Invited Review

A survey of systems analysis models in forestry and the forest products industries

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Abstract. This review describes the current state of the art of management science applications in forest land management and the forest products industry. The evolution of applications of management science to forestry problems is traced from the late 1950's to the present. While management science is extensively utilized in both the public and private sectors, many institutional and technical barriers exist to hinder an even wider acceptance. Reasons for this and possible ways to ameliorate these problems are presented.

Keywords: Management, forestry production

1. Introduction

The use of systems analysis-operations research (SA-OR) in forestry and the forest products industries has expanded dramatically since being introduced in the late 1950's. This expanded use has coincided with the rapid development of the digital computer, the continued refinement of many computer-based SA-OR tools, the increased competition for forest land and forest products, and an increasingly complex market structure facing both timberland and manufacturing plant managers.

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In response to these pressures, forest managers have turned to SA-OR to aid in evaluating alternative courses of action. Public forest land managers have been encouraged to adopt a systematic and comprehensive approach through Federal and State legislation while private forest managers involved in an increasingly competitive environment have turned to SA-OR in efforts to plan and control their timberlands as well as manufacturing, distribution and marketing systems. Lastly, managers have modernized administrative procedures through the use of comprehensive management information systems. These computer-based tools have further stimulated the use of decision-oriented SA-OR tools.

The objective of this review is to examine the rationale and historical perspective of the use of SA-OR techniques to aid managers in the forest products industries. Thus, this review concentrates on applications that directly affect and involve managers. The objective is to review the types of SA-OR modeling techniques that are normally encountered in a SA-OR textbook.

The approach taken is to examine the role of SA-OR tools within broad areas of application. Hence, we have chosen to organize our paper by following the forest production process from tree nursery to final product. Although we emphasize timber production and forest products manufacturing, this review differs from previous reviews which have been organized by the type of SA-OR tool, and not by the application.

2. Previous SA-OR surveys

A variety of symposia, workshops, conferences and meetings have discussed the role of SA-OR in forestry and the forest products industries. A representative sample of these is shown in Table 1

Table 1
Previous works dealing with SA-OR in forestry and the forest products industries

Item	When
Forest Management Control Conference, Department of Forestry, Purdue University, Lafayette, Indiana	1960
IBM Forestry Management Conference, International Business Machines, Mobile, Alabama	1964
IBM Seminar on Operations Research in the Forest Products Industry, International Business Machines, San Francisco, California	1965
Mathematical Models in Forest Management, University of Edinburgh, Scotland. Published as British Forestry Commission Forest Record No. 59	1965
Operations Research Application to Sawmills, School of Forest Resources, University of Georgia, Athens, Georgia	1969
Operational Research and the Managerial Economics of Forestry, British Forestry Commission Research Station, Alice Holt Lodge, England	1970
Workshop on Computer and Information Systems in Resources Management Decision, Annual Meeting of Society of American Foresters, Cleveland, Ohio	1971
Planning Systems and Control, Department of Forestry, University of Freiburg, Federal Republic of Germany	1973
Systems Analysis and Forest Resources Management, School of Forest Resources, University of Georgia, Athens, Georgia	1975
Operational Forest Management Planning Methods, Bucharest, Romania. Published as U.S.D.A. For. Ser. Gen. Tech. Rep. PSW-32, Berkeley, California	1978
Simulation Techniques for Operational Planning and Control, Department of Forestry Technique and Forest Products, Agricultural University, Wageningen, The Netherlands	1978
Symposium on Forest Management Planning: Present Practice and Future Decisions, School of Forestry, Virginia Polytechnic Institute, Blacksburg, Virginia	1980

and serves to illustrate both the pervasiveness of SA-OR throughout the world and the variety of applications in forestry and the forest products industry.

Several authors have compiled bibliographies of forestry applications of SA-OR. Noteworthy examples of such bibliographies are Schreuder (1969), Schopfer and Hofle (1970), Bare (1971), Martin and Sendak (1973), Bare and Schreuder (1976), Field (1976), Cawrse (1979), Martell (1982), and Navon and Weintraub (1982). The present paper brings these surveys up to date.

3. Forest management: timber production

3.1. Nursery operations

We begin our review of SA-OR in forestry and the forest products industries by examining applications in the operation and maintenance of forest nurseries. Although many possibilities exist, we find little evidence that SA-OR has been used extensively in this area. Jeffers (1965) discusses a general model which utilizes both simulation and mathematical programming. The simulation model requires inputs describing: (a) forecast demands, (b) actual demands, (c) weather conditions, and (d) physical inventory of the number of plants. The simulator predicts the number of plants grown and the number of seeds in stock. Mathematical programming is used to allocate plants to planting areas and to nursery units and to allocate seed lots to nursery units. Model output consists of an annual plant allocation, a nursery program, a seed store program, and a set of productivity and conversion factors.

Grevatt and Wardle (1967) developed two linear programming (LP) models to aid in nursery planning. Their first model is designed to program sowing, transplanting, and storage of nursery stock with demand constraints so that the operation is run at least cost. The second, a transportation model, allocates the nursery stock to meet the demands of different forests so that haul cost and deviation between supply and demand for trees are minimized.

Atkinson (1974) discusses a model where both simulation and mathematical programming are used to control the operations in a nursery. The simulation model determines the cost of growing seedlings of various types in different nurseries and the LP model allocates seedling production to the different nurseries.

