FOREST PLANNING IN JAPAN AND THE US
A REVIEW AND RECOMMENDATIONS FOR IMPROVED PLANNING MODELS[1)]

by

Dietmar Rose and Masahiro Amano

INTRODUCTION

Examination of the key laws establishing guidelines for planning in both Japan and the US reveals quite similar philosophies and procedures. This observation should come as no surprise because the important functions of forests for the stable development of national economies, for continuous supplies of forest products, and social welfare have been recognized in most countries of the world. Only the most highly developed countries, however, have established by law strict guidelines and procedures for planning the nation's resources and are involved in comprehensive planning. We will examine similarities and differences between planning procedures in Japan and the US and try to assess their strong and weak points. From this, we hope to develop recommendations incorporating the best features of each planning procedure.

The Forest Planning System, established under the provisions of the Forest Law in Japan, requires the Government to establish a comprehensive, long-range target for forest management, the development of nation-wide forest plans, and basic plans for National Forests and private and other public forests (Minowa and Nagumo 1981). The logical primary planning units are basically 29 river basins.

Planning in the US is guided by two major laws. The 1974 Forest and Rangeland Renewable Resoures Planning Act (RPA) and an amendment to this law by the 1976 National Forest Management Act provide a framework for comprehensive, long-range, and continuing planning of the Nation's natural resources. RPA requires the preparation of two documents, a renewable resources Assessment and a Forest Service Program, every 10 and 5 years, respectively. While the Assessment looks at all forest resources independent of ownership, the Program describes specific plans for the federally owned National Forests. These plans naturally can not ignore the role of forests in other ownerships, but do not explicity develop alternatives for the latter.

One constraint imposed on forest planners both in Japan and the US is a non-declining even-flow constraint. It implies that future hervest volumes are not permitted to decline. Non-declining even-flow has been at the center of a major controversy in the US. With large surplusses of overmature timber on the west coast of the US, this administrative constraint can lead and probably already has led to inefficient allocation of resources. Forest planners have set harvest levels unnecessarily low out of fear that future harvest requirements might not be met in violation of the law. This conservative attitude also can contribute to lower economic efficiency of timber management plans.

The Authors-Dietmar Rose is proffesor, College of Forestry, University of Minnesota; Masahiro Amano is research scientist, Japanese Forestry & For. Prod. Res. Inst. This paper was prepared during a scientific visit of Dr. D. Rose at the For. & For. Prod. Res. Inst. by the invitation of the Japanese Science and Technology Agency.

In this report, we do not want to examine specific policies established by the administrations of the respective countries, but want to concentrate on the specific model or models that have been adopted for planning. Among these models, Linear Programming (LP) is a key model in both countries planning processes, while other models have been largely ignored especially in the US.

Vastly better tools are available today to forest planners than only a few decades ago. Simplistic formula methods for calculation of allowable timber cuts have been replaced with sophisticated simulation procedures, allowing comparison of alternative management activities before actual implementation, and with optimization models that can provide optimal management schedules over time.

National Forest Planning in the US has put all its stakes into one highly sophisticated linear programming (LP) package called FORPLAN. While forerunners of this model such as the Timber Resources Allocation Model (RAM) (Navon 1971) were applied to single resources such as timber, FORPLAN was designed to tackle multiple-use aspects of National Forest Management (Johnson, Jones and Kent 1980).

In Japan, LP is also an essential component of the national planning model under development at the Forestry and Forest Products Research Institute (FFPRI). Because of restrictions imposed on LP formulations by technical limitations of computers, japanese scientists have developed a two-stage process which combines output from aggregated LP solutions with a simulation model for the development of operational plans. This approach is considered better than the single reliance on LP for development of plans that can guide national policy maker, but that also serve as operational plans at the field level.

A number of questions have been raised as to the adequacy of LP models such as Timber-RAM as a long-range planning tool (Chappelle, Mang and Miley 1975). Recently, FORPLAN has been subject of two critical evaluations (Walker 1982, Apple 1982).

A closer look at LP and alternative models for planning such as simulation is required to avoid the serious problems which are surfacing in US National Forest Planning.

Timber management plans for the National Forests can not ignore the role that private and other public forests play in supplying timber and other products for local, regional, national and international markets. Nonetheless, the preoccupation with deriving globally optimum timber management plans for individual National Forests in the US and total reliance an one LP model have stood in the way of effective linking of plans to other ownership plans. It is naturally quite difficult to predict what private owners will do with their forests, how market prices will affect their cutting decisions and how incentives will influence cutting and planting programs.

The FFPRI in Japan has developed an interesting approach that utilizes cutting records to derive empirical probabilities of age-classes of individual species to be cut as well as regressions predicting distribution parameters as function of external factors such as government subsidies, and market prices for forest products. These probability estimates, called Gentan probabilities (Suzuki 1984), are used in a Markow-type projection of age-classes of an initial inventory into the furture. A simulation program has been developed by Amano (1981) which performs these projections. The model can be used to simulate different scenarious reflecting distinct price trends and government subsidies. The dependence of cutting probabilities on these

factors leads to different cutting programs, cutting volumes and age-class distributions over time. Interpretation of simulation results can provide useful guidelines for establishing forest policies as well as provide a useful input into the development of plans for National Forests that are responsive to and coordinated with most likely timber management scenarios of private and other public owners.

