A comparison between Regional and Multi-catchment Forest Harvest Scheduling

O. Chikumbo[a] **and R. Bradbury**[b]

[a] *The Swedish University of Agricultural Sciences, Department of Forest Resource Management and Geomatics, Umeå S-901 83, Sweden.* (*Oliver.Chikumbo@resgeom.slu.se*)

[b] *Tjurunga Pty Ltd., 9 Scott Street, Narrabundah, ACT 2604, Australia.* (*roger@tjurunga.com*)

Abstract: Modelling sustainability was demonstrated for the Eden Management Area, by formulating a multi-objective optimisation problem with spatial constraints. However, due to the eight sub-catchments in the area that require somewhat different management strategies, it was necessary to pursue a multi-catchment scheduling problem, where each district (sub-catchment) is managed independently while at the same time attaining objectives that depend on the accumulated district outputs. In this paper, a comparison is made between the multi-catchment scheduling (independently managed sub-catchments) and the regional (combined sub-catchments) results.

Keywords: Harvest scheduling; Spatial constraints; Ecosystem management; Metropolis algorithm; Habplan.

1. INTRODUCTION

Heuristic search algorithms are now making it possible to optimise for spatial harvest scheduling of large-scale forest ecosystems. Spatial issues relate to environmental issues that can be carefully planned for simultaneously with the harvesting of timber. Foresters are taking greater care of the forest ecosystems than in the past and managing for the ecological vitality of these ecosystems, hence ecosystem management or sustainable forest management. Ecological vitality implies that the forest remains dynamic or self-sustaining and self-repairing in the face of fires, insect attack, frost, harvesting and other disturbances. Optimising for the vitality of a forest ecosystem is about dealing with conflicting objectives with a main goal of a management strategy outcome that guarantees the long-term ecological vitality of the ecosystem being utilised.

In this paper we present two formulations that use a heuristic search algorithm for strategic forest planning with detail that may be useful at an operational level. Strategic planning is a long-range process that provides a framework for guiding and constraining short-range planning (i.e. operational planning). Some might argue that there is an intermediate process called tactical planning. This may be appropriate, depending on the needs and unique managerial approaches to planning. Tactics determine how the actions in which an organisation intends to engage will actually be executed [Lane and Maxfield, 1996]. The level of detail in forest strategic plans tends to blur the distinction between strategic and tactical planning and therefore tactical planning will not be considered in this paper. In other words, strategic planning is concerned with long-range activities and broad goals, leaving the specific objectives to be articulated through operational planning. In the context of forest planning, strategic planning incorporates decisions that have the potential to cause great changes, including demands on resources either directly by affecting major actions, or indirectly by triggering significant chain reactions among related activities. Therefore, the concept of inter-relatedness between issues is a characteristic that, perhaps more than magnitude, can make decisions strategic [Spencer, 1985].

We look at the advantages and disadvantages of these two formulations and comment on the possibility of using both formulations for forest planning. The two formulations are a multidistrict harvest scheduling (MDHS) one and a regional harvest scheduling (RHS) [Chikumbo et al., 2000] targeted at reflecting the impact of harvesting and utility of non-timber values in the forest whilst maintaining ecological vitality. The two formulations are based on the Eden Management Area (EMA), that covers *198 000* ha in the state of New South Wales, Australia.

The reason we explore these two formulations is an attempt to establish a paradigm for modelling and managing forest ecosystems sustainably. Our contributions in this paper will in no doubt steer other researchers in the direction of further developing the ideas presented here.

2. THE EDEN MANAGEMENT AREA

The EMA has a complex over storey species composition and age structure of native forest. There are four broad forest types that include the Dry Shrubby, Dry Grass, Moist and Intermediate Shrubby. The Dry Shrubby type dominated by silvertop ash (*Eucalyptus sieberi*), covers the largest area occurring in the southeast of the EMA. Moist forest occurs in the northwest (tablelands) and grassland in the southwest. Wildfires, the successional process and selective logging between the *1800s* and the late *1960s* [SFNSW, 1994] contributed to a multi-aged forest (MAF) structure. Currently there are four significant fire regrowth forests that include *1952, 1956, 1968* and *1980* age classes. Integrated harvesting (i.e. harvesting operations for both sawlog and pulpwood) has resulted in *26* age classes (1972-97) of regrowth forest. About *24 146* ha are unavailable for harvesting due to fauna, flora and stream buffer reservation.

