# A Model for Clustering of Harvest Activities in Long Term Forest Planning

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**Abstract:** Models used in long-term forest planning were generally, until recently, non-spatial. The locations of harvest activities were considered first in lower, more short-term steps of the planning hierarchy. However, now that issues related to biodiversity, recreation and road planning have to be considered, this is no longer a viable option. The spatial arrangement of harvest activities affects parameters such as the proportion of undisturbed interior forest and the sites of new roads. Thus, in long term planning the spatial location of harvesting operations needs to be taken into consideration. However, including spatiality in long range planning complicates planning problems, and requiring the development of new methods and approaches. This study presents a new approach for clustering harvest activities in time and space in long-term forest planning. The planning problem essentially consists of maximizing the weighted sum of the net present value of future forest management and the clustered volume of timber to be harvested. This objective is subject to the restriction that a certain volume should be harvested each period. Since the spatial dimension leads to a problem that is difficult to solve with ordinary optimisation techniques, the ensuing problem is solved with a heuristic technique called simulated annealing. In a case study the suggested approach is applied to a landscape consisting of 2600 stands in southern Sweden. The results indicate that the model is effective for clustering the harvest and that it is possible to aggregate the harvest with a limited sacrifice of the net present value.

*Keywords:* Harvest scheduling; Spatial relationships; Optimisation

## 1. INTRODUCTION

Until recently, non-spatial modelling was generally used in long-term forest planning. The locations of harvest activities were considered first in lower, more short-term steps of the planning hierarchy. However, since issues related to biodiversity, recreation and road planning now have to be considered, this is no longer a viable option [Baskent and Jordan, 1991; Hunter, 1999]. One problem where spatial relationships between units have to be addressed is the scheduling of harvests in time and space. Dispersing clearcuts is a major contributor to the decline in forest interior habitats, *i.e.* the fragmentation of old forest [Franklin and Forman, 1987; Spies et al., 1994]. Since many interior species need a certain area of contiguous undisturbed forest, the reduction of forest interior habitats affects the biodiversity in the landscape [Harris, 1984]. As an alternative to dispersing clear cuttings, progressive cutting has been proposed. Clustering the harvests in time and space would allow more forest interior habitats to be sustained in the landscape and fragmentation to decrease [Franklin and Forman, 1987; Li et al., 1993; Gustafson, 1998]. Clustering the harvests is also consistent with financial goals since road maintenance and entry costs can be reduced.

Including consideration of spatial relationships in long-term forest planning will increase the complexity of the task. One reason for this is that a spatial model for scheduling the harvest requires characterization not only of the state of each stand, but also the state of its neighbours, implying that non-linear relationships between decision variables or integer variables will have to be used [Öhman, 2001]. The focus of the majority of the literature concerning spatial relationships in forest planning is how to include restrictions on the maximum opening size and development of efficient solution techniques for these kinds of problems. However, the type of problem studied in this paper, the clustering of areas to be harvested, is a connectivity problem, *i.e.* stands with certain conditions should be located adjacent to other stands with similar conditions. Problems like these sometimes differ in nature from maximum opening size problems, depending on the criteria and constraints used for forcing stands together.

There are relatively few studies describing approaches for creating connectivity both in space and time, especially in an optimisation framework, in the landscape. The object of this study is to present a new model for aggregating harvests in space and time in long-term forest planning. The model was applied in a case study to a landscape consisting of 2600 stands where considerations were are also paid to biodiversity and recreation.

