ROADPLAN: A Tool for Designing Forest Road Networks

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ABSTRACT

The ROADPLAN model produces a road network plan for a forest area that is being accessed for the first time. It is based on a raster geographic information system (GIS), for each cell of which the harvesting priority (based on available merchantable volume) is known and the cost of road construction can be estimated. Wood transportation cost ($/$m^3$.km) is assumed to be constant. All potential cutblocks, taking into account specified volume and area constraints, are first identified. For each cutblock, the cost of constructing potential road links to all points on the existing network and the cost of transporting wood over each link and along the network to one of the access points to the area are calculated. At every step the cutblock with the minimum combined construction and transportation cost (in $/$m^3$) is added to the network. The model was developed and tested on data from a simulated forest, and then further evaluated on a 100 000 ha forest block in northern Ontario where it was found to produce realistic networks similar to that planned for the area. Compared with existing models, ROADPLAN permits considerable flexibility in generating the road network.

Keywords: *road planning, cutblock selection, computer simulation, raster geographic information system.*

INTRODUCTION

A component of integrated forest management planning in Canada is a road plan that shows the network of forest roads to be constructed over a period, usually five years. The roads are required to access stands scheduled for harvesting during the period. Selection of the stands has become a complex problem as the needs of all users of the forest resource have to be taken into consideration and not just the needs of the forest industry for timber. To aid the forest management planner, a number of decision support systems have been developed in recent years that take advantage of Geographic Information Systems (GIS), Database Management Systems (DBMS), and advanced analytical methods. Examples of these are the HSG wood supply model [8], the simulated-annealing based model of Lockwood and Moore [6], mixed integer planning models [4,9], and GIS-based models [1,10,11,13,16]. In mountainous areas, where slope is an important factor in laying out a road system, digital terrain models are used [5]. Fridley and Schiess [3] developed a computer-aided engineering system that integrated a GIS with existing models for cutblock selection and layout and transportation planning in mountainous terrain.

Where the area in which harvesting is to take place is fairly extensively covered by roads, the planning of additional access is usually straightforward because there are few alternatives to be considered. Planning in such cases concentrates on the selection of the optimum route from each harvested stand, or landing, to the appropriate mill; thus transportation cost is an important factor.

Where an area is being accessed for the first time, roads may be non-existent and the planner has the task of designing an extensive new network at the lowest possible cost. In such cases, the cost of road construction is the major contributing factor to overall cost.

Some models [e.g., 12] assume that the nodes (harvested stands or landings) are predetermined and the construction, maintenance, and transportation costs are known for every possible link. Other models [e.g., 9,14] select harvest areas and the road network simultaneously. Another approach is to divide the area into a grid of cells that may vary in size from 50x50 m [13,14] to 1x1 km [2]. Each cell is then assigned a rating related to road cost based on topography, soil type, ownership, etc. Douglas and Henderson [2], Minamikata [7], and Phillips et al. [11] use the minimum path algorithm to generate a minimum cost network. Other methods, such as Monte Carlo integer programming, do not guarantee optimum solutions but are more efficient in complex situations.

The ROADPLAN model outlined in this paper is designed to develop a road network for a previously unaccessed area. It creates cutblocks of a specified maximum area (with a specified minimum volume), based on harvesting priority, and links each to any point (i.e., not necessarily a node) on the existing

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road network. A leave-strip or buffer may be designated around each cutblock in which no harvesting may take place for at least 15 to 20 years, which is greater than the balance of the planning period (usually five years). The model does not produce an optimum or minimum cost solution but can be used as a simulation tool to test different values for construction and transportation costs, and for the constraints. Compared with most existing models, ROADPLAN permits considerable flexibility in generating the road network.

DATA

Initial development of the model was done using a simulated forest of 7800 1-ha cells. Once the initial procedures had been implemented, further refinement and testing was done using data from the northwestern section of the Iroquois Falls Forest Management Unit (FMU) in northern Ontario (Figure 1). This area was chosen because of the quality of the database (GIS and forest resource inventory) that was available and because there was also a preliminary road network plan with which to make comparisons. The area was 120 000 ha, of which approximately 100 000 ha was within the FMU. Existing roads came only to the southern boundary at two separate points. A third road came to the eastern boundary but, as it was not extended or linked with the network planned for the area, was not considered as an access point.