The EMA consists of *5734* operational management units that are identifiable on ground and conveniently digitised as a GIS layer for planning purposes. A total of *29 141* ha is taken by fauna and flora reserves, and stream buffers. Production forestry is spread over an area of *168 859* ha of which *44%* is the MAF resource and the remaining *56%* regrowth forest, both managed (logging) and fire-induced.

3. HEURISTIC SEARCH ALGORITHM

The reason we used a heuristic search algorithm for the two formulations was because the problems were large combinatorial optimisation problems, which are notorious for taking exponential time in problem solving when using conventional optimisation techniques, even on powerful computers. This is because conventional techniques are designed for straight-forward exhaustive search, either calculus-based (seeking local extrema by solving a set of nonlinear equations resulting from setting the gradient of the objective function to zero) or enumerative (seeking local optima by hopping on the function and moving in a direction of the local gradient: hill-climbing) [Goldberg, 1989]. In contrast, heuristic search algorithms employ a random choice as a tool for directed search. In this paper the heuristic search algorithm used for the optimisation of the two formulations was the Metropolis Algorithm (MA) [Press et al., 1992].

The MA avoids brute force or exhaustive search by employing a probabilistic search that samples only the 'important' states of a system. For a general forest harvest scheduling problem with spatial constraints, a typical state would be associated with the following information:

- neighbourhood positions of the management units;
- area size of each management unit
- possible management options for each management unit;
- number of management units;
- yield and spatial constraints; and
- Monte Carlo step size.

The MA, therefore, does not waste a whole lot of time/effort examining improbable states. For example, a lattice with > 10^{100} number of states can be successfully sampled by only 10^{6} states using the MA routinely. The vast majority of the 10^{100} states are of such high energy that they have negligible weight in the Boltzmann probability distribution (low energy states are exponentially favoured) and need not be sampled [Chandler 1987]. More succinctly, the MA efficiently calculates 'thermal' state averages by considering only a limited number of the very many possible states of a system. The Monte Carlo steps are necessary to relax the system to equilibrium through the successive sampling process of the states that follow a Markov process (i.e., each state is constructed from the previous one).

4. PROBLEM FORMULATIONS

The multi-objective functions of the two formulations were expressed as an additive sum of the different objective components.

A MDHS problem for the EMA sawlog production was formulated that allowed the simultaneous control of a super-objective component of sawlog output composed of sub-objective components from the *8* sub-catchments. The super-objective sawlog output was specifically set to attain an accumulated output of *20 000*m^3 for the first *22* years and left open for the rest of the planning horizon. These years were deemed crucial because they involved harvesting mostly the MAF and in the process converting to high intensity forest production as the case with the regrowth forest.

The RHS formulation did not have this sub-catchment partitioning, although it had the same management unit configuration as in the MDHS formulation. The RHS formulation was based on the concept of maintaining ecological vitality, where each sub-ecosystem of the forest is given equal weight as other sub-ecosystems. This is because vitality relies on all sub-ecosystems interacting for integrative functioning of the whole. If one component is damaged through negligence or over-use, the whole system loses its functionality and therefore, will not self-repair or self-sustain in the face of anthropogenic disturbances. The functioning whole in the RHS formulation involved the assessment of the following ecological and economic yields:

- sawlog and pulpwood production from STANDSIM [Opie, 1972];
- costs and revenue for harvesting and other forestry operations [Chikumbo et al., 1999];
- water production from AQUALM, water surface run-off model [WP Software, 1992];
- sediment production [Croke et al., 1997]; and
- arboreal marsupial population [Davey, 1989].

The choice of these components was largely determined by the availability of data and meeting the expectations of policy-makers. The objective components therefore, included sawlog, pulpwood, net present value for harvesting and other forestry operations, water production and sediment production outputs. The goal was:

- to ensure that arboreal marsupial populations are not threatened by maximising a spatial forest structure that guaranteed a suitable habitat for the marsupials;
- to maximise sawlog (as for the MDHS formulation) and pulpwood production;
- to maximise net present value such that forestry jobs for the larger population in the EMA are secure;
- to minimise the sediment production from harvesting operations, thereby controlling soil erosion and subsequent risk of polluting water streams; and
- to maintain water quantity levels from two sub-catchments such that the availability of drinking water and irrigation was not threatened.

