AN ABSTRACT OF THE DISSERTATION OF

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Designing timber harvesting units is a challenging task. The task requires decision making on logging equipment, landing site, cable road profile, road location, and transportation system. Traditionally forest planners have done the task manually. However, the manual method makes it difficult to examine many alternatives and the harvest plans depend heavily on the experience of the individual planners. Furthermore, increased environmental concerns require more sophisticated planning procedures. Thus, it is challenging to find not only economically and environmentally "feasible" solutions but also "good" solutions by the manual method. Tools for detailed analysis and systematic evaluation of alternatives become essential for better planning of harvesting operations.

This study develops a methodology with the purpose of assisting the planners in designing cable logging unit layout. The methodology combines a cable logging operation planning problem with a road network planning problem and optimizes them simultaneously. It incorporates modern computer software languages, Geographic Information System (GIS) technology, and optimization

techniques that have become available during the last two decades. The methodology includes logging feasibility and cost analysis to evaluate alternative cable roads and yarding equipment. Once the feasible cable road alternatives are identified, the methodology formulates two cost minimization network problems. The networks represent variable and fixed costs associated with yarding and truck transportation activities to move logs from the stump to the mill. The methodology uses a heuristic network algorithm as an optimization technique to solve the network problems. One of the two cost minimization network problems is for cable logging operation planning and the other is for truck transportation planning. Each of the network problems 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 that can be used as a decision support system. The model is applied to an actual harvest area of 93 ha. A total of 40 candidate landing locations with 2,880 cable roads from 2 yarding equipment alternatives were evaluated. The model found 1,719 feasible cable road alternatives by conducting the logging feasibility and cost analysis. Two cost minimization network problems were developed. A total of 141,139 links and 1,926 timber parcels were developed in the network problem for cable logging paths. In the network for solving road location problem, a total of 95,904 links were developed to connect 13,522 grid cells included in the planning area. After 47.2 hours for 10 repetitions on Pentium III 1GHz speed desktop computer, the heuristic network algorithm solved these network problems and selected a total of 19 landings and 155 cable roads to harvest 8,064 m^3 of logs from 1,926 timber parcels over the planning area. A total of 2.85 kilometers of new access roads were proposed as a part of the solution for this application. Overall yarding and road costs for timber harvest in the planning area was \$416,675 (\$51.67/m^3).

Although the exact solution could not be verified, the solution obtained with this methodology when coupled with sensitivity analysis can be considered as a feasible and good harvest operation plan for the management goals. By providing systematic and analytic tools, the computerized model presented in this study can be used as a decision support tool assisting the forest planners in designing timber harvest layout.

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

by
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Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Woodam Chung, Author

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

INTRODUCTION

Designing timber harvesting units is a challenging task. The task requires the planners to make decisions related to logging equipment, landing sites, logging profiles, road locations, and transportation systems. To make these decisions, the planners must consider various logging operation factors such as topography, timber volume and location, logging equipment, and many others that ultimately affect the physical feasibility and economic efficiency of the logging system. Furthermore, increased environmental concerns have brought additional considerations and requirements into timber harvesting operation planning and harvest unit design. These include water and wildlife habitat protection rules (Oregon Department of Forestry (ODF) 2000).

One focus in the evolution of forest resource management is on environmentally-sensitive forest operations. The questions for resource management planning are shifting from "what" to do to "how" to do it (Rummer et al. 1997). Many state agencies in the United States provide standards for forest practices so that the operations can produce better environmental results. In

Oregon, a landowner or contractor must develop a harvesting operation plan to comply with Oregon's Forest Practice Rules (ODF 2000). A significant number of the rules are directed toward timber harvesting, forest roads, and accompanying activities in regards to stand damage, soil and water protection, riparian management, and sensitive wildlife habitat (Adams 1996).

Environmental regulations on forest operations may increase timber harvesting costs. Forest planners or engineers making decisions in harvesting operation planning are faced with the challenges to develop a "good" alternative that accomplishes both environmental and economic objectives that are often in conflict.

The general procedure of timber harvest operation planning and unit layout consists of paper planning, field verification, and implementation (Kellogg 1999). Paper planning includes logging and road designs, identifying control points, determining physical and environmental feasibility, and cost appraisal. After alternatives are developed during paper planning, a preferred plan is selected among alternatives. Timber harvest operation planning and unit layout is time consuming and expensive (Kellogg 1998). A well-designed plan will reduce layout costs by minimizing fieldwork as well as benefit logging costs and enhance work safety.

Traditionally, engineers have done the operation planning and harvest unit layout manually using topographic maps or simple functions of Geographic Information Systems (GIS). However, it is difficult to develop and examine many alternative plans by the manual method. Moreover, additional environmental considerations have increased the complexity of planning and design procedures. Thus, it is a challenging task to find a not only economically and environmentally "feasible" but also "good" operations plan by the manual method. Systematic tools for detailed analysis and evaluating alternatives are essential for better harvesting operation planning and harvest unit layout. The challenge of moving timber from the stump to the mill at reasonable cost with less environmental impacts might require improvements not only in logging technology but also in planning procedures.

LITERATURE REVIEW

This study has two main goals. One is to develop a methodology for simultaneously optimizing a cable logging layout and road network using a mathematical programming technique. The other is to develop a decision support system which implements the methodology while integrating existing knowledge related to GIS, ground profile analysis, cost estimation, harvesting production rates, and environmentally-sensitive forest operations.

The literature review starts with introducing the existing knowledge which has been used in timber harvest operation planning and harvest unit layout. Then, it covers several mathematical models that have been utilized in forest resource planning including a heuristic network algorithm which is used in the methodology presented in this study.

The last section of this literature review introduces various decision support systems (DSSs) that have been widely used in forest harvest scheduling and transportation planning. The remaining part of this section introduces existing decision support tools developed for designing cable logging layout and addresses their limitations.

APPLICATIONS OF GIS AND REMOTE SENSING TECHNIQUES IN FOREST PLANNING

A GIS has become a vital analysis tool for land and natural resource management planning. The introduction of GIS and remote sensing techniques to forestry have greatly improved forest planning procedures by increasing the efficiency of the planning process and expanding the scope of the planning problems. The methodology developed in this study requires a GIS containing data including a Digital Terrain Model (DTM), forest inventory, existing roads, and streams. This section reviews the applications of GIS and remote sensing techniques in forest planning, emphasizing the GIS data required for this methodology.

GIS in forest planning

GIS is playing a key role in forest planning. A GIS stores both the geographic and numerical structure of the forest stands and links that spatial database to the planning models. Due to increased environmental concerns, the spatial considerations and analysis that GIS provides have become essential in forest resource management planning (O'Hara et al. 1989, Baskent and Jordan 1991). Spatial analysis techniques also allow the forest managers to consider not only timber extraction but also wildlife and aquatic habitat quality in land management activities (Bettinger 1996). Sessions et al. (2000) developed a long-term harvest schedule for one of the Oregon State University Research Forests based on spatial details provided by GIS software. Their harvest schedule required additional spatial considerations that include maintaining the area of mature contiguous forest, restricting opening size, spatially grouping harvest units, and considering location of riparian zones.

Dykstra (1992) applied a GIS to a short-term timber harvest scheduling. In his application, the GIS is used in 1) delineating compartment areas with stream buffer, harvest restriction areas, and watershed boundaries, 2) analyzing logging and transportation feasibility using slope classes, 3) storing and retrieving forest inventory data, and 4) generating maps showing treatment plans.

Applications of the digital terrain model (DTM) in forest operations design

The DTM is a grid map in which equally sized grid cells contain their unique elevation. It has been widely used in analyzing terrain conditions for timber harvest operation designs. Many existing forest planning models and tools also require a DTM as basic source data for ground slope and profile analysis. Twito et al. (1987) developed a program, MAP, to produce a DTM, which would be the source of terrain data for further logging analysis. In MAP, the DTM is produced by manually tracing contour lines from a topographic map. Reutebuch (1988) developed a computer program, ROUTES, to help engineers with estimating grades and distances along a possible road route using a DTM. Nearhood (1992) used a DTM in planning a ground-based harvesting system. He developed a prototype GIS model in which the planners can use a mouse or digitizer to delineate the harvest area boundary, potential landing locations, and possible skid trails. Becker and Jaeger (1992) developed an integrated system consisting of a combination of GIS and an interactive planning technique (CAD) for road design. In this system, possible route locations can be interactively planned on a DTM. Chung and Sessions (2001) optimized the location of a forest road network on a DTM using heuristic problem solving techniques considering road constructing costs, truck transportation costs, and the spatial allocation of harvesting units.

High resolution DTMs are becoming available with advanced remote sensing techniques. For example, Light Detection And Ranging (LIDAR) (Kraus and Pfeifer 1998, Means et al. 2000) technology has been used to develop high resolution DTMs. Coulter et al. (2001) generated a high resolution DTM (1m x 1m) from LIDAR data to estimate forest road earthwork.

GIS and remote sensing for forest inventory

Traditionally, ground sampling was the only method to estimate species composition and measure tree variables such as height, diameter, and volume. Although field work for a forest inventory is still required, a large part of the field work has been replaced with other remote sensing techniques such as large-scale aerial photographs (Aldred and Hall 1975) or satellite imagery. Franklin et al. (1986) used Landsat image and digital terrain data for coniferous forest classification and inventory. Leckie (1990) integrated different remote sensing technologies such as aerial photographs and satellite imagery with other information sources using a GIS for forest inventory and management. He also pointed out that satellite imagery is cost-effective compared to aerial photographs. Fiorella and Ripple (1993) used Landsat Thematic Mapper (TM) data to evaluate young conifer stands and described the relationships between TM band values and age of young Douglas-fir (*Pseudotsuga menziesii*) stands using data regression and correlation.

As remote sensing techniques are advanced, more accurate and higher quality data become available. Kraus and Pfeifer (1998) developed a high-resolution terrain model in forest area using airborne laser scanner data, which was a new remote sensing technique. Means et al. (2000) applied airborne scanning LIDAR data to predict forest stand characteristics. They found LIDAR data could be used to estimate stand characteristics accurately and the method is cost-effective compared to traditional field methods for forest inventory.

SKYLINE PAYLOAD ANALYSIS

One of the earliest treatments of tensions in cable harvest systems in North America was done by Mills (1932). Davies (1946) converted the analytical work of Mills into graphical and tabular methods. Lysons and Mann (1967) extended Davies' work and published a handbook to provide a skyline tension analysis that utilized tabular and graphical approach for the solution of single span and multispan skyline catenary problems. Mann (1969) first derived payload equations for running skyline systems. To solve skyline catenary equations efficiently, Carson and Mann (1970) developed an iterative solution procedure. They also developed a simplified approach to the running skyline design problem to determine the load path of a running skyline (Carson and Mann 1971).

Carson (1975) examined skyline analysis with log drag for the running skyline. Tobey (1980) found that when logs have one end suspension, there could be considerable difference in the payloads. Shortly afterward, Falk (1981) developed a package for hand-calculators to calculate the allowable payload of cable logging systems considering the effect of partially suspended logs with the front end of the log off the ground. Kendrick and Sessions (1991) considered stretch of the skyline to develop simplified methods for calculating the carriage height above the ground along a standing skyline. Using the method in Kendrick and Sessions (1991), Brown and Sessions (1996) developed an algorithm for determining the maximum log load which can be carried along a standing skyline where the logs are either fully suspended or partially suspended above the ground.

Several computer programs were developed for the practical solution of cable logging profile analysis on desktop systems. Carson (1975) developed four computer programs, which were extended by Sessions (1978), to determine load-carrying capability for single and multispan standing skylines and single span running skylines. Chung (1987) considered mechanical characteristics of cable logging systems in a computer program package developed for six cable logging system options. Live skyline, slackline, and highlead systems were added in his program. Recent computer programs have improved user-interface and graphic display functions for the basic analysis technique. LOGGER PC (Jarmer and Sessions 1992) has become the standard for skyline payload analysis in the Pacific Northwest region and many other places.

ESTIMATING CABLE LOGGING COST

Numerous time studies for cable logging production and cost have been conducted for various equipment, regions, and silvicultural harvesting methods. LeDoux (1985) developed stump-to-mill cost equations for six different cable yarders for mountainous terrain in the eastern United States. He also added cost equations for the Clearwater yarder developed by the USDA Forest Service

(LeDoux 1987). In both studies, he used nonlinear multiple regression analysis to estimate the delay-free cost based on the independent variables which include average tree diameter (DBH), average slope yarding distance, and average volume removed per acre.

Hochrein and Kellogg (1988) developed linear regression models for delay-free yarding cycles for a small (Koller K-300) and a midsize (Madill-071) yarder at a light and a heavy thinning intensity in Douglas-fir stands in western Oregon. The regression models are based on the independent variables of slope distance, lateral distance, number of logs, slope, and thinning indicator. In addition to predicting yarding cycle time, several detailed time studies were conducted to calculate total yarding costs. Edwards (1992) suggested methods of time study for logging planning, felling, yarding, and road/landing change. Kellogg et al. (1996b) developed separate regression equations to predict felling cycle time. In order to determine total harvesting costs, they also calculated the costs to move the logging equipment to the site, set it up, tear it down, and move it out including lowboy transport, following the methods in Edwards (1992). Kellogg et al. (1996a) added logging planning and road/landing change costs to felling and yarding costs in order to compare total yarding costs between clearcut and group-selection harvesting methods.

Several computer simulation models were developed for estimating yarding costs. Sessions (1979) developed a yarding simulator to simulate yarding in clearcuts, partial cuts, and pre-bunch and swing operations These ideas were extended by McGaughey (1983), LeDoux (1983), and McGaughey and Twito (1987). THIN (Butler and LeDoux 1983) was developed to aid forest managers in the evaluation of alternative thinning systems for young-growth stands in mountainous terrain. With the input data of log location, volume, area, terrain, labor, equipment, and yarding method, the model simulates the harvest operation and calculates production rates as output. Using the THIN model, Starnes (1984) transformed existing equations for estimating skyline thinning turn time into easy-to-use linear production rate equations which are based on only three easily obtained independent variables: cut volume per acre, average slope yarding distance, and average log volume. He also pointed out limitations of the linear equations which inherently contain an inaccuracy due to a strong nonlinear relationship between production and log volume data.

A computer program for cost calculations (PACE) was developed by Sessions at Oregon State University (FAO 1992). The program is composed of three parts: machine rate calculations, road construction calculations, and harvesting production and unit cost calculations. All three calculation parts are combined to develop production and unit cost estimates. Another example of computer programs developed for estimating harvesting costs is the PPHARVST (Fight et al. 1999). The program was specifically developed for use in management planning for ponderosa pine (*Pinus ponderosa*) plantations. The equipment production rates, which were developed from existing studies and harvesting systems, included a cut-to-length harvester-forwarder system, a whole-tree/log-length skidder system, and a skyline cable system. This program can be applied to both clear and partial cutting.

ENVIRONMENTAL IMPACTS OF TIMBER HARVESTING AND RIPARIAN MANAGEMENT

This section briefly reviews the nature of environmental impacts related to timber management activities and introduces the timber harvest practices designed for prevention and mitigation of such impacts. Accelerated rates of soil erosion and sedimentation to streams, changes of stream temperature, and reduction of large woody debris may be the principal environmental consequences of timber harvesting.

Accelerated soil erosion and sediment production

Forest management activities, especially timber harvest, can accelerate the rate of landslides and surface erosion from harvest units and forest roads. Swanson and Dyrness (1975) assessed the impact of timber management activities by measuring levels of slide occurrence in roaded and clear-cut areas relative to forested areas in western Oregon. Slide erosion from clear-cut areas was 2.8 times greater than that in forest areas. Along road rights-of-way, slide erosion has been

30 times greater than on forested sites. Amaranthus et al. (1985) documented a similar result occurred in the Klamath Mountains of southwestern Oregon. Their records of debris slides over a 20-year period showed that erosion rates on roads and landings were 100 times those on undisturbed areas, while erosion on harvested areas was seven times that of undisturbed areas. The Oregon Department of Forestry (ODF) conducted a ground-based landslide inventory after a series of storms in 1996 in western Oregon (Robison et al. 1999). The ODF study indicates that there is a greater landslide density and landslide erosion volume in the recently clearcut stands (0 to 9-year age class) as compared to the mature forest stands.

Forest roads have long been considered as the major source of accelerated erosion. The effects of forest road construction in accelerating erosion have been extensively documented. Brown and Krygier (1971) measured the impact of road construction on the suspended sediment yield and concentration from three small watersheds in the Oregon Coast Range. The results of their study indicated sediment production was doubled after road construction. Krammes and Burns (1973) estimated the amount of landslides along the roads in the Caspar Creek watersheds in northern California; 500 cubic yards of soil and rock material from cut banks was deposited on the road along 2,000 feet of road. Landslides along the fill slopes contributed an estimated 150 cubic yards directly to the stream. Swanson and Dyrness (1975) and Amaranthus et al. (1985) also reported the impact of forest roads on the increase in landslide erosion.