## 2. MODEL DEVELOPMENT

The problem addressed in this paper is to delineate areas for harvesting for each of the $P$ planning periods in a landscape consisting of $I$ stands. Two objectives are addressed in the presented model, the first is to maximize the net present value (NPV) from forest management and the second is to maximize the clustering of cuttings in space and time during the $P$ periods. The NPV is the sum of discounted (time periods one to infinity) revenues from timber and costs for harvest operations and regeneration. The cost does not, however, include entry costs (transportation of harvesters, road maintenance, etc.) or timber transportation costs. The two goals are subject to the restriction that a certain volume, $\overline{V}_p$, should be harvested each period. For each stand, there are $J_i$ treatment schedules, *i.e* a set of treatments from period 1 and onward for a management unit. Associated with each treatment schedule is its NPV, $D_{ij}$, and volume harvested in period $p$, $V_{ijp}$. Only integer solutions are valid for the decision variable $X_{ij}$. This means that if stand $i$ is assigned a treatment schedule $j$, the variable $X_{ij}$ is set to one; otherwise it is set to zero. The approach for clustering the harvest in time and space is based on a criterion denoted effective volume, $EV_{ip}$, for stand $i$ in period $p$. Thus, the EV should be seen in the model as a spatial modelling concept, *i.e.* a criterion for aggregating the harvest in time and space and not as a measurement of the volume harvested each period. $EV_{ip}$ is the sum of harvested volumes from stand $i$ and neighbouring stands in period $p$ and adjacent periods $t$. For each $p$, $t$ goes from 1 to $P$. However, the volume harvested in period t is discounted by $e^{-\beta|p-t|l}$ where $k$ is the length of the period and $\beta$ is the factor that decides the influence of clustering on the harvest in time. The factor, $\beta$, is exogenously defined by an analyst. By setting $\beta$ to a high value the expression $e^{-\beta|p-t|l}$ will be close to zero for all $t \neq p$ and the stands will only be counted as clustered if activities in adjacent stands take place in the same period. On the other hand, by setting $\beta$ to a low value, close to zero, it does not matter in which period the harvest take place to be counted as clustered as long as the harvest activities take place in adjacent stands. It is assumed that a stand only has an EV in period $p$, if it is assigned a treatment schedule that includes a thinning or final felling in period $p$, *i.e.* the indicator for a treatment schedule having a treatment in period $p$, $Y_{ijp}$, is one.

The mathematical formulation of the model is as follows:

$$\text{Max } z_1 = \sum_{i=1}^{I} \sum_{j=1}^{J_i} D_{ij} X_{ij} \tag{1}$$

$$\text{Max } z_2 = \sum_{i=1}^{I} \sum_{p=1}^{P} EV_{ip} \tag{2}$$

s.t

$$\begin{aligned} EV_{ip} &= \sum_{j=1}^{J_i} Y_{ijp} X_{ij} \\ &\times \sum_{l}^{N^i} \sum_{j}^{J_l} \sum_{t=1}^{T} V_{ljt} X_{lj} e^{-\beta|p-t|k} \end{aligned} \tag{3}$$

$$\sum_{i=1}^{I} \sum_{j=1}^{J_i} V_{ijp} X_{ij} = \overline{V}_p \qquad \forall p \in P \tag{4}$$

$$\sum_{j=1}^{J_i} X_{ij} = 1 \qquad \forall i \in I \tag{5}$$

$$X_{ij} = \{0,1\} \qquad \forall i \in I, \forall j \in J \tag{6}$$

Objective (1) is to maximize the NPV from all stands and Objective (2) maximizes the EV from all stands and all periods. The two-objective problem is converted into a single objective problem by weighting the two objectives together;

$$\begin{aligned} \text{Max } Z = w_1 &\sum_{i=1}^{I} \sum_{j=1}^{J_i} D_{ij} X_{ij} \\ + w_2 &\sum_{i=1}^{I} \sum_{p=1}^{P} EV_{ip} \end{aligned} \tag{7}$$

with weights $w_1>0$ and $w_2>0$ such that $w_1 + w_2 = 1$. The resulting single-objective problem can then be solved a number of times with a suitable mathematical programming method under different weight combinations to generate a range of non-inferior solutions, *i.e.* solutions where one objective can be improved only by sacrificing the other objective. By using different weight combinations exogenously defined by an analyst, an efficient frontier or trade-off curve is generated. The trade-off curve can then be used for quantifying the trade-offs between the two goals. Equation (3) gives the EVs for stand $i$ in period $p$. Here $N^i$ is the set of stands that are adjacent to stand $i$, including stand $i$ itself. Two stands are considered to be adjacent if they share a common border or a common point. Equation (4) ensures that the volume constraints are fulfilled each period. Finally, equations (5) and (6) ensure that only one treatment schedule is assigned to each stand.