The vector GIS for the area was converted to a raster GIS with a "pixel" size of 50x50 m. To reduce the size of the database and computing time, these pixels were then grouped into "cells" of 250x250 m (6.25 ha). For each cell the following values were calculated from the inventory data:

1. The average volume of merchantable species (spruce, fir and jack pine) in m^3/ha.

2. A "roadability" factor.

The roadability factor was based on the number of pixels within the cell that were classified as water or muskeg (e.g., if 15 pixels were water or muskeg, the roadability factor would be 15/25 or 60%). This factor would then be used to increase the baseline road construction cost for the cell (e.g., if the baseline cost was $20 000/km, the adjusted cost would be 20 000 x 1.60 = $32000). Cells with a roadability factor greater than 80% were considered to be inaccessible to roads. A more realistic roadability factor, based on more extensive and detailed field information not available for this study, would be preferred.

In determining roadability, the ROADPLAN model does not take into account slope and other topographical features of the landscape and so would not be applicable in mountainous conditions. Including slope in the model would greatly increase its complexity; for example, a cell could no longer be considered roadable in all directions but only where slope permitted construction. This could result in two adjoining cells both being "roadable" but not directly "connectable."

METHOD

The first step was to calculate the volume of wood that was available for harvesting in each cell. This consisted not only of the wood in that cell but also of the merchantable wood in the surrounding cells that were within a specified maximum forwarding distance. In each case, only those cells containing more than a specified minimum merchantable volume per ha were included in the calculations. To be considered as the centre of a cutblock, the overall average volume for the potential cutblock must have also exceeded a specified minimum value. For each cell that qualified as a potential cutblock, the straight-line path, or link, to each cell on the existing road network (initially one of the two access points) was determined, together with the cost of constructing the road link and the cost of transporting the potential harvest to the appropriate initial access point. The combined cost, Cm, was calculated as:

$$C_m = (F / 1000)\left\{\sum_{j=1}^{L_n} c_j + \sum_{i=1}^{n}\sum_{j=1}^{L_i} T_{ij} \cdot W\right\}$$

where:

Cm = the combined cost of constructing the link and of transporting the harvested wood to the appropriate access point ($/$m^3$)
m = the set of all possible links between the cutblock and existing road cells
F = cell dimension (m)
c_j = construction cost in cell j of link n ($/km)
T_{ij} = transportation cost in cell j of link i ($/$m^3$.km)
L_i = number of cells in link i
n = number of road links connecting the cutblock to an access point (link n being the final link to the cutblock)

W = transportation cost weighting factor

If any cell on the straight line between the cutblock centre and a road cell included a cell that was "unroadable" (inaccessible to roads and identified by a negative construction cost), that path could not be considered as a link. For each potential cutblock, the link with the minimum value of C_m (C_{min}) was retained.

In the preliminary testing of the model, when realistic values for construction and transportation costs were used, the length of road was minimized, which resulted in a tendency for the road links to circle round on themselves (most noticeable when the construction/transportation cost ratio was high). This was because network construction is incremental; once a road link had been selected it could not be replaced later by what may overall be a less costly route. The transportation cost weighting factor, W ($\geq$1), was introduced to reduce the construction/transportation cost ratio so that more emphasis was placed on reducing travel distance in selecting road links. W only affected this ratio, and not the actual cost, so the overall result was generally a reduction in delivered wood cost and more realistic networks.

Once the values of C_{min} had been calculated for all eligible cells, the cells MIN_1 and MIN_2 with the two lowest values were identified. MIN_1 was selected as the next cutblock centre and the minimum cost link between it and the existing road network added to the network. If cell MIN_2 was still a potential cutblock centre (i.e., harvesting from MIN_1, or the establishment of a leave strip, had not reduced its volume below the allowable minimum), its C_m values for the potential links with the addition were calculated and its C_{min} value revised if necessary. A local search was then conducted of the area surrounding the new link to determine if there was a potential cutblock with a lower C_{min} value. As before, the cell with the lowest C_{min} value became the next cutblock centre and was connected to the road network by the minimum cost link.

In the above situation, if cell MIN_2 was no longer an eligible cutblock centre and there were no eligible potential cutblock centres within the local search area, the model searched the entire area again for the next cutblock. There is also the option of specifying a maximum number of successive local searches before the model is forced to search the entire area. Except where noted, this number was 5 for the tests described here.