Increases in ground slope are usually related to the rate of erosion to increase. McCashion and Rice (1983) observed that the amount of road-related erosion increased with the slope traversed by the road. Their study on assessment of erosion sources along 344 miles of logging roads in northwestern California documented that 19 percent of the total amount of road studied, which had cross slopes of sixty percent or more, accounted for 51 percent of the total erosion measured.

Soil erosion from road construction and logging practices increases suspended sediment in stream channels. A paired watershed study conducted by Beschta (1978) in the Oregon Coast Range showed that suspended sediment production after road construction, logging, and slash disposal was significantly increased. Another impact of soil erosion is reduced site productivity. Swanson et al. (1989) documented that soil erosion such as surface and debris slide following clear-cutting and slash burning may diminish site productivity because erosion causes loss of nutrients, soil biota such as mycorrhizae, and soil organic matter.

Harvesting operations can change the infiltration capacity of forest soils causing surface erosion through a process of soil compaction. The amount of surface erosion caused by harvesting operations may vary depending on site and soil characteristics. In western Oregon, it was documented that erosion associated with infiltration-limited overland flow occurs only on sites that are drastically disturbed and compacted (Fredriksen 1970).

During the past three decades, extensive effort has been put into enhancing the environmental performance of timber harvesting activities with regard to landslides. Most progress made for the prevention and mitigation of accelerated erosion has come through the establishment of Best Management Practices (BMPs) and state forest practice rules (Skaugset et al. 2002). These BMPs and forest practice rules include detailed regional requirements for timber harvesting and its accompanying activities; how forest roads are located, constructed, and maintained, and the protection of streamside areas and water (Adams 1996, ODF 2000). Modern harvest systems such as long-span cable systems and the use of full or partial suspension require fewer roads and leave less ground disturbance than older systems. Forest roads can be better located, constructed, and maintained. Protection zones around streams or buffer strips are used to limit the amount of disturbance to streambed and banks.

Stream temperature and large woody debris

Streamside logging may affect water temperature, which influences many of the physical, chemical and biological properties of an aquatic system. Removal of forest vegetation along channels by timber management activities allows more solar radiation to reach the stream surface, increasing water temperature. Brown and Krygier (1970) reported that average monthly maximum temperatures increased by 14 ˚F one year after clear-cut on a small watershed in Oregon's Coast Range. Krammes and Burns (1973) documented that opening of the canopy for road construction increased summer water temperatures in a watershed of Caspar Creek in California.

Altered levels of stream temperature and light regime after logging can have both positive and negative consequences for aquatic habitat (Hicks et al. 1999). These effects are well documented particularly for salmonid production in western North America. Hicks et al. (1999) mentioned that one of the potentially positive effects of elevated light and temperature during summer is increased food production for fish. Holtby (1988) found slight temperature increases in late winter and early spring after clear-cut logging of the basin of Carnation Creek, British Columbia, led to the earlier emergence of coho salmon (*Oncorhynchus kisutch*) fry and an increase in the length of the summer growing season. He also found fingerlings entered the winter at a larger size and survived the winter better after logging, which resulted in more yearling smolts in the following spring. Although positive effects of elevated water temperature have been reported, the effects are good only where the temperature is within thermal tolerances and preferences of fish (Beschta et al. 1987). Beschta et al. (1987) reviewed potentially negative effects of stream temperature changes by logging on salmonids. These include inhibition of upstream migration of adults, increased susceptibility to disease, higher metabolic rate resulting in low growth efficiency of salmonids, and reducing the fitness of existing populations with deleterious consequences to production.

Streamside logging is not only associated with water temperature but also with the amount of large woody debris in streams, sedimentation, channel morphology, bank stability, and other factors that ultimately alters the productive capacity of a stream for fish (Beschta et al. 1987).

Large woody debris (LWD) is an important component of the stream ecosystem. LWD controls stream channel morphology by influencing flow and sediment deposition (Sullivan et al. 1987), regulates the storage and routing of sediment and particulate organic matter (Bilby and Likens 1980, Bilby and Ward 1991), and enhances the quality of fish habitat in all sizes of stream (Bisson et al. 1987). Bilby and Likens (1980) found removal of organic debris dams led to a dramatic loss of organic carbon from the small stream ecosystem. Bilby and Ward (1991) surveyed amount of LWD in streams flowing through old-growth, clear-cut, and second-growth forests and found that many changes in LWD abundance, characteristics, and function occurred very rapidly following removal of streamside vegetation. They reconfirmed the necessity of retention of standing trees along stream channels during timber harvest to provide a source of future LWD.

Currently available BMPs and forest practice rules for riparian areas focus on retaining understory vegetation and avoiding ground disturbance to protect water quality and fish habitat (Adams 1996). For example, the Oregon's forest practice rules designate the areas where vegetation and trees must be retained. All understory vegetation within 10 feet of the high water level, all trees within 20 feet of the high water level, and all trees leaning over the channel must be retained

(Adams 1996, ODF 2000). In addition, ODF has classified streams and set the width of riparian management areas where additional vegetation retention and operational rules must be applied. Along fish-bearing streams, it is often required that additional trees in the riparian management areas be protected to provide shade, food for aquatic organisms, and woody debris for in-stream habitat.

MATHEMATICAL MODELS FOR FOREST RESOURCE MANAGEMENT PLANNING

Hierarchical approach

Forest resource management planning involves decisions on silvicultural prescriptions, harvesting, road construction, and truck transportation. Typically forest planning procedures use three hierarchy levels of decision making that include strategic, tactical, and operational levels (Weintraub and Cholaky 1991, Church et al. 1994). At the strategic level, managers analyze a given forest globally with aggregate temporal and spatial data (strata-based) over a long time horizon (Weintraub and Bare 1996). Spatial considerations such as site-specific constraints and road access are usually left to the tactical level of decision making. The planning horizon for tactical planning is shorter than strategic planning. Operational planning, which is the last step of the hierarchical approach, is for guiding actual forest management activities, typically involving a single period plan for individual treatment units. Operational planning usually requires detailed information and analyses. The size of the mathematical formulation is large and relatively many decision variables are involved in the operational planning (Murray and Church 1993).

The hierarchical approach to forest planning may be necessary since it simplifies the analysis at each level requiring different dimension of information details. However, as more precise data and better hardware capability are developed, the collapse of planning from hierarchical levels into a single process has also appeared (Sessions and Bettinger 2001).

Linear programming

Linear Programming (LP) has been applied to strategic forest planning since the early 1970's and became the most widely used technique in the United States. The main advantages of LP are that it can generate the exact solution to a problem and it allows the user to examine more than one criterion at a time, for example, maximize present net value (PNV) subject to non-declining yield (Nelson et al. 1991). One of the earliest LP models was Timber RAM (Resource Allocation Model) which was designed to help formulate plans which are efficient with respect to timber volume harvested, costs, or revenues, and which are consistent with specific management policies and available resources (Navon 1971). Another widely used LP harvest scheduling model in the early 1970's was MAXMILLION (Ware and Clutter 1971) developed for even-aged industrial forests.

In order to deal more effectively with site-specific environmental questions, MUSYC (Multiple Use-Sustained Yield Calculation Technique) was developed by Johnson and Jones (1979). However, this model was basically a more sophisticated timber management strata-based model (Iverson and Alston 1986) in which location-specific issues could not be easily addressed (O'Hara et al. 1989).

Another LP model, FORPLAN (Johnson and Stuart 1987) was developed by the USDA Forest Service to combine functional resource planning with integrated land-use planning. Whereas Timber RAM and MUSYC only analyzed commercial timberland, FORPLAN with sophisticated formulations including many decision variables could accommodate all lands and water in the forest (Iverson and Alston 1986). However, explicit spatial considerations were not included in any of the above LP models.

Mixed integer programming

As the planning process moves from the strategic level to the tactical and operational levels, there are increasing spatial details and constraints that require explicit spatial planning procedures. The first attempt to introduce spatial aspects into models may be related to road construction problems. Since road construction options involve 0-1 variables, integer programming (IP) has been used to solve forest planning problems including road building options. Sullivan (1974) established one of the first attempts to model road construction problems, where decisions on road networks were made independently from decisions on land management. Implementing mixed integer linear programming (MIP) made it possible to integrate road building and land management into one model (Kirby et al. 1986, Weintraub and Navon 1976). Jones et al. (1986) evaluated four analytical approaches for integrating land management and transportation planning and concluded that using simultaneous consideration of roads and resource scheduling with IRPM (Integrated Resource Planning Model) using MIP technique provided the best solution (Kirby et al. 1986).

Heuristic approaches

Due to the sophisticated spatial constraints at the tactical and operational level of the planning process, the model size of problems increases and easily exceeds the limitations that can be solved optimally by traditional MIP approaches. As a result, heuristic programming techniques that provide near-optimal solutions with less cost and computational time have been developed and applied to the combined planning of road building and resource management. Nelson and Brodie

(1990) applied the random search technique, Monte Carlo Integer Programming, to solve forest planning problems that include adjacency and roading constraints. Sessions and Sessions (1988) developed SNAP (Scheduling and Network Analysis Program) to solve tactical harvest planning problems where wildlife habitat connections are considered. The solution approach in SNAP includes a series of heuristics based on random search and a shortest path algorithm to solve adjacency, habitat connection, and road building problems. Murray and Church (1993) investigated three methods for generating operational forest plans, based on common heuristic optimization approaches: interchange, simulated annealing, and tabu search. They showed these approaches provide near optimal solutions in relatively short amounts of computer time. Lockwood and Moore (1993) applied simulated annealing to a harvest scheduling problem having block size constraints, adjacency delay, and objectives to meet harvest volume targets.

Environmental concerns led to important modifications in planning models (Weintraub et al. 2000a). As the goals of forest management broadened from maximizing economic value to ecosystem management, planning models have to consider more complex spatial aspects related to the protection of wildlife and aquatic habitat, scenic beauty, and reduction in soil sedimentation and erosion. Heuristic approaches developed for solving combinatorial problems in other industries are increasingly applied to complex forest planning problems. Bettinger et al. (1997) used a tabu search method to schedule timber harvest subject to spatial wildlife habitat quality goals. They demonstrated that a tabu search algorithm could be developed to simultaneously meet spatial wildlife goals with other decision choices. Bettinger et al. (2002) applied eight types of heuristic techniques to three increasingly difficult forest planning problems where the objective function maximized the total amount of land qualified for certain types of wildlife habitat. The eight heuristic techniques include random search, simulated annealing, great deluge, threshold accepting, tabu search with 1-opt moves, tabu search with 1-opt and 2-opt moves, genetic algorithm, and a hybrid tabu search / genetic algorithm search process. The authors showed that except for the random search method all the other heuristic techniques are "appropriate" for all three wildlife habitat management problems described in the paper.

Combined mathematical programming techniques with heuristics

While the heuristic programming techniques introduced by Bettinger et al. (2002) were "independently" developed as operations research models, "conventional" mathematical models such as MIP and network programming have been combined with heuristic rules to overcome the limitations of problem size and expand their applications to tactical and operational levels of planning.

A heuristic integer programming (HIP) procedure was developed to solve IRPM-type MIP problems (Weintraub et al. 1994). The HIP procedure starts with an initial LP solution, and then uses the heuristic rules to set to 0 or 1 selected road project variables that were fractional in the LP solution. Another LP solution is generated based on the new LP matrix implementing the modified road variables. This process repeats until no further modifications are found.

Combined with other mathematical algorithms or heuristic rules, network programming techniques have been applied to tactical forest planning focusing on road building and transportation problems. The Timber Transport Model developed for the USDA Forest Service during the early 1970's is an example of combining MIP with network programming (Sullivan 1974) for solving fixed and variable cost forest transportation problems. In those problems, fixed cost is usually defined as road construction cost, involving 1-0 integer variables, while variable cost is defined as hauling cost, a function of timber volume. The Timber Transport Model first develops candidate routes from entry points into the network to candidate exit points using a N^{th} best path algorithm (Hoffman and Pavley 1959) considering only variable costs. Then, it optimally selects among the candidate routes to determine the combination of routes and volume assignment that minimized the sum of the fixed and variable costs. Due to the limitations of problem size that can be efficiently solved by MIP, the number of candidate routes per entry point was limited, which may provide solutions far from optimal.

Solving such large fixed and variable cost problems in forest transportation planning led to applying heuristic techniques to network algorithms. The Prorate algorithm (Figure 1) in the MINCOST program developed by Schnelle (1980) is an example of a heuristic that embeds the shortest path algorithm. The Prorate

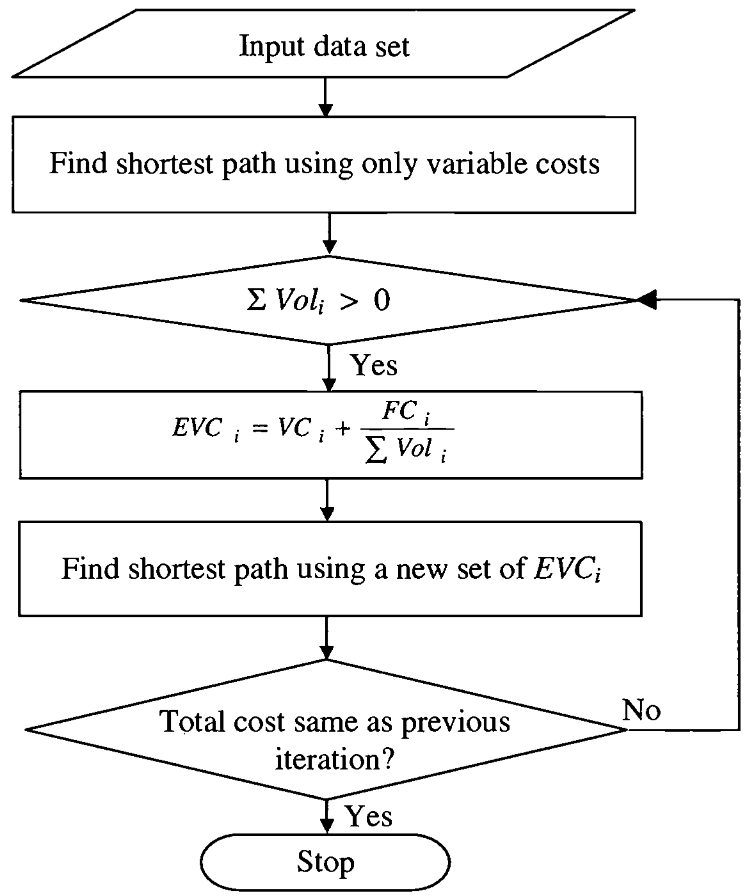


Figure 1. A flowchart for the Prorate algorithm.

algorithm solved a series of variable cost problems by converting the fixed costs into equivalent variable costs by dividing the fixed costs by the volume transported over the link. The equivalent variable cost technique had been previously applied by Cooper and Drebes (1967) as part of a heuristic solution to solve the fixed charge problem using linear programming.

$$EVC_i = VC_i + \frac{FC_i}{\sum Vol_i} \qquad 1.$$

where, EVC_i : equivalent variable cost for link i

VC_i : variable cost for link i

FC_i : fixed cost for link i

Vol_i : volume transported on link i

The shortcomings of the Prorate algorithm were illustrated by Wong (1981) in a series of examples that showed that the Prorate Algorithm could stall in a local minimum. The NETCOST algorithm (Weintraub and Dreyfus 1985) and the NETWORK algorithm (Sessions 1985) are similar to the Prorate Algorithm but each uses a series of rules to avoid stalling in a local minimum.

