THE ROLE OF NETWORK ANALYSIS TECHNIQUES IN RESOURCE MANAGEMENT PLANNING

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Planning for resource development and management considers the accessibility provided by a transportation network. Two applications of network analysis techniques for resource planning in national forests are described—transportation for timber activity and administrative travel in national forests. The access to timber and the haul costs on transportation facilities influence the timber resource development pattern. A minimum-path algorithm is adapted to provide several measures of the effectiveness of a transportation system in servicing possible timber sales, available mills, and available markets. Use of this procedure in evaluating alternative timber resource development plans is described. The administration of national forest activities requires periodic inspection and servicing of activities. A technique for finding the optimal routing of administrative travel is investigated. The method is based on a modified branch-and-bound technique used in solving discrete programming problems.

•THE MANY types of travel in national forests can be classed into two broad categories: recreational travel and nonrecreational travel. Procedures developed by this study to analyze recreational travel are discussed elsewhere (2, 3). Procedures to analyze nonrecreational travel are discussed here. Nonrecreational travel in national forests is associated with many diverse activities. Techniques to analyze travel for two of the most important of these activities are presented in this paper. These techniques are a timber transport model and an administrative travel model.

Both of these are network analysis models. They are used in this situation, in preference to demand models, for a number of reasons. First, because both types of travel are characterized by low daily traffic volumes, demand models would be affected adversely by the high variability encountered in analyzing and estimating small quantities. Second, because timber transport travel patterns are quite irregular over a day, and even over a season, it would be difficult to find an appropriate theory on which to base an associated demand model. Third, the route of interest may be based on different criteria for different applications. For example, timber transport analysis is most often based on minimum transport cost, fire attack travel on minimum travel time, and campground service on either. The use of demand models to perform the analyses would tend to obscure this important underlying issue.

TIMBER TRANSPORT COST ANALYSIS TECHNIQUE

Definition of Problem

Timber harvesting is a major activity in national forests. Under a timber harvest program, the timber in designated areas is sold by bid to logging contractors when the trees within the area have reached maturity or have been damaged by insects, fire, or blight.

Many road investments in national forests are prompted by the need to provide accessibility to these timber harvest areas. One principal consideration in selecting road construction or improvement projects is the relative timber transport cost associated with each alternative project. To a lesser extent the designation of the harvest areas themselves is influenced by these same costs.

Consequently, a method was developed to determine the minimum-cost routes for transporting timber through a forest transportation network (4). Here "transport cost" is interpreted in its most general sense and may correspond to either travel cost, travel time, or travel distance. These minimum costs indicate the effectiveness of proposed transportation systems in serving traffic generated by timber-cutting activities. The technique that computes the minimum haul cost routes associated with a given road network-harvest area combination is called the "timber transport model."

This problem differs from other minimum-path problems in that the transport of timber products to market is done in two stages. Logs are cut, trimmed, and loaded at the timber harvest areas, called "timber sales." They are then hauled to mills for processing into lumber. These mills may be located within the forest area or at some distance from the forest. After processing, the finished lumber is then hauled to the markets, which may be railheads, ports, or urban areas. Both legs of the trip from sale to market are included in this analysis of the problem.

Description of Technique

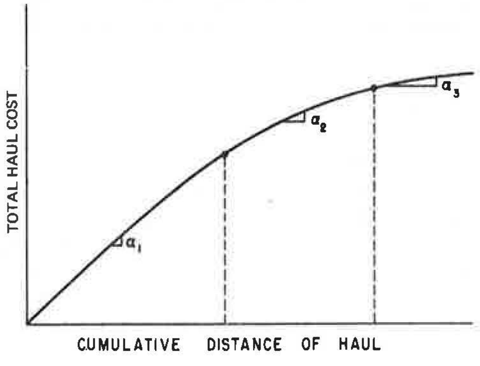
The timber transport model determines the minimum travel path through a transportation network for a timber sale-mill-market combination by minimizing either travel cost, travel time, or travel distance. The choice of the criterion to be minimized is made by the analyst. To aid in the evaluation of the selected routes, the values of the other impedance measures are also determined; for example, the travel time and travel distance are also calculated over each minimum travel cost path.

