in Linear Programs". Oper. Res. Vol. 28. pp. 1299-1309.

(This research was partly supported by Fondecyt under Grant 90-1070.)

A Decomposed Hierarchical System for Forest Land Use Allocation Decisions with Public Participation

H. Schreier, W.A. Thompson, G.C. van Kooten, and I. Vertinsky

Forest Economics and Policy Analysis Research Unit, University of British Columbia, 2206 East Mall, Vancouver, British Columbia, V6T 1Z3, Canada.

Abstract

In this paper, we describe a design for an hierarchical decentralized system for forest land use allocation. In British Columbia, attention in managing public forest lands has traditionally focused on those activities that generate revenues for the Crown, namely, timber harvesting. More recently, the focus has broadened to include other uses of the forest (e.g., recreation, wildlife). In response to an increase in public environmental concerns, the focus has now shifted to a new domain — that of reconciling non-use benefits (e.g., biological diversity) with the benefits of alternative uses of forest land. The difficulty in evaluating non-use benefits and deciding upon forest land allocation lies in the fact that such benefits involve different reference systems and stakeholders. An optimal decision process requires reconciliation of local (regional) and global (provincial) objectives. In principle, a comprehensive global optimization problem can be formulated, but in practice, such a formulation is infeasible since much of the trade-off data must be derived by active participation of local stakeholders in the planning process, and the size of the problem makes it intractable.

A decentralized system with central coordination through the use of "shadow" prices is proposed in this paper. The land allocation problem is decomposed into regional and local subproblems. Each subproblem is solved with the solution fed back into a provincial master allocation plan. The solution process involves an iterative approach whereby the cumulative effects of local allocations are reflected in changes in relative values in the provincial master plan for different cost and benefit dimensions. These are then fed back to recalculate local allocation solutions. The paper provides details about the proposed system. It also provides examples of the type of variables to be included in the system and proposals regarding their measurement.

Introduction

Forests in British Columbia are largely owned by the province. The great economic importance of timber production often overshadowed other valuable contributions made by forests to human welfare. Since markets do not exist for non-timber services and goods derived from the forest, decisions concerning harvesting do not reflect the optimal use of the forest from the perspective of society (even when legislation mandates the management of the forest for all the diverse social benefits that can be derived from its use and existence). Domestic and international pressures resulted in shifts in forest policy and management practices, favouring more vigorous correction of market failures by government interventions. The problem is that often the constraints imposed on forest management as a result of a complex political process do not improve the supply of non-timber goods and services, or produce them at costs which exceed their benefits to society.

Difficulties to correctly evaluate non-timber benefits is only part of the problem of managing the forest resource. Lack of information, the high costs of processing existing information and the lack of decision tools which provide quality solutions acceptable to the public are all causes of failures of the public management of the forest resource. To gain acceptability by local stakeholders and utilize knowledge of local experts, new policies mandating public participation in the management of the forest and allocation of its land among alternative users are being introduced in British Columbia. There is also a desire to shift forest management into a true multi-use paradigm from the traditional practice of dominant use paradigm (where alternative uses of the forest are reflected as regulatory constraints rather than as a part of the benefits to be maximized).

The project described in this paper focuses upon developing a decision methodology that can provide a solution to the desire of the government to involve local stakeholders in the decision process while pursuing a province-wide optimal solution to the forest management and land use allocation problem.

There are several conceptual and practical difficulties that one faces in developing such a methodology. These include:

(1) The 'size' of the problem.
(2) The need to process and use in the decision algorithm, data with different levels of spatial resolution and aggregation (e.g., some variables require specific knowledge of particular topographic features for implementation in the local level, but only the use of aggregates is required in evaluating provincial objectives).
(3) The need to allow local stakeholders to voice their preferences and have their preferences reflected in regional solutions.
(4) The need to reconcile provincial objectives with local objectives.

To deal with these issues we propose here an hierarchical system which combines the use of a structured decision process at the regional level and a simulated market at the provincial level. We start the paper by illustrating some of the difficulties of problem definition stemming from the fact that preservation and timber values of the forest are difficult to conceptualize and measure. We also illustrate how some "existence values" (e.g., biodiversity) have different meanings at different levels of the system. We then provide an overview of the proposed hierarchical decision system. Next we follow up with a description of the regional decision methodology and the provincial coordination system. Two alternative ways of simulating a province-wide market system for non-timber values are proposed to help reconcile regional decisions with global provincial values.

Sources of Conflict: Preservation and Other Non-Timber Values

Non-timber values result from both using the ecosystem and preserving it. Use values often relate to recreational activities such as hiking, fishing, hunting, camping and viewing. These values are relatively easy to measure, at least compared to non-use values such as preservation. Preservation value includes option value, existence value and bequest value. Option value is the amount of money that an individual who anticipates visiting an old-growth forest, for example, would pay to guarantee future access to the forest, even though he or she is uncertain as to whether they will ever make such a visit. Existence value is the amount a person is willing to pay for the knowledge that the natural environment is preserved in a particular state (viz., old growth). Bequest value is defined as the willingness to pay for the satisfaction derived from endowing future generations with a natural environment.

In addition to preservation value, if the current and future returns from the decision to harvest an old-growth forest are uncertain, then, in general, it is not correct to replace the uncertain returns by their expected values in calculating the present value of the decision to preserve the land. By using expected values in calculating the net present worth of delaying development, the value of preservation is underestimated. The difference between the value obtained using expected values and the true value under uncertainty — the shortfall — is quasi-option value (Fisher 1988). This is the loss of options that an irreversible decision entails. Thus, if there is any chance that some uncertainty is resolved by delaying development, the decision to develop or preserve favours preservation, but it does not imply that preservation will always be the preferred strategy. Preservation value differs from quasi-option value mainly because the former implies no future development, while the latter is simply a measure of the benefits of delaying development to a date when development yields greater benefit.

There are other values that have not been considered in managing the B.C. forests, some of which are related to the amount of timber growing or not growing in a stand. Benefits of sequestering carbon in growing trees are related to a stand's timber volume, but domestic grazing values, for example, are not likely to be dependent on the amount of timber in a stand (at least after some point), nor is production of some forms of wildlife. Viewing, hiking, fishing and some other forms of recreation will be related to the age of trees and the ecosystem, as will preservation of some wildlife species. It is difficult to establish optimal policies where non-market values are related to ecosystem attributes other than the stock of a species or amount of timber in the forest.

Finally, there is no information about the benefits that forest land uses provide in terms of watershed function (water quality, flood control and impact on the fishery), climate control, soil erosion, and biodiversity.

There is a substantial literature in economics pertaining to preservation of endangered species, wildlands and biodiversity (e.g., Krutilla 1967; Arrow and Fisher 1974; Fisher 1988). In the Pacific Northwest, concern centres about endangered species (viz., Northern Spotted Owl) and the preservation of old-growth forests; in the tropics, deforestation is blamed for the destruction of ecological systems and the subsequent loss of unknown numbers of plant and animal species; in the Great Plains region of North America, conversion of wetlands to agriculture forever alters both the landscape and ecology. Development of such lands is a problem because we do not know if the plant or animal species that become extinct contained information that may have enabled us to find an alternative source of liquid petroleum, a perennial variety of corn, or a cure for cancer. The benefits from any of these discoveries could be enormous.

Biodiversity is an example of a forest value that takes on different meanings at different levels of spatial aggregation. The term biodiversity refers in a general sense to the variety of life forms. Depending upon context and scale, biodiversity encompasses a number of different aspects of biological variety and variability (Burton et al. 1992). The biological "entities" can include alleles or genotypes in a population, species or species' associations within a biotic community, or species, other genera or ecosystems within a landscape or larger geographic unit.

A large number of values have been proposed for biodiversity. These include: commercial products from non-timber species (McNeely 1989), e.g., pharmaceutical products from wild plants (Levin 1976; Brooker et al. 1989; Shiva 1990); sources of breeding material for improving productivity, nutritional value and resistance to pests, disease and environmental stress (Myers 1979; Iltis 1988); and indicators of ecosystem health (Patton 1987), e.g. lichens as indicators of air pollution (Hawksworth and Rose 1970). Managing to maintain biodiversity is a form of hedging against uncertainties such as changes in commercial values of biological products, changes in social values and changes in climate. As Burton et al. (1992, p.232) note:

> "... the value of biodiversity ... is analogous to the value of diversification within regional economies. Diversity may constrain short-term productivity and profitability, but helps ensure against complete disaster."

Maintenance of biodiversity provides flexibility for adapting to these changes if and when they occur. It has also been argued that biodiversity is important for ecosystem productivity and stability (Rosenzweig 1971; Franklin et al. 1989). Finally, biodiversity has nonpecuniary values, particularly aesthetic and existence values (Easley et al. 1990; Leopold 1949; Potter 1971; Norton 1982).

As noted above, the value of a particular form of biodiversity is likely to vary substantially among stakeholders. For example, the use of noncommercial species as indicators of ecosystem health is likely to be of greatest interest to local stakeholders. In contrast, the great diversity of ecosystems in British Columbia may have existence value for all citizens of the Province. Worldwide concerns about the potential loss of old-growth forests indicate the existence of global stakeholders in the forests of B.C. (who may back their claims using influence on consumers).

The Problem of Hierarchical Decision Making: The B.C. Context and the Proposed Methodology

There is general agreement that public forest land in B.C. should be allocated so as to maximize net social benefit. In order to do this, social values must be incorporated into the decision process in terms of preferences and trade-offs among conflicting objectives. To the extent practical, the most appropriate and comprehensive forest data base and best technical and scientific information must be used. The assumptions and uncertainties in the analysis must be made explicit. Land use allocations that are strictly dominated by alternative allocations should be eliminated (i.e., "lose-lose" alternatives should be screened out).

Present forest allocation in B.C. centers around timber supply analysis. The objective of this analysis is to provide information about the implications for the timber resource of each management option. Timber supply analyses consider two time frames: short-term (20 year), which focuses on operational feasibility, including location and scheduling of timber harvest; and long-term (200 years), which focuses on sustainability of harvest levels (i.e., long-term sustained yield). Data for the analyses are organized in various ways for the different time frames: short-term analysis uses area-based units, while long-term analysis uses strata-based units (i.e., growth type groups). The outputs of these analyses are: (1) location of operating areas and schedules for the short-term harvest; (2) long-term forecasts of harvests and sustainable yields; and (3) estimates of the impact of alternative management options on short- and long-term timber supplies.

The institutional framework for planning, analysis, implementation and regulation is provided by the B.C. Ministry of Forests. Involvement of other agencies is largely restricted to legal requirements for protecting non-timber environmental resources, such as fisheries, wildlife, wilderness and water.

However, the provincial forest management responsibility goes beyond management of timber. The problem is to maximize the aggregate production of goods and services from the forest over all the regions, subject to global measures of value and global constraints. Examples of global production and constraint measures might include a provincial measure of biodiversity, which need not be a simple sum of regional measures, or a measure of inter-regional distribution of old growth timber. As used in this definition, the goods or outputs from the forest include all the benefits that people ascribe to forests. Among these are timber, range, water, fish, wildlife, recreation, scenic, preservation, and spiritual and intrinsic values.

The regional and local problems may differ from the provincial problem. Indeed there are variables that appear only as aggregates while others have meaning or are assigned values only at the local level.

The solution to the global problem will not necessarily be the same as the set of solutions to the regional problems unless global perspectives are internalized locally. When the regional problems are solved in isolation, the results ignore global measures of production, global constraints and inter-regional transfers. They also differ from the optimal choices that would be made at the sub-region or local level. Here too, isolated resolutions to local problems ignore regional objectives and constraints, and fail to account fully for potential transfers among sub-regions or locales.

In principle, this difficulty can be surmounted within a decentralized, hierarchical, planning, decision framework. The answer to this disparity among solutions is to develop mechanisms for restructuring the problems at each lower level of aggregation so that representations of the broader objectives and constraints are taken into account.

The general approach proposed here is to follow a scheme analogous to that embodied in the decomposition principle (Dantzig 1963). This principle divides a linear program into (a) a set of subprograms corresponding to almost independent parts, and (b) a master program that ties together the subprograms. This method makes it possible for the central staff to plan the overall operation of an organization without full knowledge of the detailed operation of each part. In our scheme the objective functions for planning units are allowed to differ. The influence of the global objective function is incorporated by a system of payments and taxes as well as specific constraints on regional plans (see Figure 1). The key activity of the central planning authority is to regulate prices for scarce resources and set regional production targets in such a manner that the aggregate of the optimal solutions for the individual planning units is the optimal solution for the province as a whole.

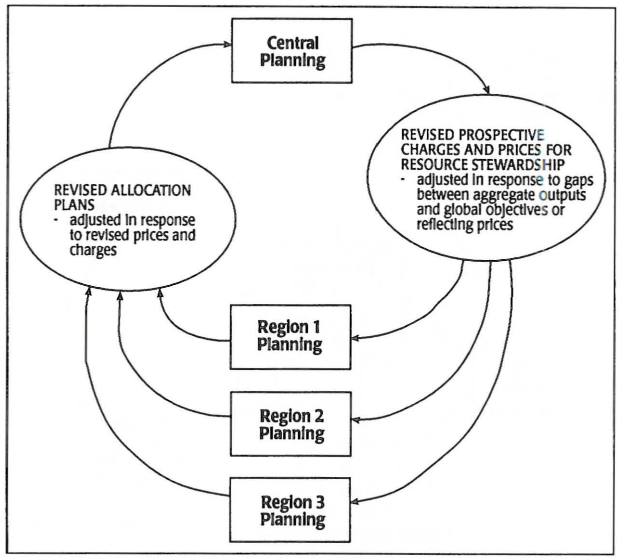


Figure 1. Information Flows Among Planning Levels.

The Regional Planning Framework

The regional planning framework we envision is depicted in Figure 2. It is to be applied iteratively, with each step improving problem definition and converging on an optimal, feasible solution. A linear programming model is used to determine the forest management plans which optimize forest outputs. In the first iteration, the objective function will be weighted heavily to traditional commercial outputs, primarily timber. Similarly, the initial constraints will be chosen in accordance with current practice.

The optimal solution is used as an input for a series of simulations, using the forest estate model. The simulation incorporates nonlinear relationships and additional details of the forest system, particularly ones pertinent to non-timber forest resources. These may include factors for which there are no variables in the LP model (although variables could be added to the LP at a later stage). Thus, the simulation can generate a richer scenario which corresponds to the LP solution. The forest estate model is also used to develop alternative scenarios, in which assumptions differ incrementally from those used for deriving the LP solution. All these scenarios are linked to a GIS data base to display their spatial implications.

Overlayed maps from the GIS which display the consequences of the simulated scenarios are used in two ways. First they are used to identify spatial interactions that were not accounted for in the simulation. For example, spatial fragmentation of wildlife habitat may be more limiting to wildlife numbers than total area. The results of these interactions are fed back into the

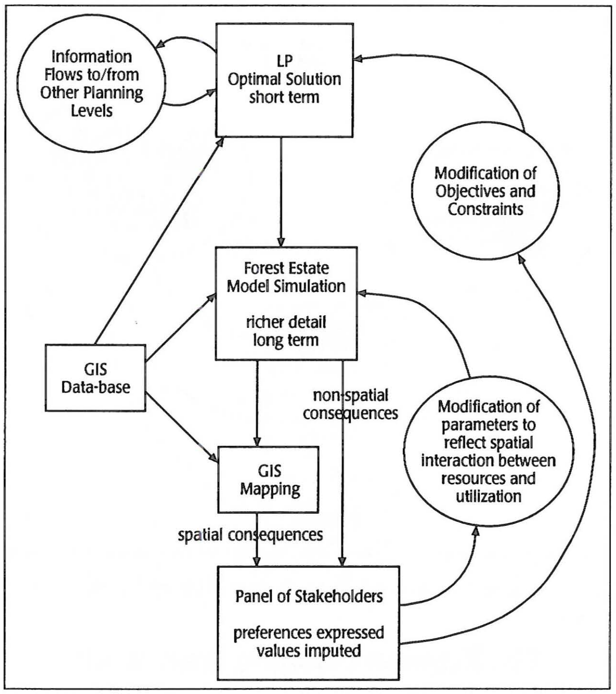


Figure 2. Forest Land Allocation Framework.

simulation model as parameter modifications, and forecasts are revised.

