Optimization of Cable Logging Layout Using a Heuristic Algorithm for Network Programming

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ABSTRACT - This paper describes a methodology for optimizing cable logging layout using a heuristic network algorithm. The methodology formulates a cable logging layout as a network problem. Each grid cell containing timber volume to be harvested is identified as an individual entry node of the network. Mill locations or proposed timber exit locations are identified as destinations. Then, each origin will be connected to one of destinations through alternative links representing different cable roads, harvesting equipment, landing locations, and truck road segments. A computerized model incorporating the methodology is introduced. The model is intended to optimize landing, harvest equipment, logging profile, and road location simultaneously using information from GIS layers. A heuristic method for network programming is used as an optimization technique in the model.

INTRODUCTION

Designing timber harvesting units is one of the most difficult tasks in forest operational planning. The task requires engineers to decide logging equipment, landing site, logging profile, transportation system, and road location based on various considerations including timber volume distribution, economic and environmental outcomes, and physical feasibility of the system. Traditionally, engineers have done the task manually, but it is difficult to consider many alternatives. Thus, it is not easy to find a timber harvest layout which is not only “feasible” but also “good” by the manual method.

With the purpose of assisting engineers in designing timber harvest layout, various computerized methods have been introduced. Dykstra (1976) developed a methodology to assist in the design of timber harvest cutting units and the assignment of logging equipment. PLANS (Preliminary Logging Analysis System) developed by the USDA Forest Service (Twito et al. 1987) has been used for developing timber harvest and road network plans based on large-scale topographic maps. PLANEX (Epstein et al. 1999a, Epstein et al. 1999b) is able to generate an approximately optimal allocation of equipment and road network based on a heuristic algorithm. However, none of the above methods has a complete analysis tool covering from cable road analysis considering topographic profiles to the simultaneous optimization of cable harvesting equipment placement and road location.

The methodology described in this study will combine a cable logging equipment assignment problem with a road location problem and optimize them simultaneously, while incorporating modern computer software languages, Geographic Information Systems (GIS) technologies, and optimization techniques that have become available during the last two decades. The methodology evaluates alternative cable layouts based on feasibility analyses of logging system and road segments, and estimation of operation costs. A heuristic network algorithm is used as an optimization technique. The entire network is divided into two parts of the network. Each part of the network is solved separately using the heuristic network algorithm while being connected to the other by a feedback mechanism. The methodology is implemented in a computerized model, which is currently being developed as a decision support tool. Upon completing the development, the model will be able to assist forest engineers in designing cable logging units by providing “feasible and good” alternatives using cost and environmental criteria.

PROBLEM FORMULATION

Cable logging operations can be considered as a series of operations that start from the stump and end at the mill. Each operation can be represented by a link connecting two consecutive operations with corresponding costs. Then, a series of operations would be a path (a series of links) forming a part of a network system. All possible links starting at each timber source would build an entire network system consisting of multiple origins, multiple paths, and multiple destinations. Then, the network problem is solved using a network solution technique.

Required Data

The methodology requires several GIS layers as input data: a Digital Terrain Model (DTM), a timber volume layer, and layers containing other logging considerations.
A DTM provides spatial and topographic information for logging feasibility analysis and estimating logging operation and road costs. A timber volume layer enables identification of the timber sources spatially, by which we can consider not only clearcut treatments but also group selection cutting systems and individual tree selection operations.

**Formulating the Network**

Figure 1 shows a series of cable harvesting operations on a DTM. The timber harvesting operations using cable systems may be categorized into two different types of operations: cable logging and truck transportation. The cable logging operation planning requires decisions on cable system, cable road, and landing location, while truck transportation planning requires selection of road locations and transportation routes.

![Figure 1. Cable harvesting unit layout as a network problem on a DTM.](image)

Each grid cell containing timber volume to be harvested is identified as an individual entry node of the network. Mill locations or proposed timber exit locations are identified as destinations of the network. Then, each origin will be connected to one of destinations through alternative paths representing different cable roads, harvesting equipment, landing locations, and truck road segments (Figure 2). Each path consists of links incurring variable costs (yarding and truck transport cost) and fixed costs (equipment cost, landing and road construction cost).

In order to solve cable logging operation and road location problems simultaneously, two different link lists are used in the network analysis: a cable road link list and a truck road link list. The cable road link list includes all possible links from the origins to alternative landings and is used to evaluate cable logging operation paths. A truck road link list consists of road links generated from the DTM, and is used to evaluate truck transportation routes from each landing to the destinations.

Once the truck road and cable road network is set up, a network algorithm solves the problem and finds the least cost path from each origin (timber entry) to one of destinations (mills) while simultaneously selecting cable road, cable equipment, landing location, and road segments to be used.

