A HIERARCHICAL APPROACH TO SPATIAL FOREST PLANNING

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ABSTRACT

This paper describes a hierarchical approach to spatial forest planning developed by Remsoft that can be used to create harvest blocks which meet maximum opening, green-up, and other constraints. The approach relies heavily on decisions and tradeoffs made during long term strategic analysis to simplify the blocking phase and to ensure that the harvest blocks generated meet long term objectives and constraints. A series of case studies will illustrate the implementation of the system on-the-ground and highlight key components of the approach.

INTRODUCTION

Increasingly, the practice of forestry is coming under the regulatory influence of many different organizations, from environmental watchdogs to Federal agencies (e.g., NEPA). Concerns over the impacts of forest operations on the forest landscape have compelled a number of agencies to take initiatives to address these issues. One result of this has been the definition of explicit limits on how forest operations should be implemented and the establishment of procedures to measure compliance with these guidelines. The American Forest & Paper Association, for example, has taken a proactive approach by outlining guidelines for member forest companies to implement sustainable forestry practices (Wallinger 1995), many of which represent a fundamental change in how forest planning and operations are practiced. In addition, many of these guidelines have a significant impact on both present and future harvest volumes.

At the same time, forest management planning, in particular harvest scheduling under spatial constraints, has witnessed notable advances in the
techniques and approaches used to solve the problem. Nevertheless, practical, comprehensive procedures and tools which aid forest managers in developing sustainable, spatially feasible management plans, at an operational-scale, are still rare. This is because the majority of techniques cannot deal with problems on the scale faced by forest managers – typically hundreds of thousands of polygons. Also, issues surrounding the actual implementation of a planning system have not yet been adequately addressed.

This paper describes an approach developed by Remsoft and used by a number of forest companies throughout North America to produce spatially feasible harvest schedules that meet long-term sustainability criteria. The approach has been shown to work on both small case studies as well as operational-sized problems.

BACKGROUND

Spatial planning problems are especially difficult to solve for three reasons. First, most scheduling problems involve large numbers of stands and/or harvest blocks. This limits the techniques that can be effectively applied to the problem simply because of the sheer size. Second, a long term look is required to address sustainability - usually several rotations. As planning horizons are increased, the decision variables and constraints necessary to represent adjacencies increase exponentially. Finally, spatial allocation and scheduling in the second-growth forest is often dubious because of the uncertainty in regeneration responses. When all of these factors are considered together, it is clear that finding a true optimal solution to an unrestricted problem is virtually impossible. As a result, every spatial planning approach has focused on finding good or near-optimal, feasible solutions, but on simplified problems.

A number of different techniques have been employed to solve spatially constrained harvest scheduling problems. These include various mixed-integer programming formulations (Meneghin et al. 1988; Jones et al. 1991; Weintraub et al. 1994; Yoshimoto et al. 1994), binary search or inventory projection models (Baskent 1990), simulated annealing (Lockwood & Moore 1990), and Monte-Carlo integer programming (O’Hara et al. 1989; Clements et al. 1990), to name a few.

Purely mathematical programming techniques are limited by the size of the problem that can feasibly be addressed and the high cost of finding solutions (Weintraub et al. 1995). To be solvable in this manner, the problem must be simplified, usually by limiting the planning horizon (Nelson & Brodie 1990), constraint set or the number harvest units. Others have combined optimization techniques and heuristics to find very good, near optimal solutions to spatial planning problems (Yoshimoto et al. 1994; Clements et al. 1990; Weintraub et al. 1995). However, none of these approaches have been demonstrated to work for problems on an operational scale.

Simulated annealing has several potential advantages over mixed integer programming, including the ability to model a large number of stands. Given sufficient computational effort simulated annealing models will theoretically converge to an optimal solution, although the time to convergence may excessive. Lockwood and Moore (1993) used simulated annealing for a problem with a large number of stands where each stand could only be considered for one treatment over the planning horizon. However, regenerated stands were not considered thus limiting the process to deal with long term sustainability issues.

