林統研誌 14 '89

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The Stand Sorting Simulator: A Heuristic Approach to Forest Harvest Scheduling*

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ABSTRACT

Trial runs with a Stand-Sorting Techniques (SST) simulator employing single or multiple sorting criteria improved harvest-scheduling results for two hypothetical Oregon conifer forests. Sorts based on two criteria were most effective. Present net worth was 79% of the solution achieved with linear programming for the same problem; volume production was equal. Costs of single computer runs were $133 for the SST as opposed to $2,722 for the linear-programming model. The SST model was shown to have qualitative advantages over traditional linear-programming models.

INTRODUCTION

Using simple formulas, forest managers once focused only on determining the harvest quantity that could be sustained, and on the allowable cut (Hann and Brodie, 1980). The advent of computers and programs like Timber-RAM (Navon, 1971) have allowed simultaneous calculation of the allowable cut and the sequence of harvesting stands. Subsequent software programs, ECHO (Walker, 1971), MUSYC (Johnson and Jones, 1979), TREES (Tedder et al., 1980), and FORPLAN (Kelley et al., 1986), have facilitated even more sophisticated planning. Although not the only technique available, linear programming is a very common approach to scheduling optimum harvests. It can generate a mathematically optimal harvest sequence for a given allowable cut. Furthermore, it facilitates sensitivity analysis of complex data sets.

Linear programming is not without significant shortcomings, however. First, when dealing with scheduling problems of large enterprises like a National Forest, information

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must be aggregated if the costs of computer runs and data preparation and entry are to be reasonable. Once aggregated, data describing stands and projecting volumes are no longer sufficiently specific for managing individual stands. Worse however, highly aggregated data, such as that for age-classes, can lead to solutions that show large portions of forest simultaneously eligible for treatment (e.g., first thinning, final harvest). The resulting irregular distributions affect stand management and scheduling, possibly masking what would be —without extensive aggregation—feasible alternatives. For example, heavy aggregation can preclude investigating possibilities for treating mixed-species stands or possibilities for species conversion along with desirable harvest levels. Species composition, diameter distributions, and other important stand descriptors can be masked. In these cases, the optimum solutions are derived from limited sets of alternatives that ignore many important trade-offs. It is these very trade-offs that could be most important for making good stand management decisions.

Typically, a harvest schedule specifies goals for area, volume, and timing of treatment for timber-class aggregates of many stands. Therefore, even with mathematically optimum solutions, foresters must use rules of thumb (heuristic solutions) to implement treatments (Chappelle et al., 1976) by separating the aggregates again into stands and setting priorities for treatment. The forester's procedure and priorities may be such that the optimal solution is never attained.

As managers commonly use rules of thumb (thinning oldest stands first, favoring stands on gentle slopes or those with easy access and established property lines) to set priorities, a logical question is, "Why not develop a scheduling model that uses these rules explicitly?" Such a model can focus on factors that foresters recognize as important, and results can be compared with those from a linear-program model using the same data to provide a basis for evaluation. This paper presents such a harvest-scheduling simulation model and compares its results to results from a linear programming model.

THE SST SIMULATOR

The Stand-Sorting-Techniques (SST) simulation model was developed to compare methods of harvest scheduling based on heuristics and linear programming (Elwood, 1984). It is written in FORTRAN 5 and run on a Control Data Corporation (CDC) 176 mainframe computer. Because it evaluates treatment of stands sequentially, one treatment at a time, rather than simultaneously, as optimization models do, there is no large matrix to solve and the requirements for computer-core memory, processing time, and costs are substantially reduced.

Developing data input for the SST model begins with the identification of important biological and economic stand characteristics. These characteristics might include, for example, age, area, productivity classification (site index), average diameter, volume, or even distance to a product market. A composite stand list is then prepared. Table 1 shows the format of such a stand list and the characteristics used in the SST simulator. Next, one stand characteristic is used as a primary criterion, and the list is sorted into hierarchical order based on that criterion. Depending on the sorting program used in conjunction with the SST model, secondary, tertiary, and more sorting criteria can be used in sequence to produce lists in which each succeeding criterion sorts stands within the groupings achieved by the previous criteria (Table 1). It is important to note that when more than one criterion is used, groupings of stands established by earlier sorts are never rearranged by later criteria, i.e., groupings established by a primary sort are never rearranged by a secondary sort, and those established by primary and secondary sorts are not rearranged by a tertiary sort. Rearrangement is always *within* groupings established by earlier criteria.