Yield data, for the two formulations, relating to all the management options for the 5734 management units, were derived from simulation models. Figure 1 shows the sources of these yield data [Chikumbo et al., 2000].

In both the formulations, block size constraints were specified where block size refers to a group of management units that are scheduled for harvest in the same period. The block size objective component was defined such that the total patch area harvested (i.e., clearfelled and not just thinned) would lie within specified block size limits. In each period several blocks would be harvested, and the neighbouring management units would remain untouched until after a specified ‘green-up’ period had expired. The green-up period allowed the cleared areas to regenerate. The RHS formulation had one common block size constraint applied to the whole EMA. The MDHS formulation had 8 block size constraints, one for each sub-catchment. It also had a common spatial constraint to all the *8* sub-catchments such that the spatial juxtaposition of management options could be controlled. This was essential to ensure that harvesting operations done in the same period in adjacent stands were preferred and could lead to a minimisation of operational and haulage costs. The economic benefits from an operational point of view could not be quantified in this MDHS model because of lack of appropriate data.

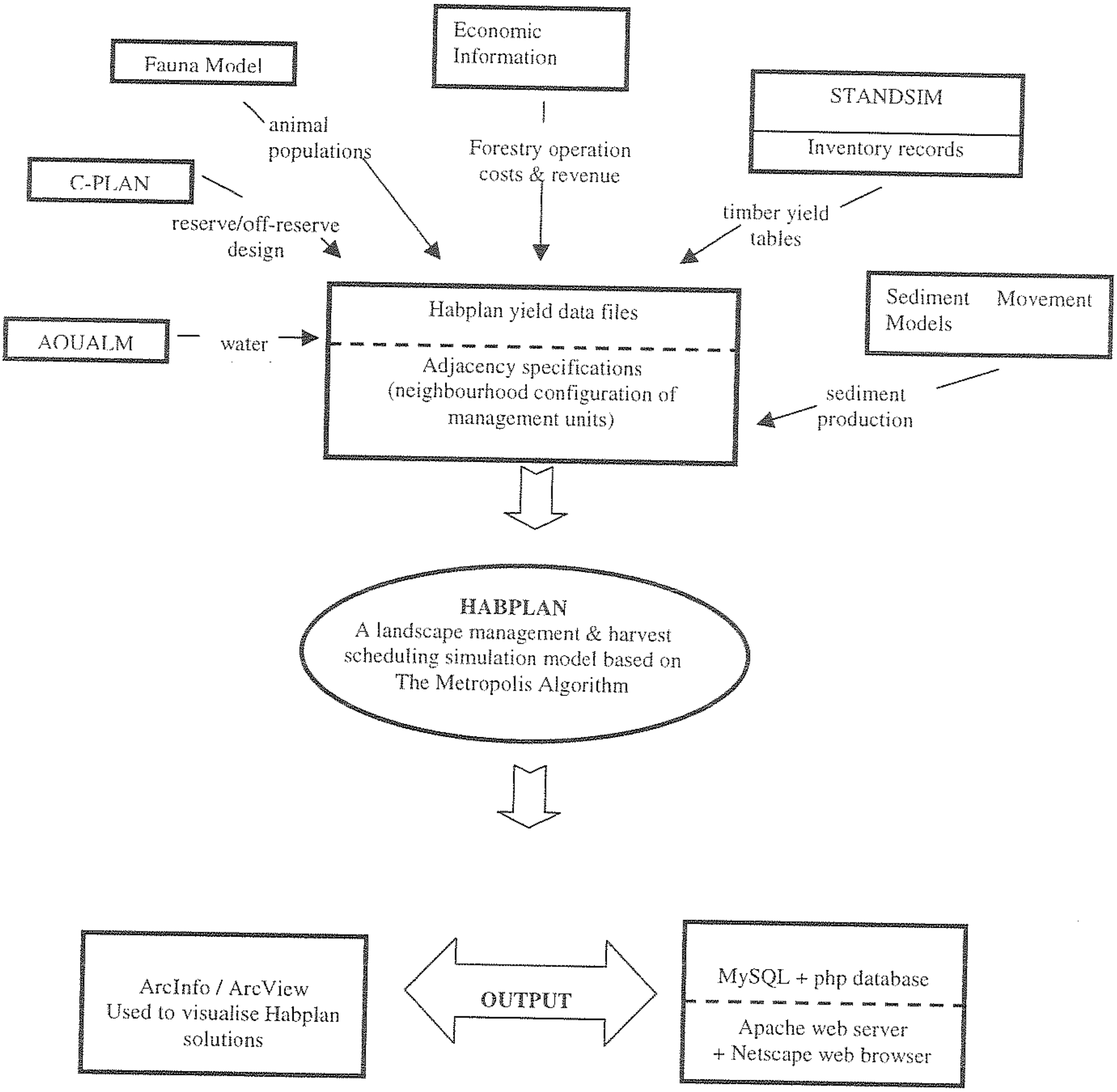

Figure 1. RHS model for the Eden Management Area [Chikumbo et al., 2000]

Therefore, the formulations for the RHS and MDHS had *7* and *18* objective components respectively. These multi-objective formulations were solved in a model called Habplan [NCASI-Forestry, 2000]. Habplan is a landscape management and forest harvest-scheduling program written in Java. Habplan uses a simulation approach based on MA with objective function weights, based on user-defined goals, that are adaptively determined at each iteration.

The multi-objective function evolved iteratively was as follows:

$$E(X^r) = \sum_{j=1}^{J} w_j^{r-1} C_j(X^r) \qquad (1)$$

where

X^r = management schedule at iteration r

w_j^r = the weight based on the iteration r schedule

$C_j(X^r) =$ the *j*th multi-objective function component whose value is evaluated at the *r*th schedule.

A management schedule involves assigning a specific management option to each of the *5734* management units and therefore the vector, X^r, contains all the possible options, a total of assigned to management units *1-5734*, $x_1^r,\dots,x_{5734}^r \in X^r$. The weights, which are evaluated at each iteration, are based on the user defined goals g_j, for each objective component. These weights are adjusted between the upper and lower limits defined for each goal component. Therefore, they are decreased if the goal, $g_j(X^r)$, is exceeded, or increased if the goal is not attained [Van Deusen, 1999]. Once a certain level of the weights are attained where no more changes between the upper and lower limits occur, then convergence has been achieved [Van Deusen, 1999]. There were a total of *66 616* options for all the *5734* management units for each of the components in the multi-objective function, that is, sawlog, pulpwood, sediment production, water production, fauna populations and present net worth.