The second use of the GIS-based maps is for evaluation of the alternative scenarios. The maps are presented to a panel of stakeholders for evaluation, along with supplementary information on selected nonspatial outputs from the simulation. Preferences of the stakeholders are solicited and conjoint analysis is used to interpret responses and derive a value function. The results of this analysis are then fed back into the LP in the form of modifications to the weights in the objective function or modifications to the constraints. Over several iterations of this procedure the forest management problem will become more comprehensively defined and the concerns of the various stakeholders more effectively incorporated.

The proposed planning framework facilitates addressing several problems common to the management and allocation of public lands. Concerns about the legitimacy of stakeholders' inputs are dealt with in two ways. First, valuation of non-market resources is done in terms of specific, local situations rather than hypothetical ones. And second, information about the consequences of alternative decisions is presented in maps, allowing incorporation of complex spatial information in a relatively simple, well understood format.

One common criticism of many planning systems is that they do not solve the correct problem. Rather they force the real problem into a form that can be solved. The iterative use of the proposed planning framework with repeated input from stakeholders and feedback to problem definition is designed to alleviate this syndrome. Thus, the framework provides the flexibility for modifying the problem definition over time in response to changes in stakeholders perceived values, markets, forest inventory or technology.

A common feature of land allocation and valuation is that the value of a tract of land for a given use depends not only upon the biophysical characteristics of the land, but also upon the biophysical characteristics and uses of the surrounding land. Thus, to improve forest land allocation decision-making, the spatial consequences of forest management must be addressed.

Forest land allocation processes have had limited flexibility for incorporating non-timber resource values into the decision-making process. The framework proposed here is explicitly designed to incorporate any (nontraditional) values introduced by the stakeholders. This is intended to facilitate conflict resolution, by incorporating negotiation and tradeoffs among stakeholders early in the planning process. Thus, the system provides opportunity to mesh stakehold participation within a framework of optimization. Stakeholder participation provides an opportunity to utilize local expertise and information as well as a vehicle for stakeholders to voice their preferences.

The Geographic Information System

Since its introduction about ten years ago, geographic information system (GIS) technology has been gaining rapid acceptance in the forestry establishment in Canada. This is not surprising, since most Canadian forestry operations take place over a large geographic domain and map-based data are a prerequisite to the efficient management and utilization of large forests. However, to date, most GIS applications in forestry have been used for standard map making.

There are several related ways in which the analytic use of GIS is envisaged in our methodology. One use for the GIS in our application is the provision of a link between the regional planning tools and local consequences. By accessing common databases with GIS technology, local and regional conflicts over goals and operational constraints could be more effectively identified and acceptable tradeoffs more easily made. The GIS is also used as a communication tool. In British Columbia, public input into forest planning at all levels is increasing. There is a need for more effective tools for articulating forest goals and values and for projecting and displaying the consequences of alternative forest policies and operational plans within a specific spatial framework. Used effectively, the GIS can provide a mechanism for consensus building. Conflicts between stakeholders can be identified and tradeoffs made explicit. Local expertise can be used to fine tune forest management decisions to take account of particular spatial features of the environment.

We are applying the GIS to the Gold Bachelor watershed in the North Columbia Mountains of B.C., an area of 43 000 hectares north of Glacier National Park. Winter habitat for wildlife in the Park is limited, making the surrounding areas critical for overwintering of many of the Park's large mammals. Past activities in the area, including forest fires initiated during railroad construction and flooding of valley bottoms by the Mica and Revelstoke dams, have significantly reduced available winter habitat outside the Park boundaries as well. At present, timber harvesting adjacent to the Park is advancing rapidly, eliminating and modifying critical habitat and threatening the sustainability of some of the key wildlife resources in the Park. In addition, the forest roads built for logging opened up new areas for recreation, leading to serious conflicts between wildlife and winter recreation. An integrated methodology is needed to bring different stakeholders together and to facilitate their interactions. Simulation and LP models linked to the GIS have the capacity to provide a neutral, integrating platform for quantitative resource evaluation and conflict resolution.

The pilot regional GIS was implemented on a 486 PC-compatible microcomputer using Terrasoft GIS software. This vector-based GIS is compatible with other, commonly used GIS software. The database was at a scale of 1:20000 and included data on topography, forest cover, recreation capability, wildlife habitat, hydrology, climate, other ecological and biophysical attributes, land use, economics, ownership, regulatory authority, and results of user surveys. This spatially referenced database provides the platform for modelling and GIS evaluation of the individual resources and their interaction.

The GIS system now in place includes modules for evaluating the suitability of forest types for difference resource uses. A comprehensive habitat suitability evaluation by season was developed for caribou. The evaluation covers individual and cumulative effects and interactions amongst the wildlife in the area. Separate habitat suitabilities were developed for each season initially, and GIS overlay techniques have been used to develop a combined habitat evaluation model. This allowed identification of areas where there are cumulative effects, competition or compatibility problems, and habitat shortages during any part of the annual cycle.

Recreation capability of the watershed is being evaluated for both winter and summer recreation. Winter recreation will consider helicopter skiing and snow-mobiling; summer recreation emphasizes fishing, camping and hiking. The evaluation will be based on usage in relation to biophysical attributes of the area and socio-economic attributes of users. The evaluation will also draw upon user surveys and consultation with the tourist industry to estimate current and anticipated future recreational use of the watershed.

In the hierarchical planning system the inputs to the GIS are the current and projected future forest inventory, conditions, activities and outputs which are provided by the regional simulation and linear programming models (see below). Outputs of the GIS are the spatial and aggregate attributes of the forest inventory over time.

To facilitate elicitation of stakeholder value functions, simulated outcome attribute profiles for ranking by stakeholders can be generated by the GIS. These will be augmented by a vector of other outcome attributes which do not require spatial display projected from the simulation. The profiles will be generated by incremental variations in each attribute using the attributes of the outcome obtained by the LP solution as a base. They will be generated so as to form a partial factorial design. Conjoint analysis will be used to derive value functions from the preference ranking of stakeholders.

LP and Simulation

Linear programming has been widely used in forest planning. At the local and regional levels, LP models are used for operational planning and harvest scheduling (e.g., Tedder et al. 1980). At the provincial and regional levels, LP models such as MUSYC (Johnson and Jones, 1980) are used for strata-based, timber supply planning. However, LP models are very cumbersome to use for solving large allocation problems with spatial constraints (Iverson and Alston, 1986). Bare and Field (1987) have criticized the use of the FORPLAN system on several other grounds: the models are too large, too poorly understood and too costly; the models do not adequately treat linkages between strategic, tactical and operational planning; and the models are not compatible with the institutional framework of decision making for the U.S. National Forests. An effective approach to counter these disadvantages of LP is to augment the analysis by using them in conjunction with additional tools, in particular, forest estate models.

Forest estate simulation models project the dynamic changes of a complex forest inventory in response to an extensive array of management activities and environmental inputs. These projections include the state of the forest inventory, inputs and outputs of forest management activities, and economic costs and benefits of these and any other forest activities. Their ability to simulate these in rich detail, over a long time horizon provides a method for comprehensive examination of the anticipated outcomes of alternative management plans. Forest estate models can easily accommodate nonlinear relationships which must be approximated in LP formulations. These models also allow examination of the consequences of alternative hypothetical exogenous impacts on the forest estate and its outputs. However, present models do not include spatial data on the forest inventory, thus motivating the linkage with GIS.

The forest estate simulation model projects the forest inventory and timber harvest for a given forest area over time. The forest inventory is drawn from the shared data base. Other inputs are a harvest plan and specifications for forest protection, silviculture and economic conditions. The management specifications can be varied to examine the effects of different combinations of practices on inventory and timber yield. The projected outcomes can then be used to evaluate alternative harvest plans and restrictions in terms of commercial and non-timber benefits.

The model structure is shown in Figure 3. The forest inventory is drawn from a data base common to all components of the planning system. The forest area will usually be a region managed as a sustained-yield unit. The inventory is divided into a number of analysis units, according to dominant species (commonly known as growth types), site quality, silvicultural treatment, age and associated resources. Polygons in the GIS data base may be treated individually or combined according to how the model is being used. The model projects the inventory forward in time in 5 year increments by advancing the age classes and calculating the changes due to timber harvest, fire and pest losses, regeneration and stand tending. Forest growth is computed from volume-age relationships which are specific to each combination of growth type, site class and silvicultural treatment. Finally, the impacts of changes in the forest are simulated for wildlife, fish and recreation.

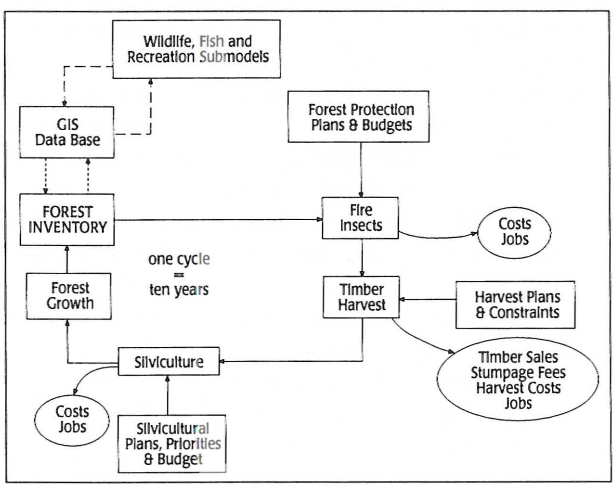


Figure 3. Flowchart of the forest estate simulation model.

The timber dynamics and outputs of the model are determined by five submodels: protection, harvest, silviculture, economics and growth. Impacts of changes in the forest inventory and forest management activities on non-timber uses are simulated by separate submodels for wildlife, fish and recreation, using the periodic outputs of the forest estate model as their input.

The protection submodel calculates losses of forest area caused by fire and insect pests. A fraction of the losses are available for salvage; the remainder is divided between age class 0 and regeneration delay according to specification of an area specific model parameter. Fire losses are based upon mean losses for the given forest area, depending upon growth type, silvicultural treatment and stand age. These historic rates can be modified by parameters reflecting additional investment in fire monitoring, preparation and control activities. Effects of "slow" pest and disease problems (e.g., root rot) are treated implicitly in the volume-age relationships and in regeneration success rates. Two types of major pests are simulated: those that cause a significant loss of growth (e.g., western spruce budworm) and those that cause significant mortality (e.g., mountain pine beetle). Pest damage rates depend upon growth type (many species are not susceptible), age, silvicultural treatment and model parameters reflecting investment in pest monitoring and pest control. Base rates for pest damage are determined from historic data for the given forest region. Costs of fire and pest monitoring and treatment are accounted in the economics submodel.

The timber harvest submodel determines the classes of forest to be cut based on input cutting targets and user-specified cutting priorities and constraints. Depending upon the particular use of the model, the cutting targets can be specified as a single total volume for each simulated period or as a detailed plan which specifies volumes to be harvested from each growth type by age class. If the model is run with less detailed cutting plans, the harvest submodel employs user-specified rules to allocate the cut to growth types by age class. In either case, cutting priorities and constraints are used to allocate the cut to specific geographic locations. Harvest costs, stumpage and timber revenue are accounted in the economics submodel.

The silviculture submodel provides a framework for exploring the implications of alternative silvicultural programs. The following treatment options are available: planting, precommercial thinning, commercial thinning and fertilization. When an area receives a simulated treatment, the treated area is assigned to a different analysis unit, which has a different volume-age relationship and a different value-age relationship (see below). Costs and labour requirements of silvicultural activities are accounted in the economics submodel.

The economics submodel calculates the financial costs of, and returns from, the simulated timber management and harvest activities. It also calculates associated employment. Gross revenue from harvest for each analysis unit is calculated as the volume of timber removed times the specific price for that growth type and age class. These prices (value-age relationships) are user specified. Harvest costs are broken into two parts: tree to truck cost and haul cost. The former depends upon growth type, past silvicultural treatment, age and terrain, and is calculated from published relationships (Williams and Gasson 1986; Williams 1987; Sterling Wood 1989). Haul costs are directly proportional to distance to the mill. Access costs are calculated once per period as the costs of road building and maintenance necessary to access the timber which is to be harvested. Cost per kilometer depends upon slope, soils and region. Direct employment is calculated as volume harvested times region specific labour productivity plus silviculture and forest protection employment. Induced plus indirect employment within British Columbia is calculated as 1.1 person-years per person-year of direct employment (Jacques and Fraser 1989).

Forest growth for each forest land class is based upon user specified volume-age relationships. These give the average merchantable timber volume per hectare for each age class of the given combination of forest growth type, site quality and silvicultural treatment history. The source for these relationships depends upon the specific region being modelled. Relationships for naturally regenerated stands can be based upon published data from permanent sample plots. For silviculturally treated stands, a stand growth simulator (e.g., TIPSY)calibrated for the region is probably the best source for volume-age relationships.

The final step in the simulation cycle is the simulation of the response of wildlife, fish and recreation to the simulated changes in the forest and the forest management activities. Wildlife reproduction and survival depends upon availability of suitable habitat throughout the year, interactions between species and interference from human activities. Changes in the forest inventory from logging, regeneration and natural losses alter available wildlife habitat. The spatial arrangement of suitable habitat also influences wildlife numbers by determining the ease of movement between seasonally different habitats and the frequency of interactions between wildlife species and between wildlife and disruptive human activities. The fish model assumes that the size of fish populations depends upon water quality and fishing intensity. Fishing intensity is simulated by the recreation submodel. Changes in water quality depend upon erosion, which are determined by the level and location of logging and road building. Their effects upon erosion rates depends upon soils, topography, forest regeneration and operating standards (e.g., width of stream buffers). The recreation submodel simulates levels of five recreation activities: helicopter skiing, snow-mobiling, fishing, camping and hiking. The level of each activity depends upon global and local demands, cost, access, recreation quality, recreation regulation and investment in general regional and local tourist facilities and services.

By linking the forest estate simulation model to the GIS, the spatial consequences of a given simulated scenario can be displayed and examined. These displays can include any information available in the simulation. For example, the forest inventory can be interpreted in terms of a viewscape from a particular point. Changes in the forest over time would then be displayed as scenic changes over time.

Links Between Global and Regional Planning: Pseudo Markets

The global or provincial-level problem is linked to the regional problem via a system of charges andprices. Charges are levied for such things as stumpage and forage; prices consist of per unit subsidies or transfers paid for the provision of stewardship over provincial resources. While the Province charges for use of resources, it also provides incentives to regional suppliers of environmental commodities according to the value these resources have to the province as a whole. For example, local stakeholders such as loggers or ranchers can be charged higher stumpage or grazing fees while, at the same time, given incentives to provide ecological commodities. This approach to resolving resource conflicts is both economically efficient from a provincial point of view and compatible with historic property rights.

The reason for focusing on the region or local level as the provider of resources is because decisions are made at that level. Tradeoffs among the various uses of forest land resource are implemented locally. That task requires knowledge about the productivity of forest land in production of timber, wildlife, recreation services and other uses, a knowledge that is available at the local level. But tradeoffs also require knowledge about the values of various uses to citizens of the province, and this knowledge is only available at the global level. Although there are practical difficulties to implementing a system of charges and compensation — a system of prices for all resources—, the methodology we propose is designed to overcome these problems, providing an efficient, effective and fair allocation of the forest resources among competing stakeholders[1].