The size of the local search area can be varied. For the tests performed in this study, all cells within at least 16 cells of the added link (or to a boundary of the test area) were searched. A value smaller than 16 would reduce the time spent on each local search but would probably increase the number of total searches and the total computing time.

The model was run until no more cutblocks were found or until one of the following constraints was met or exceeded:

1. Maximum volume to be harvested
2. Maximum length of additional road
3. Road construction budget.

Where one or more of these constraints was used to build a road network in stages (e.g., to identify the annual road construction needs), the entire area was searched at the initiation of each stage. This may have resulted in a network slightly different from the network that would have been obtained in a single pass with no constraints. As each new link was added, no attempt was made to revise the previously defined network to minimize the total cost of construction and transportation.

Table 1 summarizes the input variables and constraints and gives their base values.

RESULTS

Test 1: *Base test.*

The base test was done in five stages using the values given in Table 1. This simulated an annual wood procurement of 250 000 m^3 for five years. The results are summarized in Table 2 and the resulting road network is shown in Figure 2, together with the limits of the cutblocks and the surrounding leave strips. Although theoretically circular areas of 177 ha, the actual cutblocks will vary in shape and size (but always $\leq$ 177 ha) because only those cells containing at least 75 m^3/ha of merchantable wood are included in the block. All cells within a leave strip are excluded from harvesting during the life of the planning period. Also shown in Figure 2 are the unharvested cells containing more than 75 m^3/ha of merchantable wood.

Table 2 shows that the target of 250 000 m^3 was met for the first four years (stages) but, in the fifth year, only 131 000 m^3 was available and the remain-

Table 1. List of input variables and constraints for ROADPLAN with their base values.

Variable	**Value**
Pixel size (m)	50x50
Cell Size (m)	250x250
Maximum forwarding distance (m)	750
Leave-strip width (m)	750
Road right-of-way width (m)	50
Road construction cost ($/km)	50 000
Transportation cost ($/m^3.km)	0.20
Transportation cost weighting factor	10
Minimum cell volume for harvesting (m^3/ha)	75
Minimum average cut-block volume (% of minimum cell volume)	100
Construction cost constraint ($)	none
Maximum volume constraint (m^3)	250 000
Maximum road-length constraint (km)	none
Maximum number of successive "local searches"	5

ing merchantable wood was either not sufficiently concentrated to meet the minimum average cutblock volume constraint or was inaccessible (i.e., it could not be linked to any cell on the existing road network). All wood cut on the road rights-of-way (approximately 2% of the total harvest) was salvaged. For the first four years the area and volume harvested, and the road construction cost, remained relatively constant. However, the cost of transporting wood to one or other of the access points increased, resulting in a near doubling in overall average cost from $11.35 to 21.10/m^3. ROADPLAN can constrain construction cost and could be modified to constrain total cost. If this were done, it would result in a declining harvested volume as the road network extended further from the access points.

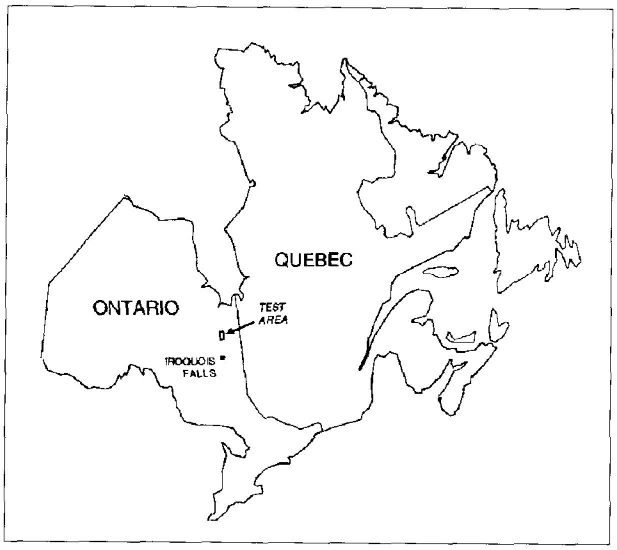

Figure 1. Map of eastern Canada showing the location of Iroquois Falls and the test area.