A digital representation of the forest road network must be prepared. Nodes representing the locations of timber sales, mills, and markets must be included therein. A "link" is used to represent a section of roadway that is homogeneous with respect to road class and geometrics. Each link is characterized by its road class, length, and either travel time or average link speed. If the characteristics of a section of road change significantly, that section of road would be represented by more than one link, since, due to the effects of grade and geometrics, link characteristics may be quite different for opposing directions of travel.

The program can accept the network data on either cards or magnetic tape. An optional routine in the program will generate a magnetic tape in the appropriate format. Another routine is available that will update and edit the network data on tape. The network representation provided by the network data management system, developed under this study, satisfies the data requirements for both recreational and nonrecreational models. However, a simpler network representation can be used to analyze timber—that is, one with some travel time and travel cost data omitted.

Timber haul cost functions that reflect transport cost characteristics on forest roads have been defined by the U.S. Forest Service (Fig. 1). Each haul cost function is represented by three linear segments, with the marginal cost α_1 (in dollars per truck-mile) applying at any point within the first distance increment, α_2 within the second, and α_3 within the third. Since cost characteristics differ for log and lumber transport, separate haul cost functions have been developed for each. These unit cost functions also vary by class of road, forest roads varying in character from single-lane dirt roads to high-standard highways. The model can accept up to 10 haul cost functions for both log and lumber transport.

Figure 1. The general haul cost function.



The output of the program identifies the least transport cost route for every sale. Included in each route are a least-cost mill and market to which each timber sale has been assigned by this program. The values of the three impedance measures over the best route are also output. A recent modification to the program provides a summary of the number of times each link of the network is used in the minimum-cost paths for all the timber sales analyzed and the volume of timber carried by each.

Logic

The timber transport model uses a shortest-path algorithm developed by the Road Research Laboratory in Great Britain (6). This is an outgrowth of the Moore algorithm developed by the U. S. Bureau of Public Roads. The algorithm is of the tree-building type wherein the minimum path is found from a specified origin to all destinations. However, once a satisfactory destination is reached, the algorithm stops; hence, a complete tree is not built. This algorithm was chosen both because it is very efficient and also because it accommodates a simple and easily understood network representation. This is desirable because many of the users of this technique will have only limited knowledge of network theory.

The minimum-path algorithm is first applied with each mill serving as an origin in turn and with the markets serving as destinations. The algorithm searches until the closest market to each mill is identified. These pairings of mills with markets and the transport costs between every pair are saved. More than one mill may be tied to a single market.

The model then applies the minimum-path algorithm to each timber sale as an origin in turn, with the mills as destinations. As each mill is reached, the incremental transport cost from the mill to its "tied" market is added and the total transport cost for that sale-mill-market combination is compared to the previous minimum. The lesser cost combination of the two is saved. The algorithm continues until the minimum cost paths to all mills, and to their tied markets, have been considered. In this way, the model determines the least cost sale-mill-market routing for all timber sales under consideration.

Applications

This technique was the first analytical model developed by the study. The primary objective was to provide an efficient procedure for evaluating the timber haul costs for timber sales, which this method does. However, the possible applications of this technique go beyond that originally intended.

The timber transport model is useful for planning future transportation networks. Forest management plans must provide direction for the future timber harvest program, indicating the locations, approximate quantities of timber, and scheduling of possible timber sales as well as specification of a future transportation network. The model can be employed to investigate the efficiency of various transportation network alternatives for serving the timber travel generated by the proposed harvest plans. The total transport costs are determined for each alternative network by summing the products of the expected number of trucks generated by the timber sales and the route haul cost rates per truckload for all timber sales. The differences in these total costs indicate the relative efficiency of the various network alternatives for a particular timber harvest plan.