In developing timber management plans for its National Forests, FFPRI has developed a two-stage approach including LP and simulation. LP is utilized to develop a planning framework for derivation of operational plans using simulation. Technical limitations of computers and the need to run LPs with highly aggregated data have been recognized as limiting the usefulness of LP to establishing the boundaries within which more detailed, operational plans need to be developed.

THE TIMBER MANAGEMENT SCHEDULING PROBLEM

To the Operations Research Analyst, the timber management scheduling (TMS) problem might at first seem to be just another production scheduling problem. In a very general sense this is true; however, a number of factors complicate the problem:

(1) The tree is both a product and a factory. Harvesting the tree also destroys the factory. The long production periods for timber make long planning horizons essential. Most timber harvested over the next decades will come from trees already planted.

(2) Forests contain multiple resources. Timber is not the only output produced. Recreation, wildlife, wilderness, water, and grazing are also valuable outputs. These outputs are difficult to value because of their non-market nature.

(3) Long planning horizons require long market forecasts. Future timber demands and prices are difficult to predict. Forecasts of 30 years or more must seem absurd to planners outside forestry.

(4) Trees contain multi-products. It is not uncommon for multiple products to be produced from a single tree; however it is seldom correct to assume that tree components have a highest and best use. For example, in some cases it might be desirable to burn pulpwood size material or even sawlog size material. Harvesting costs and relative market demand are key factors influencing end-use.

(5) Timber stands contain multiple tree species. Tree species mix can have a significant impact on the economic value of a stand. For example, two stands both with eighty percent aspen volume would still be significantly different in value if the remaining volume of one was red pine and the other was birch. Classifying existing stands into a manageable number of stand types is not a simple or straightforward task.

(6) Management actions have spatial interdependencies. Spatial interactions are significant in several respects. Roadbuilding is one good example. Accessing one stand often leads to reduced access costs of nearby stands. Habitat improvement for wildlife is another good example; the benefits are dependent on the actions scheduled for surrounding stands.

(7) Existing timber inventories are often incomplete. Uncertainty surrounds estimates of current timber volumes. Many National Forests contain large acreages. Inventories are only sampled, with the most recent information available for some areas five years or more old.

(8) Uncertainty surrounds timber growth projections. Timber volumes for typical ages and homogeneous stands (single species) can be predicted fairly accurately. Problems develop when factors such as tree mortality or species interactions are recognized. Long projections which depend on ingrowth (appearance of new trees) are also difficult to make.

(9) Impacts of management on non-timber resources are difficult to measure or quantify. Compared to timber, very little is known about the response of other resources to management actions. Measuring responses is difficult, and relatively new compared to the similar data on timber production.

(10) Site productivity is difficult to estimate for alternative species. The existing inventory of the stand gives an excellent indication of site productivity for the species present, but the productivity of the site for species not present are often difficult to estimate.

(11) Budgets are uncertain. Available budgets often limit the actions implemented. Future budgets are difficult to predict. Schedules that can be easily adapted to deviations from projected budgets are desirable.

(12) Government regulations limit alternatives. Typical limitations are the size of clearcuts for individual stands and non-declining even-flow requirements for the forest as a whole.

(13) Economies of scale are sometimes significant. Costs of management can not necessarily be reduced to "average per acre" costs. Fixed costs of, stand access, sales administration, or equipment transport can be significant, especially on small sales.

(14) An existing management system is in place. Changing the system can be expensive. In the National Forest System, the district is the basic management group. Objectives for planning are usually considered in a forest-wide context with little recognition given to the district directly.

(15) A forest usually supplies timber to several markets. Transport costs can be an important component of the overall cost of supply. Recognizing these costs as well as any demand limitations of specific markets should be an important part of the planning process.

(16) Wood technology is changing and will continue to change! Utilization standards will continue to change. Waferboard is a good example of a recent change in the US; aspen can now be utilized to produce a product that is highly competitive with softwood plywood.

CRITERIA FOR EVALUATING PLANNING MODELS

It is apparent from the above list of potential problems in developing timber management schedules that finding of a quantitative model which can deal with most or all of the different aspects is highly unlikely. For many good reasons, LP models have been formulated most frequently for timber harvest scheduling. LP just like any other model has some serious shortcomings, but before a choice between alternative models is made it is necessary to define a few criteria for evaluating planning models. The selection of a model will also depend to a large degree on the purpose of the planning process, e.g., strategic planning vs. operational planning.

It is difficult to define one criterion to evaluate any type of planning model. More realistically, a large number of factors need to be considered. One might base an evaluation on a number of questions:

(1) Does the model generate solutions that are at least theoretically sound (valid)?

(2) Does the model develop an implementable plan or can results be used to develop an implementable plan?
(3) How can the model fit into the general planning process?
(4) Will the planning process be cost effective with this model?
(5) Would different planners reach different results?
(6) Can the plan be made flexible and responsive to questionable model assumptions about the future?
(7) Is the model large enough to recognize most of the pertinent data?
(8) Is the planning model understandable or viewed as a black box?
(9) Does the model deal effectively with uncertainty aspects?
(10) Is the model transferrable to other users?
(11) Does the model allow for adjustments to specific situtations?
(12) Can model results help evaluate specific alternatives not recognized in the model?