The licensee for the Iroquois Falls FMU, Abitibi Price Inc., has a preliminary road plan to access the area and this is compared with the Test 1 network in Figure 3. There are broad similarities between the two plans but also some anomalies. The two main branches, emanating from the fork a few kilometres north of the main access point, follow the same general paths, at least in the lower half of the area. In the northwestern section, both networks provide access to the same areas although there are differences in branching. The ROADPLAN network provides greater access to the central northern sections, but the biggest difference is in the northeast where only the company plan provides access. This is somewhat surprising as there appears to be little concentration of merchantable stands in that section (unharvested merchantable cells are indicated in Figure 2). There are possible reasons for building roads there—for fire protection, for access to gravel, or because some stands with a merchantable volume of less than 75 m^3/ha may be harvested in practice. The data used for the ROADPLAN test assumed that a relatively high proportion of the section was water or muskeg. This would have lowered the accessibility to roads and that, together with the lack of concentrated merchantable cells, would have deterred ROADPLAN from assigning cutblocks and roads.

Other Tests:

A number of tests were performed to investigate the robustness of the ROADPLAN model in developing feasible networks under a range of input variable values and constraints. The results are, of course, only applicable to the Iroquois Falls FMU; additional testing under other conditions would be required to verify the model's general applicability. The present series of tests should reveal weaknesses in the model and indicate where refinements could be made. The differences from the base test (Test 1) and the results are summarized in Table 3.

Test 2: *Leave-strip width = 1500 m.*

Doubling the leave-strip width theoretically increased the reserved area around each circular

Table 2. Summary of results for base test (Test 1).

Year	No. of cutblocks	New Road (km)	Area harvested (ha)	Leave strips (ha)	Average cutblock size (ha)	Volume harvested ('000 m^3)	Construction cost ('000 m^3)	Transportation cost ('000 m^3)	Total cost ('000 m^3)	Cost (s/m$^{3)}$
1	16	39.9	2471	6425	146	268	2379	658	3037	11.35
2	16	45.4	2300	6369	136	261	2798	1101	3898	14.95
3	17	40.1	2436	6406	137	265	2250	1477	3728	14.08
4	16	42.3	2146	6306	128	251	2501	1700	4201	16.77
5	10	31.0	1393	4125	131	157	1932	1373	3305	21.10
Total	**75**	**198.7**	**10705**	**29206**	**136**	**1200**	**11861**	**6309**	**18169**	**15.14**

Note: Areas and volumes harvested includes road rights-of-way (totals: 499 ha and 24804 m^3) outside the cutblocks. The road right-of-way is assumed to be 50 m.

Table 3. Summary of ROADPLAN tests.

Test No.	No. of cutblocks	New Road (km)	Area harvested (ha)	Leave strips (ha)	Average cutblock size (ha)	Volume harvested ('000 m^3)	Construction cost ('000 m^3)	Transport-ation cost ('000 m^3)	Total cost ('000 m^3)	Cost (s/m$^{3)}$
1	75	198.7	10705	29206	136	1200	11861	6309	18169	15.14
2	49	168.2	7573	46950	144	861	10188	4504	14692	17.07
3	71	177.7	10567	28019	143	1209	10835	7083	17919	14.82
4	199	380.9	23790	56163	115	2277	22650	11523	34173	15.01
5	131	217.4	16917	0	127	1914	13244	10767	24011	12.55
6	31	146.3	4729	76225	136	516	9432	2369	11801	22.85

Differences from the base test (Test 1: see Table 1):

Test 2: Leave-strip width = 1500 m.
Test 3: Transportation cost weighting factor = 1.0.
Test 4: Minimum stand volume for harvesting = 50 m^3/ha; minimum average cutblock volume = 50 m^3/ha; maximum number of successive local searches = 10.
Test 5: Leave-strip width = 0.
Test 6: Leave-strip width = 3000 m.

