Scheduling Forest Road Maintenance Using the Analytic Hierarchy Process and Heuristics

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The management of low-volume roads has transitioned from focusing on maintenance designed to protect a capital investment in road infrastructure to also include environmental effects. In this study, two models using mathematical programming are applied to schedule forest road maintenance and upgrade activities involving non-monetary benefits. Model I uses a linear objective function formulation that maximizes benefit subject to budgetary constraints. Model II uses a non-linear objective function to maximize the sum of benefits divided by the sum of all costs in a period. Because of the non-linearity of the constraints and the requirements that the decision variables be binary, the solutions to both problem formulations are found using two heuristics, simulated annealing and threshold accepting. Simulated annealing was found to produce superior solutions as compared to threshold accepting. The potential benefit for completing a given road maintenance or upgrade project is determined using the Analytic Hierarchy Process (AHP), a multi-criterion decision analysis technique. This measure of benefit is combined with the economic cost of completing a given project to schedule maintenance and upgrade activities for 225 km (140 miles) of road in forested road systems within western Oregon. This combination of heuristics, cost-benefit analysis, environmental impacts, and expert judgment produces a road management schedule that better fits the current road management paradigm.

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1 Introduction

Maintenance systems for low-volume road networks have a long history in practice and in the literature. Most of these systems, such as the World Bank's Highway Design and Maintenance Standards Model (HDM-3, and more recently HDM-4), focus on maintaining adequate drivability standards (Riley and Bennett 1995) to benefit local industries and communities (Conrad 1987). In recent years, the forest sector in the western United States and elsewhere has been moving away from a model of maintenance programs designed to protect capital investments in road infrastructure (Long et al. 1987) towards maintenance programs that also consider the potential environmental impacts caused by poorly maintained roads (Logan 2002). The trend of including environmental considerations in road management and design is evidenced by the growing discipline of road ecology (Forman et al 2002, Murphy and Wing 2005).

Models such as the HDM-4 use a benefit-cost approach to prioritizing maintenance projects. The cost is a direct monetary estimate of what it will take to complete a given project and the benefit is a reduction in the Vehicle Operating Cost (VOC) to all road users. VOC is a purely monetary measure that takes into consideration repair and maintenance of vehicles, fuel costs, travel time, and vehicular accident costs (Riley and Bennett 1995). Each component increases as the road roughness increases with road deterioration. Empirically derived models have been completed for most road surfacing types that describe the deterioration of the road surface with factors such as traffic patterns, weather, and maintenance strategies (Paterson 1987). While non-monetary benefits for road maintenance have been suggested (Faiz and Staffini 1979), they are rarely incorporated into decision models.

We present an alternate approach to setting maintenance priorities through a multi-criterion decision analysis method, the Analytic Hierarchy Process (AHP) (Saaty 1977), to determine the potential benefit gained from completing a given maintenance project. This measure of benefit is then used in two formulations of a road maintenance scheduling problem. The first formulation maximizes benefit received from completing a set of maintenance and upgrade projects, the second maximizes a benefit-cost ratio. The strength of these approaches is that non-economic and subjective factors can be incorporated in the analysis.

The problem presented here considers 2389 potential maintenance and upgrade projects over a 10-year planning horizon requiring routine maintenance, additions of crushed aggregate in preparation for timber extraction, and maintenance and upgrade projects, resulting in 47 780 integer decision variables. Two heuristic search techniques, simulated annealing (Kirkpatrick et al. 1983) and threshold accepting (Dueck and Scheuer 1990), have been developed to solve the problem. Both are neighborhood search techniques that accept all solutions that are either better than the current solution or satisfy other criteria. For simulated annealing a non-improving solution is accepted if a randomly generated value is less than a value calculated using the degree of un-improvement (the difference between the last accepted objective function and the objective function under consideration) and a value, called the temperature, which decreases with time. The probability of accepting a worse solution decreases with time. The algorithm stops when the temperature reaches a minimum value. For threshold accepting a non-improving solution will be accepted if it is within an acceptable interval from the current solution. This acceptable interval, or threshold, decreases with time until only solutions that are better than the current solution are accepted. The algorithm will stop when a given number of iterations have been completed with no improvements made in the solution. Both threshold accepting and simulated annealing have been successfully applied on a number of problems.

In this paper, we will first present a brief introduction to AHP, including its theoretical background, and apply AHP to the analysis of road maintenance and upgrade scheduling. Two problem formulations are developed and each is solved using two heuristics, threshold accepting and simulated annealing.

2 Methods

2.1 The Analytic Hierarchy Process

The AHP involves four steps: structuring the problem as a hierarchy, making pairwise comparisons among attributes to determine the user's preferences, reducing attributes to relative values, and ranking alternatives. AHP requires that problems be constructed as a hierarchy, a process termed hierarchical decomposition, such that the overall goal is represented at the top of the hierarchy with objectives and sub-objectives of that goal below. Objectives are decomposed until the base of the hierarchy is reached. The base of the hierarchy (those objectives or sub-objectives with no attributes below them in the hierarchy) contains the attributes that are used to compare alternatives. An attractive benefit of AHP is that attributes can be quantitative or qualitative and can be measured on any scale as long as that scale is constant within each attribute.

Pairwise comparisons are made between the attributes within each group of attributes at each level of the hierarchy based on the contribution of each attribute to the element directly above them in the hierarchy. For the example problem used here (Fig. 1), three questions would be asked of the decision maker at the second level of the hierarchy:

1) How important is minimizing impacts to streams as compared to minimizing road failure in minimizing the environmental and economic costs of forest road failure?
2) How important is minimizing impacts to streams as compared to minimizing forest practices act violations in minimizing the environmental and economic costs of forest road failure?
3) How important is minimizing road failure as compared to minimizing forest practices act violations in minimizing the environmental and economic costs of forest road failure?
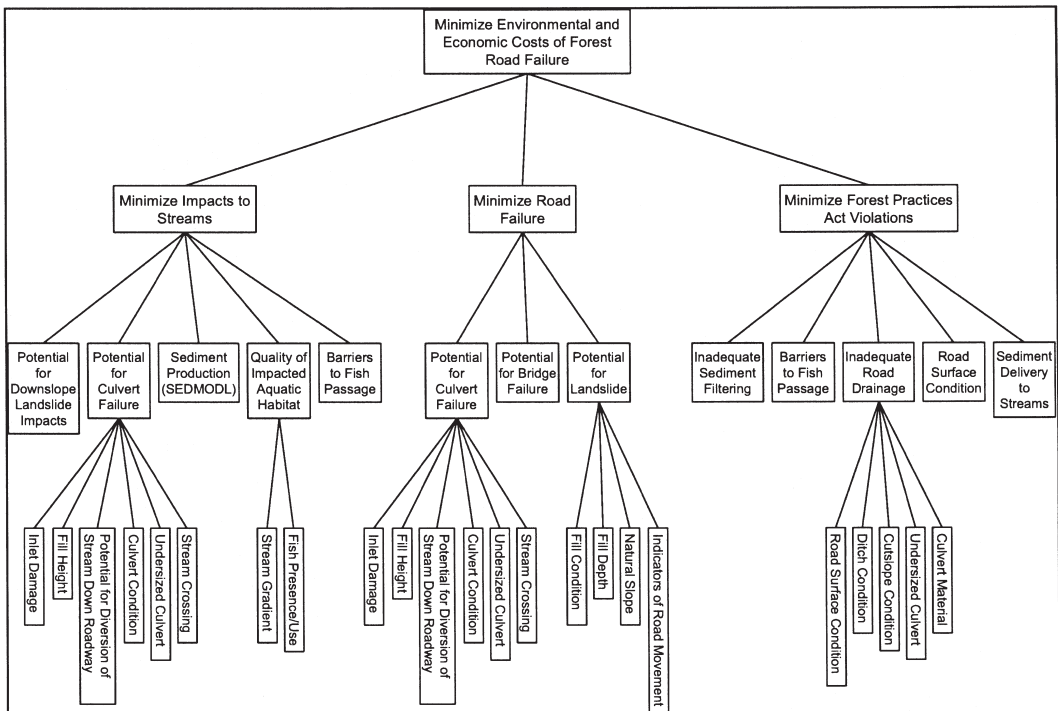
The most prevalent scale used to carry out these

Fig. 1. Hierarchy used to minimize environmental and economic costs of forest road failure.

comparisons is Saaty's Fundamental Scale (Saaty 2000). The Fundamental Scale is composed of the integers between one and nine where one signifies equal importance between the attributes and nine is used when one attribute is strongly more important than the other. Reciprocals of these scale values are used to express the strength of the weaker of the two attributes. AHP does not require the decision maker to be completely rational or consistent in completing these pairwise comparisons (see Coulter 2004).

The result of each set of pairwise comparisons is expressed as a positive reciprocal matrix such that $a_{ij} = a_{ji}$, i, $j \leq n$, where n is equal to the number of elements being compared within one set of pairwise comparisons. Various methods for calculating attribute weights from this matrix have been proposed. Saaty (1977, 2000) advocates using the principal right eigenvector while others (Lootsma 1996) have promoted the use of the normalized geometric mean of the rows of the priority matrix, also called the Logrithmic Least Squares Method (LLSM). Both the eigenvector and LLSM have strong mathematical and theoretical backing (Fichtner 1986) and both have been used extensively in practice with little difference in the results (Crawford 1987).

The magnitude of the decision maker's inconsistency in completing pairwise comparisons is measured using a Consistency Ratio (CR). The CR is formed by the ratio of the Consistency Index (CI) of a matrix of pairwise comparisons and the Random Consistency Index (RI) for a matrix of the same size. The CI is found using the largest eigenvalue (λ_{max}) corresponding to the principal right eigenvector and is equal to $(\lambda_{max} - n)/(n - 1)$ where n is the number of attributes being compared to create a n by n square matrix. The RI is the average CI of many matrices completed with random entries (see Saaty 2000). In practice, pairwise comparisons are adjusted until the CR of each matrix is less than or equal to 0.1, or ten percent. As CR increases, confidence that the resulting vector of weights accurately represents the decision maker's preferences decreases correspondingly.

Weights are derived through a pairwise comparison technique and are multiplied by the relative value for each attribute of each alternative. Relative values for individual attributes can be derived

in many ways including pairwise comparisons between categorical data, linear interpolations based on the maximum or minimum value under consideration, or utility functions as defined by the decision maker. The overall score for each alternative is aggregated using an additive function of the product of each attribute weight and its associated relative attribute value.

AHP allows for the inclusion of less than perfect data both in the attribute values and in pairwise comparisons. For example, data for cutslope height could be included as a continuous, directly measured value, an estimate to the nearest meter, or as a categorical variable that describes a range of values (i.e. 1–3 meters). The more precise and certain both attribute values and pairwise comparisons are the more certainty the user can have in the outcome of an analysis.

2.2 Application

The Oregon State University (OSU) College of Forestry maintains approximately 225 km (140 miles) of primarily gravel surfaced low-volume roads located in five separate forested tracts in Western Oregon. Most of these roads are closed to vehicular public access but are maintained for timber extraction and the support of teaching and research activities.

A road inventory was completed for all roads within OSU ownerships in 2002. The inventory data were stored in a Microsoft Access database. Each road was divided into one or more road segments as defined by the length of road between road drainage structures, intersections with other roads or trails, or changes in road condition. The 225 km (140 miles) of road were divided into a total of 2389 road segments.

The benefits of road maintenance were assessed based on the negative impacts of current road conditions. In this light, AHP was used to structure the problem as a hierarchy with an overall goal of minimizing the total cost, both environmental and economic, of forest road ownership (Fig. 1). This overall goal was decomposed into three objectives, minimizing the environmental impacts to streams, minimizing the incidence of road failure that could potentially lead to both environmental and economic costs, and minimiz-

Table 1. Summary of the types of maintenance and upgrade projects identified.

Type of project	Number of road segments
Install a cross-drain culvert	693
Install a stream crossing culvert	58
Install a bridge	20
Blade and roll	10
Construct an overflow (broad-based) dip	42
Pull unstable fill	8
Total	831

ing Forest Practices Act violations. Each of these three objectives was further decomposed into a total of 31 attributes used to compare each of the alternatives.

Pairwise comparisons were completed at each level of each branch of the AHP hierarchy and the eigenvector method was used to derive weights for each attribute. The attribute weights were then applied to each of the 2389 road segments to calculate an overall score value. The overall score for each alternative was a value between 0 and 1 where higher overall score values indicate greater benefit than lower overall score values.

Projects were identified for each of the 2389 road segments (Table 1). Of these projects, the majority involved the upgrade of the road drainage system, including the installation or replacement of cross-drain culverts, stream crossing culverts, bridges, and overflow dips. Sediment delivered to streams and fish passage are often the major road maintenance issues in western North America. The replacement of a cross drain culvert is triggered when the existing culvert is either damaged, smaller than 0.45 meters (18 inches) in diameter, or constructed of material other than double-walled plastic. The new installation of a cross drain culvert is also recommended when the existing road design does not adequately filter road runoff prior to a stream crossing, for example when a ditch drains directly to a stream. For stream crossings when fish are not present, culvert replacement is encouraged when the recommended culvert size based on drainage area exceeds the current culvert size. When fish are known to inhabit a stream or when fish use is

unknown and the culvert is blocking fish passage or too small based on drainage area, replacing the current culvert with a bridge is the only option considered. Barriers to fish passage were determined based on the depth of the downstream resting pool and the jump from the resting pool to the culvert outlet, both measurements collected during the road inventory. The construction of an overflow (broad-based) dip was included any time the road inventory stated a moderate or high risk of diverting a stream down the length of the road if a culvert were to fail.