MAJOR PROBLEMS OF LP PLANNING MODELS

The planning process in US National Forests is well established by administrative directives and considerable experience has been accumulated in the recent planning phase. Valuable lessons can be learned from the problems being experienced in US National Forest Planning. These problems are not so much problems of the planning process and the chosen quantitative model, but problems of technical limitations of even our largest computer which limit the usefulness of LP formulations. The problems can not be totally overcome by other models, but suggest that other techniques must be explored and that possibly several models need to be utilized to deal with planning problems.

The timber management scheduling problem is obviously a large and complex problem. Before taking an axe to the LP applications currently in progress, it seems appropriate to first emphasize the positive aspects of the National Forest planning process. LP models such as Timber RAM and FORPLAN certainly have provided a structure for addressing the forest management problem. The major utility of these models stems from having identified the major components of the forest management system and the major relationships among those components. In this process, the need for improved and new data has become apparent. It was a gigantic and rapid step to attempt to implement FORPLAN on a National level. It is unrealistic not to expect some major problems in the process.

No LP harvest scheduling model can be classified as long-range since future harvest levels are assumed known and factors of production are fixed over time (Chappelle et al. 1975). If future harvest levels or economic values change, optimal solutions are also likely to change. Such changes are especially crucial for optimal immediate actions which after implementation are usually irreversible and in light of new information often turn out to be non-optimal.

A serious limitation of LP in National Forest planning is model size. The decision variables in the model represent specific management alternatives for specific units of land. The decision variables can be defined in a number of different ways, however, a basic problem is that the number of distinct land units that can be recognized in practice is limiting. Questionable assumptions are often made in terms of stand age, species composition, stand density, site quality, etc., and factors such as transport distance are often ignored.

Planners both in Japan and the US have to deal with mainly technical limitations imposed on them by even the largest comuters and have been forced to solve problems with highly aggregated data sets. The Japanese Timber Planning Subsystem limits timber classes to a maximum of 150 data aggregation schemes as described by Amano (1981). FORPLAN limits users to 600 timber classes. In any case, these numbers are not even sufficient to solve realistic size single-use timber harvesting problems. The latter can easily require many thousand timber classes for development of implementable, operationsl plans. Such problems, if solvable at all, would require excessive computer times of decades or centuries. Linear programming is an optimization technique, but if model size limits its ability to recognize imprtant real world considerations, an optimal solution to a linear programming model is not an optimal solution to the real problem.

No LP model can be considered a long-run planning model. It can consider a long planning horizon, but that characteristic alone does not make it a long-run planning model. In the long run, production factors are not fixed. But to use these models, harvest levels must be fixed for all periods in the planning horizon. Because of this requirement, decision makers should question the value of the management actions prescribed for the first period by so called "optimal" solutions.

The problem of uncertainty surrounding economic values, yield values, demand projections, and other entities is an area of major concern since sensitivity analysis in LP has been a largely neglected and costly process. If we could determine to which entities the solution is most sensitive, it would be possible to construct a more manageable sensitivity analysis with those values having higher degrees of uncertainty.

Poor data are problematic in any planning model. The problem with the National Forest planning process is the use of data with verying amounts of precision in one overall model structure. Data are treated as determinstic and with the same degree of confidence or weight assigned to them. Without question, timber related data are best supported and documented. To accomodate inclusion of other uses such as recreation, data aggregation is necessary, leading essentially to the throwing away of available, more detailed information on timber for the sake of including often low precision data on wildlife, water, fish, etc. The need for aggregation also causes questions on how to formulate aggregation classes. The personal bias of a specific planner will determine this process and, thus, the type of output. (Different planners will decide on different ways of data aggregation.) Several factors stand in the way of actually achieving the optimal solution. One problem is that different managers can develop different implementation plans because of the aggregated nature of the solution. More seriously is the requirement that attainment of the optimal soulution requires that the resource management schedule must be followed throughout the planning horizon. It is likely that already taken actions will turn out to be far from optimal and often irreversible. To achieve optimality, naturally all the assumptions of LP, proportionality, additivity, divisibility, and certainty, must be satisfied.

The cost effectiveness of the FORPLAN process is an important, but difficult question. Such an evaluation would require a quantification of model inputs and outputs and comparison with other alternatives. Such an analysis and comparison are not possible to data due to lack of information. Time requirements to run the LP model could probably be improved with better documentation and guidelines for FORPLAN users. A lack of proper documentation

and phasing-in of the process in National Forest planning has left planners with a "black box" view of the model. The FORPLAN process is, however, a huge effort that has consumed as much as or more than one million dollars per National Forest. While these costs include data collection and other items that would be incurred with other planning models also, the direct costs related to formulating and running the LP model are substantial. Apple (1982), based on a survey of National Forest planning staffs, estimated that the development of a Forest Plan requires about two years excluding data collection, and that one-half year alone was needed to run FORPLAN. Considering all the problems of applying LP management scheduling models, it is reasonable to question whether some sort of simulation model might be a more useful tool.

