Road Network Designs in Wood Supply Analysis

by

H.D. Walker¹ and W.H. Loughheed²

Abstract

A system for designing timber management strategies which considers the location, construction timing, and standards of road networks is presented. The system allows the effects of alternative road networks on economic wood supplies and timber management strategies to be assessed. A geographic information system is used to update stand attributes in response to alternative road networks, prior to analysis using a linear-programming-based forest planning model. A case study illustrating the planning system is briefly reviewed and instructions for obtaining system software are provided.

Key Words: timber management planning, geographic information system, spatial analysis, road network design, linear programming, wood supply analysis.

Résumé

Un système de conception des stratégies de gestion de la ressource ligneuse qui tiendrait compte de la localisation, de l'échéancier de construction, et des critères des réseaux routiers est présenté dans cet article. Le système permet d'étudier les effets de différentes possibilités de réseau routier sur l'approvisionnement économique et sur les stratégies de gestion de la matière ligneuse. Un système d'information géographique est utilisé pour mettre à jour les données relatives aux peuplements, en réponse aux différents réseaux routiers, avant d'analyser le problème en utilisant un modèle de programmation linéaire adapté à la foresterie. Une étude de cas illustrant le système de planification est brièvement étudié et les instructions pour obtenir le logiciel du système sont fournies.

Mots-clés: planification de la gestion de la matière ligneuse, système d'information géographique, analyse spatiale, conception de réseaux routiers, programmation linéaire, analyse de l'approvisionnement en bois.

Introduction

The design of timber management strategies requires controlling both the location and the timing of management actions. As well as scheduling harvesting and silvicultural activities within stands, this includes designing alternative road networks for transporting wood to storage locations and mills. The location, construction timing, and standards of road networks affect the areas accessible for forest operations and the expected haul costs for each cut block.

Designing and evaluating several alternative road networks is generally impracticable, because of the complexity and time-consuming nature of the task. Planners are thus typically restricted to reviewing only one or two alternative networks, often superficially at that. However, recent advances in spatial analysis realized with the use of a geographic information system (GIS) such as the Environmental Systems Research Institute (ESRI) ARC/INFO system (ESRI 1987) offer a means of improving road network design, by partially automating the process of assigning spatial and temporal stand attributes to reflect alternative networks. A GIS allows one to maintain a relational database linking the geographic location of features, such as forest stands, with their attributes.

This paper describes a system for designing timber management strategies which uses a GIS to help evaluate alternative road networks in terms of their effects on economic wood supplies. A simple wood supply model having

a linear programming (LP) structure is first presented, followed by a description of the manner in which a GIS may be used to readily update stand attributes in response to alternative road networks. A case study illustrating the planning system is briefly reviewed. A detailed discussion of the case study, and copies of all non-licensed programs required to implement the system, may be found in Loughheed (1988) and Loughheed and Walker (1988).

Wood Supply Model Structure

The Timber Resource Allocation Method (Timber RAM) modelling system (Navon 1971) was one of the first large-scale attempts at modelling the timber management planning problem using LP. A shortcoming of Timber RAM, and its successors MUSYC (Johnson and Jones 1980) and FORPLAN (Johnson *et al.* 1986), has been the difficulty of incorporating spatial considerations (Chappelle *et al.* 1976; Iverson and Alston 1986) into the LP structure. In the case of Timber RAM and MUSYC, spatial analyses were limited to increasing the percentage of accessible stand class area over time, mimicking road construction projects. FORPLAN allows further spatial analyses, although at a cost of increased model size and a requirement for integer programming formulations. (See Dykstra [1984] for an introduction to mathematical programming applications in forestry.)