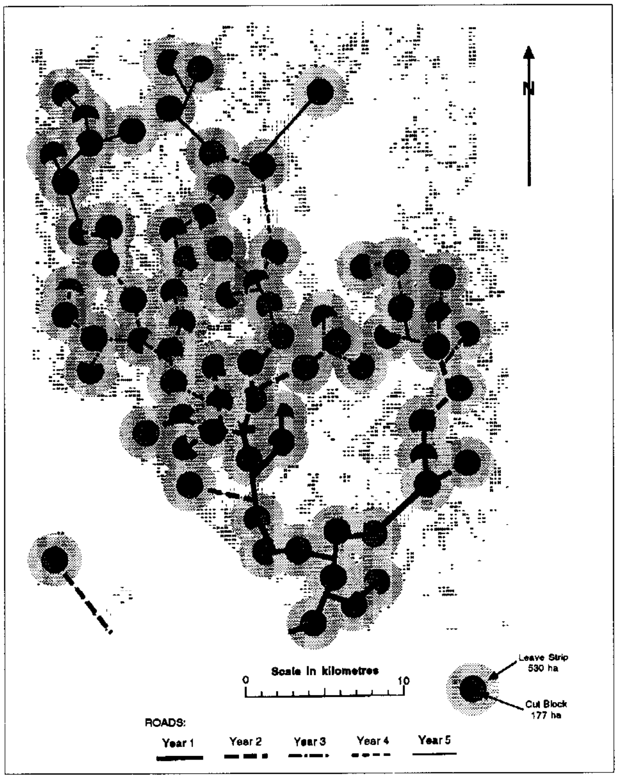

Figure 2. Location of cutblocks and road network for the base test (Test 1). Cells containing unharvested merchantable wood (>75 m^3/ha) are shown by various symbols.

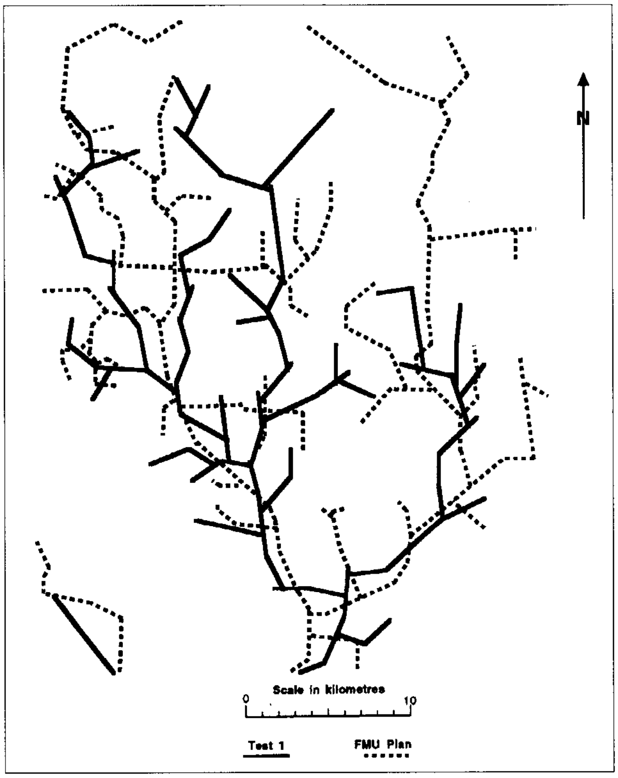

Figure 3. Comparison of the road networks produced by Test 1 with the network planned for the Iroquois Falls FMU.

cutblock by over 160% although the actual increase was only approximately 60%. The number of cutblocks, and the area and volume harvested, were reduced by approximately one-third but the total road network was reduced by only 15% resulting in an increase in average cost of nearly $2/m^3. The road network (Figure 4) is similar to that of Test 1 but with fewer fine branches.

Test 3: *Transportation cost weighting factor = 1.0.*

As would be expected, reducing the ratio of transportation cost to construction cost reduced the length of road that had to be built. Construction cost was reduced by just over one million dollars while transportation cost was increased by only a little less than $800 000. Somewhat surprisingly, in the light of earlier experience, the overall cost was reduced by $0.32/m^3. There was some evidence near the centre of the area of roads "circling round on themselves," but any increased construction cost associated with this appears to have been offset by a reduction in branching above this.

Test 4: *Minimum cell volume for harvesting = 50 m^3/ha; minimum average cutblock volume = 100% of minimum cell volume; maximum number of successive local searches = 10.*

Reducing the minimum merchantable limit to 50 m^3/ha of course increased the supply of available wood. The total volume harvested and the length of road in the network nearly doubled the values obtained in Test 1 while the area harvested and the number of cutblocks more than doubled. The average cost ($15.01/m^3) was slightly less. This was the first network to extend into the northeast corner of the area (Figure 4). Apart from an area in the northeast section and the provincial park area in the southwest, there was extensive road coverage of the area. While most tests were completed in one to two hours on a SUN workstation, this test took over 14 hours.