Baskent (1990) used an inventory projection model in combination with an aggregation heuristic to solve large-size spatial scheduling problems over the long-term. While simulation circumvents the problem-size limit inherent in purely mathematical programming techniques, the inability to balance multiple products flows was a major drawback. Moreover, any approach that schedules the harvest sequentially is susceptible to future infeasibilities as the number of options are reduced over time (Brodie & Sessions 1991; Remsoft 1996).

Others have tried to solve the problem in two steps, separating the problem based on the amount of time and spatial detail considered. Nelson et al. (1991) use such a hierarchical approach to develop spatially feasible harvest schedules. First, a stratum-based LP approach is used to solve the long-term scheduling problem subject to forest-wide constraints but without specific spatial detail. Then, in a separate step, the cut is allocated to blocks for the first few periods of the long-term planning horizon and scheduled using a Monte Carlo integer programming (MCIP) model. Beyond the problem of manually delineating blocks, the difficulty with this approach is that the only explicit
linkage between the strategic and tactical planning models is the allowable harvest and thus the tactical solution may be incompatible with longer term goals.

Jamnick and Walters (1991) also used a hierarchical approach in which the problem was solved in two distinct phases. First, a strategic planning phase in which long-term (two or more rotations), non-spatial objectives and constraints were evaluated using traditional linear programming (LP) techniques. Stand-level spatial resolution was not considered in this phase. Second, a spatial planning phase where harvest activities were scheduled subject to adjacency delay, opening size, and harvest flow constraints over a much shorter time frame (one rotation). What differentiates this approach from others is that the two phases are closely linked by the harvest timings and stand types chosen in the strategic phase (Cogswell 1996). In addition, an automated harvest block generator (Walters 1991) was used, eliminating the need to manually delineate blocks prior to the spatial phase.

**REMSOFT’S SPATIAL PLANNING SYSTEM**

For a number of years Remsoft has been refining and adapting the Jamnick and Walters approach, building on its inherent strengths, addressing its weakness and turning the approach into an implementable spatial planning system. Our design criteria included the following: the system must, a) be flexible to allow it to operate in different jurisdictions; b) be scalable, that is it should work on small problems as well as operational sized problems containing hundreds of thousands of polygons; c) be theoretically sound in terms of ensuring the long term outlooks are not ignored; d) make reasonable demands in terms of hardware, time to solution and other system requirements and finally; e) provide reasonable, near optimal solutions.

As the system was refined and tested (Walters & Feeunekes 1994; Cogswell 1996) one key strength became evident: since most of the problem is solved in the strategic, non-spatial, phase the spatial problem has been sufficiently simplified to allow our design criteria to be met. By using the results of the first phase as the starting point and attempting to implement the strategic harvest schedule, the spatial phase inherits all of the outcomes of the strategic analysis without explicitly recognizing the individual constraints. Short- and long-term tradeoffs among silviculture levels, habitat levels, spatial tradeoffs, product flows etc., have already been evaluated and optimized and are accounted for in the harvest schedule.

For example, in a strategic model it may be determined that to produce an optimal flow of some product, one should harvest 1000 acres of 40-year old pine in year five, followed by an additional 500 acres in year six. It is irrelevant to the strategic model that there are in fact twelve forest stands within the 1500 acres of scheduled area, or which of the twelve are harvested in year five versus year six. All that is relevant is that 1000 acres is cut in year five followed by 500 acres the following year. If this occurs then the objectives and constraints will be satisfied.

In the spatial phase, the problem therefore becomes one of determining which of the twelve stands should be harvested in year five and which should be harvested in year six. At this stage, it is irrelevant why 1000 acres should be harvested in year five and 500 in year six. Furthermore, if, in the spatial phase, stands are scheduled to match the optimal timings determined in the strategic phase, all of the constraints from the strategic phase will be met.