The following simple model may be represented using any of the above modelling systems. We chose Timber RAM because of its availability, relative simplicity, and ease of use. The mathematical structure has an 80-year planning horizon, a 25-year critical period for optimizing objective functions, and 16 five-year planning periods. Data and exogenous

¹Weldwood of Canada Limited, Hinton Division, 760 Switzer Drive, Hinton, Alberta T7V 1V7
²Northwood Pulp and Timber Limited, Woods Division, Box 9000, Prince George, B.C. V2L 4W2

Table 1. Data elements

Name	Notation	Function
Stand class area	a_i	Initial area of stand class i (ha)
Area accessibility	ac_{ijk}	Percentage of stand class i accessible in period k , where $k = 1, 2, \dots, t_i$
Timing of access for treatment	b_{ijk}	1.0 if stand class i assigned to regime j produces volume in period k ; 0.0 otherwise
Treatment cost	c_{ijk}	Cost (\$) incurred in period k from each hectare of stand class i assigned to regime j
Periodic flow tolerance	f_k	Maximum percentage change in harvest level from period $k-1$ to period k , where $k = 1, 2, \dots, 16$
Periodic harvest level	h_{kl}	Minimum harvest volume of species l in period k , where $l = 1, 2, 3$
Number of stand classes	m	Initial number of stand classes
Number of regimes	n	Initial number of silvicultural regimes
Last period of constrained species harvest volume	p_l	Last period in which minimum harvest levels for species l are in effect, where $l = 1, 2, 3$
Discount rate	r	Real (deflated) discount rate
Species harvest volume	s_{ijkl}	Volume (m^3) of species l harvested in period k from each hectare of stand class i assigned to regime j , where $l = 1, 2, 3$
Last period of restricted access	t_i	Last period in which only a percentage of stand class i may be accessed
Total volume	v_{ijk}	Total volume (m^3) harvested in period k from each hectare of stand class i assigned to regime j
Minimum volume	z	Minimum total volume (m^3) obtained over 25 years

variable notation is shown in Table 1. Two LP formulations, volume maximization and cost minimization with constrained volume production, are used.

The volume maximization formulation is used to estimate the maximum productive capacity of the forest, under each of the alternative roading options, to produce total harvest volume over 25 years. Costs of attaining this volume are unconstrained, so a measure of the effectiveness of the set of management regimes for producing volume is obtained.

The cost minimization formulation is used to identify the lowest-cost strategy for achieving a particular total harvest volume over 25 years. The cost minimization formulation is employed, under each of the alternative access options, after the volume maximization formulation. The maximum volume level from the first formulation is established as the required volume level, and the minimum-cost strategy for attaining this level is determined. A measure of the efficiency of the set of management regimes for producing volume may be obtained by successive LP runs constrained to progressively lower volume levels. The result of this series of LP runs is

a set of volume-cost tradeoff points and associated timber management strategies.

Variables

Several possible treatment regimes (sequences of silvicultural treatments) are defined for each stand class, where a stand class is a collection of individual stands considered to have similar biological and economic attributes. Each alternative combination of treatment regime and stand class defines a decision variable. The level of a decision variable is the area, in hectares, of a particular stand class assigned to that treatment regime.

Composite variables are used to reflect harvest volume flow constraints and accessibility restrictions (defined below). Decision and composite variable notation is shown in Table 2.

Table 2. Decision and composite variables

Name	Notation	Definition
Management variables	X_{ij}	Area (hectares) of stand class i assigned to regime j
Accessibility variables	AC_{ik}	Area of stand class i accessed in period k , $k = 1, 2, \dots, t_i$, and t_i is the last period in which only a percentage of stand class i may be accessed
Periodic harvest level variables	HP_k	Total harvest level (m^3) from all stand classes in period k , where $k = 0, 1, 2, \dots, 5$

Objective Functions

A separate objective function is used for each formulation. Objective functions used are maximization of volumes harvested (from clearcut harvest and commercial thinnings) and minimization of discounted treatment costs (establishment, tending, harvest, and transportation costs). The volume maximization objective function has the form

$$\text{Maximize VOLUME (m}^3\text{/5 periods)} = \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^5 v_{ijk} \cdot X_{ij} \quad [1]$$

The cost minimization objective function has the form

$$\text{Minimize COST (\$/5 periods)} = \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^5 c_{ijk} \cdot X_{ij} / (1+r)^{5k-2.5} \quad [2]$$

All treatment costs are assumed to be incurred at the midpoint of each planning period.