Test 5: *Leave-strip width = 0.*

This test simulated the removal of the reserved area around each cutblock and thus increased the

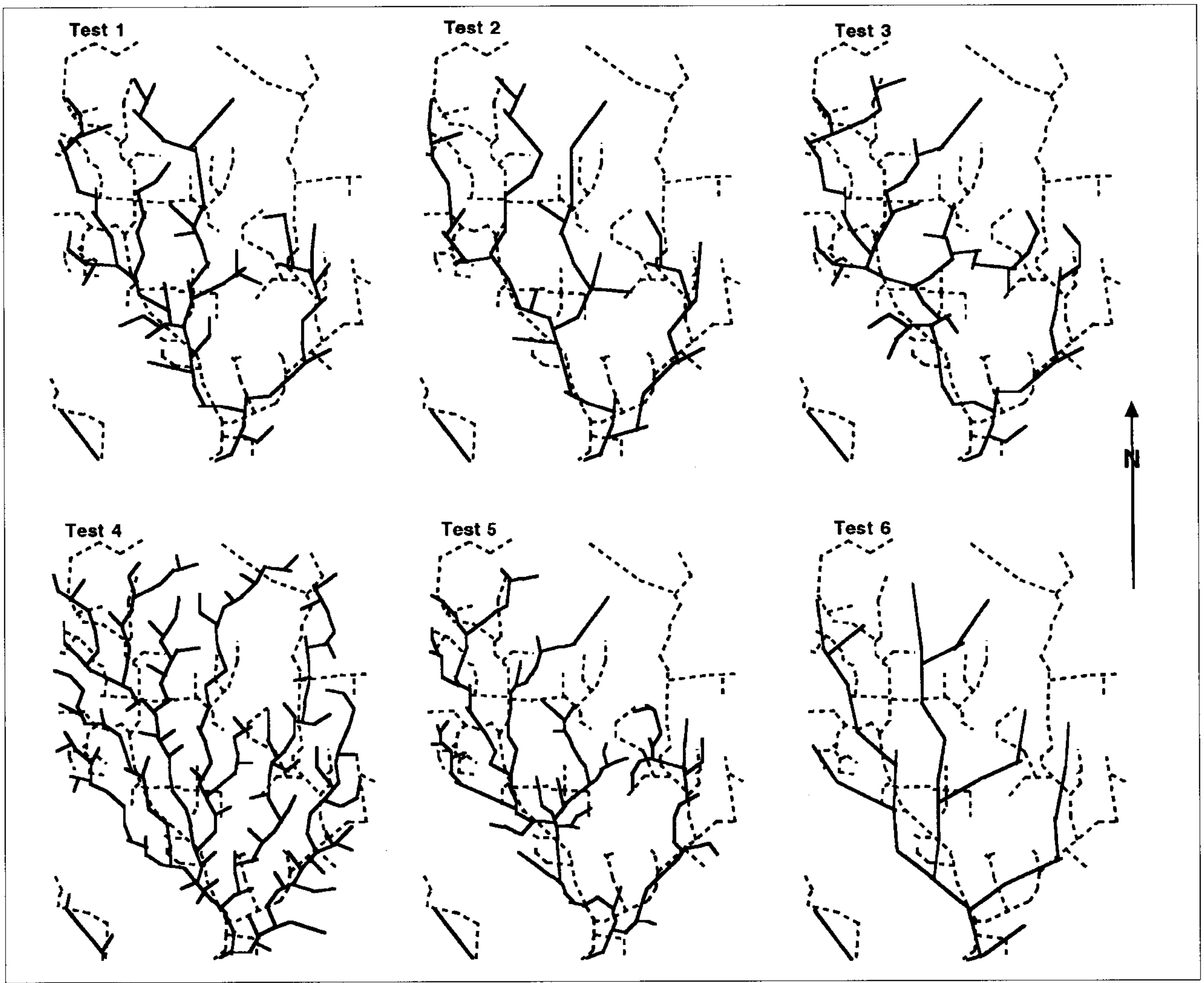

Figure 4. Tests 1-6: Comparison of ROADPLAN networks (solid lines) with the planned network (broken lines).