As discussed earlier, biophysical attributes of environmental commodities such as biodiversity vary depending on whether they are viewed from a provincial or regional perspective. Likewise, individuals discern environmental goods differently depending upon the region where they live. First of all, there is the problem of familiarity. Those with some knowledge about the ecosystem (e.g., with experience hiking through mature forests and harvested areas) are better able to value ecosystem or recreational resources when asked to do so in a contingent valuation survey (see below). Further, the environmental resource that is valued by a person living in Vancouver, say, may be quite different than the one valued by someone living in Dawson Creek, even though they are valuing the same commodity. The reason is that the person in Vancouver may have a different perspective on all ecosystem commodities than the person in Dawson Creek. While some of this difference is attributable to familiarity, the discrepancy persists even if both individuals have the same degree of familiarity, mainly because the individuals experience a different cultural milieu. Finally, even when there is agreement on what constitutes a particular nonmarket resource, two people with identical tastes may well place a different value on its existence because they live in different regions. For example, the value placed on an elk by a hunter living in a region where elk are abundant will be lower than the value assigned by a hunter living in a region where they are not. It has to do with one's location on the marginal willingness to pay or demand function.

For these reasons (and others), the values of environmental commodities will differ among regions and between regions and the province. The objective of the provincial planning agency is to provide appropriate incentives to the regions so that, when regional supplies are aggregated, supply and demand are equal for each environmental commodity at the provincial level. When this occurs for each and every resource, society's welfare attains a maximum — i.e., the sum of consumer and producer surpluses is maximized.

Since the forest resource is owned by people in the province as a whole, the aggregate use of the forest resource must reflect province-wide values. Therefore, the provincial planning agency must provide signals to the lower levels of the hierarchy concerning the value to citizens (society) of each of the various resources. There is a need to determine the marginal values of forest lands in the production of the market and nonmarket goods and services that society desires. While markets can be used to estimate demand functions for commodities such as timber products and livestock, determination of other use and non-use values will be required. It is important not only to determine average values for nonmarket resources, but it is necessary to elicit sufficient information to construct a marginal value or demand function.

We briefly consider several approaches to obtaining information about nonmarket goods and services, about non-timber benefits. These can be divided into two main categories. (1) The expenditure function or indirect approach relies upon a relationship between private goods that are traded in the market place and public goods to draw inferences about the demand for the public good. It is sometimes referred to as the indirect approach because information on goods and services traded in markets is used to value the nonmarket good or service under consideration. The travel cost method and hedonic pricing are indirect methods for deriving values of non-timber benefits from information obtained in markets. (2) The income compensation or direct approach uses questionnaires or surveys to directly elicit an individual's willingness-to-pay (WTP) for more of a public good or his/her willingness-to-accept (WTA) compensation to have less of the public good (e.g., clean air). Since this approach requires individuals to respond to hypothetical questions in a survey setting, it is also referred to as the contingent valuation method (CVM) if actual values are requested, or conjoint analysis if individuals are asked to choose between multi-attribute alternatives.

[1] Clearly one must design appropriate institutional infra-structure to implement the system. This is not a trivial administrative problem and therefore one should regard the proposals for providing global coordination through a province wide simulated market as a long term solution that must be introduced gradually.

Each method for deriving nonmarket values has its advantages and disadvantages. The travel cost method is used for valuing recreation opportunities by imputing people's WTP in terms of actual costs borne by users of the resource. Its advantages are that (1) data on site visits are usually relatively straightforward and inexpensive to obtain, and (2) actual expenditures are used. Its disadvantages include (1) questions concerning the value of travel time (i.e., what is the opportunity cost of travel or does it constitute a benefit?); (2) a visit may be part of a multi-destination trip, so that costs should be apportioned among destinations; (3) aggregation over visitors ignores possible substitutes; and (4) non-use values are ignored.

The hedonic price method assumes that the value of a good can be determined as a function of its attributes. For example, the value of a hypothetical recreational site is a function of such factors as distance, crowding, facilities, recreational quality (viz., water quality), uniqueness, availability of alternate recreational sites, and viewscapes. Statistical methods are used with market data to estimate nonmarket values. Its disadvantages are (1) difficulty in controlling for all the significant variables that affect price; (2) insufficient market data; (3) dependence upon assumptions about the underlying price relationships and that markets function perfectly; and (4) the fact that expectations of future trends significantly affect prices, making it difficult to isolate the influence of site characteristics. In many situations the disadvantages outweigh the advantages, limiting the applicability of the hedonic pricing technique.

Conjoint measurement is a marketing technique that uses revealed choice among goods with different characteristics (as in hedonic pricing) with a survey that asks people to choose among or rank hypothetical alternatives to impute the values of the characteristics. Its main advantage is that direct monetization of benefits is not required; thus, trade-offs can be derived without using market information. Other advantages and disadvantages are similar to those of using any survey technique and relying on hypothetical choices.

Finally, the contingent valuation method (CVM) is an attempt to explicitly elicit information concerning the minimum level of compensation required by an individual to forgo receiving a particular level of a public good or the maximum amount the individual would be willing to pay to obtain the nonmarket good or service.

> "Contingent valuation devices involve asking individuals, in survey or experimental settings, to reveal their personal valuations of increments (or decrements) in unpriced goods by using contingent markets. These markets define the good or amenity of interest, the status quo level of provision and the offered increment or decrement therein, the institutional structure under which the good is to be provided, the method of payment, and (implicitly or explicitly) the decision rule which determines whether to implement the offered program. Contingent markets are highly structured to confront respondents with a well-defined situation and to elicit a circumstantial choice upon the occurrence of the posited situation. Contingent markets elicit contingent choices" (Cummings et al. 1986, p.3).

The individual values obtained from the survey are then summed to obtain a value for the unpriced or nonmarket commodity.

CVM is useful because it is often the only means available to value non-use benefits of forest resources. However, the contingent valuation method has been criticized because it requires an individual to respond to hypothetical situations. As a result, various types of bias may occur, and these biases can only be avoided through proper design of the contingent valuation device and proper training of those who are responsible for gathering the required data. But a more serious criticism has been levelled against CVM that casts doubt about what the values obtained by this method actually mean. The argument is that individuals are not valuing the good or service in question (e.g., preservation of biodiversity in general, or a particular species or view), but, rather, are purchasing moral satisfaction. This problem and the related problem of imbedding (assigning identical value to, for example, preserving grizzly bear as to the preservation of all species) are discussed by Kahneman and Knetsch (1992a, 1992b) and Smith (1992).

If reliable demand functions can be estimated, it is possible to simulate a market. The global model that we envision is an iterative, market simulation model that is similar in some respects to a general equilibrium trade model (see Figure 1). The global planner begins by choosing a set of prices (perhaps a vector of zero prices) for each of the commodities under consideration. These are provided to regional decision makers (fed into the regional models). Passed back to the global planner are the amounts of each commodity provided in each region. Local preferences are reflected in the supplies that are forthcoming. Based on these responses and using the global model, relative and absolute prices are modified to encourage production of more or less of each commodity or service as needed to equilibrate supply and demand in each market. The new vector of prices is passed on to the regions and revised levels of the goods and services are made available in each region. By a process of iteration, global demand is equated with the sum of supplies from each of the regions. Thus, simulated markets are created for nonmarket goods and services, with the regional planners simulating the supply curves and the central planner simulating the demand curves. When excess supplies and demands are all zero, society attains an optimal allocation of resources among and within regions.

An alternative approach to modelling the global decision is similar to that used by FORPLAN. In this case, the central planner chooses to maximize stumpage revenue, say, subject to a number of environmental and regional resource constraints. The environmental constraints indicate the desired levels of each of the commodities as determined in public hearings for example. The solution to the LP model provides the shadow prices for the environmental commodities, and these values can be used to elicit supplies of ecological goods and services from each of the regions.

Concluding Remark

Our strategy for system development is based on the principle that each component can be used separately. The GIS system can operate as an independent vehicle for conflict identification. The regional LP and simulation can be used to derive regional plans without links to the GIS, using predetermined objectives, or objectives based on stakeholder surveys. The derived "demand" functions for non-timber values used in the simulated market can be used within policy and project evaluation frameworks such as cost-benefit analysis. It is, however, the linking of the various levels in the methodology which may provide a powerful new tool for comprehensive planning.

References

Arrow, Kenneth J. and Anthony C. Fisher, 1974. "Environmental Preservation, Uncertainty, and Irreversibility", Quarterly Journal of Economics 88:312-19.

Bare, B.B. and R.C. Field, 1987. "An Evaluation of FORPLAN From An Operations Research perspective". In FORPLAN: An Evaluation of a Forest Planning Tool. Proceedings of a symposium, November 4-6, 1986, Denver, CO. Gen. Tech. Rpt. RM-140. Rocky Mountain Forest and Range Expt. Sta., USDA Forest Service.

Brooker, S.G., R.C. Cambie and R.C. Cooper, 1989. "Economic Native Plants of New Zealand", Economic Botany 43:79-106.

Burton, P.J., A.C. Balisky, L.P. Coward, S.G. Cumming and D.D. Kneeshaw, 1992. "The Value of Managing for Biodiversity", Forestry Chronicle 68:225-237.

Cummings, Ronald G., David S. Brookshire and William D. Schulze (eds.), 1986. Valuing Environmental Goods: An Assessment of the Contingent Valuation Method. Totowa, H.J.: Rowman and Allanheld.

Dantzig, G.B., 1963. Linear Programming and Extensions. Princeton, NJ: Princeton University Press. 632 pp.

Easley, A.T., J.F. Passineau and B.L. Driver, comps., 1990. The use of wilderness for personal growth, therapy, and education. Gen. Tech. Rep. RM-193, USDA For. Serv., Fort Collins, CO. 197 pp.

Fisher, Anthony C., 1988. "Key Aspects of Species Extinction: Habitat Loss and Overexploitation". In Environmental Resources and Applied Welfare Economics edited by V. Kerry Smith. Washington: Resources for the Future. pp.59-69.

Fischhoff, B., P. Slovic, and S. Lichstenstein, 1980. Knowing What You Want: Measuring Labile Values. In Cognitive Processes in Choice and Decision Behavior (T. Wallsten, ed.) Erlbaum-Hillsdale, NJ.

Franklin, J.F., D.A. Perry, T.D. Schowalter, M.E. Harmon, A. McKee and T.A. Spies, 1989. Importance of ecological diversity in maintaining long-term site productivity. In, Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems (D.A. Perry, R. Meurisse, B. Thomas, R. Miller, J. Bole, J. Means, C.R. Perry and R.F. Powers, eds.) Timber Press, Portland, OR. pp. 82-97.

Gunton, T.I., G.C. van Kooten and S. Flynn, 1991. "Multiple Accounts Analysis and the Evaluation of Forest Land Use Conflicts". In The Future of Our Forests, Background Studies, Volume 2. Victoria: Forest Resources Commission (A.L. Peel, chairman), 22pp.

Hawksworth, D.L. and F. Rose, 1970. "Qualitative Scale for Estimating Sulphur Dioxide Air Pollution in England and Wales Using Epiphytic Lichens", Nature 227:145-148.

Iltis, H.H., 1988. "Serendipity in the Exploration of Biodiversity: What Good are Weedy Tomatoes?"

In Biodiversity (E.O. Wilson, ed.) Nat. Acad. Press, Washington, DC. pp. 98-105.

Iverson, D.C. and R.M. Alston, 1986. The Genesis of FORPLAN: A Historical and Analytical Review of Forest Service Planning Models. Gen. Tech. Rep. INT-214,Intermountain Forest and Range Expt. Sta., USDA Forest Service.

Jacques, R. And G.A. Fraser, 1989. "The Forest Sector's Contribution to the Canadian Economy", Forestry Chronicle 65:93-96.

Johnson, K.N. and D.B. Jones, 1980. A User's Guide to Multiple Use-Sustained Yield Resource Scheduling (MUSYC). USDA Forest Service, Fort Collins, CO.

Kahneman, D. and J.L. Knetsch, 1992. "Valuing Public Goods: The Purchase of Moral Satisfaction", Journal of Environmental Economics and Management 22:57-70.

Kahneman, D. and J.L. Knetsch, 1992. "Contingent Valuation and the Value of Public Goods: Reply", Journal of Environmental Economics and Management 22: 90-94.

Krutilla, John V., 1967. "Conservation Re-Considered", American Economic Review 57: 777-86.

Leopold, A., 1949. A Sand County Almanac. Reprinted 1966. Oxford Univ. Press, New York. 289 pp.

Levin, D.A., 1976. "Alkaloid-Bearing Plants: An Ecogeographic Perspective", Amer. Nat. 110:261-284.

McAllister, Don E., 1991. "Estimating the Pharmaceutical Values of Forests, Canadian and Tropical", Canadian Biodiversity 1: 16-25.

McNeely, J.A., 1989. Economics and Biological Diversity: Developing and Using Economic Incentives to Conserve Biological Resources. Columbia Univ. Press, New York. 232 pp.

Myers, N., 1979. The Sinking Ark: A New Look at the Problem of Disappearing Species. Permagon Press, New York. 307 pp.

Norton, B.G., 1982. "Environmental Ethics and Nonhuman Rights", Environmental Ethics 4:17-36.

Patton, D.R., 1987. "Is the Use of Management Indicator Species Feasible?" West. J. Appl. For. 2:33-34.

Potter, V.R., 1971. Bioethics: Bridge to the Future. Prentice-Hall, Englewood Cliffs, NJ. 205 pp.

Rosenzweig, M.L., 1971. "Paradox of Enrichment: Destabilization of Exploitation Ecosystems in Ecological Time", Science 171:385-387.

Shiva, V., 1990. "Biodiversity, Biotechnology, and Profit: The Need for a Peoples' Plan to Protect Biological Diversity", The Ecologist 20:44-47.

Smith, V.K., 1992. "Arbitrary Values, Good Causes, and Premature Verdicts", Journal of Environmental Economics and Management 22: 71-89.

Sterling Wood Group Inc., 1989. Expected Delivered Log Costs for Areas Treated Under the Canada-British Columbia Forest Resource Development Agreement. FRDA Report 079. Forestry Canada, Victoria.

Tedder, P.L., J.S. Schmidt and J. Gourley, 1980. TREES: Timber Resource Economic Estimation System. Volume 1, A Users Manual for Forest Management and Harvesting Scheduling. Research Bulletin No. 31a, Forest Research Lab., Oregon State University, Corvallis.

U.S. Water Resources Council, 1983. Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies. Washington, D.C.: Mimeograph, March 10. pp.137.

Williams, D.H. (ed.), 1987. The Economic Stock of Timber in the Coastal Region of British Columbia: Technical Appendices. Report 86-11, Vol. II. Forest Economics and Policy Analysis Research Unit, University of British Columbia. 78 pp.

Williams, D.H. and R. Gasson, 1986. The Economic Stock of Timber in the Coastal Region of British Columbia. Report 86-11, Vol. I. Forest Economics and Policy Analysis Research Unit, University of British Columbia. 22 pp.

A Decision Support System to Help Forest Managers Evaluate Silvicultural Strategies and Tactics

R.G. Davis

Ontario Ministry of Natural Resources, Forest Policy Branch, 70 Foster Drive, Sault Ste. Marie, Ontario, Canada, P6A 6V5

D.L. Martell

Faculty of Forestry, University of Toronto, 33 Willcocks Street, Toronto, Ontario, Canada, M5S 3B3

Abstract

This paper describes a decision support system (SilviPlan) that forest managers can use to help evaluate silvicultural strategies and tactics for specific sites in accordance with forest-wide objectives. The system is based upon strategic and tactical silvicultural mathematical programming planning models linked with a geographical information system. Detailed site-specific silvicultural prescriptions for the first ten years of a long planning horizon, and more general harvesting and regeneration schedules for subsequent ten-year periods, are incorporated in the tactical model. Managers can employ the geographical information system to subjectively delineate candidate sites on which harvesting and silvicultural activities might take place in the first ten years, and describe eligible silvicultural treatments and timings for each site. The tactical model identifies an operational schedule that produces the greatest sustainable yield of one or more timber species in the whole forest, given the candidate sites and treatments specified by the managers. The system is demonstrated on a 90,000 hectare forest in northeastern Ontario.

