ADDRESSING ENVIRONMENTAL CONCERNS IN FOREST MANAGEMENT MODELS[1]

J. G. Borges[2] and H. M. Hoganson[3]

ABSTRACT.-- There is an increasing awareness of the value of forests for wildlife and biodiversity protection, recreational uses and aesthetics. The effort to supply wood in order to satisfy the demand of timber related products is increasingly constrained by spatial considerations - how to layout the harvests in order to account for other demands from the forests. The spatial arrangement of harvests has become a critical environmental concern. Nevertheless, modelling spatial aspects of forest management remains a challenging problem. A modelling approach to spatial constraints in forest management will be discussed. Preliminary results will be presented. The spatial conditions generated by the model may be viewed as an output of the forest. The potential to assess the impact of adjacency constraints on these forest spatial conditions will be addressed.

INTRODUCTION

Research on quantitative modelling of forest management scheduling has traditionally evolved within a strategic management framework (Covington et al. 1988). Strategic models usually aggregate stands because of computational constraints and lack spatial resolution (Nelson et al. 1991). However, the implementation of forest plans requires spatially feasible prescriptions. Detailed forest inventories, the development of GIS technology and prior research efforts provided the integrated functionality of available software tools and a solid base for harvest spatial design analysis. Nevertheless, modelling spatial aspects of forest management remains a challenging problem.

Heuristic techniques based on the decomposition of a linear programming (LP) master problem such as the ones developed by Hoganson and Rose (1984) and Lappi (1992) avoid stands aggregation and have the ability to recognize considerable spatial and inventory detail within a strategic planning framework. Nevertheless, the demand of non-timber outputs impacts the opportunity set for harvest scheduling alternatives. In addition to the ability to recognize individual stands in the output of a harvest scheduling model managers must take into account the interactions between management decisions in neighboring stands. The spatial conditions generated by a model (e.g. amount and type of forest edge and interior space) become an additional forest output.

The issue of spatial relationships analysis within forest management models has been addressed in recent research work. The integration of adjacency constraints in the process of forest management model building and solving has received considerable attention (e.g. Nelson et al. 1991, Jones 1991, Weintraub et al. 1994, Murray and Church 1995 and Snyder and ReVelle 1996). Nevertheless, the large scale attributes of most forest management problems complicate significantly the process of model solving.

The research presented in this paper focused on the development and application of a technique to solve forest management problems with adjacency constraints. These involve the definition of an exclusion period: the number of planning periods that must elapse between the implementation of two similar management actions in any two adjacent stands. Hoganson et al. 1994 and Borges et al. 1994 have showed that a dynamic programming based heuristic may circumvent computational constraints to solving this particular combinatorial optimization problem. In this paper, further research developments are presented.

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[2]Assistant Professor, Departamento de Engenharia Florestal, Universidade Técnica de Lisboa, Tapada da Ajuda 1399 Lisboa Codex, Portugal.

[3]Associate Professor, North Central Experiment Station, University of Minnesota, 1861 East Highway 169, Grand Rapids, MN 55744-3396, U.S.A.

THE DYNAMIC PROGRAMMING MODEL FORMULATION

Adjacency constraints may be formulated as sums of binary variables (their values being either 0 or 1). Each of these represents a decision to be made in a stand in a particular planning period. If an activity is scheduled to be implemented in a stand at a given period, the corresponding variable will take the value 1, otherwise, its value will be 0. By constraining the sum to take a value less or equal than one, it is ensured that no conflicting activities are developed in adjacent stands. The solution of the adjacency problem consists in assigning adequate values to all binary variables: it is a combinatorial optimization problem.

Reeves (1993) classified combinatorial optimization techniques into two groups. The first includes operation research models that enable finding an optimal solution to the problem. The second includes the heuristics, which seek to approximate an optimal solution at a reasonable computational cost, without being able to guarantee optimality or even feasibility. Dynamic programming (DP) is included in the group of the former methods. Nevertheless, the technique presented by Hoganson et al. (1994) combines characteristics of both DP and heuristics. A DP model is used to find optimal solutions of subproblems resulting from the decomposition of a master forest management problem. These solutions are combined in order to approximate optimal solutions to the master problem, like an heuristic, but in such a way that if not optimality, at least feasibility is guaranteed, i.e., forest management schedules comply with the adjacency constraints included in the model.