SIMULATION - AN ALTERNATIVE TO LP IN PLANNING

After examining the general timber management scheduling problem it is apparent why many forest planners are suffering from "physics envy." The problem is large, complex, and surrounded by many biological and economic uncertainties. Planners realize that we cannot optimize. The use of FORPLAN is shifting more and more towards that of a simulation model, yet there remains a firm belief within the National Forest planning process that we can optimize. Multiple model runs are made to examine alternative goals, but it is believed that a decision must be made today on which alternative is best. The "optimal schedule" from the "optimal run" must then be implemented, and deviations from the schedule are of extreme concern because optimality is then lost.

Unless planning policies change soon, it is likely that the model itself will take the rap for the problems that will likely develop from the actions implemented. How models are used for forest planning is just as important an issue as which models are used. There is a real danger of not recognizing their limitations, and, therefore, placing too heavy reliance on the results of an individual run. Unfortunate as it may seem, large complex models and fast computers cannot eliminate the biological and economic uncertainties that plague forest planning.

Once it becomes accepted that we cannot optimize, simulation models could play an important role in timber management scheduling. Simulation models are not new in timber management planning. They have been used extensively in forest management to estimate maximum harvest levels that can be maintained over time (allowable cut levels). Some of the more common ones include: AREA (Sassaman and Chappelle 1967), SORAC (Chappelle and Sassaman 1968), SIMAC (Sassaman et al. 1972), and TEVAP2 (Myers 1974). All of these models are concerned with determining how much timber can be harvested and tend to ignore the problem of scheduling specific stands for treatment; they either assume a simple scheduling rule or require one as a model input.
A simulation model for timber management scheduling would likely include the following steps:

(1) Schedule stands for treatment.

(2) Examine the overall impact of the schedule developed. Does it meet all management requirements? And does it maximize management goals? If so, the schedule can be implemented.

(3) Otherwise, use what was leaned in step (2) to adjust the scheduling process and return to step (1).

The key to the model must be in the way it ranks stands or stand treatments. Simple rules like oldest stand first, do not take into account important economic fatcors like distance to market, or relationships between existing timber supplies and timber demands. At times it might be important to weigh heavily the impact of actions on future growth and mortality, but under other circumstances it might be best to follow a simple greedy algorithm and minimize the initial harvest plus transoprt costs.

Developing a method of prioritizing alternatives is the major difficulty in develping a simulation model for timber management scheduling. Good heuristic rules have not been identified for the timber management scheduling problem; however, very little research has been done in this area. A study is currently under way to quantify the various trade-offs between LP solutions and harvest schedules based on heuristics.[1] The prioritizing method must be responsive to the changing conditions of the forest over time. It must be snsitive to the relative levels of timber demand and supply and how these relative levels change over time. Specifically, it must be capable of determining when management needs to gear up and invest heavily in regeneration activities, and when management can cut back and rely heavily on existing inventories. To be responsive in this sense, it seems that some sort of adjusting mechanism or tuning process is essential for prioritizing alternatives within the simulation process. Supply and demand relationships are difficult to describe, and are definitely dependent on the schedule implemented.

Simulation models used for determining allowable cut levels use the fixed time step method of modelling. They mimic management by actually harvesting and growing stands over time. Each period they rank stands and harvest until the current estimate of the allowable desirable cut is reached. This approach has several inherent problems. First, forests contain multiple products. There is not one simple harvest level to achieve each period. Harvesting an individual stand usually produces timber for several products. Meeting cut levels for all products simultaneously can be difficult.

Another problem with the fixed time step method is in recognizing the many options available for individual stands, as well as the long-term impact of those actions. The situation is not always so simple as deciding whether or not to harvest. Thinnings as well as clearcuts are possible. Furthermore, full tree chipping, traditional roundwood operations, and chip and sort systems are all considered clearcuts, yet each yields significantly different products and total volumes.

Validating a simulation approach would be a difficult task. Simply comparing results to those of LP model has some difficulties because of the problems and limitations inherent to the LP approach. A key to validation and acceptance must be in a supporting theory for the prioritizing methodology.

Hoganson and Rose (1984 a,b) have identified an approach that has considerable potential. Instead of using the fixed step method for the forest as a whole, the approach moves from stand to stand scheduling all stand actions for the entire planning horizon. Stands themselves are never ranked for harvest against each other. Ranking stands can be an expensive model component. The key to the success of the proposed approach must be in the method of recognizing forest-wide considerations when scheduling stands separately. Economic shadow prices are used for this critical link.

---

1) Elwood, Norman. Heuristics Versus Optimization in Timber Harvest Scheduling. Ph.D. Thesis is progress, University of Minnesota, College of Forestry.

The technique itself is more of a search technique than an actual simulation model that mimics harvests and growth over time. It is intended to be used as a simulation model to examine elements of the problem that cannot be recognized explicitly in the model. It has three characteristics that make it extremely appealing. First, it has been proven that the solutions produced are optimal solutions to an LP formulation of the problem(Hoganson and Rose 1984b). Second, the LP formulation can be significantly larger than those currently used for timber management scheduling. Third, the computer size and time requirements do not limit its use for examining the specific assumptions of the model. These advantages are achieved essentially be relaxing the feasibility requirements on the output level constraints. This is a small sacrifice considering the uncertainty surrounding the estimates of future output levels.