The NETWORK algorithm developed by Sessions (1985) is used in the methodology in this study. The algorithm starts with sorting the entry nodes (sales) by time period and volume (Figure 2), and then solving the shortest path problem and adjusting the variable costs to include consideration of the fixed costs, FC_i for link i, associated with the best variable cost solution. The sum of the volumes, Vol_i,

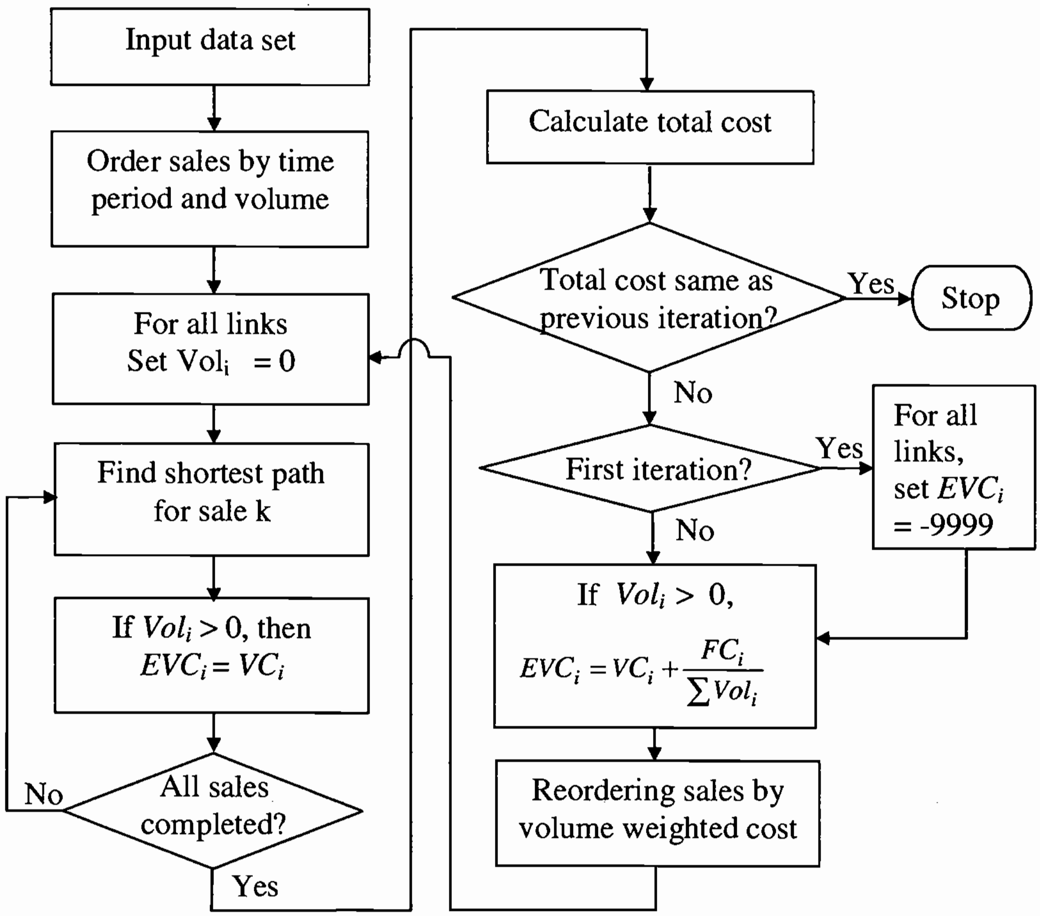


Figure 2. Flowchart of the NETWORK algorithm developed by Sessions (1985).

that went over each link are accumulated and so that at the end of the first iteration the sum of all volumes, ΣVol_i, over each link are available. The variable costs for each link, VC_i, are then recalculated using the concept of equivalent variable costs in the Prorate algorithm (Schnelle 1980). The volume over all links is then reset to zero and the next iteration started. This process continues until the same solution is repeated for two iterations. This procedure generally results in a good solution, but there are cases where construction projects (links with fixed cost) are not undertaken which would improve the solution. 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 with 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 links. Reordering sales by volume weighted cost in the following iterations is another method to diversify the search.

The NETWORK algorithm extended its applications to multiple periods, multiple product, and value maximization or cost minimization through introduction of special links. It has been also applied to solving road location problems (Liu and Sessions 1993) and determining maximum allowable weights for highway vehicles (Sessions and Balcom 1989).

As with other heuristic solution techniques, the solution from this algorithm is not guaranteed to be optimal (Sessions 1985). However, experience has shown the solutions to be quite good and the ability to solve a large problem very efficiently is attractive. The algorithm has been implemented in two computer software programs: NETWORK II (Sessions 1985) and NETWORK 2000 (Chung and Sessions 2000). Both programs have been successfully used by the USDA Forest Service, state agencies, industry, and researchers in other countries as forest transportation planning tools.

DECISION SUPPORT SYSTEMS FOR FOREST RESOURCE MANAGEMENT PLANNING

Various decision support systems have been developed to improve the decision-making process in forest management planning. This section briefly introduces to the state of the art decision support systems that have been widely used in forest harvest scheduling, transportation planning, and cable logging operation planning.

Forest planning

SPECTRUM

SPECTRUM (USDA Forest Service 1998b), an evolution of FORPLAN (Johnson and Stuart 1987), is a linear programming-based forest planning model designed to assist land managers with strategic planning. Whereas FORPLAN emphasizes on economic efficiency of forest management activities, SPECTRUM provides the analytical capability to address ecosystem management issues. The primary roles of the system are to model alternative resource management scenarios applied to landscapes through time, to explore tradeoffs between alternative scenarios, and to schedule activities using mathematical programming techniques (Greer and Meneghin 1997).

RELMdss

Regional Ecosystems and Land Management Decision Support System (RELMdss) is a Linear Programming (LP)-based optimization program that extends forest-wide, strategic planning solutions to tactical sub-units of the forest (USDA Forest Service 1998a). RELM is used to test the feasibility of the strategic solution usually coming from SPECTRUM (USDA Forest Service 1998b) on a geographically specific basis. The ability of analyzing cumulative effects and connected actions within a sub-unit and between sub-units allows planners to evaluate how alternative management scenarios may affect neighboring units. Once the strategic solution from SPECTRUM has been proportioned to sub-units via RELM, each sub-unit can then be analyzed for tactical and operational level feasibility using SNAP software (Sessions and Sessions 1993).

SNAP II

Scheduling and Network Analysis Program (SNAP) is designed to assist in the scheduling and transportation planning for harvest areas (Sessions and Sessions 1993). The program has been widely used by the USDA Forest Service and other agencies. A series of heuristic rules in the system solves harvest scheduling and road building problems considering harvesting costs, revenues, multiple species, alternative destinations, transportation systems, and wildlife habitat connections. Although solutions are quite reasonable, the solution approach has the drawback of a limitation in handling additional constraints as other heuristics for solving the adjacency problem (Weintraub et al. 2000a).

ATLAS/FPS

ATLAS developed at the University of British Columbia and recently renamed Forest Planning Studio (FPS) is a spatially explicit harvest simulation model (Nelson 2000, Perdue and Nelson 2000). The system is designed to help schedule timber harvests consistent with spatial and temporal objectives including policies related to harvest flows, opening size, riparian buffers, seral stage distributions and patch size distributions (Nelson 2000). The basic data inputs are a GIS map consisting of polygons with stand characteristics and growth and yield curves. The system can simulate how different policies will affect harvesting and retention levels across the landscape, but does not optimize harvest schedules or road building options.

Transportation planning

MINCOST / NETCOST

The MINCOST program (Schnelle 1980) basically uses the Prorate algorithm (Figure 1) to search for minimum cost paths between entry nodes (sales) and destination nodes (mills) for forest transportation plans. Weintraub and Dreyfus (1985) found that the prorating method does not always perceive the advantages of sharing the construction cost of a link with multiple sales. To improve the shortcomings of the prorate algorithm, they developed NETCOST equipped with a heuristic procedure. The algorithm uses an approach requiring the k-shortest paths between sales and destination nodes in order to get wide selection of alternatives at early stages. Another basic idea in the algorithm is a “bonus” approach for considering impacts of sharing costs among sales (entry nodes) on road construction.

NETWORK II / NETWORK 2000

NETWORK II program developed by Sessions (1985) has been widely used by the USDA Forest Service and other state agencies. The program is designed to solve fixed and variable cost, multiple period transportation problems to maximize present net worth or minimize cost. The solution approach of the program was built on the prorate algorithm in the MINCOST, but it uses a series of rules (i.e. reordering sales or replacing variable costs of unselected links with a negative value) to avoid stalling in a local minimum. The program can be learned easily, is applicable to various problems, and has a quick and good problem solving ability. Since the program uses a heuristic network algorithm, it can solve relatively large transportation problems (up to a 5000 link network problem), but the solution may not be optimal.

With an effort to improve the NETWORK II program and to apply modern computer techniques and algorithmic approaches, a new version of the program, NETWORK 2000, has been developed (Chung and Sessions 2000). The program has improved the user interface and enhanced the problem solving capacity. It also provides the users with two additional heuristic solution techniques; simulated annealing (Kirkpatrick et al. 1983) and great deluge (Dueck 1993). A Geographical Information System (GIS) interface is newly added to the program to help the users with generating a large network from GIS data. The ability to manage link capacity constraints has been added. The program has problem capacity of 20,000 links, 20,000 nodes, and 5,000 timber harvests (sales). Theoretically, each sale could take place in any time period.

NETWORK 2001

The introduction of multiple management goals and side constraints often rising from environmental considerations or requirements (i.e. open road length restrictions or road deactivations) increases the complexity of the problem. To solve such transportation planning problems, a new network algorithm (Sessions et al. 2001) was developed and is currently under test. The new algorithm combines past network approaches with modern combinatorial heuristic techniques. The route approach of the Timber Transport Model (Sullivan 1974) using equivalent variable costs is applied to generating candidate paths. Simulated annealing (Kirkpatrick et al. 1983) solves the combinatorial optimization problem of assigning the best route to each entry node of network. NETWORK 2001, implementing the new algorithm, has been developed as an analytical tool (Chung and Sessions 2001) to provide additional flexibility in analyzing road systems. While NETWORK 2000 was limited to minimizing costs, NETWORK 2001 can use weighted objective function components to minimize road system length or other link attributes besides costs. For the specific applications of NETWORK 2001, the program must be customized with specific objectives and side constraints according to management policies of each user.

Cable logging operation planning

Cascading fixed charge facilities location model

Dykstra (1976) developed a methodology to assist in the design of timber harvest cutting units and the assignment of logging equipment. In his methodology, the problem of designing forest harvest units is formulated as a facilities location problem which has a special structure called "cascading fixed charge". In order to solve the facilities location problems, Dykstra developed an approximation algorithm. The algorithm starts with finding an initial feasible solution, and then attempts to improve the initial solution by dropping or adding facilities. This algorithm was applied to a 262 acre harvesting unit design in his Ph.D. dissertation (Dykstra 1976). Five potential landing locations, four different cable logging systems, and 144 feasible cable road candidates were considered in the application. His methodology may be useful for the solution of facilities location problems and able to assist in the planning of forest harvesting operations. However, the methodology does not consider multispan skyline systems or alternative road locations, both of which result in limiting the applicable size of harvesting units and the scope of the forest harvesting operation problem. Only clearcut treatments were considered and additional constraints (i.e. landing capacity) were not permitted in his model.

PLANS

Preliminary Logging Analysis System (PLANS) developed by Forest Service (Twito et al. 1987) has been used for developing timber harvest and road network plans based on large-scale topographic maps. The model including several sub programs provides useful analysis tools for harvest unit design such as payload analysis, visual analysis, yarding cost analysis, road layout, and terrain information. The SKYMOBILE program is used to analyze individual profiles along parallel landing locations, while the SKYTOWER program is used to analyze settings that will be yarded in a fan-shaped pattern to a central landing (Twito et al. 1987). The SIMYAR program, which is a cable logging simulation model, uses a digital terrain model (DTM) describing specific harvest unit and stand conditions to estimate the costs and productivity of yarding activities (McGaughey and Twito 1987). Using a DTM, the ROUTES program allows the planner to estimate grade and distance between control points of a forest road route. The program also produces the plan view and the profile view of a selected route. However, PLANS was not designed to optimize a timber harvest operational plan. It is an analysis tool for simulating and evaluating alternative operational plans.

Operational planning tools in Chile (ASICAM / OPTICORT / PLANEX)

Andres Weintraub, Rafael Epstein, and their associates have developed a series of mathematical models in Chile to support decisions in timber harvesting, road construction, and transportation (Weintraub et al. 2000b).

ASICAM was developed based on a simulation process with heuristic rules to support daily truck scheduling decisions (Weintraub et al. 1996). The simulation model inside ASICAM considers demands and supplies for each product and availability of trucks and loaders. The model defines a desirability index for each possible trip considering the total real cost plus a congestion penalty. Heuristic rules of the model choose the best index among all trips with considering priorities given on specific trips. ASICAM has been implemented in eight of the largest forest firms in Chile and reduced costs and improved overall work efficiency (Weintraub et al. 1996).

OPTICORT is based on an LP model with a column-generation procedure (Epstein et al. 1999b). The model identifies which stands to harvest, what type of harvesting equipment to use, what volume to cut each week or period, and what products should be delivered to different destinations, while simultaneously optimizing bucking patterns (Epstein et al. 1999b).

Another mathematical model developed for timber harvesting operations in Chile is PLANEX (Epstein et al. 2001, Epstein et al. 1999a, Epstein et al. 1999b). The model is able to generate an approximately optimal allocation of harvesting equipment and access roads based on a heuristic algorithm. It minimizes total harvesting operation costs including road and transportation costs, machine move-in costs, and harvesting costs, using GIS information on topography, timber volume, roads, and site quality. The heuristic algorithm implemented in PLANEX identifies appropriate harvesting methods according to ground slope, then sequentially determines the most attractive landing locations to minimize logging costs per cubic meter, where costs include harvesting, road building, and transportation (Epstein, et al. 1999b). A shortest-path algorithm is used to provide the least cost road route from existing roads to each candidate landing. A local search routine is used to find a better landing location while considering road costs. After landing locations are identified, a heuristic routine searches the least cost road network (Epstein, et al. 1999b). A mathematical model formulation for the problem behind PLANEX allows the users to constrain maximum capacity of harvesting equipment. However, PLANEX does not have the ability to analyze topographic profiles for the physically feasibility of cable roads, which may be crucial for cable logging operations. Another shortcoming of PLANEX may be that some logging and road cost estimations within the system do not vary with yarding conditions and other road variables. This may limit the applications of the system to various topographic conditions.

Logger PC

LoggerPC (Jarmer and Sessions 1992) is a program to provide analysis for physical feasibility of cable logging systems. The program is able to analyze standing skyline, live skyline, running skyline, multispan, and highlead systems. The user provides equipment specifications including carriage and cable configuration, a description of the ground profile, and log geometry to be used. The program generates allowable log load at each terrain point, the clearance of the log above the ground, and the line tensions according to a given cable system geometry and ground profile. LoggerPC has been widely used in the Pacific Northwest and many other regions for the last decade. The new version of the program (version

4.0) with enhanced graphic user interface has been recently developed and currently under test.

JUSTIFICATION

Written plans and prior approval for timber harvesting practices are required in many states. In Oregon, the operator, landowner, or timber owner must develop a timber harvest operation plan to comply with the practices described in the regional forest practice rules to minimize environmental impacts (Adams 1996, ODF 2000).

Traditionally, forest planners or engineers manually developed timber harvesting operation plans mainly focusing on economic efficiency of logging operations. It is difficult to examine many alternatives using the manual method even though few operational factors are considered. Thus, it has always been a challenging task to find an economically and environmentally "feasible" and "good" operation plan. Although GIS is already an operational tool that can handle a large amount of information, there are relatively few decision support tools to help the forest planners especially with timber harvest operation plans (Guimier 1998). There is a demand for decision support tools that can conduct detailed analysis and evaluate alternatives while integrating large quantities of information in order to help forest planners select an "optimum" harvesting plan under their management goals.

Over the last four decades, there have been many efforts put into enhancing planning efficiency and finding a better solution to forest planning problems. Various mathematical approaches and decision support systems have been developed and applied to forest management planning. As the focus of the land management practices shifted from economic efficiency to ecosystem sustainability, mathematical approaches and decision support systems have evolved. Including spatial and environmental considerations into forest resource management planning greatly increases modeling complexity and problem size with many decision variables. Exact methods such as Linear Programming (LP) and Mixed Integer Programming (MIP) are not able to solve a large problem due to the formulation difficulties and the long computation time. As an alternative, heuristic approaches have been applied to forest planning to solve spatial goal problems in a large area.

Although various mathematical models and decision support systems have been applied to forest planning, there are not many models and systems developed to solve forest operational planning problems. Most modeling and problem solving efforts were dedicated to higher level of forest planning. The reason may be that operational planning involves detailed information and sophisticated modeling techniques that require many decision variables and large problem solving capacity for both computer software and hardware. In addition, increased environmental concerns have brought more environmental requirements into forest practices, which increase the difficulties of problem solving.

Due to advanced information and computer technologies, it becomes possible to develop sophisticated models and problem solving techniques to solve forest operation planning problems. This study is dedicated to developing a methodology incorporating modern GIS technology and a heuristic network solution technique to solve forest operation planning problems, particularly for cable logging operations.