![Figure 2. A network represents cable logging operations and truck transportation.](image)

**PROBLEM SOLUTION TECHNIQUES**

**A Heuristic Network Algorithm**

Due to their efficiency and ability to handle large-scale optimization problems, network optimization algorithms have been used for solving a wide variety of problems such as transportation, assignment, and resource allocation (Jensen and Barnes 1980). In forestry, a heuristic NETWORK algorithm developed by Sessions (1985) has been applied to forest transportation planning and other applications. This heuristic NETWORK algorithm is similar to the Prorate Algorithm developed by Bill Schnelle of the USDA Forest Service (1980) to solve the fixed charge and variable cost problem. However, the heuristic NETWORK algorithm uses a series of rules to avoid stalling in a local minimum and it also extended applications to multiple periods, multiple product, and value maximization or cost minimization through introduction of special arcs.

In this study, the heuristic NETWORK algorithm developed by Sessions (1985) is used as an optimization
technique. The algorithm calculates the minimum cost network by using a shortest path algorithm to solve the variable cost problem similar to that proposed by Dijkstra (1959). The process begins with sorting the grid cells by timber volume (Figure 3), and then solving the shortest path problem without considering the fixed costs (FC). The sum of the volumes, $Vol_i$, that went over each link are accumulated and so that at the end of the first iteration the sum of all volumes, $\Sigma Vol_i$, over each link are available. The variable costs for each link, $VC_i$, are then recalculated using Eq. 1. The volume over all links is then reset to zero and the next iteration started using the new set of variable costs. This process continues until the same solution is repeated for two iterations. To diversify the search, a negative value is substituted for each positive variable cost link not in the solution such that $VC_i < 0$ for all links with $Vol_i = 0$. The solution procedure is then repeated until the solution re-stabilizes. Each time a link with a negative value is used its value returns to its original value. This process rapidly eliminates the substituted negative values while providing an additional opportunity to consider alternative paths.

\[ VC_i = VC_{init,i} + \frac{FC_i}{\sum Vol_i} \]

where, $VC_i$ : Variable cost for link $i$, $VC_{init,i}$ : Initial variable cost for link $i$, $FC_i$ : Fixed cost for link $i$, $Vol_i$ : Volume transported on link $i$.

Solving Cable Logging Equipment Placement and Road Location Problems

For the purpose of reducing solution time and enhancing solution quality, the methodology in this study divides a large network into two sub-parts: cable logging operation and truck transportation. First, the cable logging operation part of the network is solved in order to select cable roads, cable systems, and landing locations without considering truck transportation (Figure 4). Then, total timber volume arriving at each landing is calculated based on the results of the optimization and sent to the truck transportation part as being entry volume in the road network. After truck transportation routes are optimized, road and transportation costs related to each landing are sent back to the cable logging operation part and added to fixed and variable costs for each landing in the network. In case that several landings share the same road links, the road costs on the links are divided to each landing proportional to its volume transported over the links. Then, the optimization algorithm comes back to the cable logging operation part with updated link costs and resolves the network problem.

![Figure 3. Flowchart for heuristic problem solving approach based on the shortest path algorithm.](image)

![Figure 4. A feedback mechanism between two separated network problems.](image)
A PRELIMINARY COMPUTERIZED MODEL

A computerized model implementing the methodology described in this paper is currently in development. The model starts with reading input data and generates two link lists for a network analysis. Based on the link lists, the heuristic network algorithm finds the best path from each timber source to the proposed destination.

Figure 5 shows the preliminary computerized model. As an example, the model was applied to patch-cut harvesting areas in the McDonald-Dunn Oregon State University (OSU) Research Forest and developed an alternative cable logging layout. GIS data provided information on topography, timber location and volume, and the locations of existing roads and riparian zones. The model identified feasible candidate cable roads through the payload analysis while considering terrain conditions and riparian zones. In a network assembled by the model, each timber location was identified as an entry node and the destinations of the network were any grid cells on the existing roads.

(a) timber source, (b) selected landing, (c) selected cable roads, (d) proposed roads, (e) existing roads, (f) stream buffers, (g) patch-cut areas

Figure 5. The preliminary computerized model applied to patch-cut areas on the McDonald-Dunn OSU Research Forest.

DISCUSSION

This paper introduced a methodology for simultaneously optimizing cable equipment placement and road locations using a heuristic network solution technique. This methodology is currently being implemented in a computerized model. Developing a useful model requires a good estimation of operation costs, therefore detailed cable road analysis and road cost modules are included.

Grid pixel size in a DTM directly affects the problem size for the network analysis. High resolution in a DTM would provide topographic details but exponentially increases problem size resulting in increasing solution time and demand for memory capacity. Methods to reduce problem size with a high resolution DTM may need to be explored to shorten solution time and lessen memory requirements. Reducing the number of origins by clumping several timber cells together or eliminating infeasible links from the whole network system might be alternative ways to reduce problem size.

Future improvement of this model should include the considerations of riparian zone management regimes and other environment impact of road construction. Additional constraints may enable us to restrict stream crosses and avoid road construction from unstable soil areas. Verification of the methodology described in this paper should be done in the future studies. The results from this methodology can be compared with a cable layout by manual methods or results from other optimization techniques. Also further studies to improve the efficiency of the solution technique should be taken based on the preliminary results of the planned model.

REFERENCES


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