Introduction

Forest managers face major challenges in translating forest level objectives into actions on specific sites. Although silvicultural activities are undertaken at the stand level, their effects should be assessed in terms of their impacts on both the sites treated and the forest as a whole. In this paper, we describe a bi-level decision support system that forest managers can use to help formulate land management strategies, and then evaluate silvicultural activities for specific sites in accordance with concerns particular to each site and to the forest as a whole.

A strategic linear programming model is used to evaluate forest-wide concerns, including sustainable timber yield and silvicultural budgets, over a planning horizon that spans a rotation or more. The model is linked with a geographic information system (GIS) to facilitate visual delineation of candidate sites and aid in evaluating the operational schedules it produces. Planners address site-specific knowledge and concerns by subjectively delineating candidate sites for years one to ten of the planning horizon, and defining the silvicultural treatments to be considered for each site. When defining these candidate sites and treatments, multi-disciplinary planning teams can take into account the many forest values for which detailed inventories, quantitative relationships, and precise values are commonly lacking. A tactical model then helps them choose objectively from among the silvicultural options they specify in terms of what they wish to accomplish with the forest over long planning horizons.

The approach facilitates direct comparisons of silvicultural investment in different sites and treatments. Managers can also use the system to evaluate both short-term and long-term implications of broader factors such as relationships between silvicultural budget levels and sustainable timber yield. This information is useful in setting silvicultural budgets in accordance with timber production goals, and in tailoring silvicultural tactics to different budget levels. The SilviPlan decision support system is described in greater detail in Davis (1991) and Davis and Martell (1993).

The Silvicultural Planning Environment

To make a good silvicultural decision for any particular site a manager must consider many factors including: the current and possible future states of the forest; the objectives for both the site in question and the entire forest; the sizes, locations, and productive capacities of that site and other candidate sites; the available budget; and the costs of different treatments on the site in question and all the other candidate sites.

Providing an appropriate and sustainable yield of timber of desired species and products (e.g. veneer, sawlogs, and pulpwood) is an important objective for many forest management units. A major concurrent goal is often maintaining a satisfactory carrying capacity for wildlife. Although the habitat requirements of certain wildlife species have been documented to some extent, forest stand data alone is often inadequate for estimating habitat suitability because it lacks crucial information such as understorey vegetation. The knowledge base with regard to many other forest values is much sparser yet. At present, neither inventories nor indices nor projections of demand are in place for tourism, recreation, visual quality, biological diversity, or wilderness preservation in many areas. For these reasons, these decision aids are designed to facilitate the incorporation of managers' subjective knowledge and opinions with regard to these values.

In forests under even-aged management, managers commonly undertake silvicultural operations on blocks of land that overlap portions of one or more existing stands. Original stand boundaries may not always be maintained for a variety of logistic, economic, and ecological reasons. We therefore describe the basic unit for which treatments are prescribed as a "working block" rather than a stand. A working block must be sufficiently small and homogeneous that planners feel the entire site can be considered for the same silvicultural treatment regimes at the same time. Sites that are eligible for harvesting and regeneration will constitute the majority of working blocks in most applications. However, any forested area (i.e., any subset of the forest management unit) may be delineated as a working block and considered for any silvicultural treatment.

A "silvicultural regime" is a sequence of treatments conducted over several years on a working block. An intensive or elite regime for a site to be harvested might consist of patch clearcutting followed by mechanical site preparation the following year, planting the year after that, and manual release two years after planting. A less intensive regime for the same site might be careful logging to preserve advance growth of desirable species followed by aerial seeding.

Description of the *SilviPlan* System

The *SilviPlan* decision support system is one that foresters, wildlife managers, tourism and recreation representatives, and other forest land management specialists can use together to evaluate alternative silvicultural tactics and budget levels. The system is operated in two phases: the strategic and tactical planning phases. The strategic phase helps planners develop aggregate timber supply information linked to silvicultural budget levels, and harvest and regeneration scheduling recommendations for aggregate timber strata. This information then guides the planners in the tactical phase which constitutes the crux of the contribution of this decision support system. The tactical phase entails planning for each of the first ten years of the planning horizon, site-specific silvicultural operations that are consistent with forest-wide concerns and objectives.

The general approach is conceptually somewhat similar to the hierarchical planning scheme suggested by Weintraub and Cholaky (1991) in their bi-level decision processes, but the modelling principles are different in several respects. The approach presented here does not involve the division of a forest into zones of different management emphases and then modelling each zone in tactical detail. Rather, both the strategic and tactical phases apply to the entire forest over the entire planning horizon. Instead of the strategic model assigning input and output directives to several tactical models, the strategic phase provides silvicultural recommendations for aggregate timber strata that managers can take into account when they subsequently define their tactical options.

Strategic Planning Phase

In the strategic phase, planners consider the forest in aggregate form to help identify the silvicultural budget levels that can support a sustainable timber yield of desired species, and the types of stands in which silvicultural operations should be conducted in different planning periods. They use a linear programming model that assigns area within aggregate timber strata to harvesting and regeneration intensity schedules such that the sustainable yield of desired timber species is maximized over a planning horizon of a rotation or more. Constraints include non-declining harvest volumes of desired species from period to period, minimum harvest volumes by species, silvicultural budgets, and forest structure requirements.

The model used in the strategic planning phase is a Model III linear programming formulation. Although clearcutting is assumed, harvested areas can be treated with any one of several silvicultural intensities, each of which has associated regeneration costs and yield tables; more intensive classes have higher regeneration costs and timber volumes. All harvested area is assigned to the youngest age class of one of these silvicultural intensities by the model.

Treatment options in the strategic model are restricted to clearcutting followed by regeneration within the same working group and site class, to a silvicultural intensity class determined by the model. We have not allowed for consideration of treatments such as thinning, regeneration through advance growth, or NSR rehabilitation at this level of analysis, because we feel that stand-level examination is generally required to determine whether an area is suitable for such treatments.

SilviPlan is relatively easy to use once a database of the forest is in place, because planners do not have to prepare datasets describing the forest. Instead, they run a standard query language (SQL) program that accesses the database and produces reports on the area, average species composition, and average stocking level in each timber stratum in the forest. This report is accessed directly by the strategic model without further intervention.

Analysts supply input data such as yield tables, minimum harvest volumes by species, and silvicultural budgets, and indicate the species for which sustainable yield is to be maximized. They should run the model several times with different input to gain an appreciation of how certain parameters affect the optimal solution in terms of harvest volumes of different species, post-harvesting silvicultural intensities, wood costs, and forest structure. A series of runs with different silvicultural budgets is particularly useful in demonstrating the relationship between silvicultural budgets and sustainable timber yield and arriving at a satisfactory budget level.

Tactical Planning Phase

In the tactical planning phase, planners use a more detailed forest-level optimization model to help decide what harvesting and silvicultural operations to carry out in specific parts of the forest during the first ten years of the planning horizon consistent with long-term forest-level concerns such as sustainable timber yield and budget levels. Planners identify candidate working blocks for potential treatment during the first ten years of the planning horizon and describe silvicultural options for these sites in considerable detail. Area within individual working blocks is considered for eligible silvicultural treatment regimes each year for the first ten years of the planning horizon. The tactical model then evaluates these sites and options within the context of the entire forest. From the working blocks and treatment options specified, the tactical model identifies the operational silvicultural schedule for each of the first ten years, and the harvesting and silvicultural scheduling strategy for the remainder of the planning horizon, that maximizes the sustainable timber yield of the forest. Thus, long-term forest-wide concerns directly influence the assignment of detailed silvicultural regimes to specific sites during the first ten years, while planners' short-term concerns and site-specific restrictions are met. Planners can identify the most preferred working blocks and treatments from those they identify, and they can compare alternate scenarios of working block locations and treatment options by conducting a series of "what if?" trials.

The geographical integrity and planning detail required to evaluate silvicultural intervention on specific sites in terms of long-term forest-wide concerns would necessitate far too large a model based on conventional Model I, II, or III structures, since stand identity and detailed silvicultural options would have to be preserved throughout the planning horizon. To overcome this problem, we designed a model structure that includes a variable length time period system similar to that employed by Barros and Weintraub (1982), and site specificity for the working blocks during the first ten years of the planning horizon. The scheme improves spatial and silvicultural precision in the first ten years of the planning horizon while reducing computational effort in the less critical later periods. The major difference between the tactical and strategic models is that the first ten years of the planning horizon are broken down into ten one-year periods during which treatments are restricted to subjectively delineated working blocks and can be defined with much more detail. The primary links between the two levels of analysis within the model are decision variables that represent the age class structure of the forest since the forest structure that results from the assigned treatments in year ten is passed to the more general level of analysis. Some constraints, such as non-declining harvest volumes, also span the two planning levels.

Planners delineate candidate working blocks, which can take any desired size and shape, on a map of the forest which is displayed on a GIS screen. The strategies developed during the strategic planning phase provide guidance. For instance, GIS functions can be employed to highlight the timber strata from which the strategic model recommends that harvesting be conducted during the first ten-year period. A utility program provides reports on the area, species composition, and timber volumes within blocks so planners can assess how their selections compare with the strategic phase recommendations. The more that planners deviate from the strategic recommendations, the more that the sustainable timber yield of the forest will be reduced. Plenty of extra working block area should be defined so that the model has enough flexibility to make effective choices.

It is intended that multi-disciplinary planning teams participate in working block delineation, and incorporate their knowledge regarding the physical and biological characteristics of individual stands, and social concerns connected with the forest. These definitions of candidate working blocks, and eligible treatment regimes and timings, effectively act as constraints on where, when, and what operations can be conducted, and ensure that solutions are operationally feasible and environmentally acceptable as defined by the planners. Any geographical features for which data is available, such as waterways, roads, wildlife habitat features, and recreational areas, can be displayed to help planners delineate working blocks that are efficient, feasible and considerate of other values of the forest. Criteria such as stand sizes, shapes, species compositions, and ages, as well as understorey vegetation, soil types, road access, erosion concerns, wildlife requirements help planners decide block locations and boundaries.

For each working block, managers define the treatment regimes to be considered, and record them as a series of one-time costs, such as harvesting, site preparation and planting, incurred over several years. As such, these definitions are flexible enough to accommodate almost any type of silvicultural activity over a period of several years on a site, and to account for the different costs involved in conducting similar treatments on different sites. Harvesting costs are assessed on a volume basis while silvicultural costs for each year of the regime are assessed on an area basis. Each regime has associated proportions of volume of each species harvested, from zero to 100%. Any working block can also be made eligible or ineligible for a "no treatment" option, in which case its stands are assumed to simply grow for ten years according to the yield tables. Managers specify the years in which each working block is eligible to begin treatment. These restrictions can be used to reflect considerations such as road access, wildlife habitat, harvest block adjacency, or tourism industry concerns. Finally, planners represent the expected results of each eligible treatment regime by specifying the timber stratum or strata that area within each working block is to be assigned should it receive that regime. These future strata are not confined to those of age zero or of the same working group; any point on any yield curve may be designated, so that treatments such as species conversion and NSR rehabilitation can be easily accommodated.

Much of the input data prepared for the strategic phase is automatically read as input by the tactical planning model. Harvest volumes and silvicultural costs are calculated on an annual basis for the first ten years, and by ten-year periods for the remainder of the planning horizon. For each of the first ten years, the total costs of harvesting timber and conducting silvicultural treatments in all the working blocks is constrained to be within available budgets. The output includes information on areas and volumes harvested and treated, costs, and forest structure. Analysts can use the GIS to display the silvicultural schedules produced for each of the first ten years, as well as the strategic recommendations for subsequent ten-year time periods. Such displays can help forest managers examine different working block arrangements and treatments in terms of their effects on wildlife habitat suitability, recreational opportunities, road construction, and other factors.

SilviPlan is designed to help forest managers evaluate subjectively defined alternatives. Multiple runs allow managers to compare alternate scenarios in terms of their implications for individual sites and the forest as a whole. Different sets of working blocks and treatment options can be compared in terms of the forest-wide concerns quantitatively evaluated by the SilviPlan model, and of site-specific and non-timber factors that forest managers evaluate subjectively or through some other means.

Case Study: Kabika Forest Management Plan

The *SilviPlan* system was applied to help two fourth-year undergraduate students at the University of Toronto's Faculty of Forestry prepare a management plan for a course in land management. They were planning for a 90,000-hectare section of relatively undeveloped boreal forest in northeastern Ontario which they named "Kabika Forest" after one of its primary rivers. The area constitutes part of the Iroquois Falls Forest Management Unit, which is an area of provincial Crown land managed by Abitibi-Price Inc. under a Forest Management Agreement.

Strategic Planning Phase

Consultation with the student planners revealed that they wished to maximize the combined sustainable yield of the three species that are harvested in the area: spruce, jack pine, and poplar, with the condition that at least 30,000 cubic metres of spruce were harvested each year. They also wanted to calculate, but not necessarily maximize, the volumes of other softwood and hardwood species encountered in mixed stands of the spruce, jack pine, and poplar working groups. Four silvicultural intensity classes and a 110-year planning horizon were selected as sufficient. We used yield tables adapted from those used by the Ontario Ministry of Natural Resources for the area. Other input data for the strategic phase model included the following:

- minimum eligible harvest ages for each combination of working group and site class
- anticipated post-harvest species composition (%) for each working group following treatment with each silvicultural intensity
- anticipated post-harvest stocking level for each working group following treatment with each silvicultural intensity
- average cost per cubic metre for harvesting each species
- average cost per hectare for regenerating to each silvicultural intensity
- minimum timber volumes of each species to be growing in the operable forest at the end of the planning horizon (i.e. terminal volumes)
- minimum and/or maximum desired areas in any timber stratum at any point during the planning horizon

The model was solved with *GAMS* (Brooke, Kendrick, and Meeraus 1988) mathematical programming software. The linear programming matrix had 7,894 equations, 11,236 variables, and 25,842 non-zero elements. *GAMS/MINOS* successfully found and reported on an optimal solution after 9,728 iterations in 75 minutes on a Sun Microsystems SPARCstation 1 computer. Results showed that Kabika Forest could sustain a combined annual yield of 38,357 cubic metres of spruce, jack pine, and poplar given the costs and budgets specified, provided that the recommended harvest and silvicultural schedule is followed.

We developed a relationship between investment and sustainable yield by running the model several times with different budgets specified. An investment of $7,400,000 each decade was the minimum needed to sustain a harvest of 30,000 cubic metres of spruce each year. The planners chose a budget of $8,000,000 per decade as suitable for meeting the mill requirements while maintaining a degree of security in the event of wildfire or land withdrawals.

Although spatial factors are ignored in the strategic model, the schedules produced with each run generally concurred with the principles of prime site management on biological grounds. That is, more productive sites were generally harvested at younger ages and treated more intensively than less productive sites. Rather than selecting all of the oldest strata for harvesting first, the model harvested a mix of some of the oldest age classes and some of the younger ones. In all cases, the age classes that are generally considered overmature were depleted within the first five ten-year periods.

Tactical Planning Phase

We used GIS "querying" functions to highlight all the stands within the timber strata in which the strategic model recommended harvesting be conducted during the first ten-year period. We considered these strata preferred harvest locations for the first ten years. We also displayed in other colours, those strata for which marginal costs in terms of sustainable timber yield were quite low, and considered these as secondary choices. The displays clearly illustrated the tendency of forest-level models to generate harvesting and silvicultural schedules that are operationally infeasible and/or undesirable. For instance, much of the area slated for harvest in the first ten years was located far from existing roads, and some proposed harvest blocks might have been large enough to unduly compromise wildlife habitat.