The technique can assist the analyst and/or decision-maker in his search for efficient alternatives. The existing alternatives can be modified slightly to determine the sensitivity of transport costs to changes in certain transportation links or timber sales. This technique is very effective for sensitivity analysis because the computer program execution is extremely fast.

In addition, the technique can be used to analyze the construction and maintenance costs associated with hauling timber over minimum haul cost routes. The link construction costs and maintenance costs are entered into the network data in the place of link travel times. The minimum-cost path is determined, and the associated route construction and maintenance costs are accumulated. The haul quantities are translated into estimates of total user costs by multiplying the expected number of trucks generated by every timber sale by the appropriate haul cost rates. A comparison of user and road costs can then be made.

THE ADMINISTRATIVE TRAVEL MODEL

Definition of Problem

There are several types of regularly scheduled administrative travel in national forests. These include trips to service campgrounds, to patrol areas for fire prevention, and to inspect logging activities. The origins and destinations of these trips are usually clearly defined, although the routes that are used may vary.

Administrative travel does not generate a high volume of traffic. However, significant benefits can accrue to the Forest Service, and therefore to the public, if the optimal routing to perform these tasks is determined. The reduction of costs for travel and the equitable use of available personnel through improved scheduling can significantly improve administrative efficiency. A major portion of national forest administrative travel is associated with campground service. Because of the importance of campground service routing and because it is representative of other administrative travel problems, the administrative travel model is presented in terms of its application to this activity.

In many national forests, campground service is performed by personnel of the ranger district that contains the campground. Therefore, the problem reduces to the analysis of travel on the transportation network of the ranger district. Daily campground service travel often begins at the district ranger station, and service personnel return to the station by day's end. Consequently, the origin of travel is the ranger station, and the destinations are the campgrounds and, at day's end, the ranger station.

Techniques have been developed to handle problems that are quite similar to that posed here. One of these is the "traveling salesman problem." That formulation can be solved in many ways with the aid of special linear programming and dynamic programming techniques (7, 8). However, there are two major differences between the problem posed here and the traveling salesman problem:

1. All trips begin and end at the ranger station every day of the service period, and
2. A location, in this case a campground, can be visited more than once within a service period, though it is only serviced once.

Because of these differences, this problem cannot be solved by a traveling salesman algorithm. On the other hand, there does exist an integer programming algorithm that is useful for solving this special class of discrete programming problems (9, 10). This algorithm employs a modified branch-and-bound technique. When the problem is properly formulated, this algorithm can be used to solve the optimal routing problem for campground service.

Formal Problem Statement

The problem is to determine the optimal route to service all campgrounds in a ranger district within a certain number of days. The number of days required depends on the number and sizes of campgrounds and the size and layout of the ranger district. The base of operations is the ranger station. A number of assumptions are made:

1. Each daily trip begins and ends at the ranger station; no overnight stays in the forest are permitted.
2. The minimum travel times between every pair of nodes are known.
3. A campground node can be visited more than once but only serviced once.
4. One team is assigned to perform the service for all campgrounds. If a ranger district actually has more than one team, the problem formulation can be modified accordingly.

Formulation of the Problem

The formulation of an example problem demonstrates the technique (5). The transportation system is shown in Figure 2. The ranger satation is represented by RS and campgrounds by C's. The nodes of the transportation network are numbered.

Dummy links are added to the network in the formulation of the problem. The schematic network is shown in Figure 3. A two-way dummy link is added on each camp-

Figure 2. Forest road network.