Constraint Functions

Area availability constraint functions (one for each initial stand class) ensure that the total area of each initial stand class assigned to the various regimes does not exceed the total available area of that stand class. These have the form

$$\sum_{j=1}^n X_{ij} \leq a_i, \text{ for } i = 1, 2, \dots, m \quad [3]$$

Area accessibility constraint functions (up to five for each initial stand class) restrict by period the area accessible for management. These reflect the different amounts and timings of area available for management from alternative road networks. These have the form

$$AC_{ik} \leq ac_{ik} \cdot a_i, \text{ for } i = 1, 2, \dots, m; k = 1, 2, \dots, t_i, \quad [4]$$

where the composite variable AC_{ik} is defined as

$$AC_{ik} = \sum_{j=1}^n b_{ijk} \cdot X_{ij}, \text{ for } i = 1, 2, \dots, m; k = 1, 2, \dots, t_i \quad [5]$$

A minimum volume level constraint function ensures that the total volume level produced from harvests occurring during the critical period is at least equal to a specified minimum volume level. This function links the two objective functions by specifying the volume level for which the cost objective is optimized. It has the form

$$\sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^5 v_{ijk} \cdot X_{ij} \geq z. \quad [6]$$

Moderation of harvest level fluctuations during the planning horizon is achieved by flow constraint functions which restrict harvest levels in each period to a percentage range above and below the harvest level in the preceding period. Increases to harvest levels are restricted by

$$HP_k \leq (1 + f_k) HP_{k-1}, \text{ for } k = 1, 3, \dots, 16, \quad [7]$$

where the composite variable HP_k is defined as

$$HP_k = \sum_{i=1}^m \sum_{j=1}^n v_{ijk} \cdot X_{ij}, \text{ for } k = 1, 2, \dots, 16. \quad [8]$$

Decreases to harvest levels are restricted by

$$HP_k \geq (1 - f_k) HP_{k-1}, \text{ for } k = 1, 3, \dots, 16. \quad [9]$$

Current harvest levels are period zero (0) levels.

Minimum total species volume requirements for specified periods are restricted by periodic harvest constraint functions, having the form

$$\sum_{i=1}^m \sum_{j=1}^n s_{ijkl} \cdot X_{ij} \geq h_{kl}, \text{ for } k = 1, 2, \dots, p_l, \text{ and } l = 1, 2, 3. \quad [10]$$

Linear Programming Formulations

The volume maximization formulation is

Maximize

$$\text{VOLUME (m}^3/5 \text{ periods)} = \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^{16} v_{ijk} \cdot X_{ij}, \quad [1]$$

subject to

$$\sum_{j=1}^n X_{ij} \leq a_i, \text{ for } i = 1, 2, \dots, m, \quad [3]$$

$$AC_{ik} \leq ac_{ik} \cdot a_i, \text{ for } i = 1, 2, \dots, m; k = 1, 2, \dots, t_i \quad [4]$$

$$\sum_{j=1}^n (b_{ijk} \cdot X_{ij}) - AC_{ik} = 0.0, \text{ for } i = 1, 2, \dots, m \text{ and } k = 1, 2, \dots, t_i \quad [5]$$

$$HP_k - (1 + f_k) HP_{k-1} \leq 0.0, \text{ for } k = 1, 2, \dots, 16, \quad [7]$$

$$HP_k - \sum_{i=1}^m \sum_{j=1}^n v_{ijk} \cdot X_{ij} = 0.0, \text{ for } k = 1, 2, \dots, 16, \quad [8]$$

$$HP_k - (1 - f_k) HP_{k-1} \geq 0.0, \text{ for } k = 1, 2, \dots, 16, \quad [9]$$

$$\sum_{i=1}^m \sum_{j=1}^n s_{ijkl} \cdot X_{ij} \geq h_{kl}, \text{ for } k = 1, 2, \dots, p_l, \text{ and } l = 1, 2, 3, \quad [10]$$

$$X_{ij} \geq 0.0, \text{ for } i = 1, 2, \dots, m; j = 1, 2, \dots, n. \quad [11]$$

Equation [11] describes a set of non-negativity constraint functions, which ensure that all decision variables are assigned non-negative values.