The planners heeded the strategic recommendations as much as possible in delineating working blocks. Their choices were tempered by the lack of road access and wildlife considerations such as sizes and shapes of harvest blocks. In deference to the extremely limited road access, the planners developed a 20-year secondary road access plan in concurrence with the selection of working blocks. To keep costs reasonable, they limited their road construction to five kilometres per year. Anticipated road access was the primary consideration in deciding when working blocks could be made eligible for treatment.

In addition to the strategic model recommendations and projected road access, concerns such as harvest block size, local vegetative diversity, and proximity to waterways were built into the planners' subjective decisions in delineating working blocks. Stand characteristics, primarily species composition and site class, were used to help determine whether adjacent stands were similar enough that they could be included in a single working block, or whether multiple working blocks would have to be specified so that different sets of treatments could be considered for the stands. A total of 47 working blocks were delineated. The areas and volumes contained in the working blocks were about double those recommended for harvesting in the first ten years in the strategic phase; the surplus is needed so that the model has sufficient flexibility to identify the best alternatives from the possibilities defined.

The planners designed a set of 14 silvicultural treatment regimes, each of which consisted of a series of treatments carried out over a period of up to five years. Twelve regimes involved harvesting and regeneration, and the other two involved rehabilitation of NSR land. In addition, one treatment regime is reserved by the tactical model to signify no treatment.

Each working block was made eligible for several treatment regimes, depending on its species composition, site classes, and geographical location. Each treatment regime was classed as "extensive", "basic", "intensive", or "elite" in order to help specify the aggregate timber strata to which working blocks would be assigned should they receive treatment with an eligible regime. We specified that working blocks that received careful logging treatments followed by regeneration through advanced growth were to be assigned to strata of age ten years; blocks that received clearcutting or NSR rehabilitation were to be assigned to strata of age zero. All of the working blocks were also made eligible for the "no treatment" option. Other input data, such as silvicultural budgets and minimum harvest volumes, were left the same as in the strategic phase.

The resulting linear programming matrix had 10,358 rows, 20,322 variables, and 40,086 non-zero elements. *GAMS/MINOS* successfully found and reported on an optimal solution after 10,381 iterations in 100 minutes on a *SPARCstation* 1. The long-run sustainable combined yield of spruce, jack pine, and poplar from Kabika Forest at an annual budget level of $800,000 changed from 38,357 cubic metres per year as estimated in the strategic phase, to 37,947 cubic metres per year, provided that the harvest and silvicultural schedule generated by the model is followed.

We later ran the model at a variety of budget levels and found that sustainable timber yield at each budget level was similar to that obtained in the strategic phase (Figure 1). However, no clear relationship between the strategic and tactical results were evident, because the restrictions in the locations that the model can select for harvesting in the first ten years of the planning horizon are offset to some degree by the increased silvicultural flexibility in the first ten years. For instance, some working blocks were assigned to treatment regimes of careful logging followed by regeneration through advanced growth, and ascribed ages of 10 years.

Operational schedules (i.e., which blocks were treated in which manner during each year) were plotted with GIS "querying" functions for each of the first fourteen years of the planning horizon. These maps helped to visualize the different treatments to be conducted in the forest in a particular year. Through examining a series of these maps through several years, the sequence

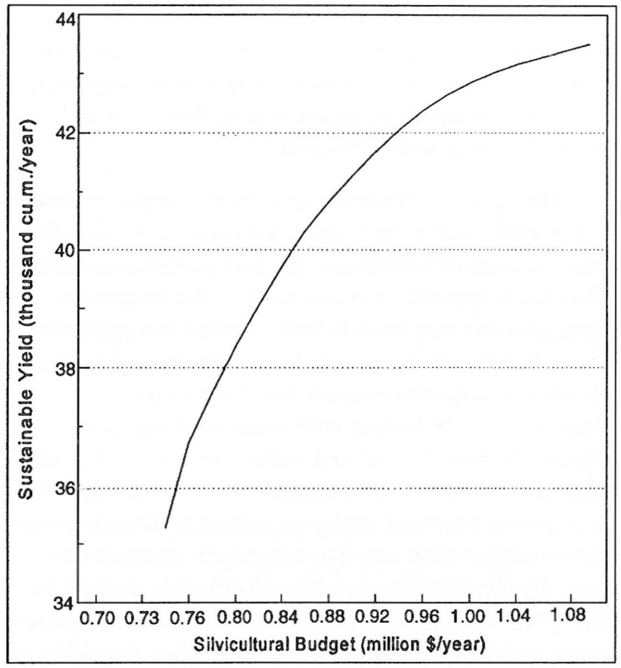


Figure 1. Relationship between silvicultural investment and sustainable timber yield.

of operations on any particular working block and the changes in the forest can easily be seen.

Discussion

SilviPlan is well suited for helping to provide forest managers with insight into silvicultural problems through experimentation and exploration. Once the GIS database is in place, the system is not difficult to use. Multiple runs allow forest managers to evaluate a number of scenarios, such as different silvicultural budgets or working block layouts, in terms of their implications for individual sites and the forest as a whole. Imaginative planning may reveal a variety of silvicultural tactics that are nearly equivalent in terms of timber production and costs, but quite different in time and space; this implies that efforts to improve values such as wildlife carrying capacity may not necessarily lead to losses in wood supply or increases in costs.

The unique structure of the tactical model allows forest managers to directly compare alternative stand treatments in terms of forest-wide timber production concerns. Although the system does not accommodate all of the flexibility of stand-level models in representing treatments such as spacing of plantations or uncertainties concerning regeneration failure, it makes it possible for forest managers to link stand-level and forest-level planning with a forest-level planning system. Less common treatments such as species conversion, NSR rehabilitation, and modified harvesting methods are easy to evaluate. SilviPlan could easily be modified to consider different objectives such as minimizing wood costs, and/or different qualities of timber, such as veneer, sawlog, and pulpwood.

The system's flexibility in defining working blocks and eligible treatment regimes are important given the many aspects of forest planning that probably cannot be adequately quantified in any model. For instance, a particular site may have to be harvested in a particular year when the equipment or labour force is available; a site close to a tourist outpost may have to receive expensive hand planting with large seedlings; a site adjacent to private land or a waterway may not be considered for chemical cleaning; and sites that are small in area, poorly accessed, rocky, or subject to intensive vegetative competition may be particularly expensive to treat. The system also provides an effective method for assessing the relationships between silvicultural budget levels and timber supply. This information should be of interest to those who set the budgets for management units, and to industrial foresters who need to know the investment required to sustain a desired wood flow.

This system embraces the basic concepts of hierarchical planning as advanced by Weintraub and Cholaky (1991) but incorporates two levels of analysis within a single model. The approach greatly simplifies the operation of the system and allows stand-level treatments to be directly evaluated in terms of long-term forest-wide concerns.

Acknowledgments

This research was supported by the Natural Sciences and Engineering Research Council of Canada, and is based on R.G. Davis' M.Sc.F. thesis at the Faculty of Forestry, University of Toronto. We wish to thank C. Amrhein, D.C.F. Fayle, and V. Timmer for their advice as members of the thesis supervisory committee. Several Ontario Ministry of Natural Resources personnel, particularly R.T. Fleet and R.G. Williams, contributed ideas and information that helped launch this project. D. Boychuk provided critical insight on issues in forestry and modelling. E. Turk and B. Cooke, now graduates of the University of Toronto, were constructive in our case study application of this decision support system.

References

Barros, O. and A. Weintraub. 1982. Planning for a vertically integrated forest industry. Operations Research 30(6):1168-1182.

Brooke, A., D. Kendrick, and A. Meeraus. 1988. *GAMS*: a user's guide. The Scientific Press, South San Francisco. xiv + 289 pp.

Davis, R.G. 1991. A decision support system to help forest managers design and implement silvicultural strategies. M.Sc.F. Thesis, Faculty of Forestry, University of Toronto, Toronto. vi + 173 pp.

Davis, R.G. and D.L. Martell. 1993. A decision support system that links short-term silvicultural operating plans with long-term forest-level strategic plans. Canadian Journal of Forest Research. 23(6): 1078-1095.

Weintraub, A., and A. Cholaky. 1991. A hierarchical approach to forest planning. Forest Science 37(2):439-460.

A Hierarchical Decomposition of Capacity and Production Decisions in Stochastic Manufacturing Systems: Summary of Results

S. P. Sethi
Faculty of Management, University of Toronto, Toronto, Ontario, Canada M5S 1V4
M. I. Taksar
Department of Applied Mathematics and Statistics, SUNY at Stony Brook, Stony Brook, NY 11794
Q. Zhang
Department of Mathematics, University of Georgia, Athens, GA 30502

Abstract

This paper presents a model of hierarchical decomposition of investment and production decisions in a manufacturing system with convex costs and with machines subject to breakdown and repair. Main theoretical results obtained by the authors in [5] are summarized. The model is deliberately kept simple for convenience in exposition. Demand facing the system is assumed to be a given constant. Production capacity can be increased by investing in capacity expansion at some time in the future. The objective is to minimize the cost of investment, production, inventories, and backlogs. The decision variables are a stopping time, at which new capacity is purchased at a given fixed cost, and a production plan before and after the purchase. The rate of change in machine states is assumed to be much larger than the rate of discounting of costs. This gives rise to a deterministic limiting problem in which the stochastic machine availability is replaced by the equilibrium mean availability. The value function for the original problem converges to the value function of the limiting problem. Moreover, two different methods are given for constructing decisions for the original problem from the optimal decisions for the limiting problem in a way which guarantees their asymptotic optimality. Error estimates for the constructed asymptotically optimal decisions are also provided. The significance of these results for the decision-making hierarchy is that the strategic level management can base its capacity decision on aggregated, rather than detailed, information from the shopfloor while the operational level management can then derive an approximately optimal production plan for the system.

1 Introduction

Most manufacturing firms are large, complex systems characterized by several decision subsystems such as finance, personnel, marketing, and operations. Moreover, these systems are subject to discrete events such as acquiring or replacing equipment, hiring and laying off of workers, introducing promotional campaigns, and machine breakdowns and repairs. These events could be deterministic or stochastic. Management must recognize and react to these events. Because of the large size of these systems and the presence of these events, exact optimal policies to run these systems may be quite difficult to obtain, both theoretically and computationally.

One way to cope with these complexities is to develop methods of hierarchical decision making for these systems. The idea is to reduce the overall complex problem into manageable approximate problems of subproblems, each of which is linked by means of a hierarchical integrative system. There are several different, and not mutually exclusive, ways in which the reduction of the complexity might by accomplished. These include decomposition into the problems of the smaller subsystems with a proper coordinating mechanism, aggregation of products along with a disaggregation procedure, replacement of random processes by their averages, etc. For further details on hierarchical approaches in production planning systems and their importance in practice, we refer the reader to surveys of the literature by Kistner and Switalski [3], Stadtler [10], Bitran and Tirupati [2], Sethi and Zhang [6], and a bibliography compiled by Bukh [1].

In this paper, we focus on the problem of a manufacturing firm that must make decisions regarding investment in capacity expansion as well as production policy in order to minimize costs of investment, production, inventories, and backlogs in an uncertain environment. Problems dealing with marketing and personnel decisions are treated elsewhere [8, 11].

The problem under consideration, termed the global problem, can be formulated as a dynamic stochastic optimization problem with a stopping time to purchase new capacity and the production rate over time before and after the acquisition of the new capacity as decision variables. In general, such problems are intractable. Either because of this intractability or because of some organizational considerations such as the presence of a hierarchical decision making structure within the firm, the capacity expansion and production planning decisions, in practice, are made at different levels of the organization. The former decisions are usually long term or strategic decisions and are in the domain of Capital Budgeting or, more generally, Strategic Planning. The latter are short to medium term tactical decisions and are usually the concern of Operations Management. The two-level decision making procedure works roughly as follows. Strategic Planning (the upper level) bases its capacity expansion decisions on some aggregated, rather than detailed, information from the shop floor. These decisions are then handed down to Operations Management (the lower level), which makes production planning decisions given the capacity decisions made at the upper level.

An important and obvious question that arises is whether there is a two-level decision procedure such as the above that is simpler than solving the global problem and is, at the same time, a good approximation to the optimal solution of the global problem. The theory developed in this paper answers the question in the affirmative under reasonable assumptions.

In order to further elaborate on what we mean here, let us provide additional details of the model considered in the paper. For convenience in exposition, we shall assume that the demand facing the firm is constant. The existing production capacity consists of machines that are subject to breakdowns and repairs and is represented by a finite state Markov process. Acquisition of additional capacity at some future time to be determined results in an enhanced capacity process represented by another finite state Markov process having a larger average capacity than the existing one. In the interest of simplicity, we assume that a fixed increment of capacity can be added at most once at a fixed cost. The costs of production and inventory/shortage are assumed to be convex. It is assumed that the rate of breakdown and repair events with and without the additional capacity is much larger than the rate at which costs are discounted. This assumption is explained in what follows.

It is important to note that the model we have formulated is sufficiently rich and representative, although deliberately simple, to illustrate the idea of asymptotic optimality in hierarchical manufacturing organizations in which long term and short term decisions are made by different organizational units. Moreover, the processes taking place in the short term are much faster than those in the long term. By a fast changing process, we mean a process that is changing so rapidly that from any initial condition, it reaches its stationary distribution in a time during which there are few, if any, fluctuation in the other processes. For example, in the case of a fast changing Markov process, the state distribution converges rapidly to a distribution close to its stationary distribution. In the case of a fast changing deterministic process, the time-average of the process reaches a value near its limiting long-run average value. Furthermore, it is possible to associate a *time constant* with each of these processes, namely the reciprocal of the rate of convergence. It is related to the time it takes the process to cover a specified fraction of the distance between its current value and its equilibrium value, or the time required for the initial distribution to become sufficiently close to the stationary distribution. The concept of a time constant is quite common in the engineering literature. In the special case of exponential radioactive decay, which is related to our exponential discounting process, a familiar measure of the time constant is known as the *half life*. Thus if ρ is the discount rate used in our model, its half life is given by $\log 2/\rho$, which is of the same order as $1/\rho$, and can be taken as the measure of the time constant of the discounting process. The reader is referred to Lehoczky, Sethi, Soner and Taksar [4, p.105, Remark 3] for further discussion on this point.

For the model described above, it is indeed possible to develop several different two-level procedures that accomplish the task. One such two-level procedure can be described as follows. The upper level solves a deterministic problem, termed the limiting problem, obtained by replacing random capacities by their averages. The solution of this limiting problem yields the purchase date for the additional capacity as well as an average production plan. The upper level releases an order to have the capacity expanded at that date and informs the lower level of this decision. With regards to the production plan, it is clear that the average production plan is not feasible for the stochastic global problem. However, one could construct from it a feasible production plan at the lower level that takes into account the information regarding the date at which the new capacity will become available. An alternative procedure for the lower level would be to resolve the detailed stochastic production planning problem given the upper level's capacity decision. This would also result in a feasible production plan. We are able to prove that either of these two-level decision procedures provides an asymptotically optimal solution to the global problem as the rates of breakdown and repair events become very large or, in other words, approach infinity.

The model developed here represents an extension of predecessor papers by Lehoczky *et al.* [4], Sethi and Zhang [7] and Sethi et al. [9] in the sense that we incorporate an optimal stopping time of the capacity expansion event in the stochastic optimal control problems studied in [4, 7, 9], that involve only the determination of optimal production plans. This gives rise to a complex, nonstandard problem and the exact optimal solution is very difficult to obtain. In order to reduce the complexity of the problem, we make use of the idea of hierarchical decision making. Namely, we derive a limiting problem, which is simpler to solve than the original problem. This limiting problem is obtained by replacing the stochastic machine availability processes before and after the capacity expansion event by their respective average total capacities and by appropriately modifying the objective function. From its solution, we construct an approximately optimal solution of the original, more complex, problem.