In this study, I consider cable logging operations as a series of operations to move timber from the stump to the mill. The operations include lateral yarding, yarding, and transportation. Each operation is represented by a link on a network connecting two consecutive operations with corresponding costs. Then, a series of operations is a path (a series of links) forming a part of a network system. All possible links starting at each timber source build an entire network consisting of multiple origins (timber locations), multiple paths, and multiple destinations (mill locations). Then, one of the network programming techniques is used to find a better solution among the alternatives.

A decision support system, developed in this study, consists of a series of programs necessary for simulating operations, formulating a network, and solving the problem. The system is integrated with GIS and other analytical tools to evaluate alternatives based on ground profiles, operation costs, and environmental constraints. Detailed ground profile and logging feasibility analyses also enable the planners to recognize difficult logging areas where careful attention needs to be paid in order to avoid operation delays or failure.

The decision support system developed in this study will be able to assist forest managers and engineers in designing cable logging unit layout by providing “good”, “feasible” alternative plans. Well-designed harvesting operation plans will not only reduce total costs but also lessen the environmental impacts and enhance work safety.

OBJECTIVES

Cable logging operations planning is vital for producing economically efficient and environmentally feasible forest operations. The planning includes cable logging operations design and access road network planning. A well-designed plan will reduce environmental impacts, increase economic efficiency, and enhance work safety. The planners have to integrate various operational considerations to make better decisions on a timber harvesting operation plan. For cable logging operations, these considerations include topography, timber volume and location, logging equipment available, landing sites, access roads, cable roads and their physical feasibility, environmental requirements, and economic efficiency.

There are two objectives in this study. The first objective is to develop a methodology for simultaneously optimizing cable logging operation planning and transportation planning. Two networks will be assembled in this methodology. One represents all possible timber paths from the stump to candidate landings through alternative cable roads. The other network represents road routes from candidate landings to the timber exits. A heuristic network algorithm will be applied to the methodology as a problem solving technique. The algorithm will search for the best route from each timber location to one of the timber exits.

The second objective is to develop a decision support system implementing the methodology in order to assist forest planners in designing cable logging unit layouts. The system is integrated with existing knowledge related to GIS, ground profile analysis, cost analysis, and environmentally-sensitive forest operations. A GIS provides the system with information on topographic, timber volume, existing roads, stream buffers, and other logging and road building restriction areas. A series of programs to be developed for the system will conduct logging feasibility and cost analysis, formulate networks for the cable logging operations and transportation alternatives, and solve the network problem to find the best timber path from the stump to the exit. The ability to interactively communicate with the planners enables the system to conduct sensitivity analysis with respect to various cable logging operation scenarios.

In order to test the methodology, it will be applied to a harvest area located in the McDonald-Dunn Oregon State University Research Forest. The results will be analyzed and sensitivity analysis will be conducted for different timber harvest scenarios.

SCOPE

This study focuses on forest harvesting operations, especially for cable logging operations and truck transportation. The intent of the study is to develop an integrated planning methodology that incorporates GIS techniques and existing knowledge related to ground profile analysis, cost estimation, harvesting production rates, environmental impacts, and mathematical solution techniques. This study does not intend to derive any cost functions or production rates for cable logging equipment, or to develop new methods to examine logging system feasibility and environmental impacts. Instead, it simulates cable logging operations and truck transportation in order to generate and evaluate alternative timber harvest operational plans based on the user-defined operating costs, equipment specifications, environmental requirements, and other design factors.

It is impossible to develop a model that can work perfectly under all possible cases of timber harvesting operations. Several assumptions are made about the methodology to guarantee the feasibility of the modeling. Thus, the scope of the problems that the model can handle is constrained. The assumptions are described below.

ACCURACY OF GIS MAPS

The methodology requires raster-based GIS maps of topography, volume and location of timber to be harvested, existing roads, major streams, and other logging restriction areas. The GIS data used in the methodology are assumed to provide accurate and correct information for further analyses. However, certain GIS data may contain less reliable information and uncertainty, although data quality will improve as GIS and remote sensing technology is advanced (Ahmed et al. 2000, Means et al. 2000). In such a case, the outputs of the methodology should be interpreted appropriately according to the accuracy and reliability of input data.

Grid cell size in a raster determines the resolution of data that directly affects the performance of the methodology. Higher resolution data may provide more detailed information, but increases the problem size and requires more solution time as well as memory capacity. A GIS allows grid cells to be any size, but the cell size should consider the accuracy and uncertainty of the data.

Since the methodology requires a raster format for input data, a GIS must be used to convert data in a vector format (i.e. line features of roads, streams, and harvesting boundaries) to a raster format. This may result in possible losses of positional accuracy (Clark 1999). Presenting the exact width of roads and streams in a raster may be limited. The methodology presented in this study ignores road width when it delineates road locations. Road width is represented by one grid cell regardless of actual road width or the grid cell size.

LANDING LOCATIONS

This methodology is not designed to discover landing locations across a given planning area. Instead, the planners should select candidate landing locations where the landing and loading requirements are met (Studier and Binkley 1974), and furnish them to the system. The methodology is to search for “good” landing locations among the candidates.

In this methodology, the landing is assumed to be a central landing where logs are yarded in a fan-shaped pattern. A grid cell on a DTM is assigned to each candidate landing to represent the location. This “landing cell” also provides the location of the tower or headspar of cable logging equipment as well as a target for a spur road that connects the landing to existing roads.

Having one grid cell on a DTM represent the location of landing, headspar, and road target simplifies the problem. In reality, however, the size of the landing should be taken into account in the planning. The requirement of landing size may vary depending on the scale and type of yarding equipment, topography conditions, timber volume to be yarded, and space for loading and transportation equipment (Studier and Binkley 1974). The headspar or tower of the cable equipment can be placed at any spot within a landing. A spur road can enter anywhere around the boundaries of the landing. Thus, the planners should recognize the gap between the modeling and the reality when implementing the outputs of the methodology on the ground.

Although this methodology does not specify the size of landing on a DTM, it is able to consider landing size in the analysis by assigning a unique landing construction cost to each landing.

CABLE LOGGING SYSTEMS

Cable logging systems considered in this study are limited to single-span and multispan standing skyline systems which are used in many harvesting operations for steep topography (Kendrick and Sessions 1991). These logging systems are illustrated schematically in Figures 3 and 4. A standing skyline is a skyline for which the unstretched skyline length does not change during the yarding for the entire corridor. The system can be used to either fully suspend logs above the ground or partially suspend logs with the front end of the log off the ground. A multispan skyline is a series of single-span standing skylines and is best suited for convex slopes (Studier and Binkley 1974). This methodology is also equipped with an automated algorithm to find the locations of any required intermediate supports. The details about the algorithm are presented in the next chapter.

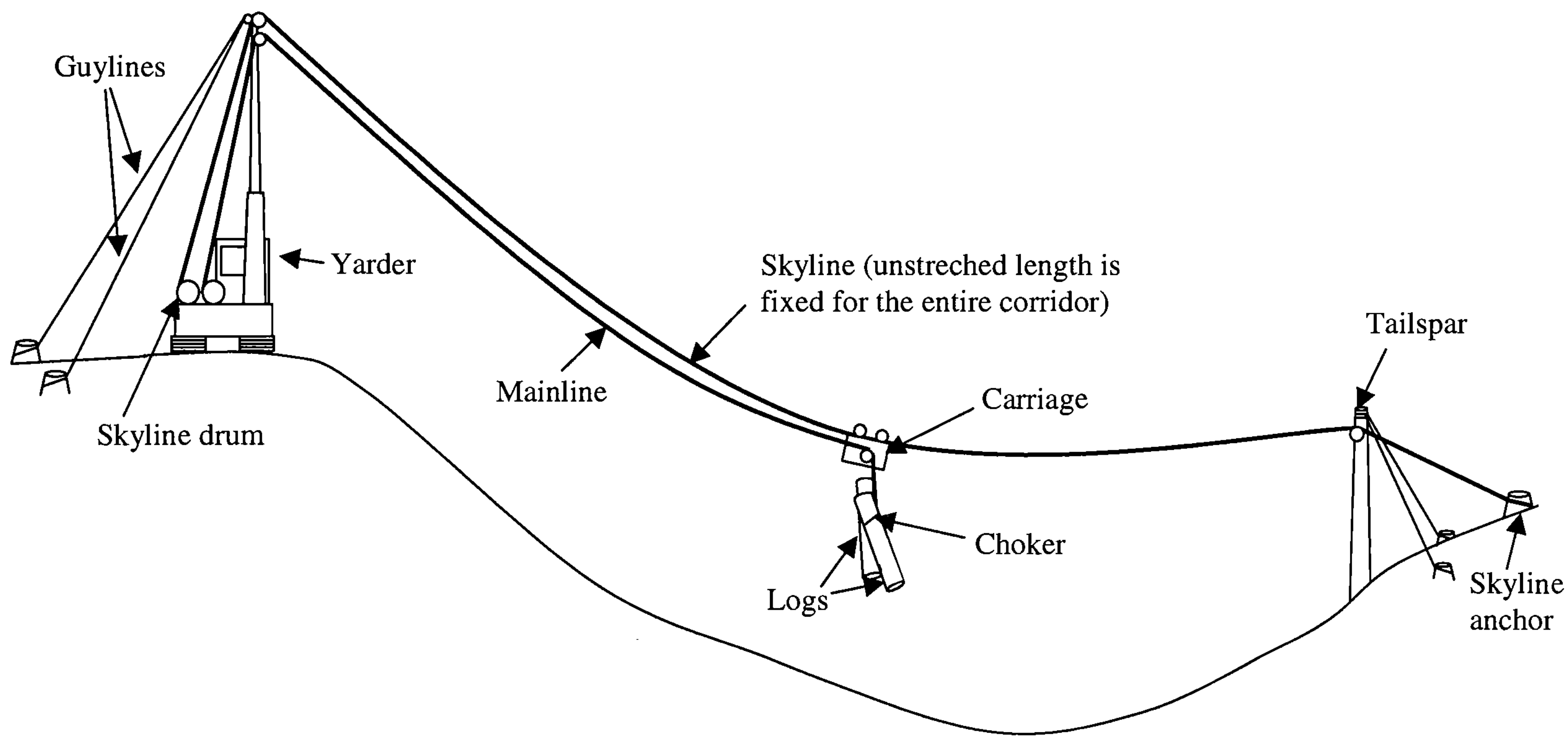


Figure 3. An example of standing skyline cable logging system

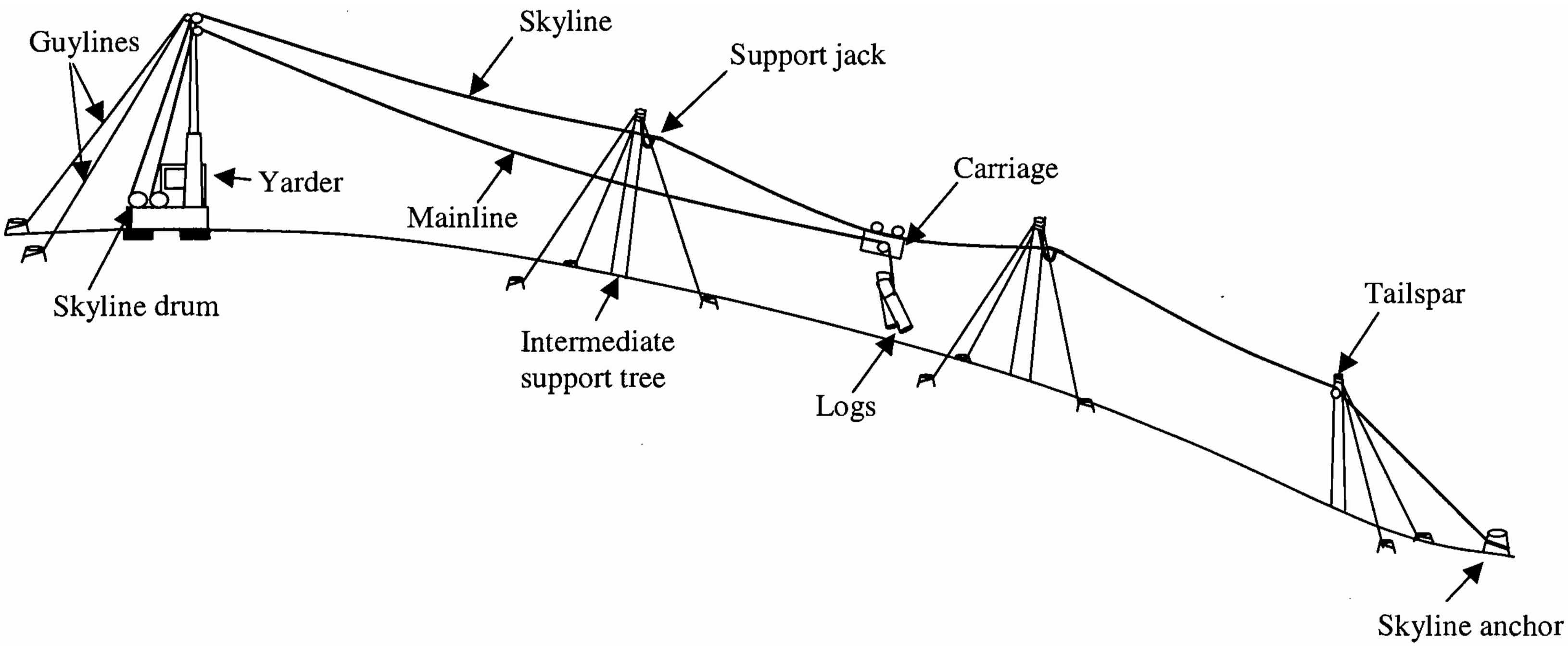


Figure 4. An example of multispan cable logging system

In addition to standing skyline systems, this methodology can be applied to other cable logging systems such as live skyline and running skyline by conducting payload analysis for those systems. Payload analysis is necessary to verify the system feasibility and estimate the maximum payload at each terrain point under the skyline corridor. However, payload analysis for a live skyline should be carefully conducted. The payload can be easily overestimated due to a gap between theory and reality of the system. Dynamically adjusting skyline tension at each terrain point, which is the theory of a live skyline system, is difficult to implement in reality. Thus, most live skylines are operated as a series of standing skylines where the line length is adjusted two or three times during inhaul.

ALTERNATIVE CABLE ROADS

The methodology analyzes cable-logging settings in which logs are yarded in a fan-shaped pattern to a central landing. Parallel skyline corridors along the road, which are typically used when yarders are moved with each corridor change, are not specifically considered in this methodology. However, if many candidate landings were placed along the road, only a few finalized cable corridors would be assigned to each landing because the optimization process of the methodology eliminates unnecessarily overlapped cable roads. Thus, this methodology is also applicable to cable-logging settings with parallel skyline corridors along the roads.

Thirty-six (36) candidate cable roads are laid out from each landing with a ten-degree interval. The number of candidates was arbitrarily determined and can change depending on the preferred analysis. Payload feasibility and maximum feasible yarding distance for each candidate cable road are determined through the ground profile analysis. The user-defined minimum design payload is the principal factor for determining the feasibility of cable roads. The methodology in this study assumes that any cable roads which have payload capability smaller than the minimum design payload are infeasible.

The methodology also assumes that guyline anchors are available anywhere around the landing and do not limit the direction of cable roads. Also, tailspar and intermediate supports are assumed to be available anywhere across a given planning area.

ALTERNATIVE ROAD LOCATIONS

Evaluating alternative road locations and truck transportation routes relies on both economic efficiency and environmental considerations. For solving road location problems, the methodology generates eight potential road segments from each grid cell on a DTM, since one cell is surrounded by eight neighbor cells and, thus, there are eight possible directions to move. Each road segment is evaluated by an "adjusted" construction cost that incorporates road building costs, topographic conditions, and other environmental considerations such as stream crossings. Unfavorable topographic conditions or many stream crossings rapidly raise the equivalent construction cost by applying user-defined multipliers to the regular construction unit cost. Truck transportation cost, which is proportional to timber volume, is also considered for evaluating alternative routes.

ESTIMATION OF OPERATING COSTS

Operating cost is one of the major criteria used to evaluate alternatives in this methodology. Although the methodology may be able to estimate operating costs for a specified planning area, the emphasis of this methodology is on evaluating alternatives based on various management considerations including not only economic efficiency but also other management concerns for which economic values are difficult to measure. This methodology allows the users to generate "adjusted" operating costs by redefining operating unit costs or applying "multipliers" and "penalty" to certain operations. These adjusted operating costs may incorporate operation difficulties, topographic conditions, and penalties on violating management constraints and on negative environmental impacts. Depending on user-defined costs and multipliers, certain adjusted costs could be close to the estimates of actual operating costs, while some others could be "weighted costs" which are intended to avoid certain harvesting activities.