3.2. Stand management

Once seedlings are grown, lifted, and transported to the planting site the manager still faces a multitude of decisions concerning how many trees (by species) to plant per acre, when and how to control competing vegetation, when to correct spacing through a precommercial thinning, when to fertilize and at what dosage, when to commercially thin and to what residual stocking, and when to begin the cycle anew. This sequence generally describes an even-aged management framework (Hann and Brodie, 1980).

For forests grown and managed under an uneven-aged system, the major decisions are how many trees (by species) to carry in each diameter class to provide a sustainable diameter distribution, when to enter each forest unit, how many trees (by diameter class and species) to remove, and what strategy to adopt in converting the existing forest structure to the sustainable diameter distribution (Hann and Bare, 1979).

Factors which complicate these tasks include the consideration of multiple objectives, uncertainty inherent with the long time periods needed for timber production, the production of benefits and costs which are difficult to measure and quantify, and the lack of adequate response information relating decisions on one resource to impacts on other resources. Nevertheless, forest managers have applied a variety of SA-OR tools to help make better stand management decisions.

The first conceptually correct analysis of optimal rotation length for even-aged stands treated timber as a maturing asset and located the optimum rotation age for an infinite series of identical rotations (Faustmann, 1849). Andersen (1976) used optimal control theory to study the problem and derived a model identical with Faustmann's. Notwithstanding the correctness of Faustmann's solution, the approach assumes all management decisions, other than rotation length are fixed. However, this is not the usual situation as the forest manager is able to modify stands by using the previously described stand treatments.

The control of stocking through thinning has received considerable attention. Amidon and Akin (1968) found an optimal solution for the joint stocking-rotation decision for an even-aged stand using dynamic programming (DP). Then, the close relationship between the calculus of variations and DP formulations of the stand management problem (or generalized Faustmann formulation) was noted by Schreuder (1971). His DP formulation used volume as the single state variable, with the decision at each stage being how much volume to remove. Brodie et al. (1978) expanded the formulation to include impacts of regeneration cost, initial stocking level, site quality, stumpage premium, and logging cost which were only implicit in earlier papers. Brodie and Kao (1979) used DP with two state variables (i.e., the number of trees and basal area) to describe the forest at each stage. Kao and Brodie (1979) also discuss the use of DP for determining the optimal thinning interval, a decision variable held constant in most DP models.

A promising alternative to DP for solving stand management problems was discussed by Kao and Brodie (1980). They used a nonlinear programming algorithm to optimize thinning and rotation lengths with continuous stocking and entry intervals. They effectively avoided the dimensionality problem and solved the problem more efficiently than could have been done with DP. A limitation of their technique is that it does not find the global optimum for each of a number of different thinnings. Thus, the same problem must be solved repeatedly for a different number of thinnings from $D = 1, \ldots, L$ with no guarantee that the global optimum will not occur with greater than L thinnings.

Fertilization treatments have been incorporated into DP formulations of optimal thinning-rotation determinations. Brodie and Kao (1979) noted that their model can incorporate both thinning and fertilization, while Schreuder and Roise (1983) show how to determine an optimal sewage sludge-thinning schedule, which is conceptually the same as the fertilization-thinning problem. Their formulation uses number of trees and volume as state descriptors with thinning, rotation, sludge application, and initial planting density being the decision variables. Additional stand management decisions can be included without expanding the state space. An illustration of this can be seen in a four state-descriptor DP model which jointly optimizes forage and timber production (Riitters et al., 1982).

The application of SA-OR tools to problems of uneven-aged stand management are rare relative to the even-aged situation. Only recently have forest researchers begun to analyze uneven-aged management questions using SA-OR techniques

(Hann and Bare, 1979). Adams and Ek (1974) pioneered the application of mathematical programming to a variety of uneven-aged stand management problems. Their effort stimulated others to pursue work concerning the development of financial maturity theory to uneven-aged stands (Chang, 1981 and Nautiyal, 1983). Additional applications of SA-OR are likely to follow in this rapidly expanding area.

Hool (1966) was one of the first to recognize and address the uncertainty problem in stand management models. He used a DP-Markov chain formulation to determine the optimal forest production control strategy to apply to a stand over a finite planning horizon. A set of states, management activities, returns and transition probabilities were used to formulate the recurrence relationship used in the DP model. Lembersky and Johnson (1975) extended Hool's formulation by considering an infinite time horizon and by using additional state variables. Kao (1982) used a probabilistic DP model to jointly optimize stocking levels and timing of the final harvest. His model incorporated uncertainty in the prediction of growth and maximized a volumetric objective function.

3.3. Growth and yield

Growth and yield modeling covers an array of topics dealing with the development of models which are useful for predicting the future condition of forest stands when subjected to a given set of management practices. The technique of simulation has been the most extensively used SA-OR tool applied in a large number of growth and yield studies. Munro (1974) classified growth and yield models into three categories: (a) whole-stand/distance-independent, (b) single-tree/distance dependent, and (c) single-tree/distance-independent. A comprehensive inventory of forest growth models is available from the Oak Ridge National Laboratory (Trimble and Shriner, 1981).

The primary concern of whole-stand models is to predict stand level characteristics such as average diameter, stocking (i.e., trees per acre or basal area per acre), stand age, and volume per acre. Whole-stand/diameter free models do not provide a prediction of future diameter distributions nor are any distributional data used in the process of developing the model. Only aggregate stand-level characteristics are predicted by this type of model. Examples of this type of model are Elliott and Goulding (1976), Curtis, Clendenen and DeMars (1981), Hamilton and Christie (1974), and Moser (1972).