The specific points addressed in the paper are results on the asymptotic optimality of the constructed production plan and the capacity expansion time and the extent of the resulting deviation from the value function of the original problem. The significance of these results for the decision-making hierarchy is that the corporate level management can ignore the day-to-day fluctuation in machine capacities, or more generally, the details of shop floor events in making decisions regarding investment in new capacity. The operational level management can then derive approximate optimal production policies for running the actual stochastic manufacturing system. The results can also be viewed as having significant implications for the design of hierarchical structures within manufacturing organizations.

The plan of the paper is as follows. In §2, we formulate the model of manufacturing system under consideration and the related global stochastic optimization problem. In §3, we define the limiting problem and state that the value function of our problem converges to the value function of the limiting problem as the oscillating rate of the production capacity goes to infinity. Then in §4, we discuss two methods of constructing asymptotically optimal decisions for the global problem starting from the solution of the limiting problem. Both feedback and open loop decisions are discussed. We also provide estimates for the difference of the constructed decisions and the optimal decisions for the global problem in terms of their associated cost functions. In §5, we discuss verification theorems, which concern the optimality conditions for our problems. Based on this analysis, we can define *switching sets*, that determine the optimal stopping time for capacity expansion. In other words, the optimal stopping time is given by the optimal trajectory's first exit time from the switching set. A simple running example is used in §2-5 to illustrate our formulation of the problem and the results derived for it. Finally, §6 concludes the paper.

Proofs of the results stated in the paper appear in [5]. The main techniques used are those of dynamic programming and viscosity solutions.

2 Problem formulation

We consider a stochastic manufacturing system with the inventory/backlog or surplus $x_t \in R^n$ and production rate $u_t \in R^n$ that satisfy

$$\dot{x}_t = u_t - z, \; x_0 = x, \tag{1}$$

where $z \in R^n$ denotes the rates of demand and x is the initial surplus level. We assume $u_t \geq 0$ and for some positive vector $p^0 = (p_1^0, \cdots, p_n^0)$ such that $p^0 \cdot u_t \leq \alpha^\varepsilon(t)$, where $\alpha^\varepsilon(t)$, is a stochastic production capacity process with ε as a small parameter in the characterization of the capacity process to be precisely specified later. Moreover, the specification of $\alpha^\varepsilon(t)$ involves the purchase of some given additional capacity at some time τ, $0 \leq \tau \leq \infty$ at a cost of K, where $\tau = \infty$ means not to purchase it at all. Therefore, our decision variable is a pair $(\tau, u.)$ of a Markov time $\tau \geq 0$ and a production process $u.$ over time.

We consider the cost function J^ε defined by

$$J^\varepsilon(x, \alpha, \tau, u.) = E[\int_0^\infty e^{-\rho t} G(x_t, u_t) dt + K e^{-\rho\tau}], \tag{2}$$

where $\alpha^\varepsilon(0) = \alpha$ is the initial capacity and $\rho > 0$ is the discount rate. The problem is to find an admissible decision $(\tau, u.)$ that minimizes $J^\varepsilon(x, \alpha, \tau, u.)$.

We take $U = \{(u_1, \cdots, u_n) \geq 0 : p_1^0 u_1 + \cdots + p_n^0 u_n \leq 1\}$, where $p^0 = (p_1^0, \cdots, p_n^0) \geq 0$. Then U is a compact convex subset of R^n. U will be used later in defining admissible decisions.

Notation. We make use of the following notation in this paper:

$\alpha \cdot U$: the set $\{\alpha u : u \in U\}$ for any $\alpha \in R^1$;

$u.$: a production rate process $u. = \{u_t : t \geq 0\}$.

Define $\alpha_1^\varepsilon(t)$ and $\alpha_2^\varepsilon(t)$ as two Markov processes with state spaces $\mathcal{M}_1 = \{0, 1, \cdots, m_1\}$ and $\mathcal{M}_2 = \{0, 1, \cdots, m_1 + m_2\}$, respectively. Here, $\alpha_1^\varepsilon(t) \geq 0$ denotes the existing production capacity process and $\alpha_2^\varepsilon(t) \geq 0$ denotes the capacity process of the system if it were to be supplemented by the additional new capacity at time $t = 0$.

Let $\mathcal{F}_1(t)$ and $\mathcal{F}_2(t)$ denote the filtrations generated by $\alpha_1^\varepsilon(t)$ and $\alpha_2^\varepsilon(t)$, respectively, i.e., $\mathcal{F}_1(t) = \sigma\{\alpha_1^\varepsilon(s) : s \leq t\}$ and $\mathcal{F}_2(t) = \sigma\{\alpha_2^\varepsilon(t) : s \leq t\}$.

We define a new process $\alpha^\varepsilon(t)$ as follows: For each $\mathcal{F}_1(t)$-Markov time $\tau \geq 0$,

$$\alpha^\varepsilon(t) = \begin{cases} \alpha_1^\varepsilon(t) & \text{if } t < \tau \\ \alpha_2^\varepsilon(t - \tau) & \text{if } t \geq \tau \end{cases} \tag{3}$$
$$\text{and } \alpha^\varepsilon(\tau) = \alpha_2^\varepsilon(0) := \alpha_1^\varepsilon(\tau) + m_2.$$

Here m_2 denotes the maximum additional capacity resulting from the addition of the new capacity.

We make the following assumptions on the running cost function G and the random processes $\alpha_1^\varepsilon(t)$ and $\alpha_2^\varepsilon(t)$.

A1) For all x, x', u, u', there exist constants C_g and k_g such that $0 \leq G(x, u) \leq C_g(1 + |x|^{k_g})$ and

$$\begin{aligned} &|G(x, u) - G(x', u')| \\ \leq\ & C_g(1 + |x|^{k_g} + |x'|^{k_g})(|x - x'| + |u - u'|). \end{aligned}$$

A2) $\alpha_1^\varepsilon(t) \in \mathcal{M}_1$ and $\alpha_2^\varepsilon(t) \in \mathcal{M}_2$ are Markov processes with generators $\varepsilon^{-1}Q_1$ and $\varepsilon^{-1}Q_2$, respectively, where $Q_1 = (q_{ij}^{(1)})$ and $Q_2 = (q_{ij}^{(2)})$ are matrices such that $q_{ij}^{(k)} \geq 0$ if $i \neq j$ and $q_{ii}^{(k)} = -\sum_{i \neq j} q_{ij}^{(k)}$ for $k = 1, 2$. Moreover, Q_1 and Q_2 are both irreducible.

Let $\mathcal{F}(t)$ denote the filtration generated by $\alpha^\varepsilon(t)$, i.e., $\mathcal{F}(t) = \sigma\{\alpha^\varepsilon(t) : s \leq t\}$. Note that the filtration $\mathcal{F}(t)$ is not determined *a priori*, since it depends on the stopping time to be determined.

Definition. We say that a control $(\tau, u.)$ is *admissible* if 1) τ is an $\mathcal{F}_1(t)$-Markov time; 2) u_t is $\mathcal{F}(t)$ adapted and $u(t) \in \alpha^\varepsilon(t) \cdot U$ for $t \geq 0$.

We use $\mathcal{A}_{\mathrm{I}}$ to denote the set of all admissible decisions $(\tau, u.)$. Then the problem is:

$$\mathcal{P}(\mathrm{I}) : \begin{cases} \min_{(\tau,u.)\in\mathcal{A}_{\mathrm{I}}} & J^\varepsilon(x, \alpha, \tau, u.) \\ \quad \text{s.t.} & \dot{x}_t = u_t - z,\ x_0 = x. \end{cases}$$

We write $v^\varepsilon(x, \alpha)$, the value function, to be the minimum cost on $\mathcal{A}_{\mathrm{I}}$, i.e.,

$$v^\varepsilon(x, \alpha) = \inf_{(\tau,u.)\in\mathcal{A}_{\mathrm{I}}} J^\varepsilon(x, \alpha, \tau, u.). \tag{4}$$

It follows immediately from (4) that

$$v^\varepsilon(x, \alpha) = \inf_{\tau} \inf_{u.} J^\varepsilon(x, \alpha, \tau, u.). \tag{5}$$

This means that we can optimize over all production plans first for any fixed τ, and then search for the Markov time τ that is optimal.

We now define an auxiliary value function $v_a^\varepsilon(x, \alpha')$ to be K plus the optimal cost with the capacity process $\alpha_2^\varepsilon(t)$ and initial capacity $\alpha' \in \mathcal{M}_2$ and no future capital expansion possibilities. The cost K is included in the definition of v_a^ε so as to make it comparable to v^ε. Therefore,

$$v_a^\varepsilon(x, \alpha + m_2) = \inf_{(0,u.)\in\mathcal{A}_{\mathrm{I}}} J^\varepsilon(x, \alpha, 0, u.) \text{ for all } \alpha \in \mathcal{M}_1.$$

For convenience, we shall call the pair $(v^\varepsilon, v_a^\varepsilon)$ as the value functions of the problem.

3 Limiting problem

In this section, we consider the asymptotic behavior of the system (1) and (4). We state that the system (1) with random capacity due to unreliable machines can be simplified and reduced to a deterministic capacity system. In a large measure, this is accomplished by showing that there exists a value function $v(x)$ and an auxiliary value function $v_a(x)$ of some system, to be determined, such that $(v^\varepsilon(x, \alpha), v_a^\varepsilon(x, \alpha)) \to (v(x), v_a(x))$ for all (x, α) as $\varepsilon \to 0$.

Let $\nu^{(1)} = (\nu_0^{(1)}, \nu_1^{(1)}, \cdots, \nu_{m_1}^{(1)})$ and let $\nu^{(2)} = (\nu_0^{(2)}, \nu_1^{(2)}, \cdots, \nu_{m_1+m_2}^{(2)})$ denote the equilibrium distributions of Q_1 and Q_2, respectively. Then $\nu^{(1)}$ and $\nu^{(2)}$ are the only positive solutions to

$$\begin{aligned} \nu^{(1)}Q_1 = 0 \text{ and } \textstyle\sum_{i=0}^{m_1} \nu_i^{(1)} = 1, \\ \nu^{(2)}Q_2 = 0 \text{ and } \textstyle\sum_{i=0}^{m_1+m_2} \nu_i^{(2)} = 1. \end{aligned} \tag{6}$$

We now define a limiting problem. We first define decision sets for the limiting problem. Let $U_1 = \{(u_0, \cdots, u_{m_1}) :$ such that $u_i \in i \cdot U\}$ and $U_2 = \{(u_0, \cdots, u_{m_1+m_2}) :$ such that $u_i \in i \cdot U\}$. Then $U_1 \subset R^{n\times(m_1+1)}$ and $U_2 \subset R^{n\times(m_1+m_2+1)}$.

Definition. We use $\mathcal{A}_{\mathrm{II}}$ to denote the set of the following decisions (*admissible decisions* for a limiting problem): 1) a deterministic time τ; 2) a deterministic $\mathbf{u}_t$ such that for $t < \tau$, $\mathbf{u}_t = (u_0(t), \cdots, u_{m_1}(t)) \in U_1$ and for $t \geq \tau$, $\mathbf{u}_t = (u_0(t), \cdots, u_{m_1+m_2}(t)) \in U_2$. Here and elsewhere in the paper, a boldface letter $\mathbf{u}$ denotes a vector in $R^{n\times(m_1+1)}$ or $R^{n\times(m_1+m_2+1)}$.

Let

$$\begin{aligned} J(x, \tau, \mathbf{u}.) = & \int_0^\tau e^{-\rho t} \textstyle\sum_{i=0}^{m_1} \nu_i^{(1)} G(x_t, u_i(t))dt \\ & + \int_\tau^\infty e^{-\rho t} \textstyle\sum_{i=0}^{m_1+m_2} \nu_i^{(2)} G(x_t, u_i(t))dt \\ & + e^{-\rho\tau} K \end{aligned}$$

and let

$$\bar{u}_t = \begin{cases} \sum_{i=0}^{m_1} \nu_i^{(1)} u_i(t) & \text{if } t < \tau \\ \sum_{i=0}^{m_1+m_2} \nu_i^{(2)} u_i(t) & \text{if } t \geq \tau \end{cases}. \quad (7)$$

We define the following optimization problem (limiting problem):

$$\mathcal{P}(\text{II}) : \begin{cases} \text{mini}_{(\tau,\mathbf{u}.)\in\mathcal{A}_{\text{II}}} & J(x,\tau,\mathbf{u}.) \\ \text{s.t.} & \dot{x}_t = \bar{u}_t - z,\ x_0 = x. \end{cases} \quad (8)$$

Let $(v(x), v_a(x))$ denote the value functions for $\mathcal{P}(\text{II})$, i.e.,

$$v(x) = \inf_{(\tau,\mathbf{u}.)\in\mathcal{A}_{\text{II}}} J(x,\tau,\mathbf{u}.)$$
$$\text{and} \quad v_a(x) = \inf_{(0,\mathbf{u}.)\in\mathcal{A}_{\text{II}}} J(x,0,\mathbf{u}.).$$

Theorem 3.1.

$$(v^\varepsilon(x,\alpha), v_a^\varepsilon(x,\alpha)) \to (v(x), v_a(x)) \text{ as } \varepsilon \to 0.$$

This result offers an important insight into the nature of the optimization problem involving a capacity process with fast state transition rates. That is, if the rate is sufficiently fast in relation to the discount rate, then the value function is essentially independent of the initial capacity state. This is because the transients die out and the capacity process settles into its stationary distribution long before the discount factor $e^{-\rho t}$ has decreased substantially from its initial value of one. Note that if it were not so, then the system would have remained at the initial capacity for a sufficiently long period of time and during which a substantial portion of the value making up the value function of the problem would have accrued, with the consequence that the value function would depend significantly on the initial capacity.

4 Asymptotically optimal decisions and error bounds

In this section and the next section, we discuss two methods to construct asymptotically optimal decisions based on the decisions for the limiting problems $\mathcal{P}(\text{II})$. We discuss error estimates for these constructed decisions. In order to do so, we need a further assumption on the running cost function G. We assume the following in the rest of this paper:

A1') $G(x,u) = h(x) + c(u)$ for convex functions $h(x)$ and $c(u)$.

We now describe our first method to construct near optimal decisions.

Method I. Let $(\sigma, \mathbf{u}.^0) \in \mathcal{A}_{\text{II}}$ denote any admissible decision for the limiting problem $\mathcal{P}(\text{II})$ where

$$\mathbf{u}_t^0 = \begin{cases} (u_0(t),\cdots,u_{m_1}(t)) \in U_1 & \text{if } t < \sigma \\ (u_0(t),\cdots,u_{m_1+m_2}(t)) \in U_2 & \text{if } t \geq \sigma \end{cases}.$$

Note that here σ denotes a deterministic (calendar) time. We take

$$u_t^\varepsilon = \begin{cases} \sum_{i=0}^{m_1} \chi_{\{\alpha^\varepsilon(t)=i\}} u_i(t) & \text{if } t < \sigma \\ \sum_{i=0}^{m_1+m_2} \chi_{\{\alpha^\varepsilon(t)=i\}} u_i(t) & \text{if } t \geq \sigma \end{cases}. \quad (9)$$

Then, the constructed decision $(\sigma, u.^\varepsilon) \in \mathcal{A}_{\text{I}}$ is apparently admissible for $\mathcal{P}(\text{I})$.