Hoganson et al. (1994) described the key elements of the DP formulation. A stage corresponds to a stand. The DP network consists of arcs that represent management decisions to be made at any particular stage (stand) and of nodes, characterized by decisions made in "unscheduled stands", that is, in stands which still have adjacency relations with stands to include later in the network. The "unscheduled" stands define the "front", that is, the state variables needed at any particular stage. The size of the "front" is variable. Nevertheless, the number of nodes will not grow exponentially because there is no need to carry information about management decisions made in "scheduled" stands, that is, in stands which do not have adjacency relations with management units to include later in the network. However, in large problems, computational constraints preclude the possibility of including all stands in the forest in a single DP network. The problem must be decomposed. For that purpose, a procedure is designed to select stands to include in any particular subproblem (DP network). The subproblems are solved sequentially and the optimal solutions to the ones solved first constrain the space of feasible solutions of the ones to solve later. Hoganson et al. (1994) considered a rectangular grid of stands and described the approach in terms of 5 basic steps:

1. Starting along one edge of the forest, consider a large strip of the forest that would result in a DP network that is of manageable size.

2. Formulate and solve the DP formulation assuming the only stands in the forest are the stands within the strip (window).

3. If the entire forest has been included in a DP window, then all stands yet to be scheduled can be scheduled according to the optimal DP solution found in step 2. Otherwise, for stands along the outside edge of the strip (subproblem) in step 2, schedule those stands according to optimal DP solution determined.

4. Re-define the strip by: (a) eliminating from the latest strip, all stands scheduled in step 3, and (b) adding to the strip, a set of stands adjacent to the strip that have not yet been analyzed.

5. Return to step 2.

THE NETWORK DEFINITION

The order in which stands are sequenced in the DP network influences model size. This in turn, determines the number of subproblems that must be considered when decomposing the master problem. Formulating the DP efficiently is further complicated when irregular shaped stands are considered. The approach to network definition may be summarized as follows:

1. Select the first stage polygon, according to the its geographical position and to the direction the window which encompasses all stands to include in a network moves. This stand will define the first front if it has adjacencies to include later in the subproblem.

2. Check stands adjacent to first stage polygon (first front). If number of nodes is lower than predefined limit then assign the second stage to adjacent stand according to geographical coordinate and to the direction the window moves. Else, assign the second stage to adjacent stand that minimizes number of states and number of stands in front in second stage. If both stands have adjacencies to include later in the subproblem, they will define the new front. Otherwise, the front will remain either with one of those two stands or, if both have no more adjacencies in the window, a new polygon is selected using the same criteria used for the first.

3. In general, in any given stage, check all polygons adjacent to all stands in the current front, and proceed as in 2. If no stands meet the requirement that the number of states does not exceed the computational limit, the network is redesigned, and the front is adjusted according to the new adjacency relations.

4. After all stands in the window have been assigned a stage number, solve the dynamic programming problem. An optimal solution to the spatially constrained subproblem is obtained. This solution constrains the space of feasible solutions of the subsequent network, which is in turn formulated using the procedure just defined. Overlapping of windows may be considered.

5. The suboptimal solution to the forest management problem is achieved when the moving window has covered the whole forest area.

APPLYING THE DYNAMIC PROGRAMMING BASED HEURISTIC

Results reported by Hoganson et al. (1994) and by Borges et al. (1994) showed that the DP based heuristic was able to confront the large scale characteristics of forest management scheduling problems. Moreover, it was shown that, in the case of regular shaped stands, this heuristic compared favorably to methods such as Monte Carlo Integer Programming (MCIP) or Column Generation Algorithm (CGA): adjacency costs were consistently lower when using the DP based heuristic. Finally, they suggested testing further case-studies and other research topics.