A Simulation Approach

For the simple case of an individual landowner who has only one timber stand and no constraints on periodic timber flows, the scheduling problem is fairly straightforward. Alternatives can be compared in terms of financial measures such as net present worth or soil expectation value. The biggest problem faced by the landowner is predicting future prices and future timber yields.

For a larger landowner who must also be concerned with relatively even flows of inputs and outputs, market prices are inappropriate for valuing stand inputs and outputs when ranking alternatives. Instead, output values must relate to some sort of shadow price that takes into account forest-wide flow constraints over time. Shadow prices in this sense can be conceptualized as market prices somehow adjusted for even-flow constraints. But future market prices are themselves uncertain. How can future prices be adjusted if they cannot be estimated precisely? This complication makes the concept of shadow pricing unappealing for simulation purposes under the goal of maximizing financial returns.

One method of dealing with future price uncertainty is to approach the problem from strictly a production viewpoint in which the goal is to minimize costs of producing specified flows of outputs over time. Specifying output levels beforehand is definitely restrictive, but by examining scheduling results for various plausible output scenarios, this problem can be somewhat overcome. With this minimum cost approach, the marginal costs of production in each period correspond directly to shadow prices; producing a unit of output reduces costs at the margin by one unit. Estimates of these marginal costs/shadow prices can serve as the basis for ranking stand alternatives.

Marginal costs of production should be fairly easy to predict for forest products. Marginal costs must be serially correlated over time because of the time required to grow trees. Almost all stands have some flexibility in terms of rotation (production) length. Rotation lengths can be shortened to capture the advantage of relatively high prices or lengthened if prices are relatively low. Under any sort of even flow policy, timber values (marginal costs) could not vary greatly between periods because if they did, rotations would be adjusted to best capitalize on the value change; the relatively high priced period would have a large output level.

A straightforward yet important advantage of the simulation approach is the ability to learn more about the relationship between marginal costs and output levels through simulation results. For example, if estimates of marginal costs result in output levels that are too high in general, then it is clear that marginal cost estimates must be decreased in general.

Furthermore, if output levels result that are too high in one period and too low in the next, the economics of timber production indicate that outputs will shift from the first period to the second period by raising the marginal cost in the second period relative to the first period.

The large size of management scheduling problems can actually be advantageous for predicting the relationship between marginal costs and output levels. With many stand types and a small increase in marginal cost (price), the number of stands coming into production is likely to be small compared to the total number of stands. A smooth predictable relationship would probably exist between output levels and marginal costs for each period. This relationship would probably be "lumpier" and less predictable if fewer stands were recognized.

The simulation approach for determining a minimum cost schedule would proceed as follows:

(1) Estimate marginal costs of production for each product in each period for the output levels desired.

(2) Use marginal costs estimates as shadow prices to identify optimal management sequences for each stand.

(3) Compare the scheduled output levels with those initially desired. If they are within satisfactory limits, stop.

(4) Otherwise use resulting output levels, the marginal cost estimates corresponding with them, and basic concepts of forest production economics to re-estimate the marginal costs. Return to step (2) with these estimates.

The biggest advantage of this approach is its ability to schedule stands separately. Model size is not nearly as large a concern when using the simulation approach as when applying alternative linear programming models.

The accuracy of the initial marginal cost estimates developed in step (1) definitely influences the number of trips (iterations) through the four steps, but experience has not shown this step to be a critical step. Basic inventory statistics such as the initial age distribution can be useful for making the initial estimate. The value of each management alternative (VAL) determined in step (2) could be expressed as :

$$VAL_{ij} = \sum_{i=1}^{N} \sum_{p=1}^{P} m_{pt} v_{ijpt} - c_{ij} + w_{ij}$$

where:

c_{ij} = the total discounted cost of management per land unit for management sequence j of stand,

m_{pt} = the discounted marginal cost estimate for product p in period t,

N = the number of periods in the planning horizon,

p = the number of product types,

v_{ijpt} = the per land unit volume yield of product p in period for management sequence j of stand i, and

w_{ij} = the discounted per land unit value of ending inventory for management sequence j of stand i.

If a long planning horizon is used, the number of possible management alternatives for each stand type will probably be enormous. At least for large-size scheduling problems, evaluating each alternative for each stand type would be a time-consuming task. However, by utilizing dynamic programming, the management alternative for each stand type with the greatest total discounted value can be identified without evaluating each

possible alternative individually.

To fit the valuation process into a structure that can utilize dynamic programming, each management alternative is defined as an initial harvest sequence followed by one or more regeneration sequences. The harvest sequence and the regeneration sequences each could contain a number of management actions, but each ends with its first clearcut. Each sequence contains a unique set of time-dependent cost and yield information.

The significant difference between harvest sequences and regeneration sequences is that harvest sequences depend on specific conditions of the stand. Regeneration sequences begin with bare land and thus depend on only the quality of the site. Instead of specifying all of the possible management alternatives for the planning horizon, only the possible harvest sequences and the possible regeneration sequences are identified. Dynamic programming is used to determine the optimal sequence mix. This approach is similar to the concept used in the Model II linear programming formulation as described by Johnson and Scheurman (1977).