## 3. CASE STUDY

The model was applied to a landscape located in the southern boreal zone of Sweden. The landscape consists of 14400 ha of productive forest land, divided into 2643 stands. It is set aside as a nature reserve, primarily for recreation and nature conservation but timber production is still important. Road building is, however, restricted. The long time taken to process applications for road building (more than two years), makes this a major impediment. Thus, the model proposed in this study was used as a tool to identify areas for which new roads should be built.

Based on considerations to biodiversity and recreation, each stand was assigned a treatment class. Four different classes were set, for stands to be treated with: 1) normal considerations, 2) treatments promoting the endangered white-backed woodpecker *Dendrocopos leucotos*, 3) postponed felling, and 4) special reference to recreational values. In addition to these treatment classes, key-habitats, corridors and two areas that were considered to be especially valuable for recreation were set aside as areas where no forest management at all was to be allowed.

The treatment simulation program GAYA [Eriksson, 1983] was used to simulate a number of treatment schedules for each stand with respect to the selected treatment class. Each schedule sets times for the allowed silvicultural measures, *i.e.* thinning and final felling, with appropriate regeneration following the harvest. In addition, a schedule with no treatment at all was generated for each stand. The NPV for each schedule was then calculated based on a three percent real discount rate. The planning horizon was set to 40 years in eight five-year periods, *i.e.* $P$ was set to eight and $k$ was set to five. The volume demand, $\overline{V}_p$ was set to be equal to the volume harvested in each period when no consideration is given to the spatial layout, *i.e.* the treatment schedule with the highest NPV was selected for each stand.

The ensuing problem was solved with simulated annealing (SA), a heuristic optimisation method [*e.g.* Lockwood and Moore, 1993]. The SA algorithm used in this study is consistent with the algorithm presented in Laarhoven and Aarts [1987]. The starting temperature was set so high that almost all solutions were accepted at the beginning of the solution procedure and the stopping temperature was set so low that no solutions with worse objective values were accepted. The cooling schedule was after some experimentation set to $t_{i+1}=0.999t_i$ and the number of iterations at each temperature was set to 400. Randomly selecting a stand and then randomly selecting a new treatment schedule altered a solution. In the SA algorithm the volume constraints were included in the weighted objective function as penalty functions. Thus, the auxiliary objective function used in the SA algorithm was as follows:

$$\begin{aligned}\text{Max Z} = w_1 \sum_{i=1}^{I} \sum_{j=1}^{J_i} D_{ij} X_{ij} + w_2 \sum_{i=1}^{I} \sum_{p=1}^{P} EV_{ip} \\ - \alpha \sum_{p}^{P} \left( \sum_{i=1}^{I} \sum_{j=1}^{J_i} V_{ijp} X_{ij} - \overline{V}_p \right)^2\end{aligned} \qquad (8)$$

where $\alpha$ is the penalty parameter associated with the volume demands. The algorithm was implemented in FORTRAN and each case was solved on a 350Mhz PentiumII computer.

## 4. COMPUTATIONAL EXPERIENCE

The planning problem was solved for different combinations of the weights $w_1$ and $w_2$, and for different $\beta$ values. In the following, two extremes of weight combinations are presented, the first (W1) with $w_1 = 1\text{-}\varepsilon$ and $w_2 = 1$ and the second (W2) with $w_1 = \varepsilon$ and $w_2 = 1\text{-}\varepsilon$ where $\varepsilon$ is an arbitrary small value >0. Weights of $1\text{-}\varepsilon$ and $\varepsilon$ respectively, instead of weights 1 and 0, were used in order to avoid inferior optima. W1 implies no demand on clustering of the harvests. Further, results are presented for $\beta = 0.2$ which is a medium $\beta$ value, *i.e.* some consideration is given to clustering between periods.

**Figure 1.** The distribution of harvest for part of the case study area in period 7 for the two weight combinations W1 (left) and W2 (right), *i.e.* no consideration and consideration to the spatial layout of the harvest, respectively.

The penalty term $\alpha$ was set individually for each weight combination. In each case the $\alpha$ was as low as possible in order to avoid bad conditioning of the problem and still ensure that the solutions deviated only by a maximum of five percent of the target volumes in each period. Because of the stochastic nature of the technique used to solve the problem, the solution procedure was repeated five times for every instance of the problem. The difference in percent between the best and worst of these five solutions for the two weight combinations was less than three percent. In further evaluation of the different solutions, the one with the highest objective value was used. In order to evaluate the performance of the suggested model the solution time for all runs was recorded and for all runs it was less than five minutes.