The SST simulator requires just one sort list for scheduling. The only other input data is a brief computer file listing harvest scheduling and stand-sorting parameters. Scheduling

TABLE 1.

Examples from a composite SST stand list showing four stands as they appear when unsorted, sorted on the basis of a primary criterion, and sorted on the basis of primary and secondary criteria.

Stand number	Site index	Age (yr.)	Diameter (in.)	Basal area (ft^2/acre)	Volume (ft^3/acre)	Area (acre)	Distance (miles)
Unsorted							
664	210	45	14.6	185	6,333	131	13
32	200	5	1.7	0	19	20	42
238	210	105	21.9	367	15,233	54	23
201	200	125	32.6	233	11,432	167	10
Sorted by decreasing site index (primary criterion)							
664	210	45	14.6	185	6,333	131	13
238	210	105	21.9	367	15,233	54	23
32	200	5	1.7	0	19	20	42
201	200	125	32.6	233	11,432	167	10
Sorted by primary criterion and decreasing age (secondary criterion)							
238	210	105	21.9	367	15,233	54	23
664	210	45	14.6	185	6,333	131	13
201	200	125	32.6	233	11,432	167	10
32	200	5	1.7	0	19	20	42

begins with consideration of the first stand on the sorted list. If it meets the minimum specifications for treatment, it is given hypothetical treatment; that is, its descriptive parameters (volume, area, risk, etc.) are adjusted accordingly. After treatment, the stand is moved to the bottom of the list, and the next stand is considered in the same way. Before progressing to the next scheduling time period, all stands in the list are "grown" for one period by adjusting their appropriate biological parameters. Processing proceeds until all harvest-scheduling goals are met, or until it is determined that some goals cannot be achieved. In the latter case, informative "error" messages are recorded on a computer file for the analyst to use in adjusting the goals and rerunning the model.

The major silvicultural options are no treatment, commercial thinning (at various intensities), and clearcutting. Users may specify the period length or accept the program default of 10 years. The model can schedule any number of periods. Its output is an Abbreviated Report plus a Management-Unit Report, Activity Schedule, and Economic Schedule available in either abbreviated or detailed versions. In full detail, the Management-Unit Report and Activity Schedule trace activity in each stand for each period throughout the entire planning horizon.

TESTING AN OREGON EXAMPLE

Testing of the SST model had two purposes: 1) to evaluate its ease of use and its processing time and 2) to compare its results with the mathematically optimal results achieved with the same data and the harvest-scheduling model Timber-RAM. Harvest schedules were constructed for two western-Oregon tracts of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], identified as "Forest 1" and "Forest 2" (Table 2).

Model runs were made with one, two, and three sorting criteria as previously described. Each criterion or set of criteria is described by its potential practical effect on the stands (Table 3). For example, with decreasing (↓) site index as the primary sorting criterion, stands of the best quality are placed at the top of the list and are thus considered for treatment first. Since it is likely that growth rates of such stands will be maximized, given proper management, "highest possible growth rates..." is the "potential effect" of sorting on the basis of decreasing site index (Table 3). Sorts made with multiple criteria were appealing because they allowed more detailed stand stratification. Descriptions of both double- and triple-criteria sorts are included in Table 3.

SST model runs with identical objectives were made with Forest-1 data to evaluate 30 sorting rules (Table 3), and the SST-generated solutions were compared with solutions

TABLE 2.

Characteristics of the forests used for testing the SST simulator.

Descriptor	Forest 1	Forest 2
No. of management units	85	654
Area (acres)	6,441	51,992
Volume		
1,000 ft^3	52,467	480,056
1,000 board feet	239,249	2,189,055
Management-unit average		
Site index (100-year basis)	178	150
Age (years)	61	61
DBH (inches)	18.3	17.2
Volume		
1,000 ft^3/acre	8.2	9.2
1,000 board feet/acre	37.2	42.1
Basal area/acre	190	198
Trees/acre	175	204
Distance (miles)	24	24
Area (acres)	76	79

generated for the same data by the Timber-RAM optimization program (henceforth called RAM). The RAM model was selected for comparison because it uses the linear-programming algorithm and because it focuses primarily on the scheduling of timber harvests. While models developed after RAM also schedule timber harvests, most were created for simultaneous optimization of other resources along with timber. This has led to larger and more complex models that frequently require more data aggregation and that are more costly to run. Despite adoption in those later models of other mathematical programming techniques such as dynamic and goal programming, the most popular of the post-RAM models, FORPLAN, still uses linear programming as its basic scheduling algorithm.