Step (3) of the simulation approach is computationally simple. Summary statistics on output levels can be collected as stands are scheduled. The only real issue is in setting satisfactory limits for deviations in output levels. Two factors are important to remember for this. First, uncertainty surrounds the problem, so meeting levels exactly is unimportant, especially for periods far in the future. Second, the magnitude of the deviations in output levels is not necessarily the only factor to consider. The marginal costs themselves are probably the most important output from the process. Too much emphasis can be placed on minimizing deviations. For example, if a marginal cost of $28.15 produces a 10-percent positive deviation, while a value of $28.20 results in a 10-percent negative deviation, then for practical purposes, the process could stop. This type of outcome of small marginal cost changes resulting in significant deviations was found in practice by Hoganson (1984).

The key to the simulation approach is step (4), the process of adjusting marginal cost estimates. Three adjustment processes based on the basic economic concepts of timber production described earlier can be used to adjust the estimates (Hoganson and Rose 1984 a,b). The simplest procedure, the Float procedure, simply moves the entire marginal cost against time curve up or down depending on the direction of shift needed. The shape process is somewhat similar except it calculates a weighted average of deviations for each time period to determine its magnitude and direction of change in marginal costs. The smooth procedure is based on the relationship between marginal costs in successive periods. It attempts to shift outputs from relatively high output periods to relatively low output periods by adjusting the difference in price (marginal cost) between the two periods. Hoganson (1984) refined these processes somewhat by using nonlinear relationships for large deviations to prevent the adjustment process from over-compensating.

Comparison With Linear Programming

A comparison of the simulation approach with linear programming (LP) shows that the simulation approach produces optimal solutions. Consider the following (LP) problem:

$$\text{Minimize} \quad \sum_{i=1}^{I} \sum_{j=1}^{J_i} c_{ij} x_{ij}$$

$$\text{s.t. (1)} \quad \sum_{i=1}^{I} \sum_{j=1}^{J_i} v_{ijpt}\, x_{ij} = M_{pt} \qquad \text{for all } p,t$$

$$\text{(2)} \quad \sum_{j=1}^{J_i} x_{ij} = A_i \qquad \text{for all } i$$

$$\text{(3)} \quad x_{ij} \geqq 0 \qquad \text{for all } i,j$$

where

A_j = the number of land units of stand type i that are present in the intitial period,

c_{ij} = the discounted cost for assigning a land unit of stand type i to management sequence j. This cost includes the value (negative cost) of ending inventory.

M_{pt} = the desired output level for product type p in period t,

I = the number of stand types,

J_i = the number of management sequences for stand type i,

v_{ijpt} = the per land unit volume yield of product type p in period t for stand type i if management sequence j is followed, and

x_{ij} = the number of land units of stand type i that are assigned to management sequence j.

The first set of constraints forces achievement of the desired outputs. The second set defines the initial area in each stand type. This second set is orthogonal, but it makes the problem large because there is one constraint for each of the many stand types. The constraints in the first set are relatively few, but they are key constraints in that they tie the variables in the second set together. Without the first set, the problem would be trivial; it could be decomposed and solved in parts, one part for each stand type.

The dual variables associated with constraint set (2) are the marginal costs (shadow prices) used in the simulation approach. The simulation approach can be explained in terms of the dual of the LP problem. With the same variable notation, the dual problem can be written as :

$$\text{(D1)} \quad \text{Maximize} \quad \sum_{t=1}^{T} \sum_{p=1}^{P} M_{pt}\, m_{pt} + \sum_{i=1}^{I} A_i a_i$$

$$\text{s.t.}$$

$$\text{(1)} \quad \sum_{t=1}^{T} \sum_{p=1}^{P} v_{ijpt}\, m_{pt} + a_i = c_{ij} \qquad \text{for all } i,j$$

(2) a_i unsigned for all i

(3) m_{pt} unsigned for all p,t

where:

a_i = the dual variable associated with stand type i,

m_{pt} = the dual variable associated with the output level constraint for product p in period t,

p = the number of product types, and

T = the number of time periods.

The dual (D1) is different from primal (P) in that it is tied together by key variables (m_{pt}'s) rather than by key constraints; the m_{pt}'s appear in all constraints and only one a_i appears in each constraint. The simulation approach assumes the marginal costs of production (m_{pt}'s) are known. Then the problem reduces to:

$$\text{(D2)} \quad \underset{a}{\text{Maximize}} \quad \sum_{i=1}^{I} A_i a_i$$

s.t.

$$\text{(1)} \quad a_i \leqq K_{ij} \qquad \text{for all } i,j$$

$$\text{(2)} \quad a_i \text{ unsigned} \qquad \text{for all } i$$

where:

$$K_{ij} = c_{ij} - \sum_{t=1}^{T} \sum_{p=1}^{P} v_{ijpt} m_{pt}$$

The constant, K_{ij}, in this formulation is the net cost of management sequence j for stand type i. It is equivalent to the negative of VAL_{ij} used in the simulation approach.

The solution found in the simulation approach is an optimal solution to the reduced dual (D2). By finding the greatest VAL_{ij} for each i, one is also identifying the lowest value of K_{ij} over j and thus determining the upper bound on a_i. Because the coefficients in the objective function, the A_i's, are all positive by definition, the optimal solution to the reduced dual (D2) must have all a_i's set equal to their upper bound.