Thus, using the estimates of operating costs as outputs of this methodology for other purposes may not be appropriate without understanding of the user-defined operating costs, multipliers, and the simulation mechanisms of the methodology.

VOLUME DISTRIBUTION

A GIS produced map for a forest inventory is used to provide information on volume and spatial distribution of timber in this methodology. The map must contain information on timber to be harvested and be in a raster data format with the same resolution as a DTM used in the analysis. Thus, each grid cell of the raster contains total volume to be harvested within the area that the grid cell represents. Using this information, the methodology recognizes timber location to be yarded and determines timber volume for each yarding cycle. If one grid cell does not contain enough timber volume for one yarding cycle, then the methodology clumps several neighbor cells together within a reachable distance by a skidding line and chokers until timber volume satisfies the user-defined design payload. On the contrary, if timber volume in a grid pixel is greater than a payload capacity that a candidate cable road can carry at the timber location, then the volume will be split into an appropriate number of loads.

A forest inventory can be obtained by field work for ground sampling combined with remote sensing techniques such as a large-scale photography (Aldred and Hall 1975), satellite images (Franklin et al. 1986, Leckie 1990), and airborne laser scanning data (Means et al. 2000). GPS and other digital survey instruments (i.e. laser rangefinder, digital compass) may increase the efficiency of ground work while providing more accurate measurements (Wing and Kellogg 2001).

Since the inventory map is assumed to contain information on only timber to be harvested, this methodology is applicable to various silvicultural methods such as thinnings, partial cuts, patch-cuts, or individual tree selection cuts as well as clear-cuts. If the inventory includes leave trees and other vegetation, additional work is necessary to edit the inventory map.

UNIT BOUNDARY

Only designated timber within a unit boundary is assumed to be harvested. Candidate landings, tailspars, and intermediate supports, however, can be located anywhere across the landscape regardless of the unit boundary. This allows the planners to find more appropriate landing locations considering topography and to simultaneously layout adjacent harvesting units (i.e. patch-cut) where a landing can be shared.

If landings or any spar trees need to be placed beyond the unit boundary where the land has different ownership, it is assumed that a suitable agreement with adjacent landowners can be negotiated.

OPERATIONAL PLANNING FOR A SHORT TIME PERIOD OF HARVESTING

The methodology presented in this study is designed to analyze a specified planning area on the current timber inventory for a short elapsed time of harvesting, assuming that the timber on the harvest area remains in a static condition for the duration of the plan. Growth and yield projection, price changes, or discounting of future costs and revenues are not included in the analysis of this methodology. Also the methodology does not consider any impacts of the harvesting operations on adjacent areas nor on the following time periods.

SUMMARY

Understanding the assumptions and limitations of the methodology discussed in this section is essential for specifying the problems to be solved and interpreting the outputs of the methodology. It is assumed that GIS input data are accurate, candidate landing locations are already determined, only single-span and multispan standing skyline systems are considered, ground profile analysis determines the feasibility of cable roads, and the "equivalent cost" is the major criterion for evaluating alternatives.

Certain information must be available to use the methodology. The input data required are described as follows:

1. An accurate Digital Terrain Model (DTM) of a planning area
2. Harvest unit boundaries
3. Location and volume of timber to be harvested
4. Location of existing roads and fish-bearing streams
5. Location of candidate landings
6. Detailed information for each of the yarding systems considered. This includes operating costs, the effect of terrain and other factors on productivity, data indicating the limitations and capabilities of the yarding system, and other system specifications for the ground profile analysis
7. Estimated construction costs of access roads and the effect of terrain on construction costs
8. Estimated construction costs for each of candidate landings
9. Areas which are subject to harvesting or road building restrictions due to expected environmental problems

Based upon the input data described above, the methodology will develop a cable logging operation and road network plan. The outputs of the methodology include items described as follows:

1. The physical layout of a given harvesting unit, showing:
   a. selected landing locations among the candidates;
   b. selected yarding system at each of the selected landings;
   c. selected cable roads at each landing;
   d. timber volume to be yarded to each landing.
2. Estimates of cable logging feasibility and costs, established by explicit consideration of environmental restrictions, timber volume, and topography
3. Detailed information on a feasible cable road, including:
   a. ground surface profile along the cable road;
   b. estimated allowable load capability at each terrain point along the cable road;
   c. estimated cycle time at each terrain point along the cable road;
   d. estimated yarding costs for each timber entry;
   e. proposed location of intermediate supports along the cable road;
   f. minimum rigging height of the tailspar tree which would be required in order to meet the minimum design payload.
4. Access road locations from existing roads to each of the selected landings

5. Truck transportation routes and timber volume from each landing to one or more designated destinations
6. Estimates of road construction and transportation costs

MODELING PROCEDURES

The first objective of this study is to develop a comprehensive methodology to assist the forest planner in planning cable logging operations and forest transportation. This involves evaluating logging feasibility through payload and ground profile analysis, estimating logging and transportation costs, formulating the cost minimization problem, and finding a solution. The methodology to be presented in this study includes a series of models and computer algorithms for each of these processes. This chapter discusses the details of models and computer algorithms developed for the methodology.

LOGGING FEASIBILITY

This section introduces the theory of skyline payload analysis and discusses the computer algorithms developed to evaluate logging feasibility for a specified cable yarding system and a specified ground profile.

Cable logging settings

Cable logging operations require a landing (tower location), cable roads, and forest roads to access to each landing for truck transportation (Figure 5). Cable roads are determined by the location of head and tailspars. External yarding distance is the slope distance from the landing to the outer cutting unit boundary (Studier and Binkley 1974), which may differ from the skyline length between landing and tailspar. Although external yarding distance defines an area to be yarded, skyline length can be extended beyond the area usually for the purpose of obtaining enough skyline clearance by placing the tailspar in a better position. Lateral yarding is essential to cover more area and volume with each cable road setup. The lateral yarding distance is usually determined by the skidding line length that can be pulled through the carriage, the lift that can be provided to the logs during lateral yarding, the steepness of the cross slope, the yarding direction, and the number of obstacles between the log pickup point and the skyline corridor. There are three types of slackpulling carriages; slackpulled by hand (mainline pulled through carriage), slackpulled by yarder (skidding line contained in a drum in the carriage or spliced onto the mainline), and slackpulled by carriage (skidding line pulled by a power device in the carriage) (Studier and Binkley 1974). External and lateral yarding distances are the principal factors to define an area to be yarded by one cable road in this analysis (Figure 5).

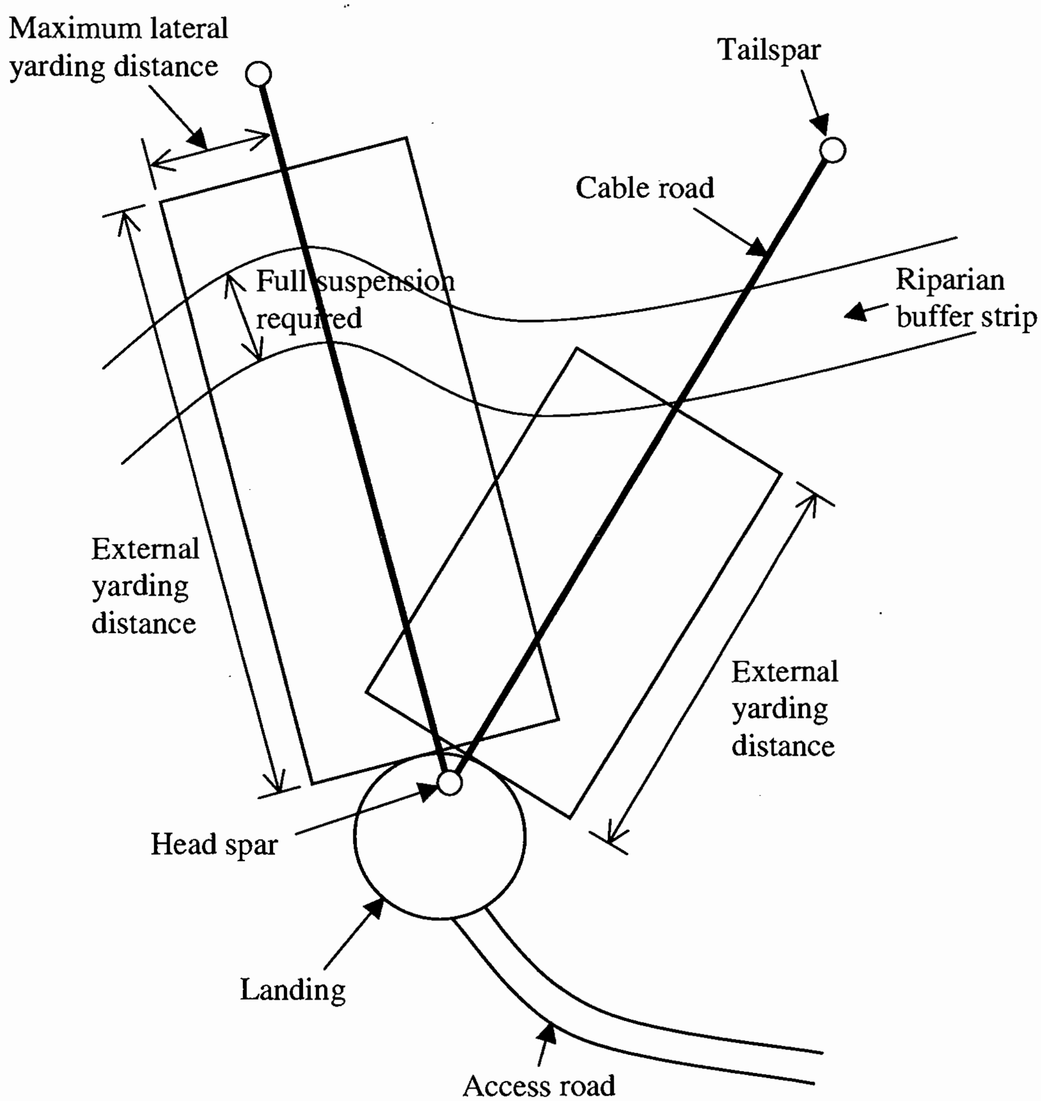


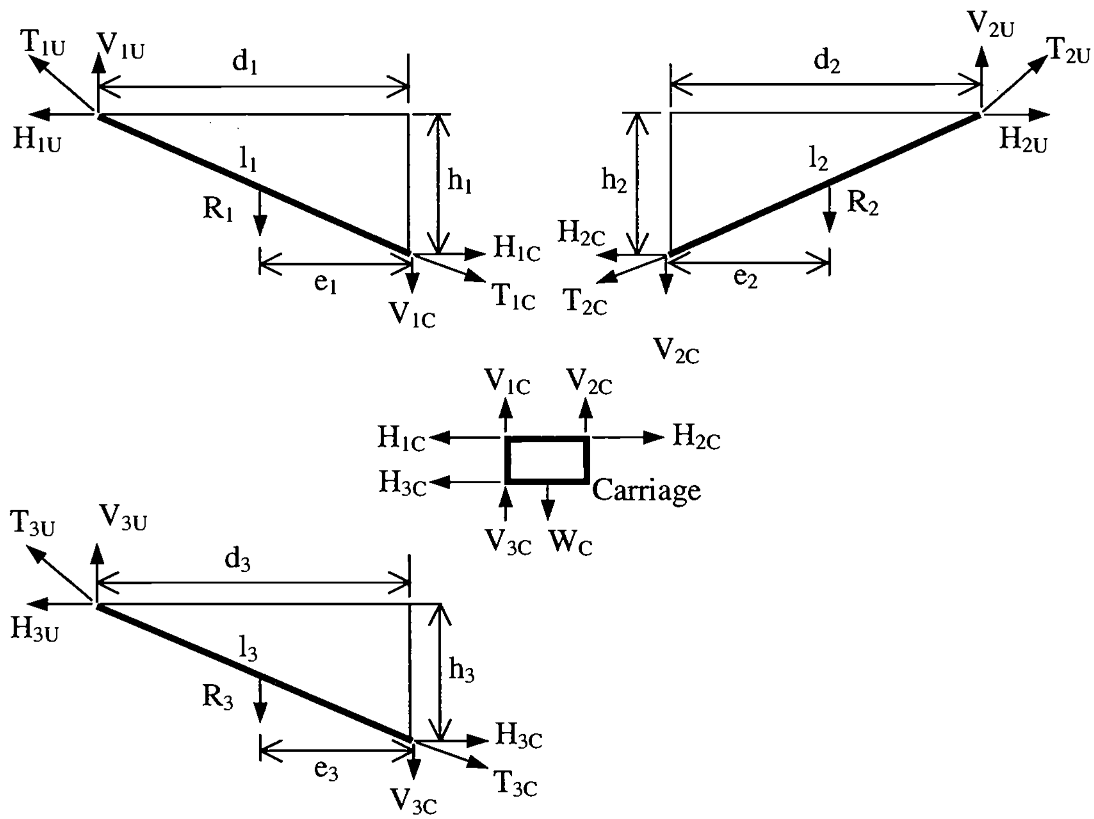
Figure 5. An example of cable road settings on a typical landing (plan view). Full suspension is indicated over the riparian buffer strip.

Payload analysis

The objective of the payload analysis is to determine the minimum log load that can be carried along a given geometry of cable road. In this study, the cable road is assumed to be physically feasible if the log load capability is greater than the user-defined minimum design payload.

Standing skyline systems with uphill yarding are modeled in this methodology. The procedure of payload analysis applied to this methodology follows the Phase I analysis (Brown and Sessions 1996), which is designed to identify the skyline length that can provide at least the minimum log clearance at each terrain point within external yarding distance. Once the skyline length is defined, the log load that produces the maximum allowable line tension at each terrain point can be calculated.

In order to estimate the load capability of a standing skyline, the cable system is divided into cable segments (Figure 6). It is assumed that the weight of each cable segment is equal to the unit weight of the line multiplied by the straight-line length of the segment. The center of mass of each cable segment is assumed to be in the middle of the segment. These assumptions which are often referred to as "rigid link assumptions" (Carson and Mann 1971) ignore the fact that the cable segment actually hangs in the shape of a catenary. However, this approximation, which simplifies the calculations, provides quite accurate solutions when the lines



Nomenclature:

T_{iU} = upper tension for segment *i*
H_{iU} = horizontal force component at the upper end for segment *i*
V_{iU} = vertical force component at the upper end for segment *I*
T_{iC} = tension at the carriage for segment *i*
H_{iC} = horizontal force component at the carriage for segment *i*
V_{iC} = vertical force component at the carriage for segment *i*
d_i = horizontal distance of segment *i*
h_i = change in elevation of segment *i*
l_i = length of segment *i*
R_i = weight of cable segment *i* ($R_i = \omega_i \times l_i$, where ω_i is weight per unit length of segment *i*)
e_i = horizontal distance from the carriage to the center of gravity of cable segment *i*
W_C = weight of the carriage

Figure 6. Geometry of cable segments for standing skyline system with skyline and mainline.

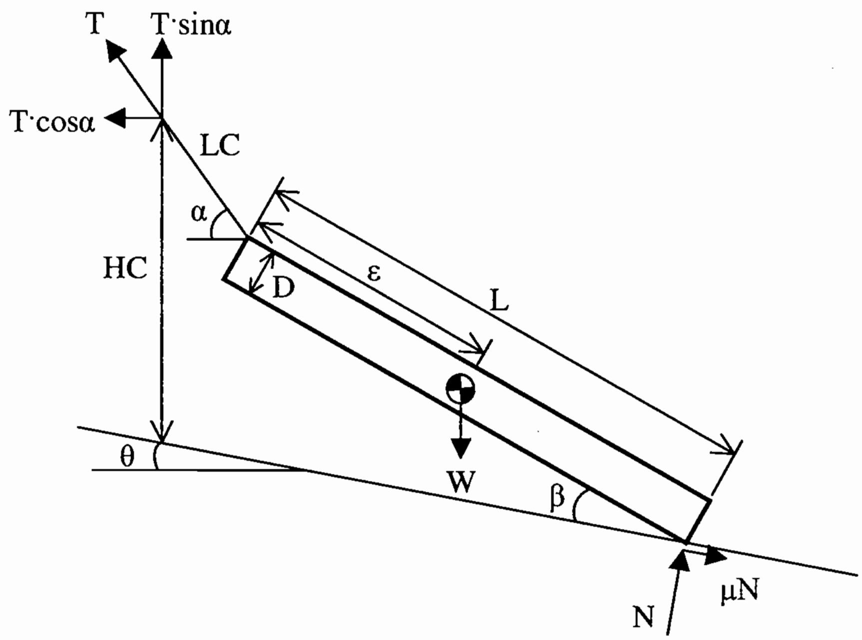
are under tension and has been widely used for payload analysis (Brown and Sessions 1996, Carson and Mann 1971).