Remark. By calendar in the parentheses above, we mean a time that can be marked on a calendar. An example would be to buy the new machine on σ. Alternatively, a deterministic time can be also expressed by a time at which a certain deterministic trajectory enters a specified deterministic set known as the switching set; see §6.

Remark. If $G(x,u) = h(x) + c \cdot u$, then the decision u_t^ε is expected to have a simpler form. In fact, if we take $(\sigma, \bar{u}.)$ to be an admissible control for $\mathcal{P}(\text{II})$. Then $\bar{u}_t \in \bar{\alpha}_1 \cdot U$ for $t < \sigma$ and $\bar{u}_t \in \bar{\alpha}_2 \cdot U$ for $t \geq \sigma$. Let

$$u_i(t) = \begin{cases} i(\bar{\alpha}_1)^{-1}\bar{u}_t & \text{if } t < \sigma \\ i(\bar{\alpha}_2)^{-1}\bar{u}_t & \text{if } t \geq \sigma \end{cases}.$$

Then $u_i(t) \in i \cdot U$. Hence, the decision constructed in (9) is equal to

$$u_t^\varepsilon = \begin{cases} \sum_{i=0}^{m_1} \chi_{\{\alpha^\varepsilon(t)=i\}} u_i(t) & \text{if } t < \sigma \\ \sum_{i=0}^{m_1+m_2} \chi_{\{\alpha^\varepsilon(t)=i\}} u_i(t) & \text{if } t \geq \sigma \end{cases}$$
$$= \begin{cases} \alpha^\varepsilon(t)(\bar{\alpha}_1)^{-1}\bar{u}(t) & \text{if } t < \sigma \\ \alpha^\varepsilon(t)(\bar{\alpha}_2)^{-1}\bar{u}(t) & \text{if } t \geq \sigma \end{cases}.$$

We will see in Theorem 4.1 that $(\sigma, u.^\varepsilon)$ will be asymptotically optimal for $\mathcal{P}(\text{I})$ provided $(\sigma, \bar{u}.)$ is nearly optimal for $\mathcal{P}(\text{II})$.

In Method I, the decision $(\sigma, u.^\varepsilon)$ is constructed directly from $(\sigma, \mathbf{u}.^0)$. An alternative is to use the fixed σ and then to choose optimal $u.$ on $\{u. : (\sigma, u.) \in \mathcal{A}_{\text{I}}\}$.

Method II. Let the calendar time σ be such that $(\sigma, \mathbf{u}.^0)$ is an ε-optimal decision for $\mathcal{P}(\text{II})$. Let us now choose $u.^{*\varepsilon}$, that is optimal for $\mathcal{P}(\text{I})$ on $\{u. : (\sigma, u.) \in \mathcal{A}_{\text{I}}\}$.

It is obvious that $(\sigma, u.^{*\varepsilon})$ is better than $(\sigma, u.^\varepsilon)$, i.e.,

$$\begin{aligned} v^\varepsilon(x,\alpha) &\leq J^\varepsilon(x,\alpha,\sigma,u.^{*\varepsilon}) \\ &= \inf_{(\sigma,u.)\in\mathcal{A}_{\text{I}}} J^\varepsilon(x,\alpha,\sigma,u.) \\ &\leq J^\varepsilon(x,\alpha,\sigma,u.^\varepsilon). \end{aligned} \quad (10)$$

Theorem 4.1.

i) Let $(\sigma, \mathbf{u}.^0) \in \mathcal{A}_{\text{II}}$ be an ε-optimal decision for the limiting problem $\mathcal{P}(\text{II})$ and let $(\sigma, u^\varepsilon.) \in \mathcal{A}_{\text{I}}$ be the decision constructed in Method I (cf. (9)). Then, $(\sigma, u^{\varepsilon}.)$ is asymptotically optimal with error bound $\sqrt{\varepsilon}$, i.e.,

$$|J^{\varepsilon}(x,\alpha,\sigma,u^{\varepsilon}.) - v^{\varepsilon}(x,\alpha)| \le C(1+|x|^{k_g})\sqrt{\varepsilon}.$$

ii) Let $(\sigma, \mathbf{u}.^0) \in \mathcal{A}_{\mathrm{II}}$ be an ε-optimal decision for $\mathcal{P}(\mathrm{II})$ and let $(\sigma, u^{*\varepsilon}) \in \mathcal{A}_{\mathrm{I}}$ be the decision constructed in Method II. Then $(\sigma, u^{*\varepsilon})$ is also asymptotically optimal with error bound $\sqrt{\varepsilon}$, i.e.,

$$|J^{\varepsilon}(x,\alpha,\sigma,u.^{*\varepsilon}) - v^{\varepsilon}(x,\alpha)| \le C(1+|x|^{k_g})\sqrt{\varepsilon}.$$

Remark. In Method II, it is possible to relax the $(\sigma, u.^{*\varepsilon})$ to be ε-optimal and still have the result in Theorem 5.1 iii) above. Of cause, we may not be able to claim (10) any longer.

The significance of ii) in Theorem 5.1 is that the corporate level (upper level) management only has to solve an upper level problem (simpler problem) and obtain a solution $(\sigma, \mathbf{u}.^0)$, while the lower level (operational level) management simply uses $(\sigma, u.^{\varepsilon})$, a scaled version of $(\sigma, \mathbf{u}.^0)$ and obtains a near optimal solution for the original problem $\mathcal{P}(\mathrm{I})$. In iii), the upper level management provides only the purchasing time σ (calendar time) and leaves the rest for the lower level management to decide. (10) says that such an approach provides a better solution than the one in ii).

In either of these methods, we should emphasize that a deterministic calendar time for capacity acquisition provides a good approximation to the optimal stopping time. Moreover, while an optimal purchase time is a stopping time, it is not suitable in practice when it comes to purchasing additional capacity at such a time. In view of this, our constructed solution provides an even better approximation to a modified global problem $\mathcal{P}(I)$ in which τ is restricted to be a class of deterministic (calendar) times.

We start with verification theorems, which will provide sufficient optimality conditions for our decisions. Then we use these theorems to define the switching sets and then by using such sets to construct decisions which turn out to be asymptotically optimal.

5 Verification theorems: Optimality conditions

In this section, we discuss optimality conditions for decisions for both the original problem $\mathcal{P}(\mathrm{I})$ and the limiting problem $\mathcal{P}(\mathrm{II})$. In order to do so, we first define the following switching sets: for any $\delta > 0$,

$$\mathcal{S}^{\varepsilon}_{\delta} = \{(x,\alpha) : v^{\varepsilon}_a(x,\alpha+m_2) \le v^{\varepsilon}(x,\alpha)+\delta, \alpha \in \mathcal{M}_1\},$$
$$\mathcal{S}^{\varepsilon} = \{(x,\alpha) : v^{\varepsilon}_a(x,\alpha+m_2) = v^{\varepsilon}(x,\alpha), \alpha \in \mathcal{M}_1\}.$$

Then, $\mathcal{S}^{\varepsilon} \subset \mathcal{S}^{\varepsilon}_{\delta}$. Moreover, let the Markov times $\tau^{\varepsilon}_{\delta}$ and τ^{ε} be defined as

$$\tau^{\varepsilon}_{\delta} = \inf\{t : x_t \in \mathcal{S}^{\varepsilon}_{\delta}\} \text{ and } \tau^{\varepsilon} = \inf\{t : x_t \in \mathcal{S}^{\varepsilon}\}.$$

Then, $\tau^{\varepsilon}_{\delta} \le \tau^{\varepsilon}$, a.s.

It can be shown that the following is a candidate for a δ-optimal decision. For $t < \tau^{\varepsilon}_{\delta}$, choose u_t to be optimal with capacity $\alpha^{\varepsilon}_1(t)$ and for $t \ge \tau^{\varepsilon}_{\delta}$, choose u_t to be optimal with capacity $\alpha^{\varepsilon}_2(t)$. More precisely, the candidate is $u^*_{\tau^{\varepsilon}_{\delta}}(t,x)$, where we define $u^*_{\tau}(t,x)$ for any $\tau \ge 0$ as follows (τ will be assigned values $\tau^{\varepsilon}_{\delta}$ or τ^{ε} in the sequel):

$$u^*_{\tau}(t,x) = \begin{cases} \operatorname{argmin}\{[u\cdot\nabla v^{\varepsilon}(x,\alpha)+G(x,u)] : u \in \alpha_1\cdot U\} \\ \qquad \text{if } t<\tau \text{ and } \alpha_1 \in \mathcal{M}_1, \\ \operatorname{argmin}\{[u\cdot\nabla v^{\varepsilon}_a(x,\alpha)+G(x,u)] : u \in \alpha_2\cdot U\} \\ \qquad \text{if } t \ge \tau \text{ and } \alpha_2 \in \mathcal{M}_2. \end{cases}$$

Theorem 5.1. *Assume that $c(u)$ is second differentiable with $\frac{\partial^2}{\partial u^2}c(u) \ge c_0 I_{n\times n} > 0$. Furthermore, there exist constants C and $k>0$ such that*

$$|h(x+y)-h(x)-\nabla h(x)\cdot y| \le C(1+|x|^k)|y|^2.$$

Let $u^{\varepsilon}_{\delta}(t) = u^*_{\tau^{\varepsilon}_{\delta}}(t,x_t)$ (resp. $u^{\varepsilon}(t) = u^*_{\tau^{\varepsilon}}(t,x_t)$). Then $(\tau^{\varepsilon}_{\delta}, u^{\varepsilon}_{\delta}(\cdot))$ is δ-optimal (resp. $(\tau^{\varepsilon}, u^{\varepsilon}(\cdot))$ is optimal).

We now discuss the optimal decisions for the limiting problem $\mathcal{P}(\mathrm{II})$. We define

$$\mathcal{S}_{\delta} = \{x : v_a(x) \le v(x)+\delta\}$$
$$\text{and} \quad \mathcal{S} = \{x : v_a(x) = v(x)\}.$$

Then, $\mathcal{S} \subset \mathcal{S}_{\delta}$. Moreover, $\mathcal{S}^{\varepsilon} - \mathcal{S} \to \emptyset$ as $\varepsilon \to 0$, i.e., for each $x \in R^n$, there exist $\varepsilon_0 > 0$ such that $x \notin \mathcal{S}^{\varepsilon} - \mathcal{S}$ for all $0 < \varepsilon \le \varepsilon_0$ in light of the convergence of the values functions.

Let C_v and C_{v_a} be the two constants such that

$$|v^{\varepsilon}(x,\alpha)-v(x)| \le C_v(1+|x|^{k_g})\sqrt{\varepsilon}$$
$$\text{and} \quad |v^{\varepsilon}_a(x,\alpha)-v_a(x)| \le C_{v_a}(1+|x|^{k_g})\sqrt{\varepsilon}.$$

Let $\delta_{\varepsilon} = (C_v + C_{v_a})(1+|x|^{k_g})\sqrt{\varepsilon}$. Then, by definition we have

$$\mathcal{S} - \mathcal{S}^{\varepsilon}_{\delta_{\varepsilon}} \to \emptyset, \text{ as } \varepsilon \to 0.$$

This means the set $\mathcal{S}^{\varepsilon}$ is close to the set $\mathcal{S}$ as ε is small.

Let us now define the Markov times for $\mathcal{P}(\mathrm{II})$ as $\tau_{\delta} = \inf\{t : x_t \in \mathcal{S}_{\delta}\}$ and $\bar{\tau} = \inf\{t : x_t \in \mathcal{S}\}$. Since $\mathcal{S} \subset \mathcal{S}_{\delta}$, $\tau_{\delta} \le \bar{\tau}$. The control can now be defined as follows: Choose $\mathbf{u}_t$ to be optimal for $t < \tau_{\delta}$ and choose $\mathbf{u}_t$ to be optimal for $t \geq \tau_\delta$. More precisely, for any deterministic time $\tau \geq 0$ (τ will be taken as τ_δ or $\bar{\tau}$ shortly), let

$$\mathbf{u}_\tau^*(t,x) = \begin{cases} \operatorname{argmin}\{[\sum \nu_i^{(1)} u_i \cdot \nabla v(x) \\ +\sum \nu_i^{(1)} G(x,u_i)] : \mathbf{u} \in U_1\}, \\ \text{if } t < \tau \\ \operatorname{argmin}\{[\sum \nu_i^{(2)} u_i \cdot \nabla v_a(x) \\ +\sum \nu_i^{(2)} G(x,u_i)] : \mathbf{u} \in U_2\}, \\ \text{if } t \geq \tau. \end{cases}$$

Theorem 5.2. *Assume A1"). Let $\mathbf{u}^\delta(t) = \mathbf{u}^*_{\tau_\delta}(t,x_t)$ (resp. $\mathbf{u}^*(t) = \mathbf{u}^*_{\bar{\tau}}(t,x_t)$). Then $(\tau_\delta, \mathbf{u}^\delta(\cdot))$ is δ-optimal (resp. $(\bar{\tau}, \mathbf{u}^*(\cdot))$ is optimal) for the limiting problem $\mathcal{P}(\mathrm{II})$.*

A simple example. Consider a firm that must satisfy a given constant demand $z \in (0,1]$ for its product over time so as to minimize its discounted cost of investment and inventory/shortage. Suppose that the firm has an existing machine, which is failure-prone with given rates of breakdown and repair. When in working order, it has a unit production capacity and when broken down, it has zero capacity, i.e, $m_1 = 1$. Assume that the demand for the firm's product is higher than the average production capacity of the existing machine. However, the firm has some initial inventory of its product to absorb the excess demand for a few initial periods. It is obvious that the firm must increase its production capacity at some future time $\tau \geq 0$. For this purpose, the firm has an option to purchase a new machine,, identical to the existing machine, at a fixed given cost of K in order to double its average production capacity. Assume that the firm has sufficient repair capacity to handle two machines even when they are both broken down during some time interval.

The problem is to find the optimal time of purchase as well as the optimal production simultaneously. More specifically, we consider the following problem:

$$\begin{array}{ll} \min & J^\varepsilon(x,\alpha,\tau,u.) = E[\int_0^\infty e^{-\rho t}|x_t|dt + Ke^{-\rho\tau}] \\ \text{s.t.} & \dot{x}_t = u_t - z,\ u_t \in \mathcal{A}_{\mathrm{I}},\ x_0 = x. \end{array} \tag{11}$$

We take $0 < z \leq 1$, $U = [0,1]$, $\mathcal{M}_1 = \{0,1\}$, and $\mathcal{M}_2 = \{0,1,2\}$. We assume further that

$$Q_1 = \begin{bmatrix} -1 & 1 \\ 1 & -1 \end{bmatrix} \text{ and } Q_2 = \begin{bmatrix} -1 & 1 & 0 \\ 1 & -2 & 1 \\ 0 & 1 & -1 \end{bmatrix}$$

The specification of Q_1 and Q_2 in our example represents the following situation. The existing machine has the breakdown rate of ε^{-1} and the system has sufficient capacity to repair it at the rate of ε^{-1}. Thus, the machine is in working order half the time on average. Furthermore, upon the addition of an identical machine, there is sufficient repair capacity in the system to repair each machine at the rate of ε^{-1}.

It should be noted that even this simple example is quite hard to solve as it involves machine purchase time, which is a stopping time to be determined. Its limiting problem can however be solved explicitly. For this reason, this example will be used throughout the rest of the paper to illustrate the theory as it develops. Furthermore, in view of this simple example, we will use the terms existing capacity and existing machine and the terms new (or additional) capacity and new machine interchangeably.

In this example, the limiting problem is given as the following:

$$\begin{array}{ll} \min & J(x,\tau,u.) = [\int_0^\infty e^{-\rho t}|x_t|dt + e^{-\rho\tau}K] \\ \text{s.t.} & \dot{x}_t = u_t - z,\ u_t \text{ is given in (7)},\ x_0 = x. \end{array}$$

We now solve the equations by considering only the case that $\bar{\alpha}_1 - z < 0$.