volume of wood that was available for harvesting to 13 244 m^3 on 131 cutblocks. However, to access this additional supply, only an additional 18.7 km of road was required, thus reducing the average cost to $12.55/$m^3$. Without the leave-strip restriction, the cutblocks tend to merge to produce harvested areas greatly in excess of the 177 ha restriction. The harvest pattern (Figure 5) is reminiscent of the days when all merchantable wood accessible from the road system was harvested without concern for other users of the forest resource. The road network (Figure 4) is similar to that of the base test (Test 1) and thus gives a reasonably good fit to the planned road system (again with the exception of the northeast section).

Test 6: *Leave-strip width = 3000 m.*

Increasing the reserved area around each cutblock reduced the volume and area harvested to less than half that obtained in Test 1 while the road requirements were reduced by only 25%. The net result was an increase in average cost to $22.85/$m^3$ (compared with costs of $12.55, $15.14, and $17.07 for widths of 0, 750, and 1500 m, respectively). The road network (Figure 4) consists of a series of long straight links, each averaging approximately 5 km, with a minimum of "fine" branches. Such straight stretches of road would not be implementable in practice, so the network can only give a general idea of where the roads should be located.

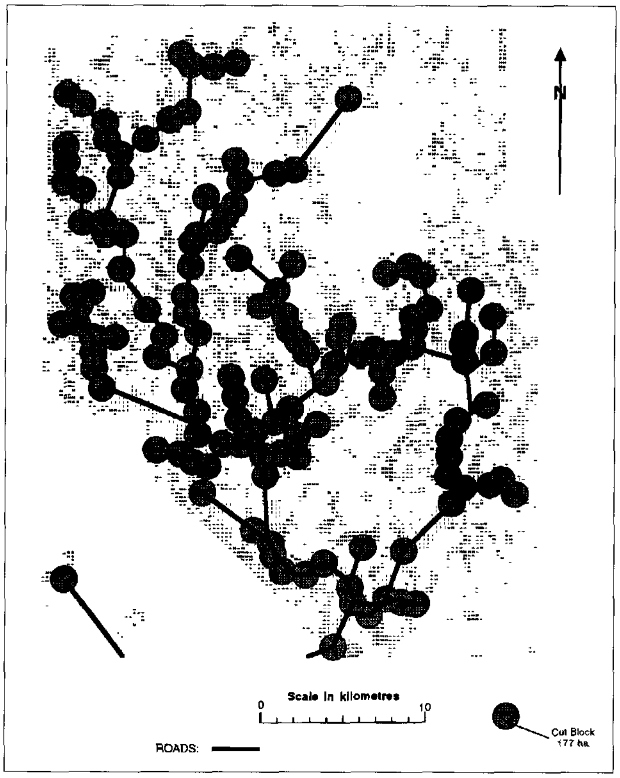

Figure 5. Location of cutblocks and road network when there is no leave strip reserved around each cutblock (Test 5). Cells containing unharvested merchantable wood (>75 m^3/ha) are shown by various symbols.

DISCUSSION

The ROADPLAN model presented here is a tool to help the road planner develop an initial road network for a forest area with little or no road access in which harvesting will be concentrated for, usually, a five-year period. It takes into account harvest scheduling priorities, in the present case based on volume per ha, and environmental considerations by means of a leave-strip, or reserve, around each cutblock where, for a period, harvesting is excluded until a forest has been re-established on the cutblock. The specific needs of wildlife and other users of the forest resource are not otherwise taken into consideration. Where reliable road construction and wood transportation costs are available, the model can provide preliminary estimates for budgeting.

By varying the input parameters and constraints, ROADPLAN can generate alternative networks. Commonalities among these networks should give a good idea of the most promising locations for at least the major roads. As no computer model can take into account all the conditions on the ground, the final location of any road can only be decided after a ground survey. One of the purposes of ROADPLAN is to indicate where such surveys should be undertaken, thus reducing the time and cost of determining the final road layout. The model also gives the planner the ability to test a range of scenarios and to provide answers to potential "What if ...?" questions.