Up to 20 hypothetical forests with irregular shaped stands were used to test the heuristic performance. Minnesota Forest Inventory Analysis (FIA) and Department of Natural Resources (DNR) plots provided the inventory data. The Decision Support System developed at the University of Minnesota provided the management data needed. Map shells were generated so that the impact of different polygon initial area ratios on the heuristics performance might be assessed. Alternative methods were used to design management units boundaries and to split polygons that exceed a predefined maximum area. Different sets of prices were considered in order to assess the impact of sustainable flow constraints on adjacency costs. The number of stands in each forest ranged from 800 to 3215. Planning horizons ranged from 5 to 8 ten-year periods. The number of management alternative types ranged from 8 to 19.

Model performance has been promising. Preliminary results showed that the DP approach still easily outperformed the CGA approach and greatly outperformed the MCIP approach (Hoganson et al. 1996). In this paper, preliminary data from one of the case studies will be reported in order to highlight some key results obtained. These relate to the heuristic's efficiency and effectiveness. The cost of adjacency constraints and the impact of window size on the solutions will be used to assess the former. The impact of starting outside edge on the solution process will be used to assess the latter.

The hypothetical forest considered here comprised 2954 irregular shaped stands and extended over an area of 28,156 ha. Most stands were mature: only 147 had an age lower than 30 years. The average number of adjacencies per stand was approximately 5. The planning horizon over which the possibility of adjacency conflicts was considered extended over 50 years (5 ten-year periods). The selection of prescriptions for each stand was made according to the potential management

spatial conflicts. In this analysis, two alternative exclusion periods were considered. In the first case, the minimum period to elapse between the clearcut of adjacent stands was of ten years. In the second, twenty years. In this framework, prescriptions available for each stand were classified according to the timing of clearcuts, if any, into seven groups - prescriptions involving a clearcut in period 1, period 2,..., period 5, involving two clearcuts, in periods 1 and 5, and, finally, involving no clearcuts during the area based-planning horizon. Afterwards, the maximum Soil Expectation Value (SEV) management alternatives were selected from each group for analysis purposes. Therefore, there were at most seven management options for any particular stand. In this case-study, 1,600 stands could be managed using at least six options; for the remaining 1,354 stands there were at least 4 management options available.

Cost of Adjacency Constraints

The cost of adjacency constraints may be computed by comparing the solutions of both the spatially constrained and the spatially unconstrained problems. The solution of the unconstrained problem may be estimated by adding the financial returns associated with the best management option for each stand. Figure 1 displays the adjacency constraints costs per hectare when no window overlay is considered. E, W, S and N in the figure represent, respectively, the eastern,