Where road surface conditions were indicated to be a problem, such as the existence of ruts or berms, it was assumed that additional grading and compaction in addition to the regular maintenance would be sufficient. Within road segments where unstable fill was indicated, the maintenance and upgrade project included removing the unstable fill.

2.2.1 Problem Formulation

The current management system of the OSU research forests requires that all but abandoned roads (those roads that have been closed between timber harvests) receive regular maintenance once every three years. This regular maintenance includes grading and compaction of the road surface and brush clearing along either side of the roadway. Three-year contracts are let for this routine maintenance. Crushed aggregate is placed on haul routes prior to timber extraction in an amount equivalent to the depth of rock that is expected to deteriorate during hauling. Whenever possible, upgrades to the road system are completed in conjunction with a timber sale. When road maintenance and upgrade projects are completed outside of routine maintenance or a timber sale contract, prevailing wage rates as set by the State of Oregon must be paid to the contractors. This additional expense is equivalent to approximately 25% of the project cost.

The 2002 road inventory data were used to determine the maintenance or upgrade activity required for each road segment. These activities included replacing or installing cross-drain culverts, replacing stream crossing structures, providing extra grading of the road surface to

Table 2. Maintenance and upgrade activity costs used in scheduling road maintenance.

Activity	Range of current costs	Cost used in modeling
Replace one cross-drain culvert (46 cm (18 inch) diameter)	$55–62 per linear meter ($17–19 per linear foot) of culvert, installed	$350 per cross drain culvert
Replace one stream crossing culvert when no fish are present (61 cm (24 inch) diameter)	$75–79 per linear meter ($23–24 per linear foot) of culvert, installed	$460 per stream crossing culvert
Install and furnish a new bridge	$26 000	$26 000 per bridge
Construct a broad-based overflow dip on an existing road	$100	$100 per occurrence
Grade and roll existing roads (routine maintenance)	$265–295 per kilometer ($430–475 per mile)	$26.75 per 100 meters ($8.15 per 100 feet)
Brushing (routine maintenance)	$185 per side per kilometer ($300 per side per mile)	$37.75 per 100 meters ($11.50 per 100 feet)
Addition of crushed aggregate surfacing on existing roads	$13 per delivered metric ton ($12 per delivered ton) for aggregate and hauling, $0.55–$2.20 per metric ton ($0.50–2.00 per ton) to place aggregate	$14.90 per metric ton ($13.50 per ton)
Pull unstable road fill	Contracts are conducted by the hour	$24 600 per 100 meters ($7500 per 100 feet)

improve drainage, and the removal of unstable fill. Average costs for each of these activities were generated using current contractor costs gathered during telephone interviews with road contractors (Table 2).

While the scheduling algorithm has the option of choosing any of the 2389 potential maintenance and upgrade projects, not all potential projects will provide a benefit. For example, some of the road segments in the road inventory database that were used to generate potential projects include the span of road between a road junction and an access gate and may only be 0.01 kilometers in length. Other road segments may be functioning properly and require nothing more than routine maintenance. In both cases, the benefit for activities outside regular maintenance, as derived using AHP, will be near zero. Only a relatively small number of potential projects have significant benefit values (Fig. 2).

Routine maintenance requirements, aggregate surfacing requirements, costs for maintenance and upgrade activities, and the benefit for completing maintenance and upgrade activities were combined to create a 10-year plan for the management of all roads within the management area. The current timber harvest plan for the next 10 years, as determined by OSU, was used to determine the location of haul routes and volumes of timber to be extracted over each.

Two separate objective functions were evaluated. Model I maximizes benefit subject to budgetary constraints:

$$\text{Maximize} \sum_{j=1}^{10} \sum_{i=1}^{2389} b_i x_{ij}$$

Subject to:

$$\sum_{i=1}^{2389} p_i x_{ij} + m_i y_{ij} + r_i z_{ij} < \text{Budget} \quad \text{for every } j$$

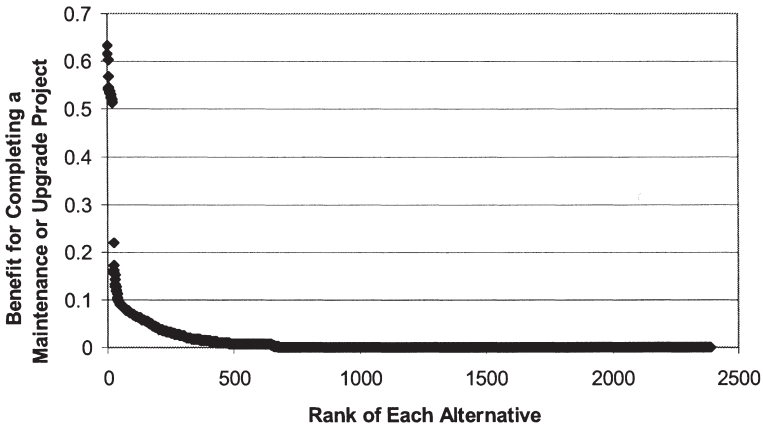$$\sum_{j=1}^{10} x_{ij} \leq 1 \quad \text{for every } i$$

Fig. 2. Distribution of benefit values (overall score generated using AHP for individual projects) for the 2389 maintenance and upgrade projects under consideration, sorted by rank.

$$\sum_{j=1}^{3} y_{ij} = 1 \quad \text{for every } i, j$$

$$y_{ij} = y_{i(j+3)} \quad \text{for } j = 1 \ldots 7 \text{ and every } i$$

$$p_i = f_1\left(x_{ij}, z_{ij}\right)$$

$$m_i = f_2\left(y_{ij}\right)$$

$$x_{ij}, y_{ij}, z_{ij} \in \{0,1\} \quad \text{for every } i, j$$

where

b_i = the benefit derived from AHP for completing project i

x_{ij} = 1 if project i will be completed in period j, 0 otherwise

p_i = cost of completing project i, $p_i = a_i$ if a timber harvest is scheduled in the same road system in the same period, $p_i = c_i$ otherwise, where $c_i > a_i$

m_i = cost of routine maintenance for road segment i, $m_i = d_i$ if more than 75 percent of the active road segments in a road system are maintained in the same period, $m_i = e_i$ otherwise, where $e_i > d_i$

y_{ij} = 1 if road segment i will receive routine maintenance in period j, 0 otherwise

r_i = cost to rock (add crushed aggregate) to road segment i

z_{ij} = 1 if road segment i will receive additional aggregate in period j, 0 otherwise

Budget = dollars allocated in each year (period) for all maintenance and upgrade activities

This maximization of benefit subject to budgetary constraints is a mixed integer programming formulation with a linear objective function. However, in this formulation, the cost of routine maintenance and projects are functions of other decision variables, creating a non-linear problem with binary variables. Therefore, a heuristic was chosen.