In the RHS formulation, the chosen management schedule, for say, sawlog output, triggered the corresponding pulpwood, sediment, water, fauna and present net worth outputs, whilst simultaneously satisfying the block size constraint.

In the MDHS formulation, a chosen schedule meant satisfying a super objective sawlog output subject to sawlog outputs from the 8 sub-catchments that had to meet unique block size constraint limits and a common spatial management options constraints. This restriction was specified such that the spatial juxtaposition of management options could be controlled. This was essential to ensure that harvesting operations done in the same period in adjacent stands were preferred and could lead to a minimisation of operational and haulage costs. The economic benefits from an operational point of view could not be quantified in this current MDHS model because of lack of appropriate data.

5. COMPARISON

Both the MDHS and RHS formulations were solved to yield the *20 000*m^3 of sawlog for the first *22* years. It should be noted though, that it was the RHS model that was solved first to see whether the vitality of the ecosystem could be simultaneously maintained whilst harvesting at this level of *20 000*m^3 in the first *22*-year period. For a comparison, a single objective sawlog maximisation problem for the EMA, without spatial constraints, was previously formulated using Linear programming [Chikumbo et al. 1999] and also using the MA, yielding a sawlog output of *40 000*m^3 for the first *22* years. This level of harvesting, however, could not be achieved when non-timber values and spatial constraints were taken into consideration and given equal weighting as harvesting of sawlog.

The MDHS formulation had the advantage that each sub-catchment could be modelled differently with better control on the spatial configuration. Also in situations where block size restrictions are violated there is always an opportunity of specifying unique sub-catchment forest management practices in order to minimise any potential environmental hazards. The problem is, the MDHS formulation does not indicate environmental impacts. In contrast the RHS formulation had no flexibility in that a common block size constraint was applied to all sub-catchments. If this block size restriction was violated, it made it difficult to isolate the problem and correspondingly relax the common block restrictions without creating similar problems elsewhere in the region.