Partial suspension with the front end of the log off the ground is considered in this analysis as well as full suspension. Partial suspension geometry (Figure 7) from Falk (1981) was used with the assumption that log has a cylindrical shape with a given length (L) and diameter (D). The log is dragged along the ground of slope θ with a log-to-ground angle of β by a short length (LC) of cable (tagline) from the carriage attached at the end of the log. The center of gravity of the log is assumed to be in the middle of the log (ε = L/2). The frictional coefficient between log and ground is μ.

With these assumptions, the angle (α) between the tagline and the horizontal, Equation 2, can be calculated using force and moment equilibrium (Brown and Sessions 1996, Kendrick and Sessions 1991, Falk 1981). The height of the carriage (HC) from the ground can be calculated, once α is known (Equation 3).

$$\alpha = \arctan\left\{\frac{L}{\varepsilon}\left[\tan(\theta+\beta)+\frac{D}{L}\right]+\left[\frac{L}{\varepsilon}-\frac{D}{\varepsilon}\cdot\tan(\theta+\beta)-1\right]\times\left[\frac{\cos\theta-\mu\cdot\sin\theta}{\sin\theta+\mu\cdot\cos\theta}\right]\right\} \qquad 2.$$

$$HC = \frac{LC\cdot\sin(\alpha-\theta)+L\cdot\sin\beta+D\cdot\cos\beta}{\cos\beta} \qquad 3.$$



Nomenclature:

T	= tagline tension
HC	= height of carriage
LC	= length of tagline cable
D	= log diameter
L	= log length
W	= log weight
ε	= distance from tagline attachment on long to the center of gravity of the log
α	= angle that tagline makes with horizontal
θ	= ground slope angle
β	= log-to-ground angle
μ	= coefficient of friction between the ground and the dragging log
N	= normal force at the point of ground contact with log end

Figure 7. Partial suspension geometry.

The maximum log load capability at each log pickup point can be estimated, if the geometry of cable segments is known with either full suspension or partial suspension at a particular terrain point along the skyline. The procedure to estimate the maximum log load capability is:

1. Apply the maximum allowable tension to the upper end of segment 1 (T_{1U}) and calculate the horizontal and vertical components of segment 1 through the relationships:

$$H_{1U} = -\frac{\omega_1 \cdot h_1 \cdot d_1}{2 \cdot L_1} + \frac{T_{1U} \cdot d_1}{L_1}\sqrt{1-\left(\frac{\omega_1 \cdot d_1}{2 \cdot T_{1U}}\right)^2} \qquad 4.$$

$$H_{1C} = H_{1U} \qquad 5.$$

$$V_{1C} = \frac{H_{1C} \cdot h_1}{d_1} - \frac{R_1}{2} \qquad 6.$$

2. Since the skyline tensions in segments 1 and 2 at the carriage are equal, the horizontal and vertical components of segment 2 can be determined using the following equations:

$$H_{2C} = \frac{\omega_2 \cdot h_2 \cdot d_2}{2 \cdot L_2} + \frac{T_{2C} \cdot d_2}{L_2}\sqrt{1-\left(\frac{\omega_2 \cdot d_2}{2 \cdot T_{2C}}\right)^2} \qquad 7.$$

$$V_{2C} = \frac{H_{2C} \cdot h_2}{d_2} - \frac{R_2}{2} \qquad 8.$$

3. The horizontal and vertical components for the mainline, segment 3 can be calculated from Equation 9 and 10, which are derived considering a horizontal force balance at the carriage.

$$H_{3C} = \frac{\tan\alpha \cdot (H_{1C} - H_{2C}) - (V_{1C} + V_{2C} - W_C) + \frac{\omega_3 \cdot L_3}{2}}{\frac{h_3}{d_3} - \tan\alpha} \qquad 9.$$

$$V_{3C} = \frac{H_{3C} \cdot h_3}{d_3} - \frac{R_3}{2} \qquad 10.$$

4. Finally, the log load can be calculated by first evaluating the normal force (N) between the log and ground when logs are partially suspended (Equation 11). Once the normal force (N) is known, the log load at the given geometry of cable system is calculated using Equation 12. If logs were fully suspended, Equation 13 is used to calculate the log load.

$$N = \frac{H_{1C} + H_{3C} - H_{2C}}{\sin\theta + \mu \cdot \cos\theta} \qquad 11.$$

$$W = V_{1C} + V_{2C} + V_{3C} - W_C + N \cdot \cos\theta - \mu \cdot N \cdot \sin\theta \qquad 12.$$

$$W = V_{1C} + V_{2C} + V_{3C} - W_C \qquad 13.$$

If the elevation of carriage is higher than that of rigging point at the tailspar, segment 2 has different geometry and Equations 7 and 8 should be replaced with Equations 14 and 15, respectively. Equations 12 and 13 should also be replaced with Equations 16 and 17, respectively, since V2C at the carriage has negative effect on payload.

$$H_{2C} = -\frac{\omega_2 \cdot h_2 \cdot d_2}{2 \cdot L_2} + \frac{T_{2C} \cdot d_2}{L_2}\sqrt{1 - \left(\frac{\omega_2 \cdot d_2}{2 \cdot T_{2C}}\right)^2} \quad 14.$$

$$V_{2C} = \frac{H_{2C} \cdot h_2}{d_2} + \frac{R_2}{2} \quad 15.$$

$$W = V_{1C} - V_{2C} + V_{3C} - W_C + N \cdot \cos 6 - \mu \cdot N \cdot \sin 6 \quad 16.$$

$$W = V_{1C} - V_{2C} + V_{3C} - W_C \quad 17.$$

A computer algorithm for ground profile analysis

A computer algorithm was developed for ground profile analysis of each candidate cable road. The DTM required for this methodology provides the location and elevation of each terrain point along a cable road. The algorithm applies the Phase I procedure suggested by Brown and Sessions (1996) to identify the maximum log load that can be carried along a given ground profile by a standing skyline system. Brown and Sessions (1996) also introduced a modified Phase II analysis to find the maximum log load associated with the unstretched skyline length. When the terrain point (critical terrain point, CP) defining the longest acceptable skyline length is different from the terrain point (limiting terrain point, LP) that has the lowest log load capability, the CP may have more clearance than the minimum specified clearance. In this case, the skyline can be lengthened and a larger log load can be carried at the LP. The modified Phase II analysis does these procedures to identify the more accurate payload capability along the profile. However, the methodology in this study does not apply the modified Phase II analysis. The result is a conservative estimate of payload capability and a simplification of the problem.

The Phase I analysis (Figure 8) includes three primary steps: 1) identifying the longest skyline stretched length that satisfies the user-defined minimum log clearance at each terrain point, 2) determining the geometry at each terrain point associated with the identified stretched skyline length, and 3) calculating the log load that produces the maximum allowable line tension at each terrain point and determines the maximum log load that the system can carry along the skyline assuming the stretched line length does not change at each terrain point.

Locating intermediate supports

Intermediate supports are required to ensure the minimum clearance of the skyline on terrain with a convex slope or a long constant slope. An automated algorithm to place intermediate supports developed by Sessions (1992) is

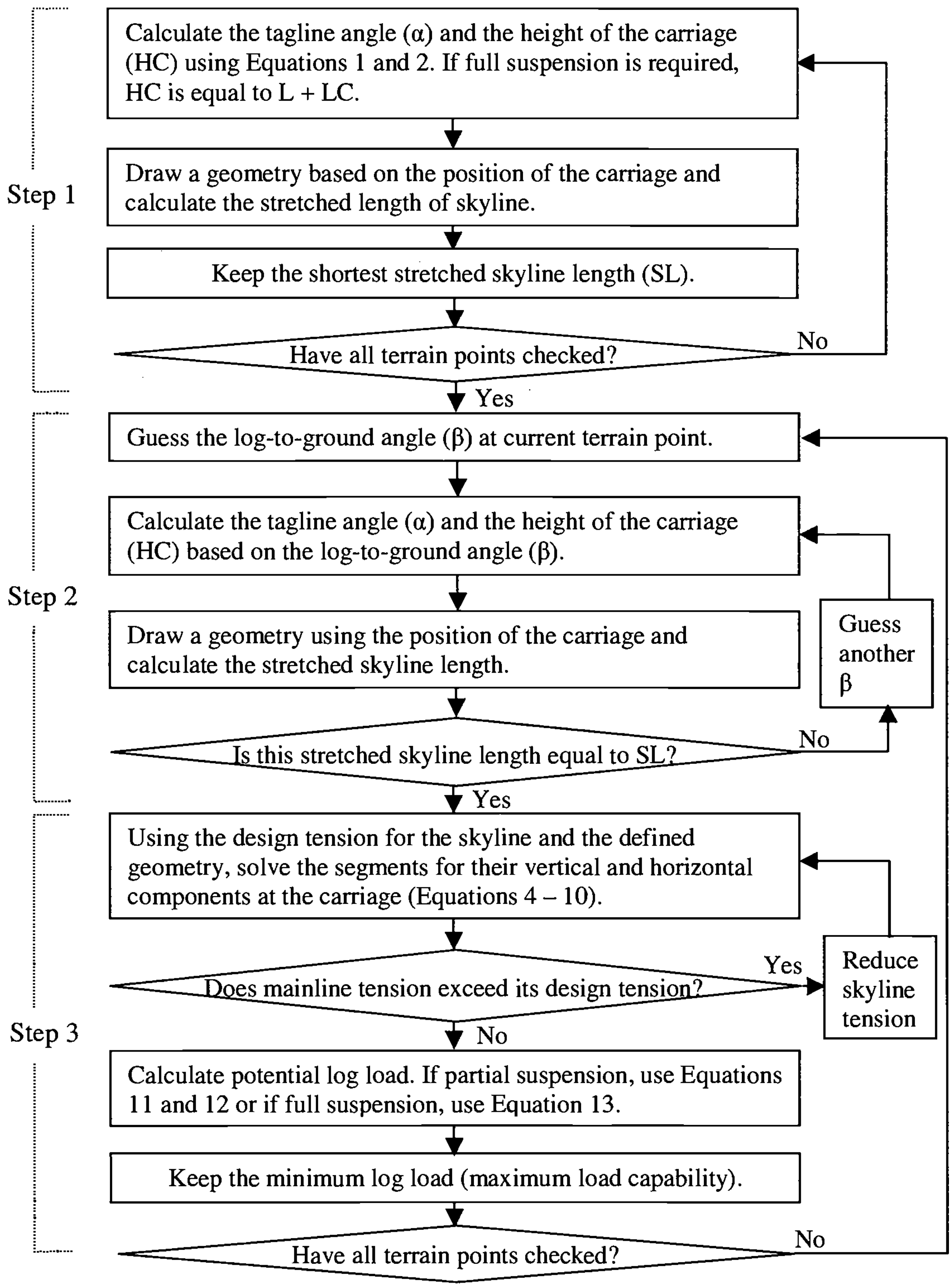


Figure 8. The Phase I analysis for determining the largest payload that can be carried from the external yarding distance to the landing.

implemented in this methodology with some modifications. The algorithm begins by placing intermediate supports on all terrain with a convex slope, then eliminating unnecessary supports using several design criteria. Since identifying intermediate support locations is mainly associated with consecutive terrain points, which are grid cells on a DTM, the algorithm may place more intermediate supports than necessary, especially when a high resolution DTM is used. If the users limit the allowable number of intermediate supports along a cable road, the algorithm tries to keep the total number under the limit by eliminating the intermediate supports that have the least impact on payload as long as the user-defined minimum design payload is achieved (Figure 10). The steps in the algorithm are presented below:

Step 1. Examine ground slopes between three consecutive terrain points along the profile and place intermediate supports on all terrain points where convex slopes are found (Figure 9a).

Step 2. Examine the slope change of the skyline at each intermediate support and eliminate the support if the slope is not convex (Figure 9b).

Step 3. Evaluate the deflection at each intermediate support assuming the intermediate support does not exist. If enough clearance is ensured, then eliminate the support. Otherwise, keep the support at the current terrain point. Allowable percentage deflection of the skyline and minimum skyline clearance above the ground are defined by the users (Figure 9c).

Step 4. Examine the slope change of the skyline at the intermediate support. If the slope exceeds the user-defined maximum slope change of skyline required for carriage passage, then this cable road becomes physically infeasible (Figure 9d).

Step 5. If the total number of intermediate supports is greater than the user-defined maximum number of intermediate supports, then temporarily eliminate an intermediate support one at a time and conduct the payload analysis described in the previous section to calculate the maximum load capability without the intermediate support that is just eliminated. Store the load capability, restore the intermediate support, and move to the next intermediate support to be eliminated.

Step 6. By comparing the load capabilities from step 5, eliminate the intermediate support that has the least effect on the load capability (the one shows the largest load capability without it).

Step 7. Repeat Steps 5 and 6 until the total number of intermediate supports satisfies the user-defined maximum number of intermediate supports. If the maximum load capability is not greater than the user-defined design payload, then stop the routine since this cable road is infeasible.