Model II maximizes:

$$\text{Maximize} \sum_{j=1}^{10} \left[\frac{\sum_{i=1}^{2389} b_i x_{ij}}{\sum_{i=1}^{2389} p_i x_{ij} + m_i y_{ij} + r_i z_{ij}} \right]$$

Subject to:

$$\sum_{i=1}^{2389} p_i x_{ij} + m_i y_{ij} + r_i z_{ij} < \text{Budget} \quad \text{for every } j$$

$$\sum_{j=1}^{10} x_{ij} \leq 1 \quad \text{for every } i$$

$$\sum_{j=1}^{3} y_{ij} = 1 \quad \text{for every } i, j$$

$y_{ij} = y_{i(j+3)}$ for $j = 1 \ldots 7$ and every i

$p_i = f_1(x_{ij}, z_{ij})$

$m_i = f_2(y_{ij})$

$x_{ij}, y_{ij}, z_{ij} \in \{0,1\}$ for every i, j

This objective function seeks to maximize the sum of benefits divided by costs over each of the 10 years and thus is non-linear. The benefit-cost ratio is calculated for each year as the sum of the benefits received from completing maintenance and upgrade projects during the year divided by the sum of all road-related costs. The objective function was the only difference between the two models, all constraints and costs were the same. For the undiscounted versions of both Model I and Model II, benefits were assumed to occur only in the period of project completion.

Formulations of both Model I and Model II that included a time preference for the achievement of benefits were also considered. For some projects, such as replacing a stream crossing structure that is currently serving as a barrier to fish passage, benefits may be realized into the future. Therefore, for those projects that included the replacement of a physical structure, benefits were assumed to occur annually in the period in which the project is funded and every year after until period ten. This assumption that benefits terminate at year ten does bias the solution by not including the same stream of benefits for a project scheduled later as compared to a project scheduled earlier. These two additions modify the objective functions as follows:

Model I: Maximize $\displaystyle\sum_{j=1}^{10} \sum_{i=1}^{2389} (b_i \mathrm{disc}_i) x_{ij}$

Model II: Maximize $\displaystyle\sum_{j=1}^{10} \left[\dfrac{\displaystyle\sum_{i=1}^{2389} (b_i \mathrm{disc}_i) x_{ij}}{\displaystyle\sum_{i=1}^{2389} p_i x_{ij} + m_i y_{ij} + r_i z_{ij}} \right]$

where $\mathrm{disc}_i = \left[\dfrac{(1+i_{\mathrm{Rate}})^{10-j} - 1}{i_{\mathrm{Rate}}(1+i_{\mathrm{Rate}})^{10-j}(1+i_{\mathrm{Rate}})^{j}} \right]$ if the

project involves a structure replacement, and $1/(1+i_{\mathrm{Rate}})^{j}$ otherwise. For both models, an interest rate (i_{Rate}) of 10 percent was used and costs were not discounted. The discounting of costs in the Model I formulation would not change the solution because the model does not consider a time preference for costs. For Model II, discounting costs at the same rate as benefits would have no impact on the solution as compared to the undiscounted solution because costs would be pushed away in time at the same rate as benefits are moved up in time.

2.2.2 Solution Method

The non-linear nature of the constraints and discrete decision variables for both Model I and Model II ensure the solution space will not be convex but instead may contain local optima. Additionally, the objective function of Model II is non-linear. A solution technique that allows the search to escape from local optima was needed. Several techniques exist to solve problems of this nature, each of which allows the algorithm to accept inferior solutions in order move away from local optima (Reeves 1993, Glover and Kochenberger 2003). For both model formulations, both a simulated annealing heuristic (Kirkpatrick et al 1983) and a threshold accepting heuristic (Dueck and Scheuer 1990) were used to set a yearly schedule for road maintenance and upgrades. Dueck and Scheuer (1990) have shown that for some problems threshold accepting performs as well or better than similar heuristics such as simulated annealing that require more control variables. Both of these are neighborhood search techniques, meaning the algorithm will perturb an existing solution slightly, in this case by choosing a new starting period for routine maintenance activities on one active road and by choosing if and when to complete one or more projects, and comparing this new solution to the old solution. If the new solution is better than the old solution, it will automatically be accepted. The difference between the two heuristics is in the acceptance of a non-improving move. If the new solution is worse than the old solution, simulated annealing will use a comparison between two values to make the decision. The first is a probability gener-

ated using two values 1) the difference between the old and new objective function values and 2) the current value of a control parameter referred to as the "temperature", a value that decreases as the solution progresses. The second is a randomly-generated value. If the random number is less than the probability then the non-improving move is accepted. As the solution progresses, the control parameter decreases and with it the probability a non-improving move will be accepted. The algorithm stops once the control parameter reaches a minimum value. For this algorithm, the control parameter was initialized at 100.000 and decreased by 5% after every 100 solutions have been accepted. The algorithm stops once the control parameter reaches 0.001 (0.010 when discounted benefit values are used). This process is repeated 20 times from random starting points with the best solution retained.

If the new solution is worse than the old solution, but not that much worse, the threshold accepting heuristic will accept the move. The criteria for "not that much worse" is set by the threshold. Threshold accepting is willing to accept larger disimprovements early in the search and is less willing to accept disimprovements as the search progresses. The acceptance of large disimprovements at the beginning of the process is introduced to make the starting condition less important. For this algorithm, the threshold value was initially set at 10% of the current objective function value. After 100 solutions have been accepted at each threshold level, the threshold value is multiplied by 0.75 until it becomes less than 10^{-4}, at which time the threshold is set to zero. When the threshold value is zero, only those solutions better than the current solution are accepted. After the model has rejected 1000 solutions in a row, the model run is complete and the best solution recorded. This process is repeated 20 times from random starting points with the best solution retained.

Control parameters were set through trial and error. For example, in threshold accepting, when the initial threshold value was set either higher or lower than 10% the algorithm would produce inferior solutions as compared with those produced with a threshold of 10%. When the threshold was set higher, the algorithm would bounce around with little direction. Lower thresh-

old values were too restrictive and the algorithm terminated before adequately exploring potential solutions. Even though the control parameters were set by trial and error to determine a good schedule, the results for individual runs were variable. As part of the strategy to avoid being stalled in a local maximum, 20 runs were examined at different starting points. The randomly generated initial solution was the only difference in the starting conditions of each run.