Whole-stand/diameter function models also predict stand-level characteristics but, through the use of continuous probability distributions such as the Weibull or Beta, characterize the distribution of diameters within the stand. Examples of this type of model are those of Clutter and Belcher (1978), Schreuder, Hafley and Bennett (1979), Burkhart and Strub (1974), and Hyink and Moser (1983). Cassell and Moser (1974) illustrate a Markovian approach to predicting diameter distributions for uneven-aged stands.

Whole-stand/diameter class models characterize the stand by dividing the diameters into discrete classes. All trees assigned to a specific diameter class grow uniformly and the sum over all classes provides the desired stand-level statistics. Clutter and Jones (1980) have developed a model of this type where the trees do not move from one class to another as the simulation progresses. Instead, the statistics describing each class change. Others, like Hann (1980) and Ek (1974) have developed models where trees move from class to class, but the statistics describing each class remain constant.

Individual tree growth and yield models predict the development of individual trees rather than aggregate stand-level parameters. If inter-tree distances are required, then the model is further classified as distance-dependent. Models of this type also require some measure of competition between adjacent trees. Examples of this class of model are those of Arney (1974), Mitchell (1975), and Ek and Monserud (1974).

Individual tree/distance-independent models do not require that the location of every tree in the stand be known. Instead, competition is computed by comparing a tree's size with other trees in the stand. Each tree in the stand is grown each growth period and a sum over all trees provides the stand-level statistics. Many models of this type have been developed in recent years. Some examples are Alder (1979), Belcher (1981) and Wykoff, Crookston and Stage (1982).

Regardless of model type, simulation appears to be the most widely used SA-OR technique for growth and yield modeling. However, recent work in this area has also involved the application of

DP to optimize the development of stands over time. This has blurred the distinction between growth and yield modeling and stand development modeling—the topic discussed in the preceding section. Examples of stand- optimization models that are closely tied to growth and yield modeling are the models of Martin and Ek (1981), Brodie et al. (1978), and Brodie and Kao (1979).

3.4. Forest-wide management concerns

While concerned with individual stand management decisions, a forest manager also recognizes that all stands in a given forest must be considered in the aggregate to ensure that specified forest-wide constraints are satisfied. Although forest analysts have worked on these problems for decades, SA-OR techniques have been applied relatively recently. Excellent reviews of SA-OR techniques used in forest-wide planning have been published by Johnson and Scheurman (1977), Navon and Weintraub (1982), Hann and Brodie (1980), and Hann and Bare (1979). The former two publications deal almost exclusively with optimization approaches while the latter two survey a variety of SA-OR methods used to analyze forest-wide problems.

Typical forest-wide questions which require analysis include when, where and how much to harvest in order to optimize some forest-wide objective function. Both simulation and optimization approaches have been used extensively to aid managers in making these decisions.

Most optimization approaches have adopted LP as the specific modeling framework. Reviews by Bare (1971), Chappelle et al. (1976), and Navon and Weintraub (1982) acknowledge the popularity of LP but also raise several criticisms about its use in forest management. Chief among these is that LP—a deterministic technique—is usually applied to a stochastic forest management system. Due to long time horizons, future uncertainties loom large in forest management planning. The impact of this uncertainty can be partially mitigated by parameterizing the LP coefficients or by using the objective of maximum present net worth to discount uncertain future values more heavily than near term values.

Another criticism is that LP allows management units to be treated under more than one alternative strategy. This leads to problems of implementation of harvest or treatment operations which are designed around whole units. Integer and mixed integer programming have been suggested to avoid fractional stands, but these techniques have not been widely applied because of the size of typical scheduling problems and their attendant computational difficulties (Bare and Norman, 1969).

Another criticism of LP is that it cannot adequately handle problems where the amount of timber affects the price at which the timber is sold without using cumbersome separable programming techniques. Hrubes and Navon (1976) developed an algorithm for use with downward sloping demand curves which uses a piecewise linear function as an approximation to the demand curve. A review of other approaches is provided by Schmidt and Tedder (1981).

When more than one objective is identified, the historical approach has been to pick one for optimization and include the others as constraints. Goal programming (GP) has also received considerable attention when multiple objectives are involved. Examples of goal programming applications in forestry are Field (1973), Schuler and Meadows (1975), Hotvedt et al. (1982), Bare and Anholt (1976), Field, Dress and Fortson (1980), and Rustagi (1976). Besides having the same problems as LP, GP is also criticized for subjectiveness when applying priorities to the different goals. Steuer and Schuler (1978) developed an interactive multiple objective LP approach to forest management problems which avoids the criterion weight problem by using interactions with the decision maker to narrow the noninferior set. The procedure uses a combination of LP and vector-maximization techniques. Bare et al. (1979) applied the STEP method to a hypothetical forest/wildlife management problem. This multiple objective LP approach also avoids the criterion weight problem.

Less attention has been devoted to the scheduling of uneven-aged forests. Loucks (1964) was one of the first to suggest the use of LP for solving uneven-aged forest management problems. Later, Navon (1975) developed an LP model which was capable of handling uneven-aged options. Buongiorno and Mitchie (1980) and Usher (1976) provide examples of models which adopt a matrix approach to uneven-aged forest management. These models, coupled with LP, can be used to answer uneven-aged management questions. Hann and Bare (1979) give a review of other SA-OR techniques useful for answering uneven-aged management questions.