The cost minimization formulation is

Minimize

$$\text{COST (\$/5 periods)} = \quad [2]$$

$$\sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^5 c_{ijk} \cdot X_{ij} / (1 + r)^{5k-2.5},$$

subject to

$$\sum_{j=1}^n X_{ij} \leq a_i, \text{ for } i = 1, 2, \dots, m, \quad [3]$$

$$AC_{ik} \leq ac_{ik} \cdot a_i, \text{ for } i = 1, 2, \dots, m; k = 1, 2, \dots, t_i, \quad [4]$$

$$\sum_{j=1}^n (b_{ijk} \cdot X_{ij}) - AC_{ik} = 0.0, \text{ for } i = 1, 2, \dots, m \text{ and } k = 1, 2, \dots, t_i, \quad [5]$$

$$\sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^5 v_{ijk} \cdot X_{ij} \geq z, \quad [6]$$

$$HP_k - (1 + f_k) HP_{k-1} \leq 0.0, \text{ for } k = 1, 2, \dots, 16, \quad [7]$$

$$HP_k - \sum_{i=1}^m \sum_{j=1}^n v_{ijk} \cdot X_{ij} = 0.0, \text{ for } k = 1, 2, \dots, 16, \quad [8]$$

$$HP_k - (1 - f_k) HP_{k-1} \geq 0.0, \text{ for } k = 1, 2, \dots, 16, \quad [9]$$

$$\sum_{i=1}^m \sum_{j=1}^n s_{ijkl} \cdot X_{ij} \geq h_{kl}, \text{ for } k = 1, 2, \dots, p_l, \text{ and } l = 2, 3, \quad [10]$$

$$X_{ij} \geq 0.0, \text{ for } i = 1, 2, \dots, m; j = 1, 2, \dots, n. \quad [11]$$

The Planning System

Within the planning system, haul costs are calculated for each of the first five periods. Minimum cost and access time are assigned as attributes to individual stands, to account for road construction. Stand access time is assumed to be the period in which the haul cost first reaches a minimum. Based on the relationship of expected travel time from each stand to the mill, "haul zones" are generated. Aggregation for each time period, based on both traditional inventory criteria and the generated criteria of access timing and haul cost, permits determining forest age structures by haul zone for each future time period. Alternative roading strategies result in different forest age structures over time.

The system consists of two primary activities, data acquisition and simulation (Figure 1).

Data Acquisition

Two levels of GIS-resident data are required. Strata data are required to categorize each stand and forest data are required to characterize the forest as a whole. Data acquisition culminates with stratification of the forest area into stand classes, based upon temporal and spatial data elements.

Figure 1. Management planning system.

Forest-level objectives and constraints are derived from the physical and economic requirements of the organization managing the forest property. Temporal data include the total volume and cost objectives and constraints on total volume harvest flows. Spatial data include digital maps containing roading alternatives for five periods into the future. Procedures suggested for designing roading alternatives vary from subjective placement to optimal road location (Weintraub and Navon 1976; Jones *et al.* 1986; Kirby *et al.* 1986). Roading alternatives are the bases for determining transportation costs.

Temporal strata-level data include age-dependent harvest costs and harvest volumes. Volume development curves, reflecting the growth and yield of a stand over time in response to alternative silvicultural regimes, and roadside harvest costs (age-dependent costs of transforming standing timber to piles at roadside), are derived.

Spatial strata-level data include location, size, accessibility, timing of access for management, and the last period of restricted access. These are derived using the haul cost algorithm described below.

The haul cost algorithm bridges the gap between strata-level and forest-level data, as shown by the boxed area in Figure 1. Zones of equivalent haul cost (haul zones) are derived as one of the criteria for stratifying the forest into stand classes. Forest-level roading alternatives affect the area in each stand class over time.