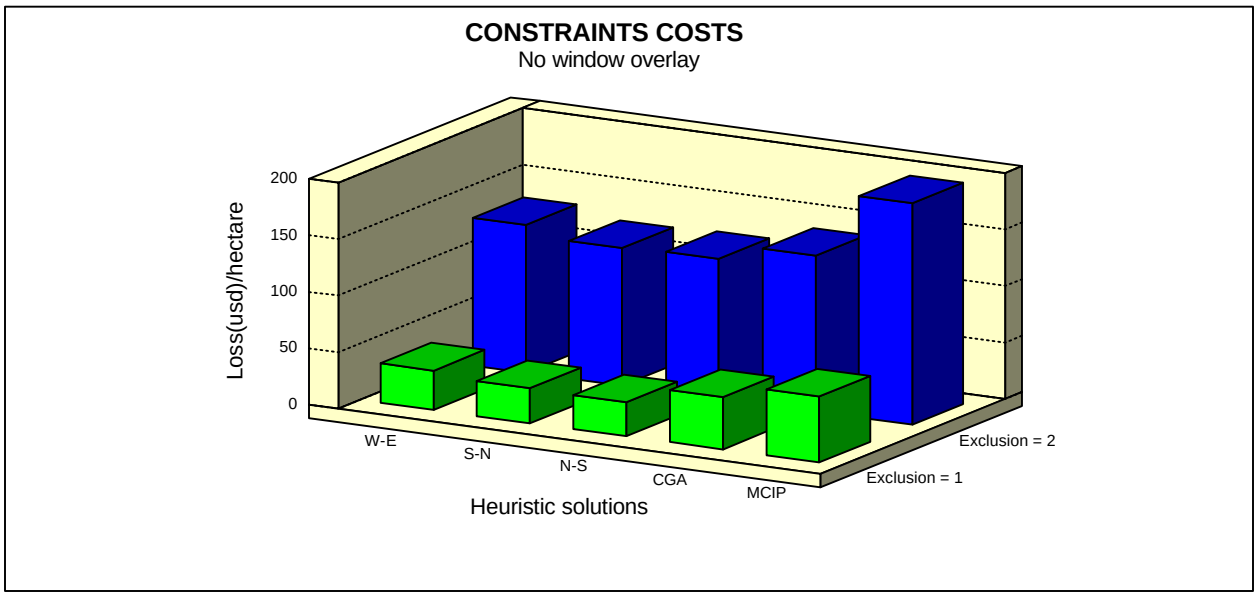

Figure 1.--Cost of adjacency constraints (no window overlay).

western, southern and northern borders of the forest - four starting outside edges were considered.

In the case of the one-period exclusion, adjacency costs varied from $29 to $35 per hectare in the case of the DP approach. In the case of the two-period exclusion, they ranged from $122 to $131 per hectare. The DP heuristic outperformed greatly the MCIP approach: best MCIP results, from a sample with size n=2954, were $61 and $206 per hectare, for, respectively, the one-period and the two-period exclusions. The CGA results were closer to the DP heuristics': $31 and $123 per hectare for, respectively, the one-period and the two-period exclusions. Nevertheless, results also showed that increasing the window overlay contributed to reduce adjacency costs. In the case of the 75% overlay (Figure 2), adjacency costs were reduced to $23 and $105 per hectare for, respectively the one-period and the two-period exclusions: the DP approach outperformed the CGA method.

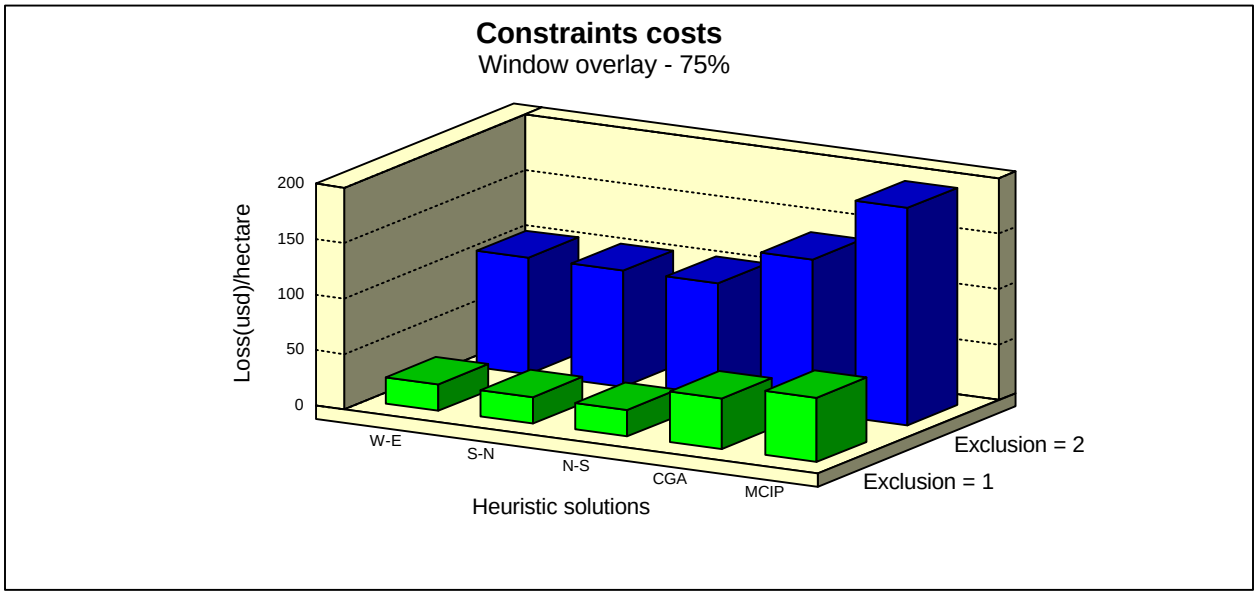

Figure 2.--Cost of adjacency constraints (window overlay: 75%).