To be globally optimum, both stand and forest-wide decisions must be derived simultaneously. Nazareth (1980) and Williams (1976) demonstrate how a finite set of stand-level treatments can be applied in a linear program by decomposition of the large problem into several smaller problems. De Kluyver et al. (1980) propose a two-stage optimization process. Their first stage uses DP to solve for the optimal thinning and rotation regime and the second stage uses a multiple objective LP model. For uneven-aged forests Hann and Bare (1979) propose a formulation using LP interfaced with stand-level information.

Another level of model complexity concerns the integration of transportation and forest management planning at the forest-level. Weintraub and Navon (1976) and Kirby, Wong and Hager (1980) provide examples of mixed integer programming models which have been proposed for this purpose. Kent (1980) discusses an LP model which integrates land allocation and forest management planning at the forest-level. This level of integration is receiving considerable attention as the U.S.D.A. Forest Service prepares a new set of land management plans for the National Forest Systems. It provides an example of one of the more ambitious modeling projects currently underway in the public sector.

Barros and Weintraub (1982) discuss still another level of model complexity when they present an LP model for a vertically integrated forest products firm. Their model jointly considers forest management, log allocation and transportation decisions.

3.5. Forest protection

Another major activity of concern to a forest manager is protecting forest resources from the destructive forces of fire, insects, and disease. Fire management has received the largest number of applications of SA-OR, and an excellent literature review of these applications has recently been completed by Martell (1982). SA-OR techniques have been suggested for use in almost all aspects of fire management.

Simulation has been used extensively to study the effect of weather, terrain, fuel, and suppression activities on wildfires. Three of the many models which have been developed are FOCUS, FORPLAN, and FIRESCOPE. FOCUS, developed by the U.S.D.A. Forest Service provides a means of evaluating different mixtures of fire fighting resources for initial attacks on forest fires (Storey, 1972). FIRESCOPE, described by Sanderlin and Van Gelder (1977), was developed to provide support for dispatchers by keeping track of the allocation of firefighting resources and for making predictions on fire containment. FORPLAN, an extension of the gradient modeling system developed by Kessell (1979), is referred to by Martell (1982) as the most ambitious fire impact policy model yet developed. It is not used to simulate fire suppression activities but to simulate the impact of fire and other disturbances on the forest. Bonnicksen (1980) discusses a simulation model used to examine the effects of brushland fire management policies and Simard (1979) uses simulation to help make air tanker base location and fleet composition decisions.

Linear, integer, and mixed integer programming have all been studied for application in allocating fire fighting equipment, crews, and other resources in the most efficient manner. Maloney (1972) and Greulich (1976) suggested mixed integer programming for helping make decisions about air tanker fleet composition and home base locations. Omi, Murphy and Wensel (1981) developed an LP model for scheduling investments in wildland fuel management activities. They subsequently applied their model to the fuel break system in southern California.

Nonlinear, quadratic, and dynamic programming have also received much consideration in fire science. Quadratic programming was utilized to maximize fire detection probability subject to a budget constraint (Kourtz, 1971). Bratten (1969) illustrated a potential use of nonlinear programming in determining the optimal allocation of forest fire fighting facilities to different fire suppression activities. Dynamic programming has been suggested and used for a variety of problems such as small fire spread and the dispatching of air tanker patrols. A recent example uses DP to minimize the delay between fire detection and initial attack by helicopters (Bookbinder and Martell, 1979).

Insect and disease control is another major activity of concern to forest managers. Simulation, because of its flexibility, has been the most heavily used technique in the study of forest pathology and pest control. Examples include studies of root rot in Douglas-fir seedlings (Bloomberg, 1979) to dwarf mistletoe in ponderosa pine (Strand and Roth, 1976). One of the most comprehensive pest management models found in forestry in the U.S. is the douglas-fir integrated management model (Brookes et al., 1978). In this model, forest stand, insect population, and socioeconomic information are all combined, and the effect of control and prevention measures are simulated.

4. Forest products

In this section, attention turns to applications of SA-OR in the forest products industry. Both product yield and process models are examined in this section. The former focus on the conversion of a raw material into a finished good while minimizing waste (or cost) or maximizing profit. The latter type of model is used to understand, control or optimize the activities of men and machines acting on a raw material to produce a specific product.

5. Product yield models

Product yield models determine how a given raw material unit should be manufactured into finished products. Such problems occur in sawing tree stems into logs, sawing logs into rough unfinished lumber, remanufacturing rough lumber into standard finished sizes, and cutting paper rolls into smaller sizes. These situations often result in complex combinatorial problems that must consider breakdown technology, raw material geometry, end product size specifications, grading rules, costs, prices, and order requirements. The development of microcomputers combined with scanning technology have made possible 'real time' control of process machinery either through on-line calculation of solutions or via preprocessed and stored tables of solutions.

5.1. Paper trim problem

The problem of how to optimally subdivide rolls from a paper machine into sizes desired by a customer is perhaps the earliest reference to the use of SA-OR in the forest products industry (Paull and Walter, 1955). Linear programming was applied to minimize trim losses incurred in the breakdown of these rolls. Initially the approach was to devise all possible cutting patterns. However, this had the disadvantage of being tedious and frequently produced excessively large LP models. A column generating technique which required generation of only enough patterns to form an initial LP basis was developed to offset this problem (Gilmore and Gomory, 1961). New candidate patterns for inclusion are generated during the simplex procedure by another SA-OR tool such as DP. Extensions of this approach have led to the consideration of multiple paper machines, paper grades, machine availability and economic factors. Progress has also been made in developing heuristic solutions to the problem (Pegels, 1967 and Haessler, 1980).