The spatial planning system developed by Remsoft includes a forest modeling system, Woodstock (Walters, 1993), a harvest block allocation and scheduling tool, Stanley (Remsoft 1996), and a collection of utilities to generate the required spatial data and view the resulting harvest blocks. Woodstock generates LP matrices using a generalized Model II formulation and produces optimal solutions for the long-term, strategic portion of the harvest scheduling problem. Using the harvest schedule from Woodstock, Stanley allocates forest stands to harvest blocks subject to adjacency, maximum opening size and harvest flow constraints.

**CASE STUDIES**

Three different case studies are presented to demonstrate how the approach is implemented, the types of information that can be generated using the system, approximate times to solutions and the way in which the strategic model can be used to control the spatial model. In particular, the case studies will illustrate the flexibility of the approach and its ability to address spatial planning problems at multiple scales. In
all examples, Woodstock was used to generate optimal harvest schedules, and Stanley was used to produce spatially feasible harvest block patterns. Solutions were generated on a Dell Dimension XPS Pro 180n personal computer (180Mhz Pentium Pro) with 64Mbytes of memory, running Windows NT. It is worth noting that all of the examples required no more that 16 Mbytes to solve.

**Case one**

In this example the effect of varying spatial regulations on final blocked solutions is illustrated. The case study is drawn from a moderate-sized pine forest located in the southern United States. The tract covers approximately 212,000 acres and is comprised of 31,917 polygons for an average of about 6.6 acres per polygon. The forest is a complex mosaic of large pine plantations, cypress ponds and natural pine. Many of the older plantations exceeded 1000 acres, well beyond the 120-acre opening size limit, and the geographic data set had been preprocessed to subdivide the large polygons into a several smaller pieces. Figure 1 illustrates a small section of this forest.

In this case the strategic objective was to maximize present net value subject to even-flow harvest and ending inventory constraints over a 40-year planning horizon. Stands were eligible for thinning and clear cut logging, as well as pre-harvest cultural treatments such as herbicide application. The LP matrix generated by Woodstock was 3,300 rows by 34,000 columns and 136,000 non zero elements. Woodstock produced the matrix in about 3 minutes and CWHIZ (Ketron 1992) found an optimal solution in about 2 minutes.

While a significant portion of the present net value was generated from commercial thinning, only clear-cuts were scheduled by Stanley. When commercial thins were included in the Stanley runs, loss due to blocking was reduced by almost half (e.g., run 9 scores were increased to almost 91 percent of optimal). However, commercial thins had much less restrictive spatial constraints than clear-cuts and were intentionally omitted so as to extend the effects being demonstrated. Values for each of the runs in Table 1 were generated by running Stanley for approximately five minutes, within which time Stanley generated approximately 500-600 different layouts, each time retaining the layout that yielded the highest score.

<table>
<thead>
<tr>
<th>Run</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
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<td>5</td>
<td>10</td>
<td>20</td>
<td>10</td>
<td>10</td>
<td>10</td>
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<tr>
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<td>-</td>
<td>-</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>500</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Adjacency delay (yrs)</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Impossible area (%)</td>
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<td>0.9</td>
<td>2.2</td>
<td>5.1</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
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</tr>
<tr>
<td>Max block (acres)</td>
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<td>1270</td>
<td>867</td>
<td>753</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>499</td>
<td>890</td>
<td>-</td>
</tr>
<tr>
<td>Avg. block (acres)</td>
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<td>92</td>
<td>115</td>
<td>53</td>
<td>39</td>
<td>44</td>
<td>52</td>
<td>52</td>
<td>75</td>
<td>90</td>
</tr>
<tr>
<td>Score(%)</td>
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<td>98.2</td>
<td>96.6</td>
<td>94.4</td>
<td>95.3</td>
<td>94.5</td>
<td>92.7</td>
<td>89.3</td>
<td>81.3</td>
<td>89.3</td>
<td>89.9</td>
</tr>
</tbody>
</table>