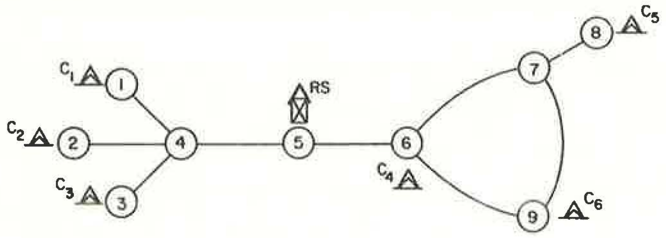
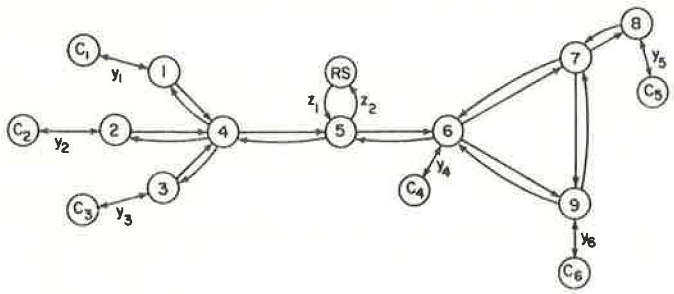


Figure 3. Schematic road network.



ground and two one-way dummy links are introduced for the ranger station. On the schematic diagram, y's are two-way dummy links and z's are one-way dummy links.

The objective function is to minimize the total travel cost

$$\text{Min } Z = \sum_{k=1}^{H} \sum_{\{(i,j)\}} c_{ij}\, x_{ijk} \tag{1}$$

where

$\{(i, j)\}$ means the set of all N links in the transportation network—each (i, j) represents an ordered pair of nodes connected by a one-way link,

Z = total travel cost,

c_{ij} = travel cost on the one-way link from node i to node j,

x_{ijk} = 1 if a trip is made on line (i, j) on day k,
= 0 if not,

N = the total number of links in the transportation network, and

H = the number of 8-hour working days needed in the service period,

subject to the following constraints:

1. Travel time to and between campgrounds plus the aggregate service time must be less than or equal to 8 hours in any one day; i.e.,

$$\sum_{\{(i,j)\}} t_{ij}x_{ijk} + \sum_{s=1}^{M} m_s y_{sk} \leqq 8 \text{ (hours)}, \text{ for } k = 1, 2, \ldots, H \tag{2}$$

where

t_{ij} = travel time on the one-way link from node i to node j,

m_s = time to service campground s,

y_{sk} = 1 if a campground is serviced on day k,
= 0 if not, and
M = number of campgrounds.

2. Each campground cannot be serviced more than once within the service period; i. e.,

$$\sum_{k=1}^{H} y_{sk} \leqq 1, \text{ for } s = 1, 2, \ldots, M \tag{3}$$

3. Each campground is serviced at least once during the service period; i. e.,

$$-\sum_{s=1}^{M} \sum_{k=1}^{H} y_{sk} \leqq -M \tag{4}$$

4. Each day at least one service trip originates from and returns to the ranger station; i. e.,

$$-\sum_{k=1}^{H} (z_{1k} + z_{2k}) \leqq -2H \tag{5}$$

where

z_{1k} = 1 if a service trip originates at the ranger station,
= 0 if not, and
z_{2k} = 1 if a service trip returns to the ranger station,
= 0 if not.

5. For each campground serviced on day k, there must exist at least one round trip routing to and from the ranger station; i. e., for campground 1,