For both methods, the initial solution randomly assigned a start period for routine maintenance to each whole road and maintenance was scheduled every three years thereafter (Figs. 3 and 4). Only entire roads were considered for routine maintenance as opposed to individual road segments. No projects are scheduled in the initial solution. Both routine maintenance and the addition of crushed aggregate to road surfaces were requirements that incurred cost yet received no benefit. Therefore, because no projects were scheduled for completion in either model formulation, the algorithm starts with an initial objective function value of zero.

During the search for new solutions, each algorithm had the option of deselecting projects for completion. The other option available was to vary the start year for the maintenance schedule of each road. The option of not surfacing a road in the year of timber extraction or not performing routine maintenance was not given.

The roads under consideration were divided into twelve road systems. The four smaller tracts were each assigned a unique road system and the largest tract was divided into eight separate road systems. Each road system consists of a mainline road with numerous collector roads branching off to different areas. Within the main tract of forestland, some of these collector roads connect with collector roads from other road systems. In order for a project to be considered as part of a timber sale contract it must be located within the same road system and scheduled during the same period as a proposed harvest. If a project was not included in a timber sale contract, a surcharge equivalent to 25% of the project cost was added to the total cost to complete that project. Additionally, if fewer than 75% of the total road segments within a road system were scheduled for routine road maintenance in a given year,
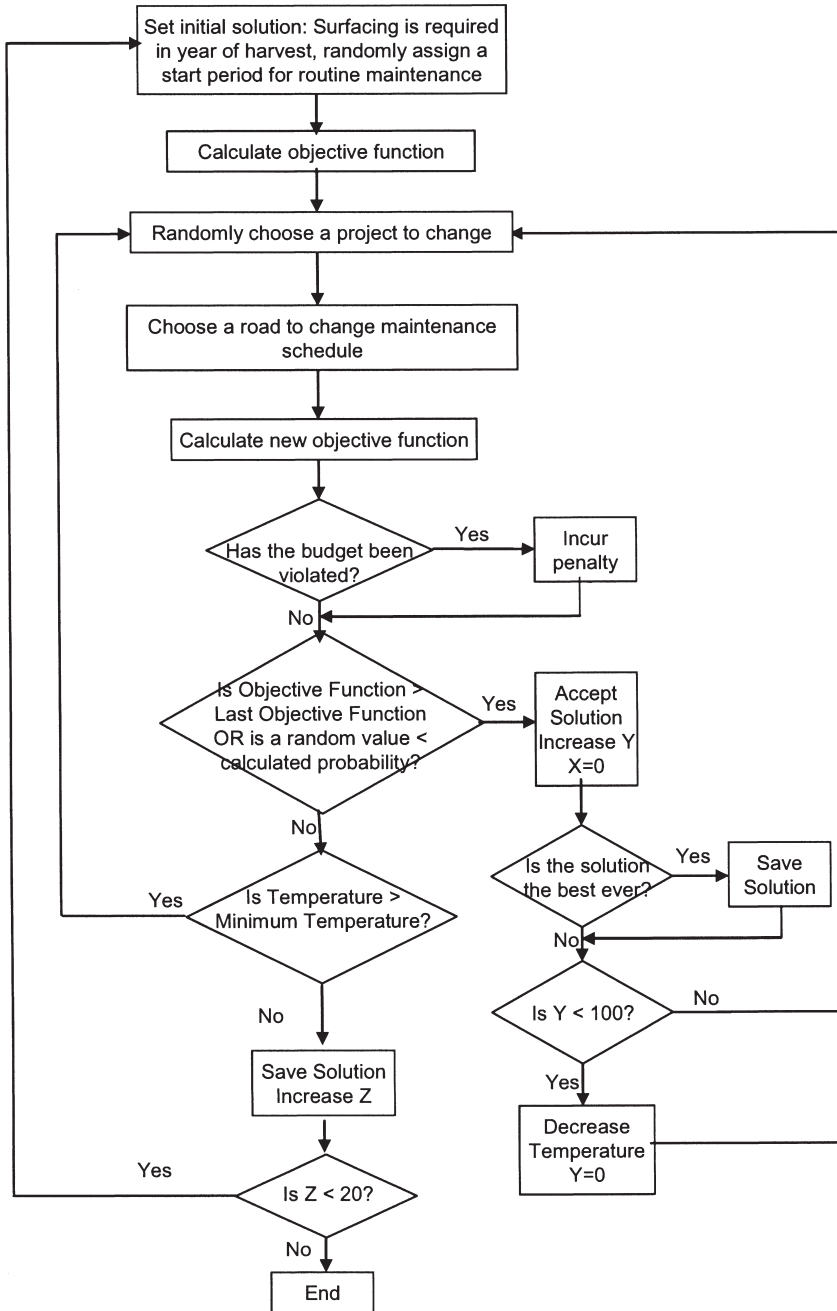
Fig. 3. Simulated annealing solution algorithm used to schedule road maintenance and upgrade activities.
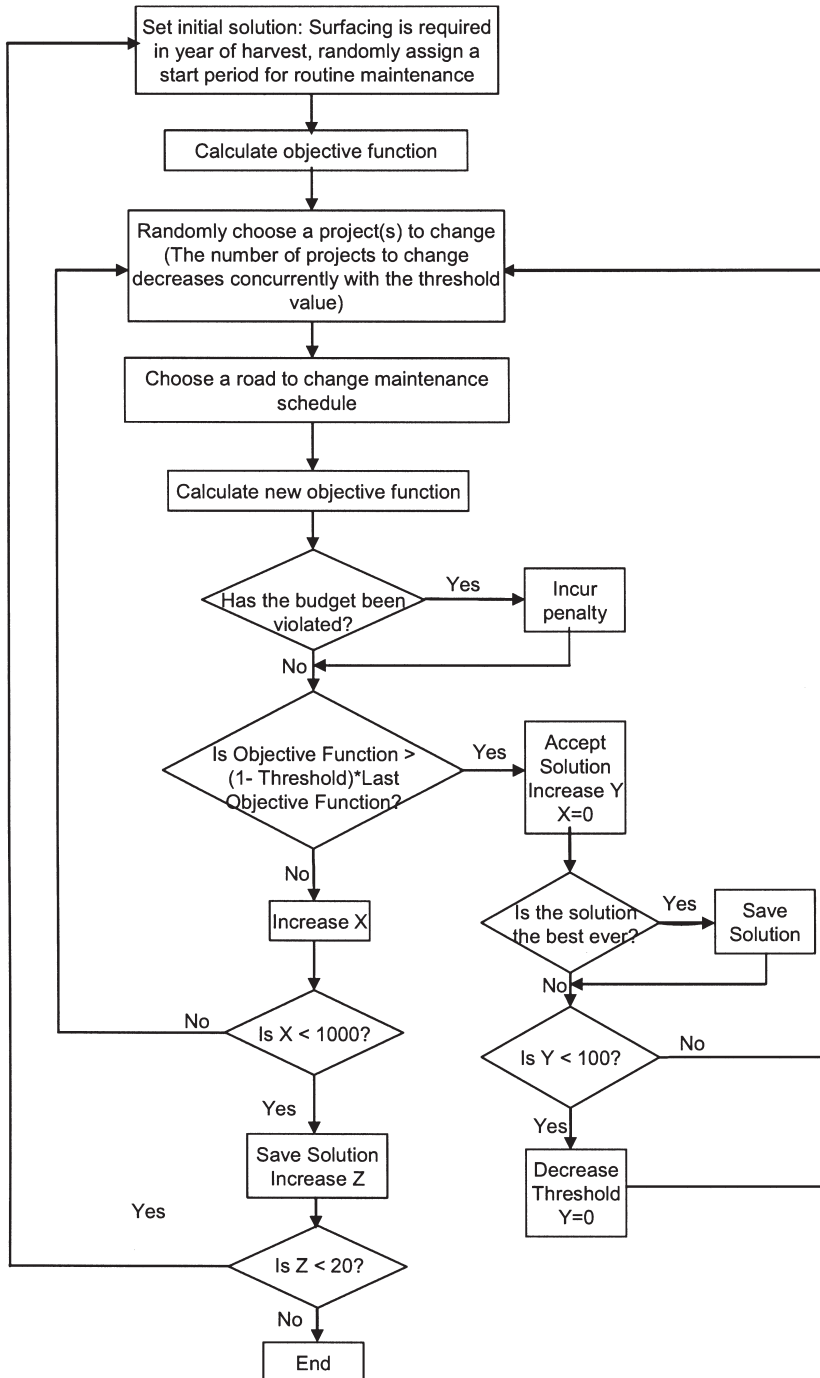
Fig. 4. Threshold accepting solution algorithm used to schedule road maintenance and upgrade activities.
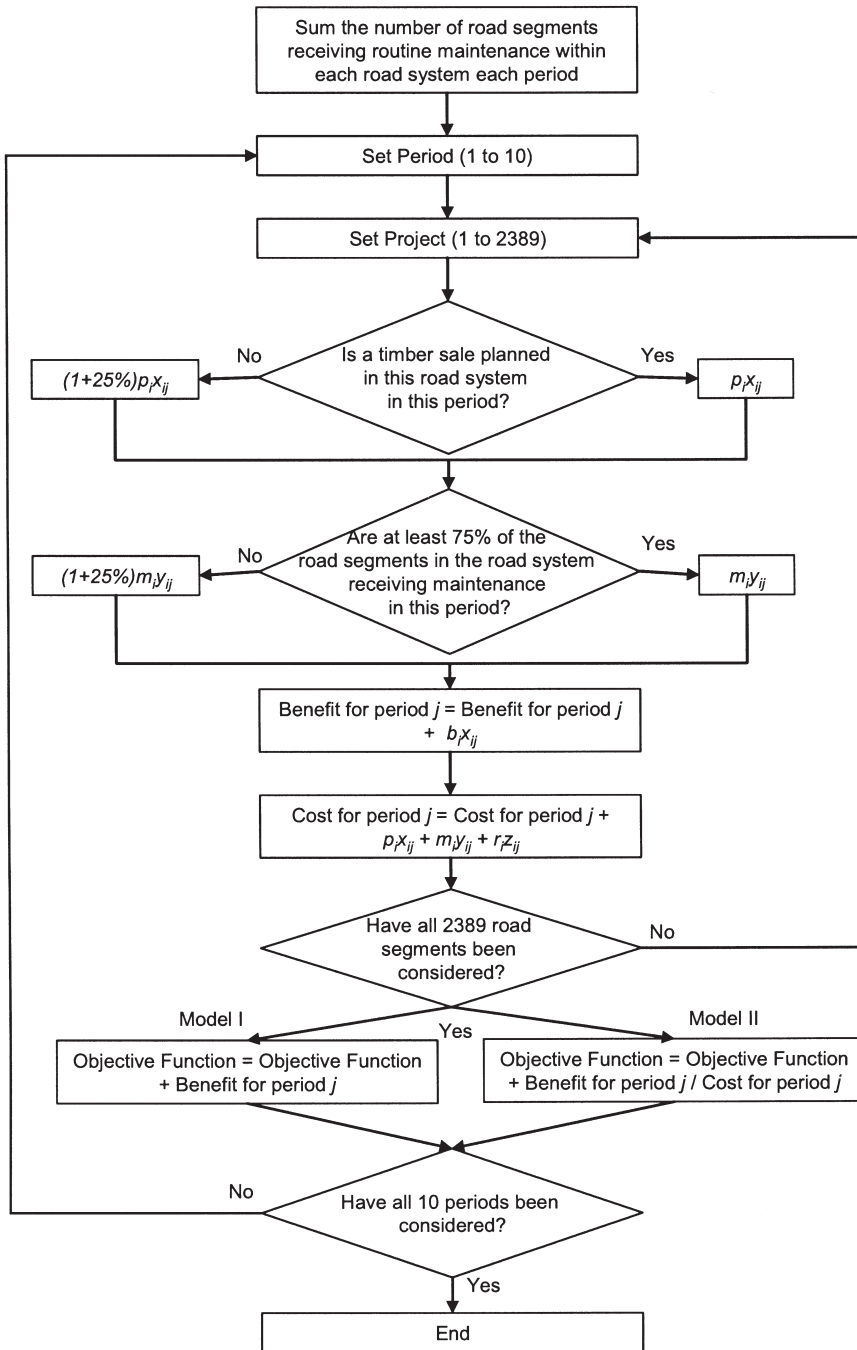
Fig. 5. Calculation of the objective function value.