The tests that have been described here are by no means exhaustive. The basic road construction cost was assumed to be $50000/km for all tests, although this was increased in each individual cell in proportion to amount of muskeg and water (lakes and rivers) in the cell. Topography was not considered in adjusting construction cost (Douglas and Henderson [2] took this into account by counting the number of contours crossed between the lowest and highest points in each cell). Transportation cost was held constant at $0.20/$m^3$.km in all tests regardless of the area or road class. The ratio of construction to transportation costs has an important influence on network design. ROADPLAN can modify this ratio, without affecting actual costs, using the weighting factor, W. Only one cutblock size, based on a maximum forwarding distance of 750 m, was used.

For the Iroquois Falls FMU test area, ROADPLAN generated reasonable networks (Figure 4). Main branches lie fairly close to the planned road network, especially in the lower half of the area. As would be expected, in each test differences become more noticeable as the branching becomes finer. The ROADPLAN road links generally have a bearing between northwest and northeast whereas the planned network has several branches on an east-west orientation that, in some cases, appear illogical. The greatest differences occur in the northeast section of the area, which is only accessed by the Test 4 network. There may be a practical explanation for some of these differences:

- provision of access for fire protection, gravel for road building, or other purposes;
- the existence of abandoned roads or tracks that require only relatively inexpensive upgrading;
- the presence of physical obstructions to road-building that are not considered in the data used by ROADPLAN; or
- constraints on water-course crossing points.

Another possible reason is that the planners did not have access to a computerized planning model, such as ROADPLAN, that would have allowed them to test a number of alternatives before deciding on the final design.

The degree of fine branching depends on the width of the leave-strip, being greatest when no leave-strip was reserved around each cutblock. As a leave-strip was imposed and its width increased, the degree of fine branching was reduced. The total length of road also decreased from 217.4 km (no leave-strip) to 146.3 km (3000-m leave-strip). Consequently, the volume of accessible wood was reduced while the cost of delivering wood to one of the two access points on the southern boundary of the test area increased (Table 3: Tests 5, 1, 2 and 6).

For all tests except Test 3, the transportation cost weighting factor (W) was set equal to 10.0. In Test 3, the weighting factor was removed (W = 1.0). The expected "route-circling" (where a road tends to circle back on itself) did not materialize although the road-link orientation (Figure 4) appeared more random than in Test 1. Route-circling may not be so important a factor as once feared but could resurface when the construction/transportation cost ratio is changed.

Reducing the merchantability limits on both individual cells and cutblocks to 50 and 25m^3/ha, respectively, resulted in almost complete coverage of the test area (Figure 4; Test 4). A network based on this configuration would give little assistance to the planner trying to decide where to undertake ground surveys because, basically, the entire area would have to be covered. Raising the limits might prove more informative.

Although ROADPLAN considers possible linkages between a potential node and all cells on the existing network, the links that are finally selected are all straight lines. This is probably not a serious disadvantage when the links are relatively short but may be misleading when the average length exceeds 4 or 5 km as in Test 6 (where the leave-strip width was 3000 m). To circumvent this problem, the initial network could be based on a 750- or 1500-m leave-strip, but only those blocks that satisfied the 3000-m constraint would become cutblocks. The "missed" blocks could be harvested later when the cutblocks have regenerated and the leave-strip restriction is removed.

There are two other disadvantages to "straight" links:

- a straight line link may not be the cheapest route between two points. This could be rectified, once the two end points have been selected, using an optimum path method (such as that suggested by Douglas and Henderson [2]) to see if there is a lesser cost route;
- the longer the link, the greater is the probability of encountering a "roadblock" (an unroadable cell) that could easily be avoided if the link could be offset to a cell on either side. Such roadblocks could also, in certain circumstances, result in potential cutblocks not being accessed.

A useful modification to the model would be the ability to interactively add, or delete, links to see if costs could be reduced.

The ROADPLAN model is not an optimizing (cost minimization) model although, by a trial-and-error process, theoretical near-optimum solutions can probably be obtained. This lack of optimality should not detract from its potential usefulness as a planning tool; most "optimum" networks are modified before they are laid out on the ground.

The present series of tests with the Iroquois Falls data indicate that ROADPLAN could be a practical aid to the planner where the combination of forwarding distance plus leave-strip width does not exceed 2250 m. For resolutions finer than the 250x250-m cell used here, this restriction may have to be reduced. Further testing on other data sets would have to be undertaken to determine the applicability of the model under other conditions.

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