Although both formulations had block size restrictions, the MDHS had a spatial management option constraint that ensured that despite satisfying the block size limits, there would be an obvious bias towards larger and uniform blocks harvested in each period. A RHS formulation with this same type of constraint would have most likely given further insight to our comparison and will be considered in our future investigations.

However, the MDHS had more objective components (*18* of them) to monitor and it can be a time taxing exercise to determine, *ab initio*, the appropriate goals for the different objective components. In our case the initial guess was done by firstly formulating individual models for each sub-catchment with a sawlog output objective and block size constraint. The solutions to these problems provided *apriori* knowledge for initialising the goals that specify tolerance of blocks outside the size limits and constraints for the MDHS model

Although the RHS had less objective components (only 7 of them) to monitor, it provided the capability to track the other components of the forest ecosystem. By giving equal waiting to the other components of the ecosystem, it was possible to harvest the forest and simultaneously maintain ecosystem vitality.

6. CONCLUSION

Both formulations have advantages and disadvantages. It seems there is no preference for the other and we propose that the best way would be to formulate and solve the RHS problem first such that optimum or near-optimum harvesting levels are determined that would not in any way compromise the vitality of the forest ecosystem. These harvesting levels could then be used in the MDHS formulation as a super objective component to be achieved, but with greater flexibility on the sub-district spatial configuration. With the appropriate economic information, the MDHS could provide operational planning capability.

7. ACKNOWLEDGMENT

We are thankful to the Bureau of Rural Sciences (PO Box E11, Kingston, ACT 2604, Australia) and State Forests of New South Wales, Australia, for allowing us to demonstrate spatial harvest scheduling using the Eden Management Area as a case study.

8. REFERENCES

Chandler, D. *Introduction to Modern Statistical Mechanics*, New York, NY, Oxford University Press, 1977.

Chikumbo, O., R.H. Bradbury, and S. Davey, Large-scale ecosystem management as a complex systems problem: multi-objective optimisation with spatial constraints. In: *Applied Complexity-From Neural Nets to Managed Landscapes*. S. Halloy and T. Williams (eds), New Zealand Institute for Crop & Food Research Ltd, Christchurch, New Zealand. p124-155, 2000.

Chikumbo, O., D. Bush and S. Davey, The trial of SPECTRUM and SPECTRAVISION as additional tools for scheduling timber harvesting in the Eden Management Area, *Australian Forestry* 62: 139-147, 1999.

Croke, J., P. Hairsine, P. Fogarty, S. Mockler, and J. Brophy, Surface Runoff Sediment Movement on Logged Hillslopes in the Eden Management Area of South Eastern NSW, Cooperative Research Centre for Catchment Hydrology, 50p,1997.

Davey, S.M., The Environmental Relationships of Arboreal Marsupials in a Eucalypt Forest: a Basis for Australian Forest Wildlife Management, Department of Forestry, The Australian National University, Canberra, Australia, 1989.

Golberg, D.E. *Genetic Algorithms in Search Optimisation and Machine Learning*, University of Alabama. Addison Wesley Longman, Inc., 1989.

Lane, D. and R. Maxfield, R. Foresight, Complexity and Strategy, In: *The Economy as an Evolving Complex System II*, W.B. Arthur, S:N. Durlauf and D.A. Lane (eds), SFI Studies in the Sciences of Complexity, Vol. XXVII, Addison-Wesley. p169-198, 1996.

NCASI-Forestry, Habplan:Software for Forest Harvest Scheduling - Documentation, National Council for Air Stream Improvement Inc., 2000.

Opie, J. E. O., STANDSIM: A general model for simulating the growth of evenaged stands. Third Conference, Advisory Group of Forest Statisticians, IUFRO, Paris, France, 1972.

Press, W. H., S. A. Teukolsky, W. T. Vetterling and B. P. Flannery., *Numerical Recipes in C: The Art of Scientific Computing*, New York, NY, Cambridge University Press, 1992.

SFNSW, Proposed Forestry Operations in the Eden Management Area: Environmental Impact Statement. State Forests of New South Wales, Sydney, Australia, 1994.

Spencer, R.D. The development of strategic planning policy in Victoria, Australia: A review. *Town Planning Review*, 56(1): 42-69, 1985.

Van Deusen, P. C., Multiple solution harvest scheduling, *Silva Fennica*, 33(3): 207-216, 1999.

WP Software, AQUALM-XP User Manual, 1992.