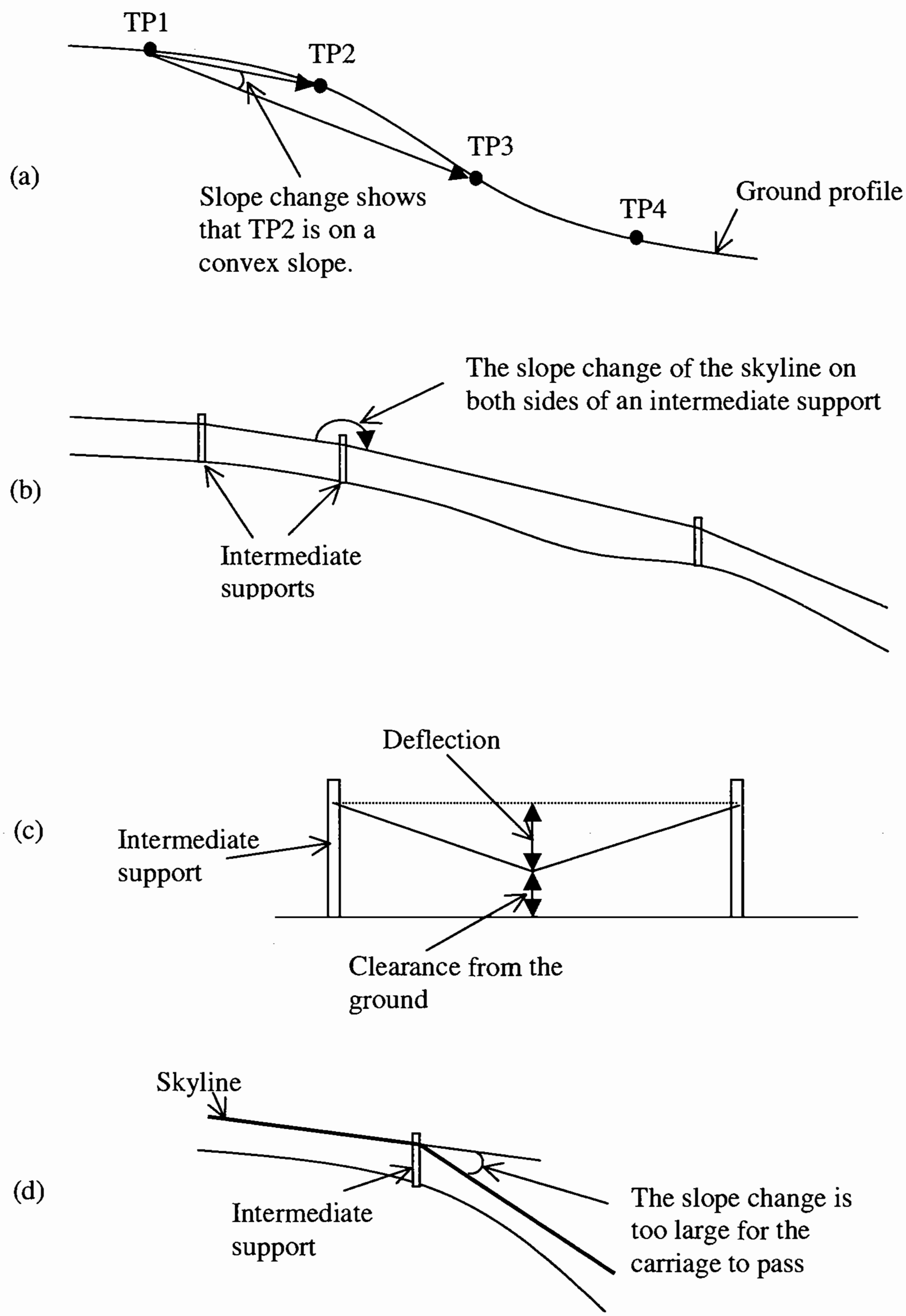
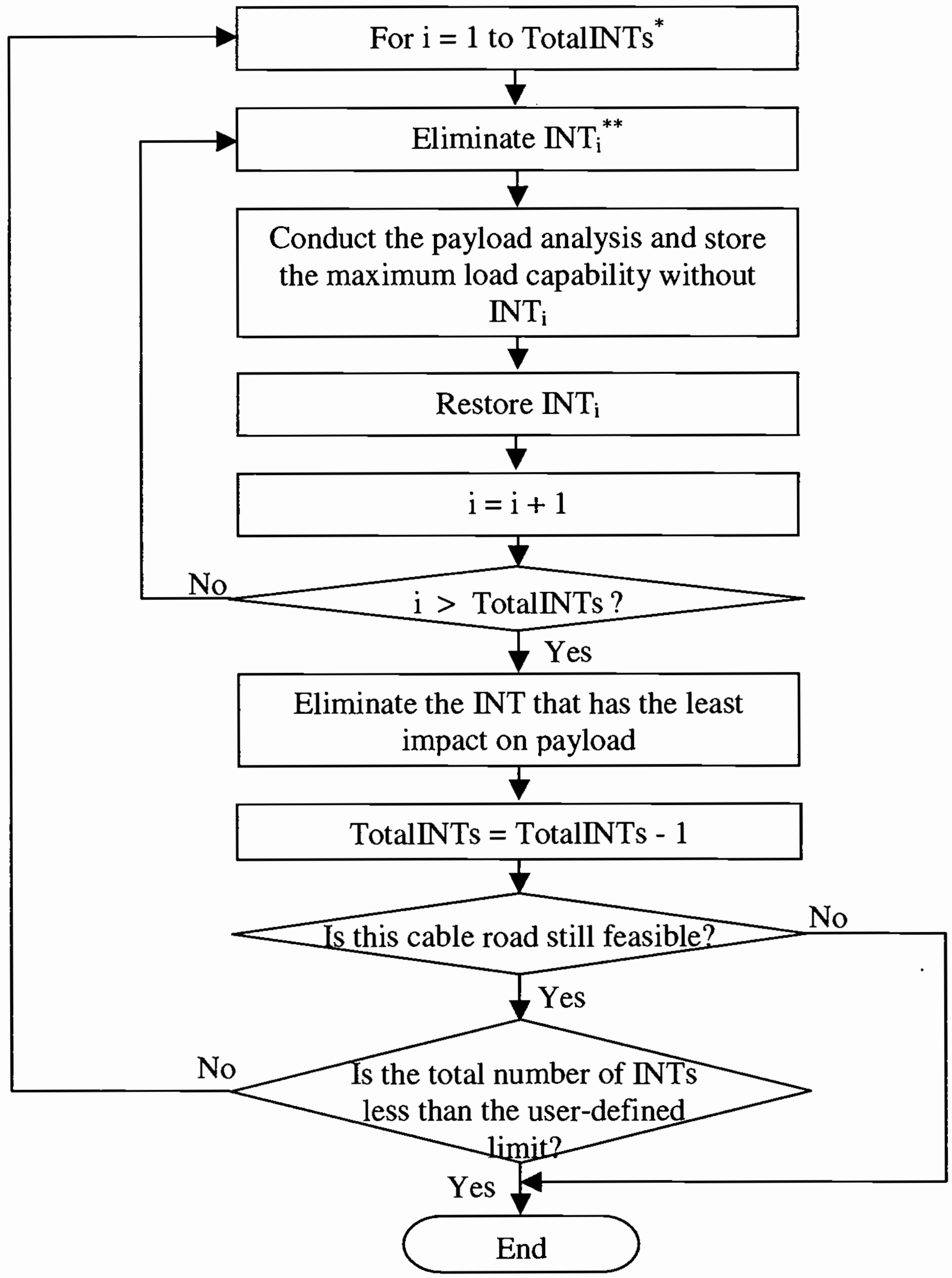


Figure 9. Design criteria on placing intermediate supports.



*TotalINTs = the total number of intermediate supports along a cable road.

**INT_i = i^{th} intermediate support from headspar (i is from 1 to the total number of intermediate supports along a cable road)

Figure 10. An iterative procedure for reducing the total number of intermediate supports.

Environmental requirement – full suspension over the riparian management areas

Full suspension is often required over riparian management areas to protect vegetation and minimize disturbance to beds and banks of streams (Figure 11). Oregon's Forest Practice Rules (Oregon Department of Forestry 2000) designate that when yarding across Type F or Type D streams, any large or medium Type N streams, lakes, or significant wetlands is necessary, it shall be done by swinging the yarded material free of the ground in the aquatic areas and riparian areas (OAR 629-630-0700). Type F includes streams that have fish use, including fish use streams that have domestic water use. Streams that have domestic water use, but not fish use, shall be classified as Type D. All other streams are classified as Type N (OAR 629-635-0200). Oregon's Forest Practice Rules (OAR 629-635-0310) designate riparian management area widths for streams (Table 1).

Table 1. Riparian management area widths for streams of various sizes and beneficial uses.

Size of stream	Type F	Type D	Type N
Large	100 feet	70 feet	70 feet
Medium	70 feet	50 feet	50 feet
Small	50 feet	20 feet	-

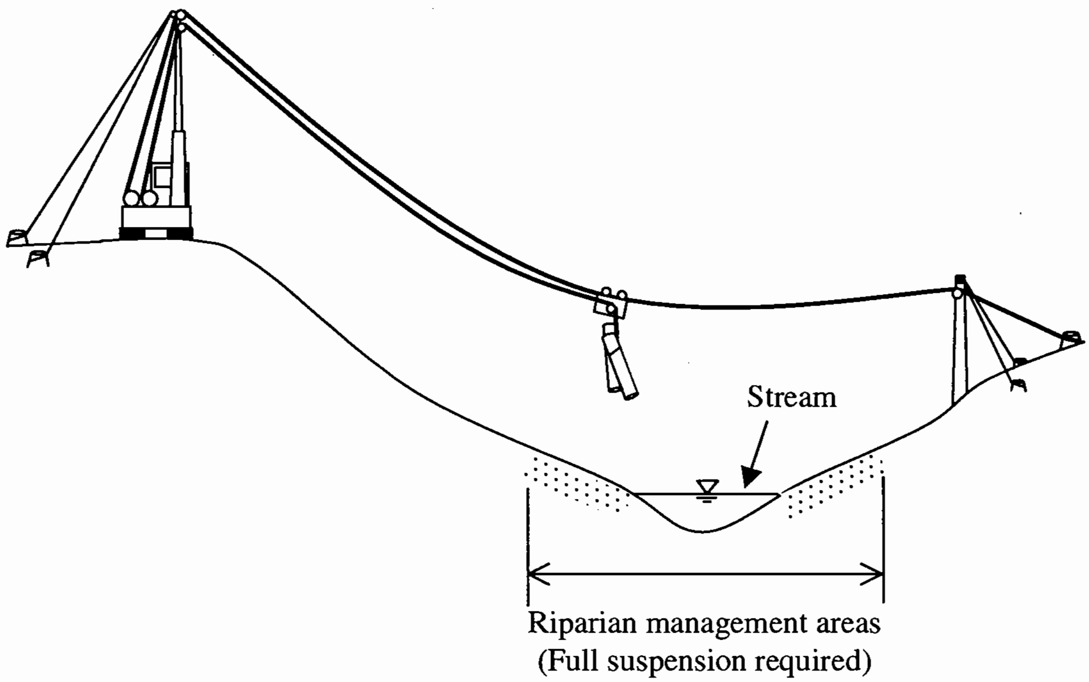


Figure 11. Riparian management areas requiring full suspension.

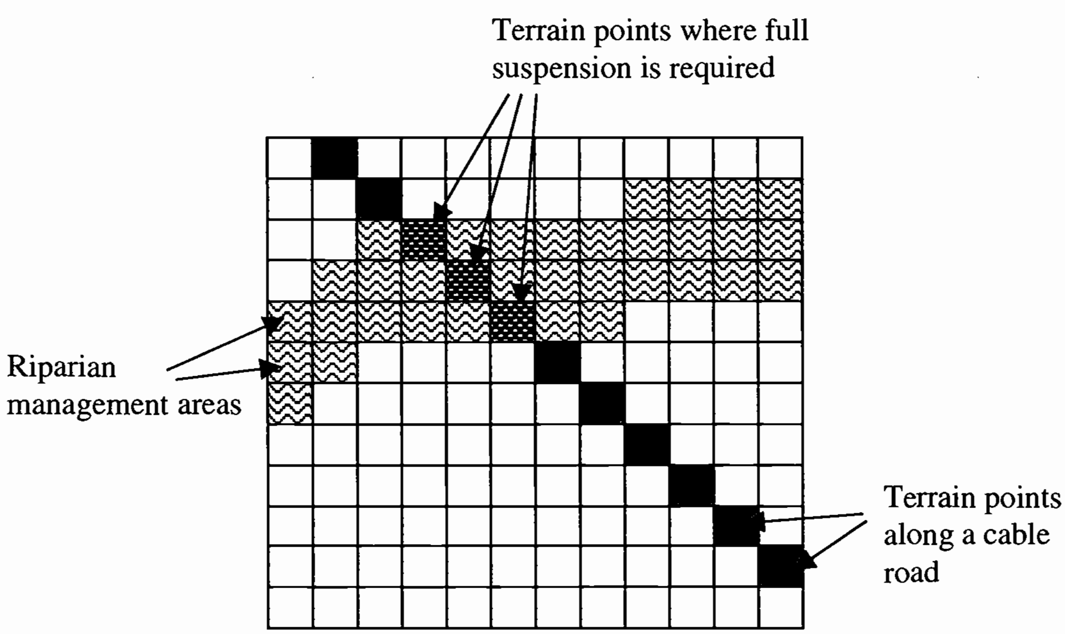


Figure 12. Riparian management areas on a DTM.

A GIS produced map for streams provides the location of the streams over the planning area for the methodology. The methodology overlays this stream coverage on a DTM to identify the riparian management areas specified by Table 1 (Figure 12). Then the full suspension requirement is taken into account during the payload analysis in the methodology.

Adjusting tailspar height

The payload analysis in this methodology allows the planners to input the range of tailspar heights and searches for the minimum height required to ensure the user-defined minimum design payload along the profile. The analysis starts from the lowest tailspar height and elevates the height in case that either the load capability along the profile does not satisfy the design payload or more intermediate supports are required than its limit. Rigging the skyline at higher position usually produces more payload capability by increasing the deflection of the skyline. It also creates higher clearance of the skyline from the ground that may reduce the number of required intermediate supports (Figure 13).

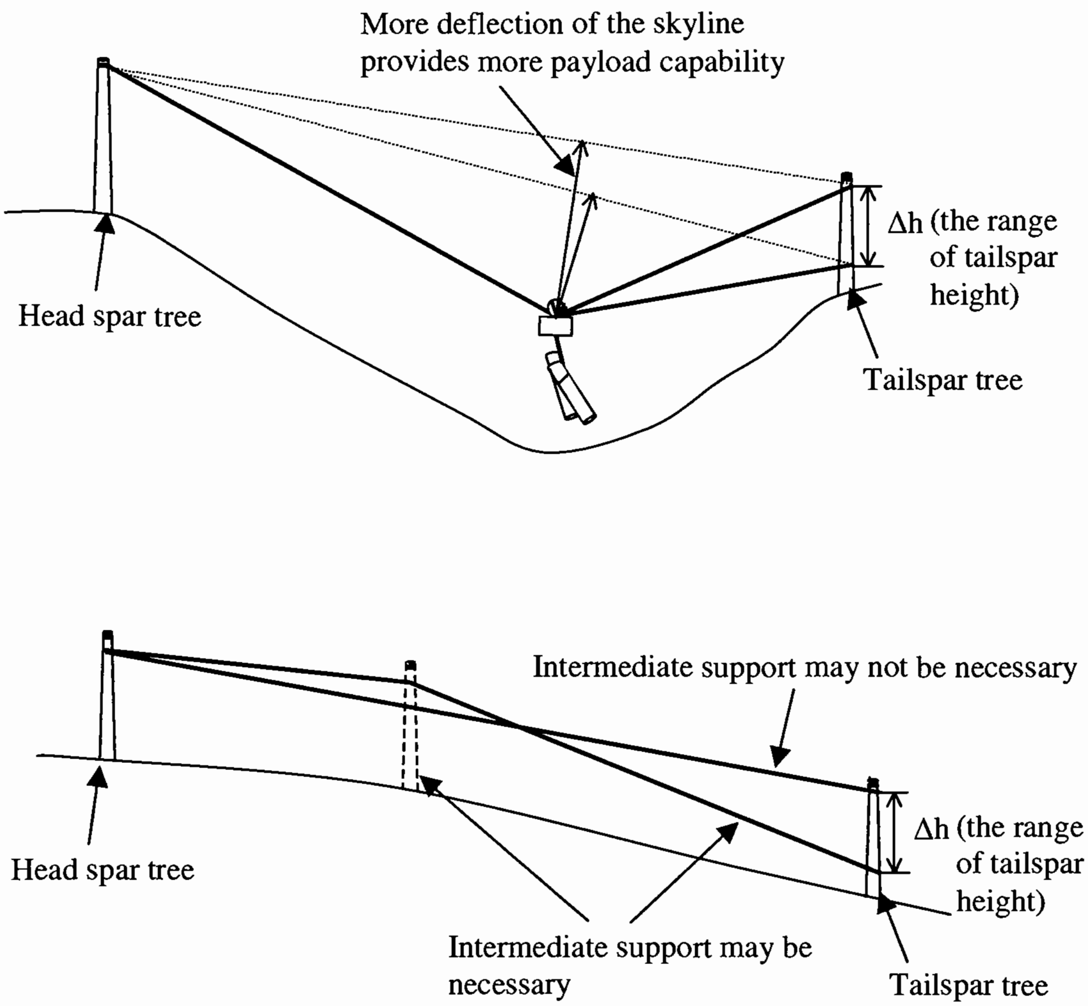


Figure 13. Effects of tailspar height on load capability and on intermediate support requirement.

Implementation of the logging feasibility analysis

The procedures for the ground profile analysis presented in this section have been implemented in a computerized model integrated with GIS techniques. The computer program generates thirty-six cable roads from a candidate landing. The initial location of the tailspar is found on a DTM based on the user-defined maximum horizontal distance of skyline. Then, the program identifies the grid cells representing terrain points along each cable road. The DTM provides the elevation of each terrain point and the stream coverage provides the location of the riparian management areas where full suspension is required. The program conducts a search for a tailspar location along each cable road that provides at least the minimum design payload at the lowest height of tailspar with the limited number of intermediate supports (Figure 14). If a cable road, which is not shorter than the user-defined minimum length, cannot produce enough payload, the cable road is assumed to be infeasible in this analysis.