The haul cost algorithm is implemented using two CPL (Command Processing Language; Landy 1986) routines. The first routine, DEFBAT.CPL, is a pre-processor which creates a CONTROL file for executing the second CPL routine. Executed as an interactive program, DEFBAT.CPL prompts the user for the data listed in Table 3. A detailed description of the map coverages (digital maps and associated attribute files) used in this process is given in Table 4. Once verified, coverage names are written from the coverage files to the CONTROL file.

The second routine, HAULCOST.CPL, performs the haul cost analysis according to the specifications in the CONTROL file. HAULCOST.CPL attaches the haul cost and time of access attributes, for each stand in the forest, to an INVEN-

TORY file. The procedure used within HAULCOST.CPL is as below.

Table 3. Data requirements

Data	Format	Comments
ROAD	map coverage	One map of all roads for 5 five-year planning periods
STAND	map coverage	Up to 20 forest stand maps
INVENTORY FILE	attribute file	Name of up to 20 files containing STAND attributes
RELATE ITEM	name	One item name common for each STAND and INVENTORY file
BARRIER	map coverage	Up to 20 polygon coverages of physical barriers to access
SEARCH TOLERANCE	number	maximum distance from a stand to the nearest road for access to be achieved
HAUL SPEED	number	Up to five classes of road assigned a haul speed (km/h)
ACCESS POINTS	number	Two-way travel time between up to five access points and haul destination(s)

Table 4. Map coverage descriptions

Coverage	Description
ROADS	Line coverage. Two-digit code to indicate the period first available and road class. For example, "25" identifies a class 5 road available in period 2.
STAND	Polygon coverages. An INVENTORY file must contain the stand attribute data, linked by the RELATE ITEM.
BARRIER	Polygon coverages. Normally a subset of STAND coverages, i.e. lakes and two-line (major) rivers. Two-line rivers must break at a bridge or a planned bridge. Islands, or "donuts" within barrier polygons result in errors, and must be removed from the barrier coverages.

1. *Initialize.* Read coverage and numeric data from the CONTROL file.

2. *Create ROADS coverage.* Create ROADS coverage representing the road networks as they would exist during five periods in the future. ROADS is coded to enable extracting of the roads existing during each period (ROAD1 through ROAD5), using the ARC ARCDIT utility (ESRI 1987).

3. *Generate minimum-distance line coverages.* Line coverages MINARC1 through MINARC5 are created containing all ROAD arcs existing in that period, the associated MINDST arcs, and all intersected BARRIER polygons. This is completed using the Fortran-77 program MINARC.F77. The program reads the arcs, removes barriers, and prints all MINDST arc endpoint coordinates to scratch files (MINDST1 for ROAD1, MINDST2 for ROAD2, etc.). The ARC GENERATE (ESRI 1987) utility creates the ARC/INFO coverages MINARC1 through MINARC5 from the scratch files.

If the distance between a stand and the nearest road is greater than the search tolerance, the stand is considered inaccessible at that time. With a fine road network, a small search tolerance is applicable, whereas broad road corridors require a large search tolerance to approximate construction of access roads. Sections of the MINDST arcs which

intersect BARRIER polygons are deleted, with hauling assumed to be along the perimeter of the BARRIER polygon. To link the MINARC and STAND coverages, each of the minimum distance arcs in the MINARC coverages is assigned the same id as the associated stand polygon.

4. *Calculate arc travel times.* Arc travel times are assigned to each arc in the five MINARC line coverages. The travel times are dependent on the arc length and the haul speed, with the haul speed determined by the road class. INFO (Henco Software 1985) processing is used for calculating arc travel times and assigning these times as the impedance or "cost" of travelling the arc.

5. *Calculate cumulative travel times.* Calculate the minimum cumulative time required to travel from a forest access point to each arc in the network. The ARC ALLOCATE utility (ESRI 1987) is used to perform this procedure. ALLOCATE determines the minimum-impedance path from the access points to each arc in the network, storing the cumulative impedance (time) as an attribute of each arc. INFO processing is used to add the two-way travel time between the mill and the forest access point for each stand.