The efficiency of the DP approach may be further assessed by checking how larger window overlays or larger window sizes impact adjacency costs. The results displayed in Figures 1 and 2 were obtained when an average window size of 4,000 ha was considered (N-S and S-N directions). Decreasing that size led to higher costs (up to $109 in the case of the 75% overlay and two-period exclusion). Increasing it did not impact the solution, which suggests that the window size considered was close to optimal. On the other hand, marginal gains resulting from increasing the window overlay successively from 75% to 90% and 95% were small (less than $1 per hectare) and decreasing which suggests that the solution may be close to optimal.

Given that computational constraints preclude the possibility of using mathematical programming techniques to solve this combinatorial optimization problem, finding a bound to the DP approach solutions is not straightforward. The solutions asymptotic behavior when window overlay and size are increased suggests that the heuristic is getting closer to that bound. Nevertheless, an alternative method was devised in order to get an approximation of that bound. Management options dropped because of adjacency conflicts when successive subproblems of a given master problem are solved were eliminated from original input files. The value of the optimal path of the master problem obtained using the DP approach is the spatially constrained optimal solution to a problem without the management options (and respective adjacency constraints) just referred to. Therefore, by solving this new problem, it is possible to approximate the true bound to the DP solution. Preliminary results show that in the case of this hypothetical forest, deviations from the spatially constrained optimal solution might be lower than 10 cents per hectare: the DP approach solutions are close to optimal.

Impact of Starting Outside Edge on DP Solution

For all window overlays, independent runs of the model were completed starting on each of the four forest outside edges (E, W, N and S). The effectiveness of the approach may be assessed by checking if the solutions are insensitive to the outside edge on which the process of network definition is started. That was the case when larger window overlays were considered. In the case of the 90% overlay and one-period exclusion solution differences were lower than 40 cents per hectare. Moreover, the same management type was chosen irrespective of the starting outside edge in the case of 1,948 stands. The number of stands where solutions from three starting outside edges match increases to 2,646. The proximity to the bound on the optimal solution suggests that there is a substantial number of feasible solutions close to the lowest- cost solution found.

Computation Costs

All problems were solved using 90 Mhz Pentiums and Microsoft Professional Basic v. 7.1. Computation costs ranged from about 1,100 seconds in the case of no window overlay to about 18,600 seconds in the case of a 95% overlay. It took about 9,000 seconds to execute the 2,954 MCIP program runs. In the case of the CGA, computation costs ranged approximately from 13,700 to 17, 400 seconds. Gains may be achieved by more efficient coding. In any case, the computational costs incurred in seeking optimal solutions appear to be reasonable

Spatial Conditions

Conditions such as the amount and type of forest edge and interior space may be analyzed in order to address environmental concerns such as wildlife habitat quality, aesthetics,... Accordingly, these spatial conditions may be interpreted as an output from the harvest scheduling model. Preliminary results suggest that adjacency costs are not very sensitive to the method used to design management units boundaries. Therefore, it appears that when designing these boundaries, environmental concerns should be emphasized. Moreover, these results show that spatial conditions vary significantly over time, even when adjacency constraints are imposed (Hoganson et al. 1996). This suggests that it may be interesting to assess the impact of relaxing some adjacency constraints in order to meet target spatial conditions. As Hoganson et al. (1996) pointed out, the DP approach enables a trade-off analysis between timber production and spatial outputs.

SUMMARY AND CONCLUSIONS

Research on forest management quantitative modelling plays an important role in providing information needed by decision-makers to address current environmental issues. Policy requirements such as the definition of maximum clearcut openings and minimum exclusion periods complicate greatly the modelling process. Meeting target spatial conditions further complicates this process. The dynamic programming based heuristic can be used to solve large scale problems incorporating adjacency constraints defined to meet policy requirements such as the ones mentioned above. Solutions appear to be close to the optimum and computation costs are reasonable. Moreover, it may be used to assess the trade-offs between timber production and spatial conditions targeted because of wildlife habitat, aesthetics and other non-timber forest output objectives. Thus, it may contribute to the understanding of the complex ecological and economic relationships within the framework of forest management scheduling, and to avoiding *a priori* decisions due to lack of knowledge of these interactions.

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