Complementary slackness conditions require each variable in the primal to be equal to zero if its corresponding dual constraint is nonbinding. The simulation approach satisfies these conditions by assigning all available land units for each stand type i to the sequence j that corresopnds to the binding constraint in the reduced dual (D2). Feasibility to the dual (D1) is guaranteed because the m_{pt}'s are unbounded, and once estimated, they are assumed fixed in solving for the a_i's. If the solution is also primal feasible, it must be an optimal solution.

Feasibility to the initial area constraints (2) in the primal (P) are guaranteed by assigning all land units to a single class. The output level constraints (2) are the only constraints that can be violated. But suppose the output level constraints in the primal were changed to the levels scheduled in the simulation approach. This would not change the feasible region of dual (D1), the complementary slackness requirements, or the solution determined; therefore, the solution would then be both primal and dual feasible and thus an optimal solution for the output levels scheduled.

Comparison with the Dantzig-Wolfe Decomposition Algorithm

The simulation approach described has some of the computational advantages of the Dantzig-Wolfe (D-W) decomposition algorithm (Dantzig and Wolfe, 1960). Littschwager and Tcheng (1967), Nazareth (1973), Harms (1973),

Williams (1976), and Berck and Bible (1984) have all applied the D-W decomposition algorithm to timber management scheduling problems with some degree of success. Both the simulation approach and the D-W algorithm decompose the problem in an essentially identical manner. Both methods can evaluate similar stand types separately by using the values of the dual variables to evaluate alternatives. Both methods can also utilize dynamic programming so that all possible management sequences for the planning horizon do not need to be evaluated separately.

The simulation approach differs from the Dantzig-Wolfe algorithm in the way it treats the coupling (key) constraints. The simulation approach attempts to utilize the economic interpretation of the timber management scheduling problem to overcome the problems created by the coupling constraints. It takes advantage of the fact that a schedule that is only "near-feasible" in terms of the coupling constraints would probably be acceptable. In the simulation approach, the coupling constraints are not recognized explicitly within the scheduling procedure. In contrast, the D-W algorithm recognized the coupling constraints explicitly, and feasibility to them is maintained throughout. The simulation approach utilizes the economic interpretation of the key dual variables to obtain a starting solution that in theory seems close to a final solution.

During each iteration of the process, basic theory is combined with what has been learned from intermediate results to re-estimate the key dual variables. Numerous changes can occur in the schedules produced between iterations. In contrast, the D-W algorithm is purely mathematical in determining an initial feasible solution and in determining the next variable to enter into the basis. Prior information or economic theory is not utilized. Solutions cannot change significantly between successive iterations because primal feasibility is always maintained.

Advantages for Planning Under Uncertainty

Several features of the model make it well suited for planning under uncertain timber market conditions. The basic design of the approach takes advantage of the uncertainty surrounding the estimates of future output levels by relaxing the feasibility requirements of the output level constraints This saves on computational costs and allows for significant increases in model size.

The approach also forces an emphasis on the marginal costs of production. With LP models it is too easy to ignore the uncertainty issues and strive to produce an optimal schedule for a narrowly defined set of conditions. Uncertainty surrounding future timber prices is a major complicating factor for timber management planning. The marginal costs of production estimated from the simulation model can help quantify the timber supply situation when the model is applied to a relatively large component of the market. An understanding of the future supply situation is essential for predicting future timber prices.

The uncertainty of future market prices makes it difficult to deal with ending inventory in LP scheduling models. Values are either assumed for it, or the model is constrained to achieve specific levels. The simulation approach has an advantage in that ending inventory values need not be specified beforehand. They can be made dependent on the shadow prices estimated and can be adjusted as shadow prices change in the scheduling process.

The primary output from the timber management planning process must be the schedule to implement in the immediate period. This schedule must be flexible in the sense that it will perform relatively well over a range of plausible future conditions. This objective is commonly referred to in USDA Forest Service doctrine in statements such as: keep options open, avoid irreversible mistakes, and manage the present to insure the future.

The simulation approach is designed with the concept that it would be applied to various plausible future output levels. A schedule for the first period could be partially developed by simply comparing the first period schedules and implementing those actions that are common to a range of plausible future conditions. Hoganson (1981) proposed one method of combining several runs of the simulation approach to rank alternatives using expected values based on shadow prices. He also proposed a method of merging several LP models together into a single model. The merged LP approach is too large for most problems, but it illustrates the limitations of current LP models that consider only one set of future conditions. The method based on the simulation approach has a drawback in that the schedule implemented can influence future marginal costs; however, it could at least serve as an interim approach until better methods are developed. The problems of uncertainty need to be better addressed in the timber management scheduling process.

APPLICATIONS

The model has been used to routinely solve huge hypothetical problems during its development and testing. One large-scale real world application exists also.

The procedure has been successfully applied to develop harvest schedules for a major region in Minnesota (Hoganson 1984). More than 6000 stand types were used to describe different species mixtures, timber products within stands, stocking classes, and distance to different markets in addition to standard characteristics such as site quality and ownership. Optimal solutions were derived for this huge problem for many different future scenarios in terms of periodic wood product requirements typically in less than 50 iterations on the marginal cost estimates with one iteration costing less than $0.50. Simulation costs were, therefore, not only far below costs for running much smaller, highly aggregated LP formulations, but provided easily implementable operational plans as well as immediate planning period action plans that will prove to be stable even under widely differing future scenarios, i.e., action plans that will not likely prove to be non-optimal because of changes in future assumptions.