6. *Calculate haul costs.* Calculate the haul cost (\$/m³) from the cumulative haul time of each arc in the five MINARC coverages. This procedure is performed only for those MINDST arcs associated with a stand in one of the STAND coverages. Haul cost is a function of the time required for a round-trip haul and the hourly labour (regular time and overtime) and machine rates (tractor and trailer). The INFO program COST accesses the cumulative impedance attributes in the MINARC coverage, calculates the haul costs, and writes the stand identifier and haul cost to a temporary file. Five temporary files are created, MINARC1.TAB through MINARC5.TAB.

7. *Determine timing of access for each stand.* Determine the period at which the haul cost first reaches a minimum. This period is considered as the time of first access. The period and the associated haul cost are written as attributes to the appropriate INVENTORY file. This procedure is implemented in INFO, using both interactive and program formats. The interactive sections relate the MINARCx.TAB files with the STAND coverage, which, in turn, is related to the INVENTORY file. The INFO program TRANSFER calculates, from the MINARCx.TAB files, the period of first access, and the associated haul cost for each stand in the STAND coverages. The resulting minimum cost period (MCP) and minimum cost (MC) for each arc are written as attributes to the INVENTORY file.

8. *Determine stand class areas.* Stand class areas are calculated using the inventory map coverages maintained on the GIS. INFO reports are used to perform the stratification based on haul zone, stratum, and age class. The stratified areas are subsequently used in simulation.

Simulation

Simulation consists of implementing the mathematical structure within the LP framework. The LP package XMP (Marsten 1986) accepts the input matrix generated by Timber RAM from the forest-level and strata-level data, and solves the LP problem. Minor changes to Timber RAM were made to include up to three volume development curves for each stand class, thereby allowing species-specific volume constraints. Timber RAM was also modified to provide reports of harvest volume by species, and harvest area totals by haul zone. These modifications were specific to the requirements of the Case Study.

Case Study

A 980-km² project area was located near Thunder Bay, Ontario. The area consisted of approximately 66 500 ha of productive forest land within the Dog River - Mattawin Forest, a 6 773-km² area of Crown Land managed by Great Lakes Forest Products Ltd. (GLFP) under a Forest Management Agreement (Ontario Ministry of Natural Resources 1985). Major species represented were: spruce (*Picea glauca* [Moench] Voss and *Picea mariana* [Mill.] B.S.P.), fir (*Abies balsamea* [L.] Mill.), jack pine (*Pinus banksiana* Ait.), aspen (*Populus tremuloides* Michx.), and birch (*Betula papyrifera* Marsh.). GLFP staff provided project data.

A preliminary stratification was used to assess requirements for age-dependent volume and economic data. Ten strata were recognized and alternative treatment regimes were developed for each stratum. For each regime, volume development curves were derived for each stratum using the stratum species composition (weighted average, by area) and the stratum density (weighted average, by area) applied to the pure species curves of Plonski (1981).

Area-based costs (\$/ha for scarification, planting, seeding, and herbiciding) were provided by GLFP staff. Volume-based costs were comprised of harvest costs and haul costs. Age-dependent harvest costs for natural stands and plantations were calculated using procedures described in Loughheed (1988). Haul costs were calculated using HAULCOST.CPL.

Alternative Road Networks

Restricted access due to road network construction was permitted for five five-year periods. Two roading alternatives were defined for the project area. Network 1 (258 km of roads) was acquired from GLFP records (Great Lakes Forest Products, n.d.), along with estimates of the proposed areas to be harvested, with no road construction planned for Period 5. Network 2 (238 km of roads) was contrived, save for the two Class 2 roads existing in Period 1. The objective of defining Network 2 was to assess the effects of an alternative access option on sustainable harvest levels, costs and treatment schedules. MINARC maps for portions of the two networks are shown in Figures 2 and 3. Table 5 shows the area accessed by each network over time.