$$y_{1k} - P_{1k1} = 0 \tag{6}$$

$$2P_{1k1} - x_{41k} - x_{54k} \leq 0 \tag{7}$$

$$y_{1k} - R_{1k1} = 0 \tag{8}$$

$$2R_{1k1} - x_{14k} - x_{45k} \leq 0 \tag{9}$$

For campground 2,

$$y_{2k} - P_{2k1} = 0 \tag{10}$$

$$2P_{2k1} - x_{42k} - x_{54k} \leq 0 \tag{11}$$

$$Y_{2k} - R_{2k1} = 0 \tag{12}$$

$$2R_{2k1} - x_{24k} - x_{45k} \leq 0 \tag{13}$$

For campground 3,

$$y_{3k} - P_{3k1} = 0 \tag{14}$$

$$2P_{3k1} - x_{43k} - x_{54k} \leq 0 \tag{15}$$

$$y_{3k} - R_{3k1} = 0 \tag{16}$$

$$2R_{3k1} - x_{34k} - x_{45k} \leq 0 \tag{17}$$

For campground 4,

$$y_{4k} - P_{4k1} = 0 \tag{18}$$

$$P_{4k1} - x_{56k} \leq 0 \tag{19}$$

$$y_{4k} - R_{4k1} = 0 \tag{20}$$

$$R_{4k1} - x_{65k} \leq 0 \tag{21}$$

For campground 5,

$$y_{5k} - P_{5k1} - P_{5k2} = 0 \tag{22}$$

$$3P_{5k1} - x_{76k} - x_{67k} - x_{56}k \leq 0 \tag{23}$$

$$4P_{5k2} - x_{78k} - x_{97k} - x_{69k} - x_{56k} \leq 0 \tag{24}$$

$$y_{5k} - R_{5k1} - R_{5k2} = 0 \tag{25}$$

$$3R_{5k1} - x_{87k} - x_{76k} - x_{65k} \leq 0 \tag{26}$$

$$4R_{5k2} - x_{87k} - x_{79k} - x_{96k} - x_{65k} \leq 0 \tag{27}$$

And for campground 6,

$$y_{6k} - P_{6k1} - P_{6k2} = 0 \tag{28}$$

$$2P_{6k1} - x_{69k} - x_{56k} \leq 0 \tag{29}$$

$$3P_{6k2} - x_{79k} - x_{67k} - x_{56k} \leq 0 \tag{30}$$

$$y_{6k} - R_{6k1} - R_{6k2} = 0 \tag{31}$$

$$2R_{6k1} - x_{96k} - x_{65k} \leq 0 \tag{32}$$

$$3R_{6k2} - x_{97k} - x_{76k} - x_{65k} \leq 0 \tag{33}$$

where

$P_{sk\ell}$ = 1 if route ℓ is used to travel from the ranger station to campground s on day k,
= 0 if not, and

$R_{sk\ell}$ = 1 if route ℓ is used to return from campground s to the ranger station on day k,
= 0 if not.

The Branch-and-Bound Technique

Branch-and-bound algorithms have been studied extensively since 1960 as a technique to solve special types of integer linear programming problems (8). The branch-and-bound technique can be applied to the campground service problem as previously formulated. The technique begins by solving the problem, using the simplex method, without integer constraints to get an initial value of the objective function Z_0. If the values of all variables are integer, then the solution of the problem has been found. If they are not, one noninteger variable is set equal to zero and the problem is solved again, giving Z_1. The same variable is then set equal to one and the problem is solved for a third time, giving Z_2. If the objective function is to be minimized, the setting of the noninteger variable that yields the minimum of Z_1 and Z_2 is retained, establishing a "terminal node" $\overline{Z}_1$. If all variables now have integer values, the final solution has been found. If some do not, the algorithm "branches" on $\overline{Z}_1$ and sets some other noninteger variable equal to zero. The problem is again solved to get a value of Z_3 for the objective function. The same variable is then set equal to one, and the problem is solved to give Z_4. If for both solutions all variables have integer values, the solution yielding the minimum of Z_3 and Z_4 is the final solution of the problem. If only one solution has all integer variables, it is the final solution. If neither solution does, the algorithm branches on a new terminal node, $\overline{Z}_2$, which is the minimum of Z_3, Z_4, and the maximum of (Z_1, Z_2). The technique continues in this manner until a solution is found that has all integer-valued variables and a value of the objective function less than or equal to any other terminal node.