5.2. Crosscutting trees into logs

At first glance, the problem of crosscutting (bucking) trees into logs is similar to the paper trim problem. This similarity led to an LP formulation that attempted to convert trees into logs and satisfy demand for various log sizes and end uses (Smith and Harrell, 1961). Unfortunately, the similarity between these two problems is only superficial as trees are found in many sizes, shapes, species, and qualities. If trees are assumed to be combinable into homogeneous groups and all possible cutting patterns are developed for each group, a very large LP model results.

An approach that attempted to overcome these difficulties led to an individual tree LP where the stem is considered to be composed of 2-foot segments (Forster and Callahan, 1968). Contiguous groups of these segments were combined into mill-to-market log alternatives and solved using LP. Aside from problem size, LP formulations fail to address a number of other critical aspects of the crosscutting problem. First, log size specifications are rarely such that they are an integer multiple of 2 feet. Instead, the appropriate segment size may be much smaller, leading to an increased size of the LP. Furthermore, the method does not properly reflect typical practices of log quality evaluation or techniques for adjusting log volume when internal defects are present.

As an alternative to LP, Alm and Troedsson (1969) and Murphy (1978) used simulation or a combination of heuristic rules for solving the crosscutting problem. Some of these studies claim to provide an optimum solution, but in fact the optimum turns out to be the best of a limited number of pre-selected patterns—with no guarantee that the global optimum is among them.

A dynamic programming approach formulated by Pnevmaticos and Mann (1972) considered the tree to be subdivided into equidistant subintervals, each of which was a DP stage. The length of the interval—chosen to be equal to the length of the smallest size log specified by management—forced all other log lengths to be an integer multiple of the smallest size. This somewhat unrealistic condition can be easily relaxed by letting the stage interval be any length such that all log lengths are an integer multiple of it. They also treated log quality as a stochastic element.

Gluck and Koch (1973) proposed an alternative formulation that considers the number of cuts as the stage variable. However, they conclude that the Pnevmaticos and Mann formulation is preferred perhaps because it is intuitively easier to explain, the accounting details are relatively simple, and it is less computationally burdensome. Briggs (1980) extended this approach by introducing a taper equation describing the shape of the tree bole, including a technique for utilizing tree defect data in conjunction with log scaling and grading rules to correctly assess log grade and volume and, incorporating equations to predict the yield of lumber, veneer, pulp or fuel products from any potential log. Finally, his model includes a detailed and flexible approach for incorporating log production and milling economics so that alternative locations of the crosscutting activity can be studied. He also proposed a DP formulation to accommodate situations in which long-length logs are produced in the woods and transported to another site for subsequent re-crosscutting into finished log sizes. Other authors have developed similar variations from the original work by Pnevmaticos and Mann (1972).

5.3. Lumber manufacture

The process of converting logs into lumber follows the crosscutting of trees into logs. This conversion process is complicated by log geometry, sawkerf, edging method, sawing method, and the mix of possible board dimensions. Although LP was initially applied to this type of problem, the area has become almost exclusively the domain of simulation. Studies by Peter and Bamping (1962), Tsolakides (1969), Reynolds (1970), and Pnevmaticos and Moland (1978) provide a variety of approaches to this problem.

Perhaps the most widely publicized studies of log-to-lumber-conversion arose from the development of the best-opening-face (BOF) program at the U.S.D.A. Forest Products Laboratory (Hallock and Lewis, 1971). By means of iterative enumeration of a fixed grid, the optimum location of the first saw cut in the log from either a volume or value yield viewpoint can be found. Results of BOF studies are tabulated by log length, diameter, and taper classes so that a computer/scanner system can control the sawing process with little human intervention.

Although the BOF system has been widely adopted by industry, its authors provide no proof that the approach produces an optimal solution. Rather, it simply obtains the highest yield solution from the grid enumerations. Furthermore, relatively little explanation of the computational procedure or other details is available.

We find few published applications of SA-OR to problems involving subsequent sawmilling operations such as lumber edging, ripping, and trimming. However, it appears that DP would be worth exploring as these problems are of essentially the same structure as the log crosscutting problem.

The SA-OR developments in the areas of crosscutting and lumber manufacturing have primarily been concerned with converting a single tree into various types of logs or converting a log into various dimensions of lumber. Until recently little has been done to consider crosscutting or subsequent activities such as lumber manufacturing as interrelated activities that should be optimized simultaneously. Further, little has been done to incorporate tree or log supply or end product constraints into a comprehensive model. Recently, Faaland and Briggs (1984) developed a DP formulation that simultaneously optimizes crosscutting, sawing of logs into live-sawn lumber, and edging lumber into finished dimensions. This study recognizes the interrelated effects of these manufacturing phases. It integrates the crosscutting study of Briggs (1980), the sawing study of Tejavibulya

(1981), and a knapsack formulation for edging, and can be used to explore the effect of changes in sawkerf, lumber thickness, and tree shape on optimal conversion to finished lumber.

McPhalen (1978) developed an LP model based on the column generating technique of Gilmore and Gomory (1961) that permits the coordination of crosscutting and log sawing subject to market demand constraints for lumber. The LP is structured to maximize lumber revenue by considering alternative patterns for tree stems with constraints on the desired quantity of different lumber sizes. New crosscutting patterns, and hence new quantities of lumber sizes to enter the LP basis, are generated via a DP algorithm that obtains the quantity of lumber for each log in the crosscutting pattern by accessing a table that contains five empirical sawing yields for each log size.