Because the SST model mechanically scheduled treatments until the prespecified harvest goal was achieved, it was expected that the volume would match the volume production of the optimal RAM schedule. But, because of time-related differences in stand conditions and values, it was not expected that it would duplicate RAM's optimal schedule PNW. The questions were: "How close could the SST-generated PNW come to the RAM-generated PNW?" and "What is the cost for respective SST and RAM model runs?" Both quantitative and qualitative measures were used to compare RAM and SST performance. Also compared were the costs for each computer run, which included execution time on the CDC computer,

TABLE 3.

Priorities for sorting stands by means of a single criterion or by multiple criteria.

No.	Sort priority	Type of stand cut first	Potential effect
Single criterion			
1	↓ Site index	Best quality sites	Highest possible growth rates for as long as possible.
2	↑ Site index	Poorest quality sites	Slow-growing stands on poorer sites converted to stands with higher growth rates.
4	↓ DBH	Largest average diameter	Slow-growing stands converted to faster growing stands. Cost per volume harvested minimized.
5	↑ Basal area	Smallest average basal area	Low or understocked stands converted to stands of higher stocking.
6	↓ Basal area	Largest average basal area	High or overstocked stands converted to stands of lower stocking.
7	↓ Trees/acre	Most dense stands	High or overstocked stands converted to stands of lower stocking.
Double criteria			
15	↓ Site index ↓ Age	Best sites Oldest stands	Older, slower growing stands converted to younger, faster growing stands. Growth rates on best sites improved.
16	↑ Site index ↓ Age	Poorest sites Oldest stands	Old, slower growing stands converted to younger, faster growing stands.
17	↓ Site index ↓ Basal area	Best sites Heaviest stocking	Overstocked stands on best sites converted to adequately stocked stands. Growth rates on best sites improved.
18	↓ Site index ↓ Volume/acre	Best site Heaviest stocked	Overstocked stands on best sites converted to adequately stocked stands. Growth rates on best sites improved.
19	↓ Site index ↓ Risk	Best sites Highest risk	High-risk stands on best sites converted to lower risk stands.
20	↓ Site index ↓ Access	Best sites Most accessible	Stands with highest volume per acre harvested with least transport and road-building cost.
22	↓ Age ↑ Basal area	Oldest Lowest stocked	Oldest, understocked stands converted to younger, adequately stocked stands.
24	↓ Age ↑ Volume/acre	Oldest Lowest stocked	Oldest, understocked stands converted to younger, adequately stocked atands.
Triple criteria			
27	↓ Age ↓ Volume/acre ↓ Site index	Oldest Heaviest stocked Best sites	Oldest, overstocked, slowest growing stands on best sites converted to younger, adequately stocked, faster growing stands on best sites.
28	↓ Age ↓ Risk ↓ Site index	Oldest Highest risk Best sites	Oldest, highest risk, slowest growing stands on best sites converted to younger, faster growing stands on best sites.
29	↓ Volume/acre ↓ Site index ↓ Distance	Heaviest stocked Best sites Closest	Overstocked, slower growing stands on best sites converted to adequately stocked, faster growing stands on best sites with lower transport cost.
30	↓ Risk ↓ Volume/acre ↓ Site index	Highest risk Heaviest stocked Best sites	High-risk, heaviest stocked stands on best sites converted to adequately stocked, lower risk stands on best sites.

↑ : indicates an "increasing sort" in which stands are arranged from the lowest (poorest) to the highest (best) value.
↓ : indicates a "decreasing sort" in which stands are arranged from the highest to lowest value.

the time required for analysts to gather and prepare input data, the personnel cost for data entry, and the time for printing output.

RESULTS

The results bracket the range over 30 runs from best to poorest. Sorting by any combination of criteria except triple-criteria rules in Forest 1 offered improvement over the average randomly selected treatment (Table 4). On the average, sorts using two criteria performed best for both forests. The best rules (20, 19, 17, 18, and 15) sorted the older stands with larger volume and higher site indices to the top of each site group and, generally, to the top of the treatment list for each scheduling period.