this same surcharge was added to account for increased mobilization costs and decreased productivity of maintenance operations. Fig. 5 shows the procedure the algorithm used to calculate the objective function value for both Model I and Model II.

The model was coded in Visual Basic within a Microsoft Access database application and run on a 2.4 GHz Pentium 4 computer. Run times varied between Model I, Model II, and heuristic but were less than one hour for a single application of the heuristic which included 20 runs of the algorithm.

3   Results and Discussion

A budget of $250 000 per year was assumed. The optimal solution found after each run of Model II showed more variation between runs than Model I (Fig. 6). With Model II, those runs with low objective function values either conducted routine maintenance in all periods or grouped maintenance activities to start in years one and three. The lower objective function values indicate runs

when the algorithm was unable to escape from local maximums and illustrate why the algorithm included multiple runs of threshold accepting in order to identify superior solutions. Across the 20 runs of each model using each heuristic, the simulated annealing heuristic produced, on average, better solutions than did the threshold accepting heuristic by 7.5% for Model I and 14.2% for Model II.

The absolute values of the two objective functions are not comparable. The objective function value for Model I is the sum of the benefit values and nearly all projects were chosen for funding. At lower budget levels when not all projects can be funded, the variation in objective function values between model runs is nearly identical between the two formulations. Because the simulated annealing algorithms consistently outperformed the threshold accepting algorithms, results from the simulated annealing algorithms will be discussed below. The comparison between Model I and Model II results is similar regardless of solution heuristic.

The Model I formulation achieved nearly 100% of the total benefit using 96% of the total budget. The Model II formulation produced a solution
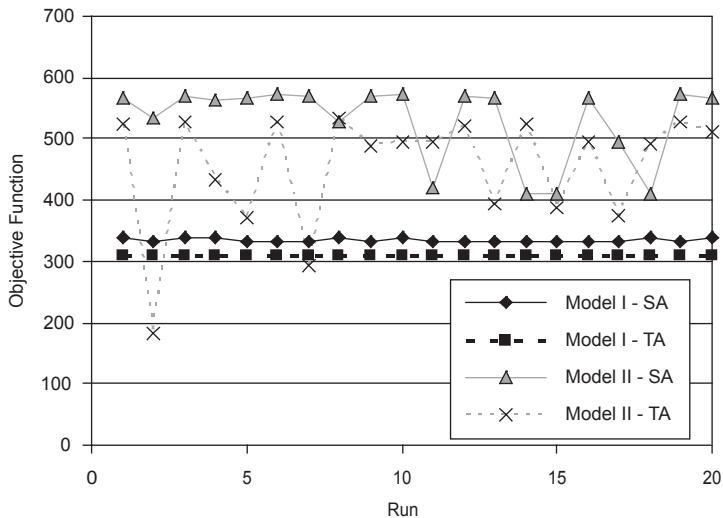

Fig. 6. Optimal objective function values for 20 runs each of Model I and Model II using both simulated annealing (SA) and threshold accepting (TA) solution techniques. The absolute values of the objective functions are not comparable between the two model formulations.
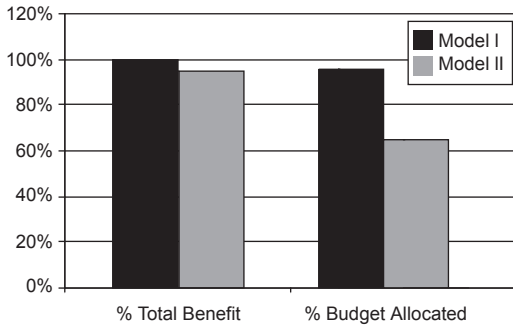
Fig. 7. Comparison of the potential benefit achieved and budget allocated during the 10-year planning period for Model I and Model II using an annual budget of $250 000.

that achieved 96% of the total benefit while using only 66% of the total budget (Fig. 7). Across the 10-year planning horizon, the benefit-only formulation (Model I) funded all maintenance and upgrade projects that provided benefit while the benefit-cost formulation funded 457 projects. The projects selected for funding that made the largest difference in total project expenditures between the two solutions is the exclusion of five bridge installations from the Model II solution. Each of these five projects would replace a stream-crossing

culvert, at the cost of $26 000 each, that is either currently passing fish but has some minor damage or a culvert spanning a stream with unknown fish use that would act as a fish passage barrier if fish were present. Additionally, the benefit-cost solution excluded a project to pull (repair) potentially unstable road fill that currently shows no signs of failure and would have cost nearly $100 000. These are projects that do provide benefit, but benefits which are not economically justified in the benefit-cost solution.

At the $250 000 budget level, all projects were funded with the Model I formulation. Within the Model II solution, there was a distinct difference between the benefit-cost ratio of individual projects chosen and not chosen for funding (Fig. 8). Projects with benefit-cost ratios less than 1 were funded opportunistically. For example, many of the projects within this range were ditch relief culverts that provide marginal benefit if replaced. If it was possible to schedule these projects in conjunction with a timber sale, they were scheduled. Otherwise, the project would have been subjected to a 25% cost premium and therefore was not often scheduled.

The benefit-cost formulation was able to decrease maintenance costs as well as project expenditures as compared to the benefit-only solution. This is a result of the cost minimization
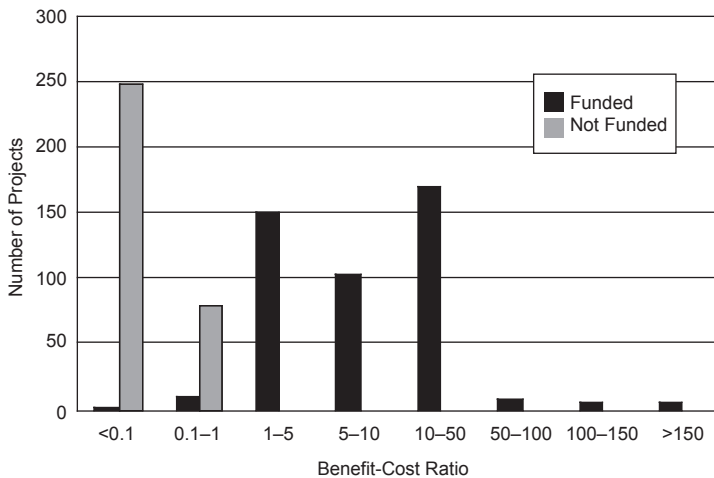