5.4. *Veneer manufacture*

The problem of converting a log into veneer on a rotary lathe has received far less attention than the lumber breakdown problem. Foschi (1976) simulated the problem of centering round and eccentrically shaped logs on the lathe and the effect on yield of improper positioning. Briggs (1977) simulated the actual breakdown into veneer as affected by veneer thickness, log eccentricity and lathe characteristics.

Perhaps the most critical phase of veneer production is the clipping process where the veneer from the log is cut into standard size sheets for subsequent assembly into plywood panels. Tobin and Bethel (1969) simulated the effects of grade requirements, sheet widths, and clipping specifications on yields. Computer automated veneer clipping systems have been introduced in industry during the past decade, but relatively little has been published as to the decision making criteria that have been used.

5.5. *Secondary manufacturing*

Secondary manufacturing activities use lumber as a raw material, and include furniture, millwork, and related industries. Studies in this area focus on procedures to predict the yield of cuttings from lumber of different species and grades (Erickson and Markstrom, 1972). Simulation has been used to determine the location of optimum lengthwise or rip cuts in boards in order to meet a given cutting goal (Stern and McDonald, 1978). Once data became available from these studies, LP was used to indicate the least-cost mixture of lumber grades that should be purchased to satisfy a particular cutting order.

6. Process models

As the demand for forest products increases, industry has been forced to utilize smaller trees and logs that are often more defective and more expensive to process than larger old-growth logs. The smaller, second growth trees pose new problems of harvesting, materials handling, and processing. Technology of wood conversion is also changing. Alternative uses for wood, such as laminated and reconstituted products, combined with a variable quality raw material has made understanding and control of the interaction between men, machines, and material involved in the conversion operation very complex. Aids are needed for understanding and coping with the complex questions involved in procuring and allocating raw material and locating facilities.

The first part of this section on process models focuses on single processes such as harvesting and sawmilling. These studies are aimed at questions of mill design, estimating productivity, and the cost or profitability as processes and raw material vary. The second part examines studies where one type of conversion facility competes in some way with another facility.

6.1. *Harvesting models*

Harvest planning is the first task faced by managers in the conversion process. Logs are produced from trees and are transported to subsequent manufacturing facilities. Unlike these subsequent facilities, harvesting is conducted in the forest environment and interfaces directly with forest management and the production of other outputs such as esthetics, water, wildlife, and recreation. The manager must devise transportation systems, design cutting units, and select and allocate equipment to units in the most efficient way.

Optimum road spacing has received considerable attention. Carter et al. (1973) developed a nonlinear programming approach to this problem.

As stated earlier, Kirby et al. (1980) and Weintraub and Navon (1976) presented a mixed integer programming approach, while Carson and Dykstra (1978) used network analysis.

Mathematical modeling techniques were used as early as 1955 to improve harvesting operations. Linear programming was used for allocating equipment (Corcoran, 1964) and to study the feasibility of pipelines to transport chips (Tabor, 1968). Others focused on specific scheduling problems using PERT/CPM (Ramsing, 1967 and Betters, 1975). Craig (1970) combined these methods, using LP to allocate equipment to settings and PERT/CPM to handle detailed scheduling logistics.

These studies generally did not account for the interactions of topography, timber size and distribution, and men and machinery. Incorporation of these factors began with Newnham (1970) who developed several models for studying the process of extracting individual stems while focusing on improving machine design. Goulet et al. (1979, 1980) reviewed the state of harvest simulation models and found little consensus on what constitutes the essential elements for harvest simulation. They also attempted to formulate criteria to guide development of the next generation of these models.

Virtually all of the models reviewed were developed for some mix of ground-based machinery such as feller-bunchers, skidders, loaders, etc. There also have been significant developments in modeling efforts devoted to cable skyline systems used on more rugged terrain. Boyd and Lambert (1969) presented a deterministic simulation of a grapple-rigged running skyline system which represents one of the earliest cable yarding applications. Their objective was to develop logging cost data for representative yarding distances so that the optimum yarding distance could be determined. A more flexible stochastic simulation of cable yarding was developed by Sinner (1973) who introduced timber and terrain characteristics for studying skyline thinning operations.

Gibson and Egging (1973) described a mathematical model for selecting optimal rubber-tired skidder landings from among several possible landing locations. Their optimization methodology combined DP with a branch-and-bound technique that avoids complete enumeration of all possible solutions. This research has been subsequently extended to the optimal location of landings for helicopter landings (Egging and Gibson, 1974). More recently, Arthur and Dykstra (1980) developed a heuristic algorithm for optimizing timber harvest layouts that assists managers in determining how individual cutting units should be designed and what specific logging equipment should be assigned to each cutting unit.

6.2. *Log allocation and procurement*

Log allocation models are usually designed to determine the allocation of logs among various facilities so as to maximize profit to meet output and other manufacturing constraints. Bare et al. (1979) provide an extensive review of SA-OR literature on this subject. Log procurement models are concerned with purchasing roundwood from a variety of sources to meet the requirements of the firm. Procurement models are designed to select the mix of log sources and purchase quantities that minimize cost (or maximize profit) while meeting the facility and source constraints. Studies by Wolfe and Bates (1968) and Thompson et al. (1968) are excellent examples of this type of study and illustrate the use of both simulation and LP.