TABLE 4.

Summary of Forest 1 and Forest 2 harvest-scheduling data produced with the SST simulator.

Sorting choice	No. runs	Present net worth ($)	
		Forest 1	Forest 2
Unsorted	5	55,796,627	485,081,630
All sorting rules	30	56,014,284	485,576,463
Single criterion rules	14	55,902,939	485,215,227
Double criteria rules	12	56,238,624	486,123,752
Triple criteria rules	4	55,775,428	485,198,921

RAM's capacity to schedule stand treatments in an optimal sequence that accommodates all constraints and feasible combinations of treatment sequences as affected by timing, stand condition, and value led to differences between the optimal RAM solution and various SST solutions in present net worth (PNW). The best SST rule achieved 79% of the PNW of RAM (Table 5) while producing equal volume. Cost per computer run was $133 for SST, $2,722 for RAM.

DISCUSSION

Although achieving 79% of the RAM-generated PNW, the actual $15 million difference in PNW (Table 5) between the optimal linear-programming solution and the best SST run initially suggests that there are no cost savings in SST simulation. But three important points should be carefully considered before concluding that linear programming clearly produces better results. First, comparison of the two techniques had to be limited to an unrealistically small case study to allow generation of a linear-program solution. For larger,

TABLE 5.

Summary of SST and linear-programming schedules for Forest 1

Scheduling method	Present net worth ($)	Volume (MCF)
SST		
Single-criterion rules		
1	57,485,163	98,684,208
6	56,946,476	98,684,208
5	54,861,789	98,694,377
2	54,693,159	98,684,207
Double-criteria rules		
20	57,668,038	98,684,207
19	57,486,661	98,684,208
24	55,367,455	98,684,208
16	54,684,974	98,684,207
Triple-criteria rules		
29	56,217,981	98,684,208
30	55,961,620	98,684,208
27	55,501,596	98,684,208
28	55,420,516	98,684,208
Linear-program		
	73,084,831	94,684,208

more realistic cases, such as for Forest 2 (Table 4), RAM solutions cannot be generated within reasonable budget limits.

Second, SST simulation permits inclusion of more stand descriptors and management factors—such as stand operability, distance to markets, and susceptibility to insects, disease, and fire—than can readily be used with linear programming. These factors are important to managers when deciding how to treat individual stands or when selecting trade-offs among treatment alternatives over time. While linear programming models can incorporate these types of descriptors, the matrix size mushrooms so quickly that solution times become impractically long and costs become impractically expensive.

Third, because of the problems of aggregation discussed earlier, although optimal solutions can be generated for large forests with linear programming, they cannot be implemented as the solution indicates. Thus, results between the optimal solution of linear programming and those of other scheduling methods are not directly comparable.

Qualitative comparison

When selecting planning models, blind reliance on quantitative criteria is inappropriate. Other, qualitative criteria should be evaluated. The importance of qualitative comparison increases when, as demonstrated here, solutions that are optimal on paper cannot be implemented with any assurance of optimality.

For a qualitative comparison of linear-program and SST approaches, the following criteria were chosen as being operationally important to managers: 1) required time to learn to run the model, interpret results, and make adjustments to get a successful solution, 2) data-input time for both initial and subsequent runs, 3) model flexibility—usefulness of results for scheduling new runs when objectives are not initially achieved, 4) treatment specificity —generation of solutions that identify individual stands or management units for treatment, and 5) model adaptability—ease in obtaining new schedules upon changes in data input.

Time for employees to learn new scheduling models represents an important organizational investment. Also important is the degree to which model results are useful if the scheduling objectives are not achieved in one run. The more that can be interpreted from a failed run, the quicker, easier, and cheaper it will be to generate successful, subsequent runs. Qualitative advantages of SST over RAM, then, are that it requires dramatically less time to learn, is more flexible in achieving scheduling objectives when a run fails, and allows new runs to be prepared with only minor data input. (Obtaining new RAM solutions requires, at best, considerable data manipulation or, worst, preparation of a new input data deck or tape.) Furthermore, SST allows stand-specific solutions to be obtained. (RAM solutions require disaggregation for implementation and depend heavily on rules of thumb to accomplish this for individual stands.) The qualitative comparisons can be summarized thus:

	Timber RAM	SST
Learning time	High	Moderate to low
Data-input time	Moderate to high	Low
Model flexibility	Low	High
Treatment specificity	Moderate to low	High
Model adaptability	Low	High

Extending SST applications

The SST simulator has promise for extended use beyond traditional scheduling. First, its simpler procedures allow solutions not practical through linear programming. For instance, scheduling can be made on an annual basis, eliminating the question of which stand to treat each year. Computer capacity in relation to the size of the forest data-base is not a problem because of the type of data storage used in the SST algorithm. Computer time and costs compared with those of linear programming runs are quite reasonable for small scheduling problems and dramatically lower for problems of practical-size.

While annual stand-treatment schedules are useful on their own, they are also useful in combination with linear programming problems with typical scheduling periods of a decade or longer. Linear programming could be used to establish the optimal schedule for the entire period and SST to disaggregate the solution to an annual schedule. Initial computer runs with the Forest-1 and Forest-2 data show promise for this approach.

Finally, the decentralized management style and proliferation of microcomputers in many agencies and industrial organizations has increased the need for microcomputer harvest-scheduling software. Because SST simulation accommodates large scheduling jobs efficiently and inexpensively, configuring it for a microcomputer is appealing. Small industrial organizations, forestry consultants, and private forest owners with sizable holdings should find its simplicity attractive. Public-forest managers should find it less expensive to run, easier to learn, and more flexible than linear-programming models.

Hoganson and Rose (1984) also recognized the limitations of linear programming for realistic harvest scheduling and suggested a heuristic approach that generated solutions identical to parallel linear-programming formulations and that eliminated the need for data aggregation. Their work further emphasized that alternatives to linear programming for harvest-scheduling problems are needed. Their approach is an improvement over simple stand-sorting rules because it responds to changing forest conditions and is sensitive to the relative levels of timber demand and supply. Of other techniques available, optimal control techniques are in an early stage of development and accommodate only limited stand detail. Linear programming requires extensive data aggregation that can be only partially overcome by decomposition or newer algorithms (Hoganson and Rose, 1984). Binary search uses some elements of the SST approach with a limited range of single-criterion harvesting priorities (Tedder et al., 1980).

SST, in contrast, lends itself to any degree of stand disaggregation and can sort with even more than the three criteria demonstrated here. Although results are not as good as those achieved with pure optimization (particularly where PNW is the objective) because of convexity of yield function, SST should give at least adequate approximations where volume is the objective. Finally, and probably most important, SST solutions on paper can be directly implemented on the ground. Managers need not find that implementation produces suboptimal results despite the tremendous amounts of time and money invested to achieve optimal solutions on paper.

REFERENCES

Chappelle, D. E., Mang, M. and Miley, R. C., 1976. Evaluation of Timber RAM as a forest management planning model. J. For., 74 (5) : 288-293.

Elwood, N. E., 1984. Heuristic development of stand treatment priorities: an alternative to mathematical programming. Ph.D. Diss., University of Minnesota, Minneapolis, MN, 123 pp.

Hann, D. W. and Brodie, J.D., 1980. Even-aged management : basic managerial questions and available or potential techniques for answering them. USDA For. Serv. Gen. Tech. Rep. INT-83, 29 pp.

Hoganson, H. M. and Rose, D. W., 1984. A simulation approach for optimal timber management scheduling. For. Sci., 30 : 220-238.

Johnson, K. N. and Jones, D. B., 1979. Timber harvest scheduling model user's guide and operations manual (MUSYC). USDA For. Serv., Fort Collins, CO.

Kelley, J. W., Kent, B. M., Johnson, K. N., and Jones, D. B., 1986. FORPLAN version 1 : User's guide. USDA For. Serv., Washington, DC.

Navon, D. I., 1971. Timber RAM—a long-range planning method for commercial timber lands under multiple-use management. USDA For. Serv. Res. Pap. PSW-70, 22 pp.

Tedder, P. L., Schmidt, J. S., and Gourley, J., 1980. TREES : Timber Resource Economic Estimation System. Vol. 1-4. Forest Research Laboratory, Oregon State University, Corvallis, OR, 366 pp.

Walker, J. L., 1971. An economic model for optimizing the rate of timber harvesting. Ph.D. Diss. University of Washington, Seattle, WA, 117 pp.