The average number of clusters during the planning horizon was recorded as the total number of clusters in all planning periods divided by the number of periods. A cluster was defined as a contiguous area of stands harvested in a single period. Note that this measurement only evaluates whether or not harvests are clustered in space in a single period and does not evaluate if the harvests are clustered between periods. The average number of clusters decreased heavily for W2 compared to W1. The figures were 78 and 232, respectively. The solutions corresponding to the two weight combinations are illustrated in Figure 1 for a part of the case study area. Note that these figure only show the distribution of harvesting operations in period 7. The weight combination W1 yielded as expected the highest NPV while W2 generated a decrease in NPV of 6.6 %. This is, consequently, the loss due to clustering of the harvest activities.

The trends in the number of clusters in each of the planning period for the two weight combinations are can be observed in Figure 2. For W1, the trend for the number of clusters was increasing, while for W2 the number of clusters decreased, with some exception, continuously during the planning horizon.

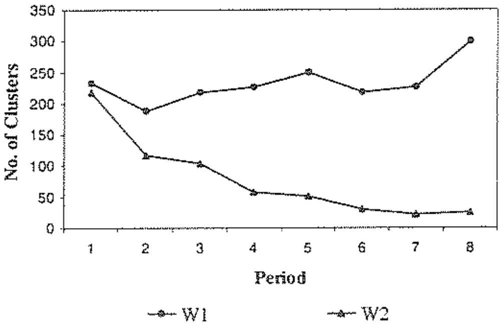

**Figure 2.** Number of clusters in each planning period for weight combinations W1 and W2 (no consideration and consideration to spatial layout of harvests, respectively).

## 5. DISCUSSION AND CONCLUSIONS

In this study a new model for clustering harvest activity in space and time is presented. The results from the case study indicate that the presented model is effective for clustering the harvest. The clustering of harvest is logically the result of that placing harvest activity in adjacent stands and periods tends to improve the EV. Further, the results from the case study indicate that the clustering of the harvest is more pronounced later in the planning horizon than in earlier periods. This could be due to a number of factors. First, initial conditions give few possibilities to cluster the harvest in the beginning of the planning horizon, *i.e.* it takes several periods to create a suitable spatial pattern. Second, variations in the average size of the stands in the different age classes also have an effect, since the young stands (which will be suitable for harvest in the future) are, on average, larger. This implies that in the future fewer but larger stands will need to be harvested to fulfill the harvest demands. Third, there is no discounting of the EV. A certain amount of EV has the same value whether it is generated today or in the future. A possible extension of the model would therefore be to include discounts of the EV.

Another possible extension of the model is to include a restriction on opening size based on, e.g., ecological, aesthetical, or soil erosion factors. This should, however, heavily increase the complexity of the problem and affect the solution time.

The results indicate that it is possible to aggregate the harvest with a limited sacrifice of NPV. A weight combination in between the used W1 and W2 shuld generate a lower loss in NPV than W2. Further, a trade of curve for the two objectives NPV and EV can be generated given different weight combinations and $\beta$ values. A decrease in NPV could be motivated by the fact that costs associated with road building *etc.* will probably decrease when the harvests are aggregated in time and space.

In the case study SA was used for solving the stated management problem. Other methods capable of solving non-linear problems could also have been selected. However, the results from the case study indicate that the selected method is a convenient choice both for finding near optimal solutions and for the relatively short time needed for implementing the algorithm and solving the problem. One reason for the short solution time is that the selected criterion EV seem to be computationally well behaved and can consequently be efficiently included in the optimization model. The short time for running the problem and to obtain a solution is in marked contrast to many other spatial approaches where the time required to obtain a solution is often considerable [Öhman and Eriksson, 1998].

It can be concluded that the presented model could be used where clustering of harvest activities is desired. By using different weighting for NPV and EV it is possible to generate a number of solutions with differing degrees of clustering. This has implications for implementation since it would allow the decision maker to generate a range of plans and then select a plan corresponding to a certain level of clustering and an acceptable decrease in NPV.

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