Since most of the harvest scheduling problems have already been solved in the strategic phase, Stanley requires very few input parameters. Those that seem to have the greatest effect on solutions are adjacency delays and the minimum acceptable and maximum opening size (Jamnick and Walters 1991). In this forest, harvest blocks were considered adjacent if they were within 300 feet of one another, and were subject to a five year green-up delay, a maximum opening size of 120 acres and a minimum acceptable block size of 10 acres (Table 1, run 9).

In addition to statistics such as minimum, maximum and average block size, Stanley calculates a score signifying how close Stanley was able to come to the strategic optimal solution. It was expected that Stanley could not exactly match optimal solutions, since Woodstock did not consider stand-level spatial constraints. When spatial constraints were imposed
and tightened, we expected the scores from Stanley to decrease accordingly. When constraints were light, Stanley generated solutions that were very close to the strategic optimal. For example, in run 6, Stanley blocked 94.5 percent of the optimal even though 2.2 percent of the area was impossible to block. In other words, Stanley was able to block 94.5 percent of the strategic optimal solution using only 97.8 percent of the eligible forest. As constraints became more limiting, scores were reduced (Table 1).

The results of the Stanley runs show two key effects on the final blocked solutions. First, as the minimum acceptable block size increased, so did the area impossible to block (Table 1, runs 1–4). This effect was attributed to the structure of the forest and not the approach and/or algorithms. The impossible area represents stands or collections of stands that, because of their location in the forest, cannot be blocked. Often these stands are isolated from others by features such as buffers, rivers or lakes. When Stanley attempts to create harvest blocks, no configuration exists that will allow these stands to be included.

Second, as the maximum opening size was decreased and the adjacency delays were increased, scores were reduced. To a large extent the reduction is a function of the forest (age classes and homogeneity of stand types within the forest, for example). However, as the adjacency delay increased relative to stand rotations, the magnitude of the reductions increased. In this forest, a five-year adjacency delay was approximately one-quarter of the average plantation rotation, the cost of which was much higher than in a forest with longer rotations. Relaxing the maximum opening size limit resulted in higher scores when the adjacency delay was long (Table 1, run 9 vs. Run 10). In this situation, Stanley was able to alleviate adjacency conflicts by aggregating conflicting harvest units to form larger blocks with a single timing choice.

**Case two**

Case two illustrates how changing the non-spatial model can affect the resulting block layouts. This forest in Western Canada is 3,191 hectares in size and contains 3,034 individual polygons. It is dominated by large tracts of even-aged lodgepole pine intersected by many trails, roads and seismic lines (Figure 2). For analysis, the forest was classified into a northern zone and southern zone. Regulations dictated that cut blocks not exceed 100 hectares and that there is a twenty-year green-up delay. Ten hectares was specified as the minimal acceptable harvest block size.

The strategic objective was to maximize the first-period coniferous volume subject to an even-flow harvest over a 200-year planning horizon, while maintaining at least 600 hectares of mature coniferous forest in every period. Stands were eligible for clear-cut harvesting after which they could either be naturally regenerated or site-prepared and planted. Two models were generated by Woodstock; harvesting was unrestricted in the first, while in the second, the north zone was inaccessible for the first seven decades. The matrix generated for the unrestricted model contained 2400 rows by 9900 columns and 48000 non-zeros, and the restricted model had 2200 rows by 8200 columns and 39000 non-zeros. Both were generated and solved in under one minute. As expected, the restricted model’s optimal solution was lower than the first (around ten percent less).