Table 5. Area accessed by Networks 1 and 2 over time

Period	Network 1		Network 2	
	Area (ha)	% of Total	Area (ha)	% of Total
1	7 483	17	8 397	17
2	8 546	19	21 502	42
3	34 442	77	34 557	68
4	44 641	100	38 715	76
5	44 641	100	50 694	100

To assess the effects of roading, haul costs, and timing of access on sustainable harvest levels, mill gate costs and harvest schedules, several problem formulations based upon Networks 1 and 2 were analyzed. Table 6 describes the alternative problem formulations. Each alternative required the accessed area to be stratified into stand classes.

The simplest area stratifications were for the CONTROL and NET1c alternatives. Both assumed a constant haul cost, resulting in stratification of the respective forest bases by age classes within strata. Figure 4 shows the area by stratum for the CONTROL alternative. Age classes were omitted for clarity, and for comparison with other forest bases.

Figure 2. Network 1 MINARC4 coverage showing available harvest area by period for Base Map 485903.

Figure 3. Network 2 MINARC5 coverage showing haul zones for Base Map 485903.

Table 6. Alternatives analyzed in case study

Alternative	Forest Base (road Network)	Access Constraints ¹	Haul Costs ²	Flow Constraints (percent)
CONTROL	Full	No	Constant (\$7/m ³)	+/- 5
NET1a	Network 1	Yes	Zone	+/- 5
NET2	Network 2	Yes	Zone	+/- 5
NET1b	Network 1	No	Zone	+/- 5
NET1c	Network 1	No	Constant (\$7/m ³)	+/- 5

¹ - Yes - Timing of access constraints included
No - Timing of access constraints excluded

² - Constant - All areas assumed in Zone 7
Zone - Areas stratified into Zones 5, 7, and 9

Figure 4. Forest structure of CONTROL alternative in period 5.

Area stratification for alternatives NET1a and NET1b was more complex because of the addition of haul zones and timing of access constraints. Three haul zones were defined at intervals of \$2/m³. The zones were termed Zone 5, 7 and 9, corresponding to the cost per cubic metre of transportation to the mill. Each stand in the forest base was assigned to a haul zone, determined by the value of its MC (Minimum Cost) attribute. Timing-of-access constraints required five area stratifications to be performed, one for each of the first five periods. The forest base in period 1 consisted of all those stands which had the MCP (Minimum Cost Period) attribute equal to 1. The period 1 forest base was stratified by age class within strata within haul zone. The stratification was repeated for the accumulated forest bases in each period (Figures 5 and 6). The period 5 forest base then consisted of all stands with MCP value between 1 and 5 (0 indicated no access, beyond search tolerance). Figures 7 and 8 depict the distribution of area among haul zones during the last period of road construction activity (final forest base) for alternatives NET1a and NET2, respectively. Both the total area by strata and the expected haul costs are affected by subjectively defined alternative road networks.

A Timber RAM datafile was created for each of the alternatives. Basic volume and economic data were the same for each alternative. Differences among alternatives resulted from the amount and timing of areas accessed, and transportation costs.

Results

Figure 9 summarizes the results of a series of simulations made with Timber RAM for the CONTROL, NET1a and NET2 alternatives. Each point represents a cost minimization objective, with a constrained harvest level over 25 years.

Figure 5. Forest structure of NET1a alternative by period.

Figure 6. Forest structure of NET1b alternative by period.

Figure 7. Forest structure of NET1a alternative in period 4 showing haul zones.

Figure 8. Forest structure of NET2 alternative in period 5 showing haul zones.

The right-most point on each curve was determined by first maximizing harvest volume, followed by minimizing costs while obtaining the maximum harvest volume.

The CONTROL mill gate costs assumed an average haul cost of \$7/m³. Higher harvest levels required that increasing

Figure 9. Production possibility curves for CONTROL, NET1a, and NET2 alternatives.

amounts of harvest area be intensively treated, at higher costs, to achieve the minimum volume constraint. At lower harvest levels, non-intensive treatment regimes were chosen, because the harvest level constraint was easily satisfied with inexpensive natural regeneration. Increasing savings would be made as volume requirements decreased.