A major consideration is the amount of computer time required to perform this analysis. At each step a linear program must be solved using the simplex algorithm, and hence the computational time would be very large for large networks. Fortunately the road networks in ranger districts are usually not extensive. Also, as implied in the example problem formulation, no nodes should be defined between intersections. All links between intersections should be aggregated and formulated in the problem as one link. The number of constraints is reduced by two for every node that is eliminated between intersections. The amount of time required to solve the problem using the simplex algorithm increases with an increase in the size of network because the number of link variables increases. Further, the computation time and storage requirements are increased because the number of terminal nodes to be investigated and saved also increases with the number of link variables.

Discussion of the Technique

As seen in the problem formulation, the specification of the constraint equations for network flows could be a formidable task for a large network. However, this tedium can be eliminated by a computer program. Such a program would take coded network data as input and generate network flow constraint equations. The other constraint equations need only be modified when there are changes in the frequency of campground service, in the number of service teams, or in other factors requiring a change in the basic problem formulation. Otherwise, the only inputs required for the model, other than network data, are the number of days in the service period and the number and service times of campgrounds.

Some situations require a modification of the problem formulation. For example, some campgrounds may have to be serviced more than once during the service period. The constraints imposed by Eqs. 3 and 4 limit the service to once and only once during the service period. If, for example, campground number 5, due to its size and heavy use, needs to be serviced twice during the service period, these constraints are modified as follows:

1. Each campground, except number 5, cannot be serviced more than once within the service period:

$$\sum_{k=1}^{H} y_{sk} \leqq 1, \quad s = 1, \ldots, 4, 6, \ldots, M \tag{3.1}$$

2. Campground 5 cannot be serviced more than once within the first service subperiod:

$$\sum_{k=1}^{H_1} y_{5k} \leqq 1 \tag{3.2}$$

where $H_1 = \sim H/2$ (first subperiod).

3. Campground 5 cannot be serviced more than once within the second service subperiod:

$$\sum_{k=H_1+1}^{H} y_{5k} \leqq 1 \tag{3.3}$$

4. The number of times campgrounds are serviced during the entire service period is the number of campgrounds plus one additional service activity:

$$-\sum_{s=1}^{M} \sum_{k=1}^{H} y_{sk} \leqq -(M + 1) \tag{4.1}$$

A desired lag between service times at campground 5 can be introduced into the campground servicing schedule by rearranging the schedules for entire days within the service period. Moving entire days around does not affect the optimality of the solution.

The number of days in the service period, H, must be specified by the analyst or administrator in the area, based on his estimate of the number of 8-hour days that the service team would need to service the campgrounds. If H is specified too small, no feasible solution to the problem will be found. If H is specified too large, an optimal solution will be found in which all the x and y variables have zero values for the extra days.

Applications

The administrative travel model has application for determining the optimal routes to service campgrounds, to patrol for fire prevention, to inspect logging activities, and to perform other administrative activities requiring regular travel to fixed destinations. Thus, the technique can be used extensively by administrators to reduce costs of travel and to schedule manpower efficiently.

The technique can be used in planning to determine the relative efficiencies of alternative networks. For any proposed resource management plan, which includes a proposed network, the model computes the minimum achievable administrative travel costs. These can be compared to the corresponding travel costs for other proposed plans to determine their relative efficiency in serving administrative travel.

By expanding the problem formulation to cover an entire national forest, the distribution of campground service responsibility and locations of ranger district boundaries can be evaluated. All ranger stations would be treated as origins, with each having a service team. In this revised formulation, each campground can be serviced by any service team. Where the total travel service costs are reduced by rearranging service responsibilities, the actual or functional ranger district boundaries could be revised.

CONCLUSION

Network analysis techniques are useful tools for resource management planning. They have the ability to analyze the efficiency of proposed transportation networks and are especially suited to the analysis of nonrecreational travel.

Two techniques have been presented in this paper. The timber transport model employs a minimum-path algorithm to generate the least travel cost route to the most economical mill and market for each timber sale. The administrative travel model uses a modified branch-and-bound technique to analyze the efficiency of a transportation network in serving administrative travel. These two models are the first of a set of techniques still being developed to aid forest planners in analyzing nonrecreational travel.

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