RECOMMENDATIONS

The availability of a model to derive optimal harvest schedules without a need for data aggregation has opened up great possibilities for developing simultaneously plans which can serve both strategic as well as operational needs. Up to now, operational plans have not been developed successfully from the strategic plans based on LP models with highly aggregated data. This lack of success has created tensions between planners and practicing foresters. The new simulation-optimization approach supports a planning process that not only develops management prescriptions or alternatives at the compartment level in line with german forest inventory (Forsteinrichtung) traditions, but it permits to quantitatively assess the many complex trade-offs among management alternatives over time to optimize a specified objective

function. This feature makes the new model vastly more powerful than compartment type examinations and more powerful than optimization models for highly aggregated data. Strong evidence suggests that operational plans developed by this new approach and subsequently implemented will prove to be much more stable and less subject to revision. Understandability and implementability of the plans should help bridge the gap between plan and practice and between planners and practioners. Only then will plans ever justify the great expenditures of time, personnel and money that are being used in their development.

LITERATURE CITED

Amano, M. 1981. A timber planning system in the National Forest in Japan. Forestry and Forest Products Research Institute, Tsukuba, Japan. 7p.

Amano, M. 1984. Timber supply projection model for private forests in Japan. Forestry and Forest Producsts Research Institute, Tsukuba, Japan, 7p.

Apple, R. L. 1982. An Analysis of FORPLAN. Master's thesis. Univ. of Minnesota, College of Forestry. 72 p.

Berck P. and T. Bible. 1984. Solving and Interpreting Large-Scale Harvest Scheduling Problems by Quality and Decomposition. Forest Science 30(1): 173-182.

Chappelle, D. E. and R. W. Sassaman. 1968. A Computer Program for Scheduling Allowable Cut Using Either Area or Volume Regulation During Sequential Planning Periods. USDA For. Serv. Res. Note PNW-93. 9 p.

Chappelle, D. E., M. Mang, and R. C. Miley. 1975. Timber RAM and Forest Management Planning: An Evaluation of a Planning Model. J. For. 74: 288-293.

Dantzig, G. B. and P. Wolfe. 1960. Decomposition Principle for Linear Programs. Operations Research 8(1): 101-111.

Harms, J. C. 1973. Network and Decomposed Linear Programming for Scheduling Forest Production. Ph.D. Thesis, Duke University.

Hoganson, H. M. 1981. Timber Management Scheduling Under Uncertainty: Two Alternative Approaches. Ph.D. Thesis, University of Minnesota.

Hoganson, H. M. 1984. Examining the Wood Energy Potential for Northeastern Minnesota. In proceedings: ASME International 84 Minneapolis Summer Conference, Tassin-la-Demi-Lune, France.

Hoganson, H. M. and D. W. Rose. 1984a. A Simulation Approach for Optimal Timber Management Scheduling. Forest Science, 30(1): 220-238.

Hoganson, H. M. and D. W. Rose. 1984b. A New Approach for Timber Management Scheduling. In proceedings: ASME International 84 Minneapolis Summer Conference, Tassin-La-Demi-Lune, France.

Johnson, K. N. and E. L. Scheurman. 1977. Techniques for Prescribing Optimal Timber Harvest and Investment Under Different Objectives--Discussion and Synthesis. Forest Science Monograph 18. 31 p.

Johnson, K. N.m D. B. Jones, and B. M. Kent. 1980. Forest Planning Model (FORPLAN). User's Guide and Operations Manual. 251 p.

Liittschwager, J. M. and T. H. Tcheng. 1967. Solution of Large-Scale Forestry Scheduling Problem by Linear Programming Decomposition. Journal of Forestry 65: 644-646.

Myers, C. A. 1974. Computerized Preparation of Timber Harvesting Plans: TEVAP 2. USDA For. Serv. Res. Pap. RM-115. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. 72 p.

Navon, D. I. 1971. Timber RAM: Long Range Planning Method for Commercial Timberlands Under Multiple Use Management. USDA For. Serv. Res. Paper PSW-70. 22 p.

Nazareth, L. 1973. A Resource Allocation Model for Land Management and a Solution Strategy that Combines Dantzig-Wolfe Decomposition and Dynamic Programming. Univ. California Berkeley College of Engineering Operations Research Center ORC 73-20. 100 p.

Sassaman, R. W., and D. E. Chappelle. 1967. A Computer Program for Calculating Allowable Cut Using Area Regulation and a Comparison with the ARVOL Method. USDA For. Serv. Res. Note PNW-63. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. 7 p.

Sassaman, R. W., E. Holt, and K. Bergsvik. 1972. User's Manual for a Computer Program for Simulating Intensively Managed Allowable Cut. USDA For. Serv. Tech. Rep. PNW-1. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. 50 p.

Walker, B. A. 1982. The Role of Quantitative Modelling in Forest Management Planning. Master's thesis. Univ. of Minnesota, College of Forestry. 63 p.

Williams, D. H. 1976. Integrating Stand and Forest Models for Decision Analysis. Ph.D. Thesis, University of British Columbia, Vancouver, British Columbia.