Fig. 8. Comparison of the benefit-cost ratios of funded and non-funded projects using the undiscounted Model II assuming a $250 000 budget.
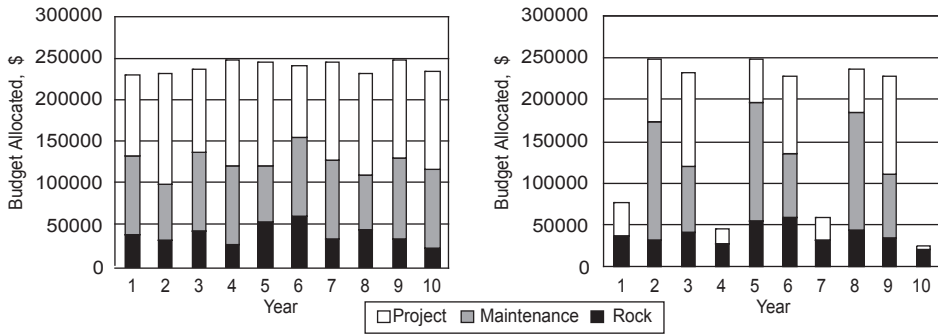
Fig. 9. Allocation of budget to projects, routine maintenance, and surfacing activities for each of the ten planning periods for a) Model I and b) Model II ($250 000 annual budget using simulated annealing).
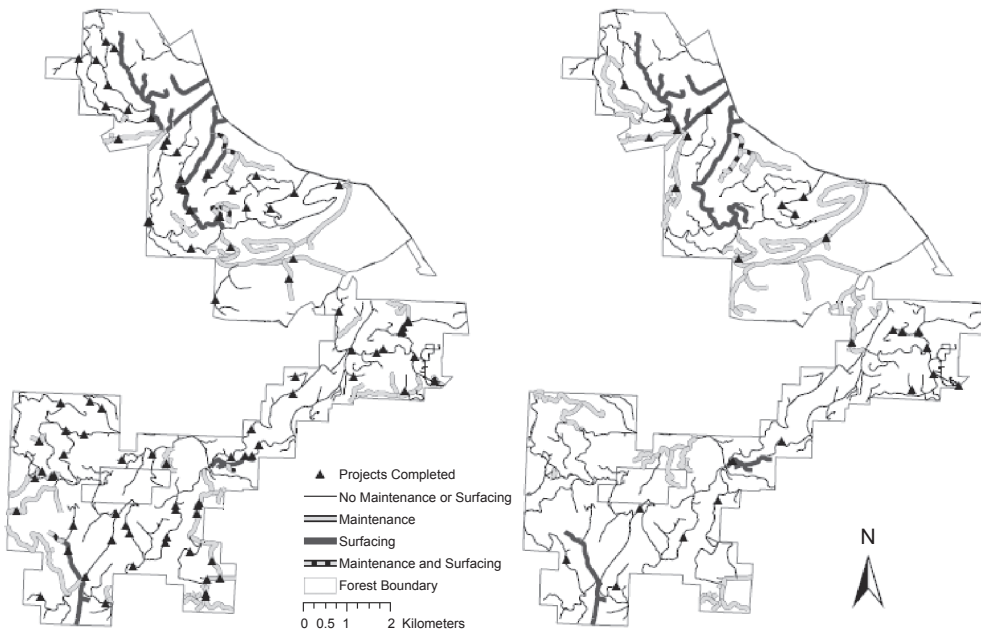

Fig. 10. Results for period 2 using the simulated annealing heuristic of a) Model I and b) Model II.

portion of the benefit-cost objective function that is absent in the benefit-only formulation.

The Model I solution allocated 48% of total expenditures to project work with 36% and 16% of total expenditures allocated to routine maintenance and new road surfacing, respectively (Fig. 9). The Model II solution allocated 36% of total expenditures to project work with 40% and

24% of total expenditures allocated to routine maintenance and new road surfacing, respectively. It is interesting to note that results using the threshold accepting algorithms were within one percent of those using the simulated annealing algorithms. The Model II solution moves all routine maintenance activities into the second and third year of the three-year maintenance cycle. An

Table 3. Comparison of total expenditures and total benefit realized across the 10 year planning horizon for two budget levels, with and without a time preference for when benefits occur.

| | $250 000 budget, undiscounted | | $250 000 budget, discounted | | |
	Total expenditures	Total benefit	Total expenditures	Total benefit	Discounted benefit
Model I	$2 406 529	33.84	$2 219 947	33.77	645.78
Model II	$1 639 269	32.14	$1 692 044	31.28	503.91
Percent difference	32%	5%	24%	7%	22%

artifact of using a 10-year planning horizon and a 3-year maintenance cycle is that maintenance activity in Year 1, 4, 7, and 10 are minimized. If a road is first maintained in Year 1 three more maintenance applications will be required. If, instead, a road is first maintained in Year 2 or 3, only two more maintenance applications will be required within the planning period.

Due to the added cost if entire road networks were not maintained at one time, the algorithm grouped maintenance when budget was limiting. In the case of Model I, the budget was not so limiting as to force the majority of each road system to be maintained at one time (Fig. 10), resulting in economic inefficiencies. For Model II, which included a cost minimization term in the objective function, the algorithm was always attempting to lower costs relative to benefits. This produced a solution where maintenance activities were much more concentrated in time and space.

Because project costs increased when not performed in conjunction with a timber sale, preference in scheduling was given by the algorithm in order to minimize costs. As a result, maintenance and upgrade projects were scheduled more opportunistically to coincide with timber sales. Since many road systems have timber sales planned for more than one year, this approach provided greater flexibility in scheduling.

Comparing expenditures and benefits for the two model formulations using both discounted and undiscounted benefits, benefits in the discounted models occur earlier for both Model I and Model II formulations over the undiscounted models (Table 3). In all cases, the Model I formulation produces a solution with a higher cost and higher total benefit than the Model II formulation with the same budget and discounting strategy.

The reduction in cost moving from the Model I to the Model II formulation is three to six times greater than the reduction in benefit for the same budget and time preference combination.

It is not reasonable to assume Model I would produce a solution similar to Model II with the same algorithm and budget constraints. Model II was able to reduce costs by eliminating routine maintenance in the maintenance cycle starting in year one. In the other years, however, Model II allocated a large percentage of the available budget to road activities. In order to get a similar solution using Model I, budgets would need to be set separately for each year.

4   Conclusion

AHP was used to define the benefit of maintenance and upgrade projects for low-volume forest roads. Two heuristics and two model formulations were compared that used this benefit term. A simulated annealing and a threshold accepting technique was used to schedule routine maintenance, aggregate surfacing replacement, and maintenance and upgrade projects for 140 miles of road in western Oregon considering formulations with and without time preferences. Both model formulations provide examples of how environmental benefits that are not defined monetarily can be incorporated into road maintenance scheduling. In addition, AHP provides a useful framework to provide quantitative measures of environmental benefit that can be used in modeling and scheduling algorithms.

The reduction in cost between the Model I (maximize benefit subject to budget constraints)

and Model II (maximize a benefit-cost ratio) formulations was three to six times greater than the reduction in benefit for the same budget and time preference combination. The choice between these objective functions remains with the decision maker and involves tradeoffs between budget expenditures and minimizing environmental impacts. Other objective functions and constraints can be substituted for the ones illustrated here. The approach demonstrated here allows road managers to incorporate environmental concerns and expert judgment into the development of a road management and upgrade schedule to a degree that is not possible with currently-available road management tools.

For this application, the simulated annealing heuristic was shown to produce superior results as compared with the threshold accepting heuristic. The characteristics of the solutions to both Model I and Model II formulations were similar between heuristics. Both heuristic search techniques provide flexible platforms for scheduling activities that can be subject to both linear and non-linear objectives and constraints.

Future work in this area could incorporate the environmental benefits (and costs) of road maintenance and use into the scheduling of other forest management activities such as timber harvesting. This would allow managers to weigh tradeoffs such as the seasonal impact of haul and resulting road standard upgrades versus seasonal market fluctuations in the decision of where and when to harvest timber.

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