Let $x^*(<0)$ and $\hat{x}(>0)$ be defined as follows:

$$x^* = (\bar{\alpha}_2 - z)\rho^{-1}\log[(\bar{\alpha}_2 - \bar{\alpha}_1 - \rho^2 K)/(\bar{\alpha}_2 - \bar{\alpha}_1)]$$

$$\hat{x} = (z - \bar{\alpha}_1)\rho^{-1} \log[2 - [(\bar{\alpha}_2 - \bar{\alpha}_1 - \rho^2 K)/(\bar{\alpha}_2 - \bar{\alpha}_1)]^{\frac{\bar{\alpha}_2 - \bar{\alpha}_1}{z - \bar{\alpha}_1}}].$$

Then the solutions of the equations can be written in terms of x^* and $\hat{x}$.

$$v(x) = \begin{cases} \int_0^{(x-\hat{x})/z} e^{-\rho t}|x - zt|dt \\ +e^{-\rho(x-\hat{x})/z}\int_0^{(\hat{x}-x^*)/(z-\bar{\alpha}_1)} e^{-\rho t}|\hat{x} + (\bar{\alpha}_1 - z)t|dt \\ +e^{-\rho[(x-\hat{x})/z + (\hat{x}-x^*)/(z-\bar{\alpha}_1)]}v_a(x^*) \\ \text{if } x > \hat{x} \\ \int_0^{(x-x^*)/(z-\bar{\alpha}_1)} e^{-\rho t}|x + (\bar{\alpha}_1 - z)t|dt \\ +e^{-\rho(x-x^*)/(z-\bar{\alpha}_1)}v_a(x^*) \\ \text{if } x^* \leq x < \hat{x} \\ v_a(x) \text{ if } x < x^* \end{cases}$$

$$v_a(x) = \begin{cases} z\rho^{-2}[e^{-\rho x/z} + \rho x/z - 1] + K \\ \text{if } x \geq 0 \\ (\bar{\alpha}_2 - z)\rho^{-2}[e^{\rho x/(\bar{\alpha}_2 - z)} - \rho x/(\bar{\alpha}_2 - z) - 1] + K \\ \text{if } x < 0 \end{cases}$$

Recall that $\mathcal{S} = \{x : v_a(x) = v(x)\}$. Thus, in this example,

$$\mathcal{S} = \begin{cases} (-\infty,\infty) & \text{if } K = 0 \\ (-\infty, x^*] & \text{if } 0 < K < (\bar{\alpha}_2 - \bar{\alpha}_1)\rho^{-2} \\ \emptyset & \text{if } K \geq (\bar{\alpha}_2 - \bar{\alpha}_1)\rho^{-2} \end{cases}$$

Let

$$\bar{u}_t = \begin{cases} \begin{cases} 0 & \text{if } \bar{x}_t > \hat{x} \\ \bar{\alpha}_1 & \text{if } \bar{x}_t \leq \hat{x} \end{cases} & \text{if } t < \sigma \\ \bar{\alpha}_2(1 - \text{sgn}\bar{x}_t)/2 & \text{if } t \geq \sigma. \end{cases}$$

where

$$\dot{\bar{x}}_t = \bar{u}_t - z, \; x_0 = x \tag{12}$$

and

$$\sigma = \inf\{t : \bar{x}_t \in \mathcal{S}\}.$$

It is not difficult to see that (12) has a unique solution. Therefore, by Theorem 5.2, $(\sigma, \bar{u}.)$ is optimal for $\mathcal{P}$(II).

Let u_t^ε denote the decision constructed by Method I. Then,

$$u_t^\varepsilon = \begin{cases} \alpha^\varepsilon(t)\bar{u}_t/\bar{\alpha}_1 & \text{if } t < \sigma \\ \alpha^\varepsilon(t)\bar{u}_t/\bar{\alpha}_2 & \text{if } t \geq \sigma \end{cases}$$

Theorem 5.1 yields that $(\sigma, u^\varepsilon.)$ is asymptotically optimal for $\mathcal{P}$(I) with an error bound of the order of $\sqrt{\varepsilon}$.

In particular, if $K = 0$, then $\sigma = 0$, i.e., to buy the new machine immediately as the machine is available *gratis*.

If $K \geq (\bar{\alpha}_2 - \bar{\alpha}_1)\rho^{-2}$, then $\sigma = \infty$, i.e., not to buy it at all, because the machine is too expensive. An immediate interpretation of this point can be given as follows: Suppose we start with a large amount of backlog. An immediate purchase of the new machine will *contribute* to the reduction of shortage at the rate of $(\bar{\alpha}_2 - \bar{\alpha}_1)$ in the limiting deterministic problem. In other words, the shortage will increase at the rate of $(\bar{\alpha}_1 - z)$ without the purchase, while it will reduce at the rate of $(\bar{\alpha}_2 - z)$ as a result of the purchase. As the initial shortage is allowed to become arbitrarily large, the new machine's contribution toward the reduction of shortage cost will approach

$$\int_0^\infty e^{-\rho t}(\bar{\alpha}_2 - \bar{\alpha}_1)t\,dt = (\bar{\alpha}_2 - \bar{\alpha}_1)\rho^{-2}.$$

Clearly, if this amount is smaller than K, the cost of a new machine, then it is certainly never worthwhile to buy the new machine.

We can also construct our asymptotically optimal decisions with the procedure described in Method II. This will be, however, much more complicated, since it involves solving stochastic control problems.

6 Concluding remarks

In this paper, we have presented asymptotic results for hierarchical capital expansion and production decisions in a manufacturing system with machines subject to breakdown and repair. We reduce the original global problem to a simpler problem and then describe a procedure to construct decisions for the original system, derived from the solution to the simpler problem. The simpler problem turns out to be a problem obtained by averaging the given stochastic machine capacities and modifying the objective function in an appropriate way. Therefore, by showing that the associated value function for the original system converges to the value function of the limit system, we can construct decisions for the original system from the optimal or near optimal decisions of the limit system. It turns out that the decisions so constructed are asymptotically optimal as the oscillation rate of the machine capacities goes to infinity, i.e., $\varepsilon \to 0$. Furthermore, error estimates of the asymptotic optimality are provided in terms of their corresponding cost functions.

On the practical side, we have emphasized, in the introduction to the paper, the significance of our results for the decision making hierarchy that exists within a firm. That is, the corporate level management can use only the summary measures of the existing capacity in making decisions regarding investment in new capacity, while the operational level management can take the arrival of new capacity at a certain future date for granted in deriving near optimal production plans for the actual stochastic manufacturing system. More generally, long term decisions in practice are made usually at the upper levels of the hierarchy, whereas the short term decisions are made at the lower levels. The results obtained in the paper, although in the case of a mathematically tractable model, are intended to provide a justification for the practice in the general context.

References

[1] Bukh, P.N.D., A bibliography of hierarchical production planning techniques, methodology, and applications (1974-1991), working paper, Institute of Management, University of Aarhus, Aarhus, Denmark, (1992).

[2] Bitran, G. and Tirupati, D., Hierarchical production planning, Working Paper # 88/89-4-14, Department of Management, Graduate School of Business, The University of Texas at Austin, Austin, TX (1989).

[3] Kistner, K.P. and Switalski, "Hierarchical production planning : Necessity, problems and

methods," *ZOR-Methods and Models of Operations Research,* Vol. 33, pp. 199-212 (1989).

[4] Lehoczky, J., Sethi, S.P., Soner, H.M., and Taksar, M., An asymptotic analysis of hierarchical control of manufacturing systems under uncertainty, *Mathematics of Operations Research*, Vol. 16, No. 3, pp. 596-608, (1991).

[5] S.P. Sethi, M. Taksar, and Q. Zhang, Capacity and production decisions in stochastic manufacturing systems: An asymptotic optimal hierarchical approach, *Production and Operations Management*, Vol. 1, No. 4, pp. 367-392, (1992).

[6] Sethi, S.P. and Zhang, Q., Hierarchical Decision Making in Stochastic Manufacturing Systems, Birkhäuser Boston, Cambridge, MA, 1994.

[7] Sethi, S.P. and Zhang, Q., Hierarchical production planning in dynamic stochastic manufacturing systems: Asymptotic optimality and error bounds, *Journal of Mathematical Analysis and Applications*, Vol. 181, pp. 285-319, (1994).

[8] Sethi, S. and Zhang, Q., Multilevel hierarchical controls in dynamic stochastic marketing-production systems, *SIAM Journal on Control and Optimization*, Vol. 33, No. 2, pp. 528-553, (1995).

[9] Sethi, S.P., Zhang, Q., and Zhou, X.Y., Hierarchical controls in stochastic manufacturing systems with convex costs, *Journal of Optimization Theory and Applications*, Vol. 80, No. 2, pp. 299-317, (1994).

[10] Stadtler, H., *Hierarchische Produktionplanung bei losweiser Fertigung,* Physica-Verlag, Heidelberg, (1988).

[11] Zhou, X. and Sethi, S., "A sufficient condition for near optimal stochastic controls and its application to Manufacturing Systems," Working Paper, University of Toronto, (1992), *Applied Mathematics & Optimization*, Vol. 29, pp. 67-92, (1994).

This work was supported in parts by the NSERC Grant A4619, URIF, and the Manufacturing Research Corporation of Ontario. Thanks are due to David Quirin for his comments.

Hierarchical Forest Planning: Some General Observations

B.B. Bare

College of Forest Resources and Center for Quantitative Science in Forestry, Fisheries and Wildlife, University of Washington, Seattle, WA 98195, USA

Forest management planning is both an art and a science. It is built upon a sound foundation embodied by the life and physical sciences, but is greatly influenced by economic and political processes. The planning process begins with the establishment of a forest policy statement — including a clear definition of forest management goals. The preparation of this statement involves the skillful reading of public desires, industrial needs, environmental responsibilities, political realities, and deeply held cultural values. This artistic craft, honed by successful politician and bureaucrat alike, must be carefully interpreted by the forest manager, blended with scientific facts, seasoned with economic reality, and incorporated into appropriate forest planning models. If properly done, this mixing of art and science will produce a forest policy statement acceptable to all concerned parties.

The development of a forest management plan is a complex undertaking. It involves the cooperation and coordination of a large number of people and resources in an effort to achieve the goals articulated in the policy statement. Furthermore, the forest system itself is a complex, large-scale system. As summarized by Haimes[1], complex systems possess the following common characteristics:

1. a large number of decision variables and state variables.
2. a large number of subsystems.
3. complex relationships between system components.
4. risks and uncertainties.
5. multiple, and often conflicting, goals and objectives.
6. multiple decision makers.
7. hierarchical organization.
8. dynamic changes in goals, objectives, constraints, and decision maker's preferences.

While one can easily agree that forest management planning problems possess these characteristics, it has only been recently that forestry organizations have begun to recognize this and build mathematical models and decision support systems reflecting this reality.

Most forest management plans, whether for public or private organizations, are developed within a hierarchical setting. Thus, the most useful modelling paradigm for the future might best be structured around this approach. As we begin to do this, I believe that we must pay specific attention to the following features:

1. explicit treatment of multiple goals/objectives.
2. explicit incorporation of multiple decision makers and constituencies where appropriate.
3. incorporation of uncertainty and risk.
4. structured feedback mechanisms.
5. recognition of the dynamic nature of the system being modelled.

It appears from reading the papers prepared for this workshop that these characteristics are being considered to some degree.

It is well recognized that the primary purpose of a hierarchical philosophy is to increase our understanding and predictive capabilities by pursuing the simplification inherent in the decomposition of the large system into its constituent subsystems. This point is well made in several papers presented at these proceedings. As pointed out, this has the practical side effect of relieving us from the computational burden associated with manipulating a large, monolithic model. And, this reduction in computational burden appears to be one of the principal driving forces behind the adoption of the hierarchical approach in forest planning. Thus, we see a family of hierarchical models linked with a GIS emerging as replacements for the single large-scale models of the recent past.

A second reason for selecting a hierarchical approach is to build more spatial resolution into forest planning models. This is largely the outgrowth of recent experiences with large scale models. Oftentimes, disaggregated solutions from these highly aggregated models do not produce acceptable solutions at the lower levels of spatial resolution. Thus, a series of linked models appears to offer great promise for dealing with these complexities.

However, to focus solely on the saving of computational time and the gain in spatial sensitivity is to miss the central advantage of adopting a hierarchical approach. As pointed out by several authors at this workshop, we need to pay more attention to the hierarchical nature of the decision process itself, and it is here that the ideas of multiple objectives, multiple decision makers, feedback loops, and uncertainty play a very important role. And, this is where we need to devote more research effort in the next five years.

Hierarchical systems can be classified according to a variety of criteria. To date, most forest planners have concentrated on those dimensions involving space, time, and organizational-level. But, we have not devoted comparable levels of attention to clarifying the decision-making process, developing formal feedback mechanisms, or recognizing the dynamic nature of the system we are managing. Whether we follow a top-down or bottom-up hierarchical approach, we must take these factors into account.

Individual papers presented at this workshop differ greatly in their scope and complexity. For instance, some deal exclusively with timber production, others with timber and wildlife, and still others with the full multiple use spectrum; some papers are theoretically-oriented while others stress algorithmic or computational results; some define two-level hierarchies (say, strategic and tactical) while others are concerned with multi-level hierarchies; some treat cutting units as predefined exogenous entities while others treat them as endogenous items to be defined within the model; some treat cutting units as integer units while others assume them to be continuous and subject to fractionalization; and some include transportation along with other silvicultural activities while others do not. Most models discussed are deterministic and only embody a single objective.

The papers differ greatly in their definition of the feedback mechanisms that link the various levels of the modelling hierarchy. For example, some of the top-down approaches are driven by shadow pricing schemes while others only set quantity targets for lower level models to satisfy as constraints. No paper addresses the use of shadow prices in more than a two-level hierarchy. The bottom-up approaches received less attention at this workshop although several past efforts were reviewed.

Related to, but distinct from, the hierarchical approach is the topic of data aggregation. Clearly, many of the models presented at the workshop involve aggregation — especially at the strategic level. Yet, resolution of the best way to perform this task and/or its impact on the ensuing analysis is separate from the hierarchical character of the system being studied. Questions concerning data aggregation persist in the absence of the adoption of a hierarchical approach.

Another point brought out in several papers is whether or not the strategic model's objective function value(s) provides an upper bound on the objective function value(s) for the tactical model. In some of the papers this is the implicit assumption, while other authors maintain that as the model is disaggregated at the tactical and/or operational levels, additional flexibility might lead to an objective function value(s) larger than that obtained for the aggregated strategic-level model. There appears to be a trade-off between aggregation at one level of the modelling hierarchy and disaggregation at a lower level.

It is clear that we need to delineate whether we are referring to the modelling aspects, the organizational aspects, the decision making aspects, or the planning system aspects when discussing the subject of hierarchical systems. In any particular organization, these may or may not be synonymous. Failure to articulate the origins and nature of the hierarchical characteristics of the problem being addressed led to a considerable degree of confusion at this workshop.

In formulating research agendas for the near future, we must recognize that information processing capabilities will continue to increase dramatically in the near term making it possible to solve larger and larger model formulations. Second, analysis tools will continue to increase in capability, albeit at a slower pace. Third, conflicts over resource use and the need to undertake more sophisticated levels of planning will continue to increase. It is imperative, therefore, that users of hierarchical approaches clearly state their reasons for adopting the approach. If it is solely for reducing the computational burden, one may be better advised to stick with a single-model approach. However, if it is to better model the decision environment, then the hierarchical approaches discussed in the workshop offer great promise.

End Notes

Haimes, Y.Y. 1982. Modeling of large-scale systems in a hierarchical multi-objective framework, In: Studies in Management Science and Systems, Vol. 7, pp. 1-7, North Holland Publishing Company.