Both strategic solutions were run through Stanley for 100 years into the future. The only difference between the two runs was the strategic harvest schedule used by Stanley- the spatial constraints were identical in both cases. In the first case, Stanley blocked 95.6 percent of the strategic optimal solution after five minutes (over 4600 alternative layouts evaluated), and blocks were distributed throughout the entire forest (both management zones) in all periods. In the second case, 96.1 percent was blocked after five minutes, and no harvest blocks were located in the north zone prior to period seven. What is worth noting here is the way...
that the results were produced. That is, using the hierarchical approach, we were able to control the general location of blocks by changing the strategic model which is a relatively simple process and not the spatial model which would be a much more complex operation.

**Case three**

The final example represents a large operational scale problem representative of the type of problem faced by forest planners today. Case three comes from a large tract of land in Eastern Canada. The forest covers approximately 176,884 hectares and is comprised of 88,843 polygons, averaging about 2 hectares per polygon. The forest is being intensively managed for softwood pulp and logs. Stands were eligible for a several pre-harvest treatments including planting, spacing and thinning; harvest treatments included clear-cut and two pass logging. The forest is highly fragmented, containing numerous riparian buffer, habitat exclusion zones, and roads. Figure 3 depicts a small section of the forest.

![Figure 3. Forest used in example three. Area shown represents one of the 76 maps sheets in the entire forest.](image)

The strategic objective was to maximize spruce-fir harvest volume subject to even-flow harvest and ending inventory constraints over an 80-year planning horizon. Additional constraints limited the production of hardwood volume and the amount of planting and spacing within each planning period. The periodic change in the area within broad forest cover types was also limited to maintain biodiversity levels over the long term. The LP matrix generated by Woodstock was fairly large, approximately 9,800 rows by 71,000 columns and 922,000 non-zeros. Woodstock produced the matrix in about 15 minutes and CWHIZ found an optimal solution after about 35 minutes.

Spatially feasible harvest blocks were created for 25 years into the future, subject to a maximum opening size on clear-cuts of 100 hectares, a minimum acceptable block size of 5 hectares, a ten-year adjacency delay and maximum harvest flow fluctuation of ten percent. Two Stanley runs were required to allocate all of the harvest activities to blocks because the spatial restrictions for partial harvest activities were different than those for clear-cut harvesting. The first Stanley run (clear-cuts) evaluated about 1000 different block layouts in around 30 minutes while the second run (partial harvest) required about 35 minutes. In both cases, the layout that provided the highest score (nearest to optimal) was kept. When the results from the two runs were combined, Stanley was able to allocate 89.8 percent of the strategic optimal. The final block layout contained 4000 harvest blocks ranging in size from 5 to 100 hectares with an average of 45 hectares.

The ability of the approach to deal with problems of this size is well illustrated in this case. To carry out a similar analysis using the more traditional approaches, including manual blocking would take something in the order of weeks if not months to produce a single block layout, rather than the thousands produced in a matter of hours using this approach.

**SUMMARY AND CONCLUSIONS**

In summary, the system is based on a hierarchical approach introduced by Jamnick and Walters, that greatly simplifies the solution of the overall problem. It demonstrates that the spatial complexity of the problem can be increased and solved without increasing the complexity of the spatial algorithm. In effect, the two phases worked together to solve a more complicated problem.

The three case studies presented show that the approach works at various spatial scales, on realistic-sized problems and consider long-term tradeoffs. Pseudo-spatial resolution, in which subforest areas are recognized, can easily be accommodated in this planning phase allowing for the distinction of features
such as watersheds, management units, forest districts, etc. A key factor is that long-term tradeoffs and constraints are handled in the strategic phase, and the software required to allocate stands to specific periods (spatial phase) can therefore be much simpler. Also, since the long- and short-term phases are so closely linked, any changes to the strategic model are directly communicated to the spatial stage.

Work is ongoing to refine the system.

**LITERATURE CITED**


Remsoft Inc. 1996. Final report: Design and development of a tactical harvest blocking/scheduling tool. Study funded through the Canada-British Columbia Partnership agreement of Forest Resource Development: FRDA II.