Once the raw material supply is at the plant, the problem is how to use it in the most efficient manner. There are three major categories of products: lumber, plywood, and pulp and paper. Each of these categories, though interrelated, have separate processing problems.

6.3. *Sawmill models*

Studies utilizing LP, queuing theory, PERT, and simulation have been described for dealing with problems of the sawmill process. Simulations of cutting were described in an earlier section of this paper. Linear programming formulations typically include all or some of the following elements: (a) log supply (including size and grade distribution), (b) lumber and residue product sales (including marketing requirements and restrictions), (c) machine processing rate data based on time studies which are combined with shift length to form machine availability constraints, (d) results of product recovery studies which provide data used in formulating materials balance equations which show the distribution of the volume of a log of given size and grade into various sizes and grades of lumber and residue, and (e) log and finished lumber inventory capacities.

Using these components, LP models have been formulated to determine the most profitable mix of products to produce from a given supply of logs; to determine how changes in mill organization such as the acquisition of new equipment would affect profitability; to determine what types of logs contribute the most to profitability as an aid in log procurement; to determine the effect of single vs. multiple shift operations; and to study the nature of optimum log or lumber inventories and levels of production over time. Studies by Jackson and Smith (1961), McKillop and Hoyer-Nielson (1968), and Sampson and Fasick (1970) are examples of these formulations. While these LP models have proven very useful, they do not address detailed aspects of mill operations such as the random order of log inputs, the flow of pieces of various sizes and shapes between different pieces of machinery, in-process buffers, random downtime occurrences of machines, and bottlenecks (Sampson 1979).

For more dynamic analyses of a sawmill, researchers have turned to other techniques such as simulation and queuing theory. Clapham and Lambe (1963) used queuing theory to research the appropriate manpower and speed of the green chain of a cedar mill, while Maurer (1968) applied a single server queue with a poisson arrival and an exponential service time to model the edging and trimming problem. Carino and Bowyer (1982) developed a method for determining least cost solutions to materials flow problems using queuing theory combined with a direct search optimization algorithm.

One of the earliest sawmill process simulation models was developed by Martin (1971). This model, developed for hardwood sawmills in the Northeast, contained a headrig component which simulated the cutting of logs into boards or cants using line sawing. The model also included debarking, edging, trimming, resaw, and green chain components. All service times were independent of piece characteristics and input options were available for determining whether a blocked machine should stop working or divert its output to a non-saturated queue.

Aune (1974, 1977) developed a simulation model for a complex British Columbia dimension sawmill. His model simulated log breakdown in great detail and is flexible enough to cover a wide range of small log softwood dimension mills. Wagner and Taylor (1983) developed SPSM, a southern pine sawmill model which is a combined network and discrete event model that incorporates equipment, production rates, labor, log quality, lumber quality, prices, costs, and materials flow to predict the production and profitability of proposed new mills or changes to existing mills.

6.4. *Veneer and plywood manufacture*

Development of SA-OR in the veneer and plywood industry parallels that in sawmilling. Linear programming was the technique initially used and included components analogous to those outlined in the sawmill section of this paper. One exception is the materials balance equation component in plywood manufacture which is divided into two parts. The first part uses results of recovery studies to determine the conversion of the volume of a log of a given size and grade into various thicknesses and grades of veneer. A second set of materials balance equations assembles these veneers into various thicknesses and grades of plywood. The studies by Bethel and Harrell (1957), Koenigsberg (1960), Ramsing (1968), Yaptenco and Wylie (1970), and Wellwood (1971) are examples of formulations using the basic components that have addressed various managerial problems.

Much SA-OR attention in the 1970's was devoted to particular aspects of the veneer and plywood production process. Palka (1970) developed a model for predicting veneer lathe settings and in a later study (Palka, 1975) modeled veneer cutting as a plane-strain, quasi-static, elastic problem. This model was found to be an accurate predictor of lathe settings and the ensuing veneer thickness and quality. Klamecki (1978) used nonlinear programming to solve for optimal lathe setting.

6.5. *Pulp and paper*

The pulp and paper industry has been the leader among the forest products industries in utilizing SA-OR techniques. Nonlinear optimization was used in modeling pulping processes as early as 1960 (Carroll, 1960), and other techniques such as simulation (Hewson, 1960) and DP (Mitten and Nenhauser, 1963) were applied first in this sector.

Linear programming has been used by researchers to study problems of marketing, inventory storage, and handling, transportation, and raw material procurement. Foster (1969) used LP to determine the least-cost species mix. It also has been used to optimize production in a manufacturing complex producing different types of pulp, paper, and board products (Petersen, 1969), and to optimize a system that includes a kraft pulp and paper mill, an effluent treatment facility, and a river (Parker, 1969).

Simulation is the most widely used SA-OR technique in the pulp and paper industry. Simulators have been designed to study inventory and procurement problems (Hewson, 1960; Hamilton, 1964; and Galbraith and Meng, 1981) and the pulping and recovery processes (Sullivan and Schoeffler, 1965).

A modular program called general energy and material balance system (GEMS) has been applied to a variety of pulp and paper problems including mill design, integration of new technology into existing mills, evaporator system analysis, steam, and power balancing. The interested reader is referred to Thomas (1979) and Treiber and Boyle (1980) for specific examples.