The results of NET1a and NET2 indicate the effects of the partial forest base lowering the maximum sustainable harvest level. The total area accessed by NET2 was 50 649 ha by period 5, while NET1a accessed only 44 641 ha by period 5. Roding in NET2 was more intensive than NET1a, resulting in more area accessed at an earlier time. The effect on sustainable harvest is observed in Figure 9 in two ways. First, NET2 has a lower mill gate cost than NET1a throughout, caused by the larger forest base allowing more periodic harvest to be from less costly stand classes. Second, the slower rise in the slope of NET2 was the result of the larger forest base satisfying the harvest level constraint requiring less harvest area be treated intensively than NET1a at the same harvest level. Detailed harvest schedules for the various alternatives may be reviewed in Loughheed (1988).

To explore the reasons for the shape of the NET1a production possibility curve, two additional series of Timber RAM simulation runs were made. Both NET1b and NET1c omitted timing of access constraints, while only NET1b included haul costs. NET1c then was different from CONTROL only in the partial forest base. Figure 10 shows the results of these simulation runs. Removal of the timing of access constraints has the dual effect of increasing the maximum sustainable harvest level and decreasing the intensively treated area required to achieve a given harvest level, which in turn reduces the mill gate cost.

Figure 10. Production possibility curves for NET1a, NET1b, and NET1c alternatives.

Discussion

The case study showed that the planning system is capable of addressing the problem of jointly designing timber management strategies and primary road networks. For those organizations already supporting ARC/INFO and a database, the system presents an additional opportunity for exploiting GIS analytic potential. The system provides a means of determining, by period, the area available for harvest within each stand class, resulting from alternative road networks. Treatment schedules should therefore be more implementable than where timing of access is ignored, although treatments specified for each stand class in a five-year period must still be allocated by planners in terms of annual treatments to stands. This provides an opportunity for operational planning suited to the individual organization. However, usefulness of this or any planning system is still limited by the quality of the available database.

The system is not restricted to timber management planning. For example, HAULCOST could be used on a smaller time scale for operational planning. The additional attributes could also be used for producing maps of accessible areas by time period, and haul cost zones. HAULCOST can be modified to perform the analysis based on other parameters. COST.PG calculated haul costs based on travel time, but any descriptor of the arc may be used with any function to calculate impedance values to be used in the ALLOCATE procedure. Users familiar with the tool may adapt it to their particular situation.

Transferability of the system described in this paper may be difficult because of the required access to a GIS and a maintained database. Use of HAULCOST requires access to the ARC/INFO GIS. However, modifications to the various programs

available in Lougheed (1988) and Lougheed and Walker (1988) are possible. Changes would require knowledge of Fortran programming, ARC/INFO commands and CPL programming. Modifications to the HAULCOST algorithm may require changes to only the ARC/INFO or CPL routines, a relatively simple task. Changes to the MINARC.F77 program would require knowledge of the internal ARC/INFO data structures, and would be a relatively major undertaking. Licensed software used to develop the system described in this paper includes:

- ARC/INFO Geographic Information System (ESRI 1987);
- Lotus 1-2-3 spreadsheet system (Lotus Development Corporation 1985);
- WordPerfect text processing system (WordPerfect Corporation 1985);
- XMP mathematical programming system (Marsten 1986);
- F77 FORTRAN compiler (Burns 1985); and
- PRIMOS operating system (Lamb and Landy 1982).

Figure 11 shows how the various components of the planning system are linked.

Copies of Lougheed (1988) and Lougheed and Walker (1988), including the non-licensed software required to implement the system, may be obtained from:

Socio-economic Analysis and Planning Unit, Great Lakes Forestry Centre, 1219 Queen Street East, Sault Ste. Marie, Ontario P6A 5M7 CANADA

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- ① Acquire data
- volumes and harvest costs (PC)
- coverages and inventory files (Prime)
- ② Derive data
2a - spatial (haul costs and timing of access by stand)
2b - non-spatial (volume and economic classes)
- ③ Transfer data (Kermit)
- Prime to PC
- ④ Edit datafile
- Lotus 123, WordPerfect
- ⑤ Transfer datafile (Kermit)
- PC to Prime
- ⑥ Solve LP model
- ⑦ Report LP solution

Figure 11. Linkages among system components.

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