6.6. *Secondary manufacturing*

Secondary manufacturing involves industries such as furniture manufacture in which lumber is the raw material that must be cut, shaped, assembled, and finished. Pennick (1966) used LP to help make efficient use of limited lathe time in a small wood-turning firm. This work was subsequently expanded to study the problem of machine loading in a furniture plant (Pennick, 1968). Fasick and Lawrence (1971) used LP to analyze a mill making furniture rounds while Hafley (1970) developed a DP lumber procurement model for use in the furniture industry that considered alternative sources over time. Hanover et al. (1973) used LP to determine the optimal lumber procurement to satisfy a particular furniture cutting order.

Araman (1977) used simulation to evaluate a proposed design for a furniture part rough mill. Model results indicated that the initial mill design would fall 25 percent below the production goal set by management. Subsequent design revisions were tested and a solution was found that met the desired goal.

7. Evaluation

The preceding review has demonstrated the pervasiveness of SA-OR in forest resources management and the forest products industry. This suggests that SA-OR is playing a pivotal role in the development of policy and the facilitation of sound resource decisions. However, it also appears that only a fraction of the SA-OR works cited in this review are actually used by decision makers in a routine manner. Reasons for this are discussed below followed by some possible ways to ameliorate these problems.

In his earlier review of uses of SA-OR in forest resources management and the forest products industry, Bare (1971) identified several problems which hindered greater managerial acceptance of SA-OR. These were: (a) minimal use and understanding of multiple criteria decision making tools, (b) difficulties with incorporating nonquantifiable and/or nonmarketable benefits into the analysis, (c) suboptimization introduced by incorrectly specifying system boundaries in order to deal with a more manageable problem, and (d) the underutilization or mismanagement of SA-OR groups within organizations. These technical barriers still exist today and continue to contribute to the lack of greater SA-OR utilization. However, another set of barriers exists. These institutional barriers also play a significant role in contributing to the problem. Brill et al. (1982), Liebman (1976), Walker (1982), Greenberger et al. (1976), and Mar (1974) provide excellent discussions of these institutional barriers especially as they relate to public sector problems. A few of these are briefly listed below.

First, many of the decision situations facing forest managers are complex and involve significant amounts of technological uncertainty. Because of this, all relevant aspects surrounding a decision can not be adequately captured by most SA-OR models. Second, major qualitative factors are necessarily omitted from most SA-OR models thus further contributing to an erosion of model adequacy.

Third, many modelers have been more interested in model development than model implementation. Often decision makers have been excluded from discussions related to model development and have only been introduced into the problem solving process when model development was completed. Barring problems of technological uncertainty, most decision makers are suspect of a complex model which is dumped on them if they have had little or no input during stages of model formulation and development. This is especially true if the model is viewed as displacing the decision maker or diminishing the authority of same.

Fourth, many decision situations involve a multiplicity of goals, and these goals must be satisfied within a multi-decision maker environment. The history of SA-OR contains many examples of successful applications which involve a single well-defined objective. However, multi-objective models, which better describe many public sector planning problems, are more complicated and have not been as widely accepted.

Lastly, modelers have been enamoured with building large data intensive models which are directly linked to data bases. This tendency to produce 'packages of models' has further complicated the implementation of models because most large models require modification before use. This often leads to frustration as these models are not designed to be easily modified. Rather, by design, they are developed to be all inclusive. Yet, new unforeseen uses often arise to thwart potential users. Recently, with the introduction of microcomputers, the trend has turned to the development of small modular models which do not rely on large volumes of data. These highly interactive models offer the promise of greatly reducing the turnaround time between problem identification and solution.

Walker (1982) suggests that the 1980's will witness further development along these lines. For example, he discusses the linkage of microcomputers with management information systems. While this would facilitate the timely use of small modular models it could also lead to suboptimization within a firm or agency. It further assumes that the information contained in the management information system is stored in the right form for use by many diverse users. If it isn't, it is likely that each user may be forced to develop their own data base. This could lead to increased costs and/or replication of effort within the organization.

Turning to the role of SA-OR models themselves, Brill (1979), Brill et al. (1982), and Liebman (1976) argue that analysts and decision makers must recognize that a qualitative change in philosophy must occur if SA-OR models are to play a more significant part in the policy formation and decision making processes in the future. They believe that the most productive role of SA-OR models is to generate and expose alternatives and not to produce optimal or satisfactory solutions. This suggests that model development and solution should be viewed as only one part of the total analysis undertaken to resolve a problem. We endorse this view and suggest that this is the appropriate role of SA-OR models in both the public and private sectors. We further believe that multi-objective mathematical programming models can greatly aid in this endeavor. To date, little use has been made of these models in forest resources management and the forest products industries. While these models will not totally solve most planning problems, they can greatly facilitate the development of new alternatives that can be further evaluated by decision makers and policy analysts.

In summary, we believe that SA-OR models still have an important role to play in the development of solutions to many of our forest resource management problems. While the development of new modeling technology has slowed in the past ten years and many decision makers have experienced disillusionment with existing models, we believe that this has contributed to the realization that analysts must alter their perception of the policy formation process to ensure that SA-OR continue to play a viable role in the future. Certainly, the rapid evolution of microcomputer technology has stimulated the development of small modular modeling approaches to problem solving. While this in and of itself will not guarantee the future success of SA-OR modeling, it does serve to point out that SA-OR analysts must adapt to these changing situations or risk the consequence of playing a diminishing role in the future. We are confident that analysts will begin to work more closely with policy and decision makers in an effort to bring the best SA-OR technology to bear on the significant problems facing resource managers.

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