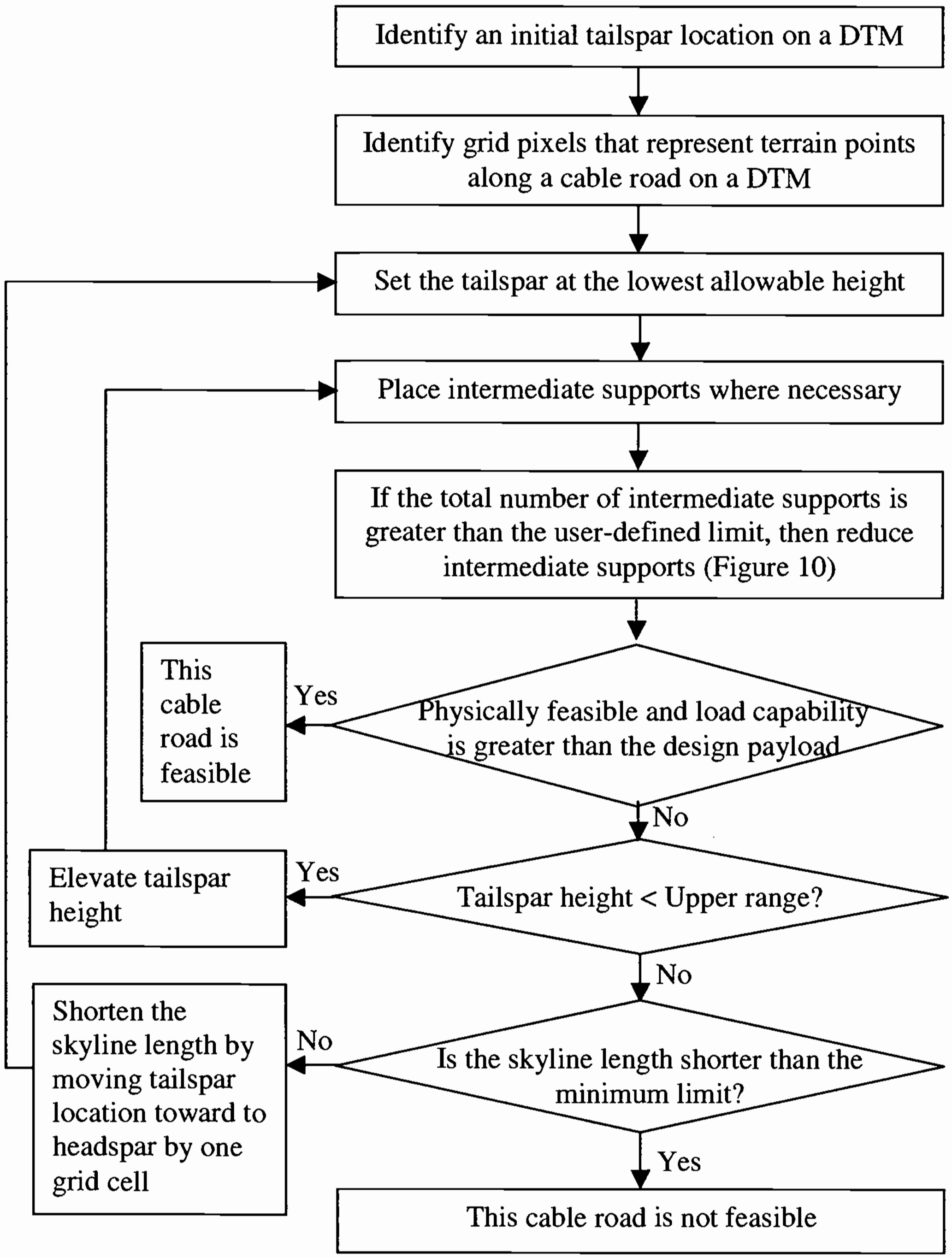


Figure 14. The algorithm to determine the logging feasibility of a cable road.

COST ANALYSIS

Minimizing total cost of the timber harvest operation is one of the main objectives of the forest planners. The methodology in this study includes a cost analysis module that estimates cable logging and transportation costs for alternatives. Logging and transportation costs in this study are classified into two cost factors: variable and fixed costs. As defined in the previous chapter, variable cost is a function of timber volume, while fixed cost is one-time cost regardless of timber volume. In logging operations, variable costs include felling, yarding, loading, and hauling costs, and fixed costs include road and landing construction, yarding equipment move-in, and cable road emplacement costs.

The cost analysis module simulates cable logging operations. The logging feasibility analysis discussed in the previous section is used for estimating yarding costs as well as determining the feasibility of specified cable logging systems considering terrain conditions and minimum payload. The module starts by identifying log pickup points and timber volume to be yarded from each log pickup point, then measures total yarding time for a turn of logs from each log pickup point to each of the eligible landings. Finally, the module estimates yarding costs for a single turn of logs by applying the yarding system operating costs to the yarding cycle time. The hourly costs of each yarding system include machine owning, operating, and labor costs. Felling costs are assumed to be constant for alternative yarding systems, and thus are not considered in the analysis, but are added later to provide the estimates of the total logging and transportation costs. Loading cost is assumed to be included in the hourly costs of the yarding system since the hourly costs also take account of loader and its operator. Truck time during loading and unloading cost at the mill are not included in the analysis, but can also be added for total cost appraisal.

Total transportation costs in this analysis include road building and hauling costs. Transportation costs, which vary with the user-defined unit costs and terrain conditions, are analyzed separately from the yarding costs in the module. The details on how to estimate costs in this methodology are described in the following sections.

Load building simulator

In order to estimate the yarding cost of a single turn of logs over a cable road, the location of the log pickup point and timber volume for a turn must be identified. A GIS layer for timber volume provides information on location and volume to be harvested in a given harvesting area. Using the GIS volume information, a load building simulator, developed for this methodology, determines timber parcel locations and volume and log pickup point at each parcel.

The simulator starts from sorting grid cells of the GIS timber volume layer by volume in descending order (Figure 15). Then it checks each of sorted grid cells with its harvesting timber volume. If volume in a grid cell is greater than the user-defined design payload, the load building process is not necessary and the cell is assumed to be an individual timber parcel. The center of the grid cell will be the log pickup point. However, if a grid cell contains volume less than the user-defined design payload for a single turn, the simulator searches for logs in the adjacent grid cells within the user-defined effective distance from the selected grid cell until the sum of volume becomes greater than the design payload (Figure 16). The logs are assumed to be hooked together and the effective distance is assumed to be either a choker length or the length of slackpulled mainline that allows reaching adjacent logs. These combined cells form an individual timber parcel and the log pickup point is assumed to be the location of the grid cell that has the largest volume among other cells within the parcel (Figure 17).

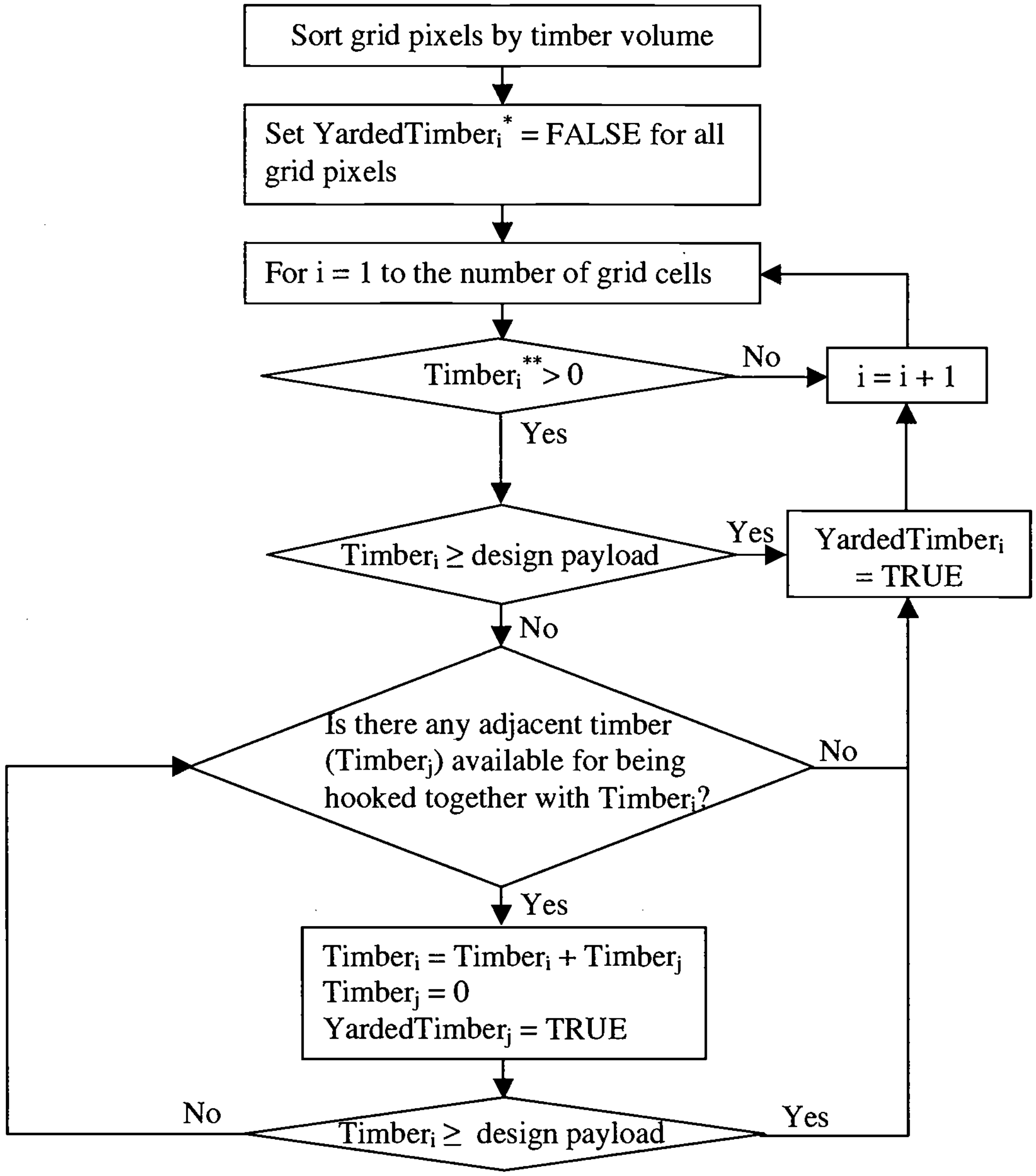
Once all locations of log parcels and the timber harvest volume at each parcel is identified, the number of turns from each parcel is determined based on the timber volume and the load capability of each of the appropriate cable roads at the log pickup point. This differs from the procedure used by Dykstra (1976a) as this methodology allows the maximum payload to vary with terrain points along a cable road. In many analyses the payload at a limiting terrain point (i.e. 3,270 kg in Figure 17) is assumed to be the maximum load that can be carried along the entire cable road. This is true only when the loaded carriage has to pass the limiting terrain point (T.P. 5 in Figure 17). If logs are loaded ahead of the limiting terrain point, then the maximum payload is not limited by that point. For example, if logs are loaded at terrain point 4 in Figure 17, the terrain point 4 becomes the limiting terrain point and the maximum payload increases to 5,150 kg. The cost analysis module developed for this methodology considers the location of log pickup point when it estimates the expected volume per turn and determines the number of turns from each timber parcel. Thus, the number of turns (T) for parcel *i* over cable road *j* by means of yarding system *k* to landing *l* is determined as follows:

$$T_{ijkl} = INT\left(\frac{V_i}{MP_{ijkl}}\right) + 1 \qquad 18.$$

where T_{ijkl} = the number of turns required to yard logs in parcel *i* to landing *l* over cable road *j* using yarding system *k*

V_i = total timber volume to be yarded in parcel *i*

MP_{ijkl} = maximum allowable payload at the log pickup point in parcel *i* yarded to landing *l* over cable road *j* using yarding system *k*



YardedTimber$_i^*$ = a TRUE/FALSE variable that indicates whether timber in grid cell *i* is already yarded or not

Timber$_i^{**}$ = timber volume to be harvested in grid cell *i*

Figure 15. A flowchart for the load building simulator that determines timber parcels and timber volume in each parcel.

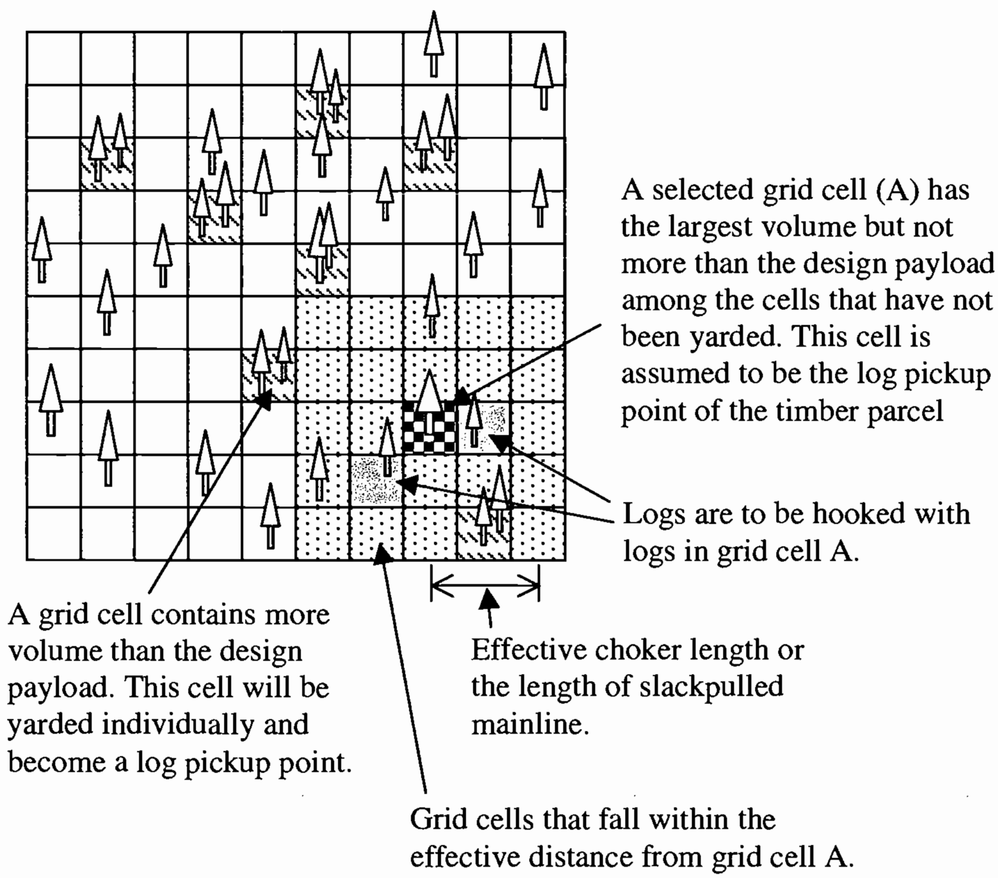
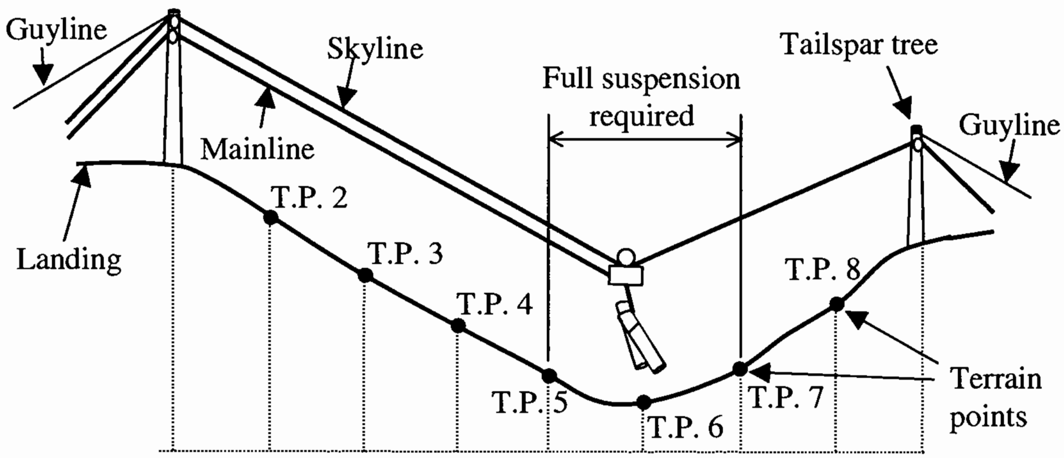


Figure 16. Determining the location of log pickup point at each timber parcel.



Net payload (kg)	6150	5670	5150	3270	3500	3330	4570
Allowable payload to landing (kg)	6150	5670	5150	3270	3270	3270	3270

Figure 17. Determining the maximum allowable payload at each terrain point.

Estimating yarding cycle time

Yarding cycle time can be divided into several time components representing activities that are required to transport logs from the stump to the landing via cable yarding system. The components typically include outhaul, lateral out, hook, lateral in, inhaul, and unhook (Edwards 1992, Alarid 1993). For this study, each time component is defined as follows:

1. Outhaul: begins when carriage starts away from the landing; ends when carriage stops at the point intersection of the cable road and a line drawn perpendicular to it from log pickup point.
2. Lateral outhaul: begins when carriage stops at the point intersection of the cable road and a line drawn perpendicular to it from log pickup point and pulling of the skidding line starts; ends when pulling out the skidding line stops and skidding line reaches logs.
3. Hook: begins when skidding line reaches logs; ends when attaching chokers to logs is completed.
4. Lateral in: begins when attaching chokers to logs is completed; ends when logs arrive at the skyline corridor.
5. Inhaul: begins when logs arrive at the skyline corridor; ends when carriage stops and logs come to rest on the landing.
6. Unhook: begins when carriage stops and logs come to rest on the landing; ends when carriage starts away from landing.

Figure 18 illustrates where each time component occurs. Total delay free yarding cycle time for a turn of logs is estimated as the sum of each time component as follows:

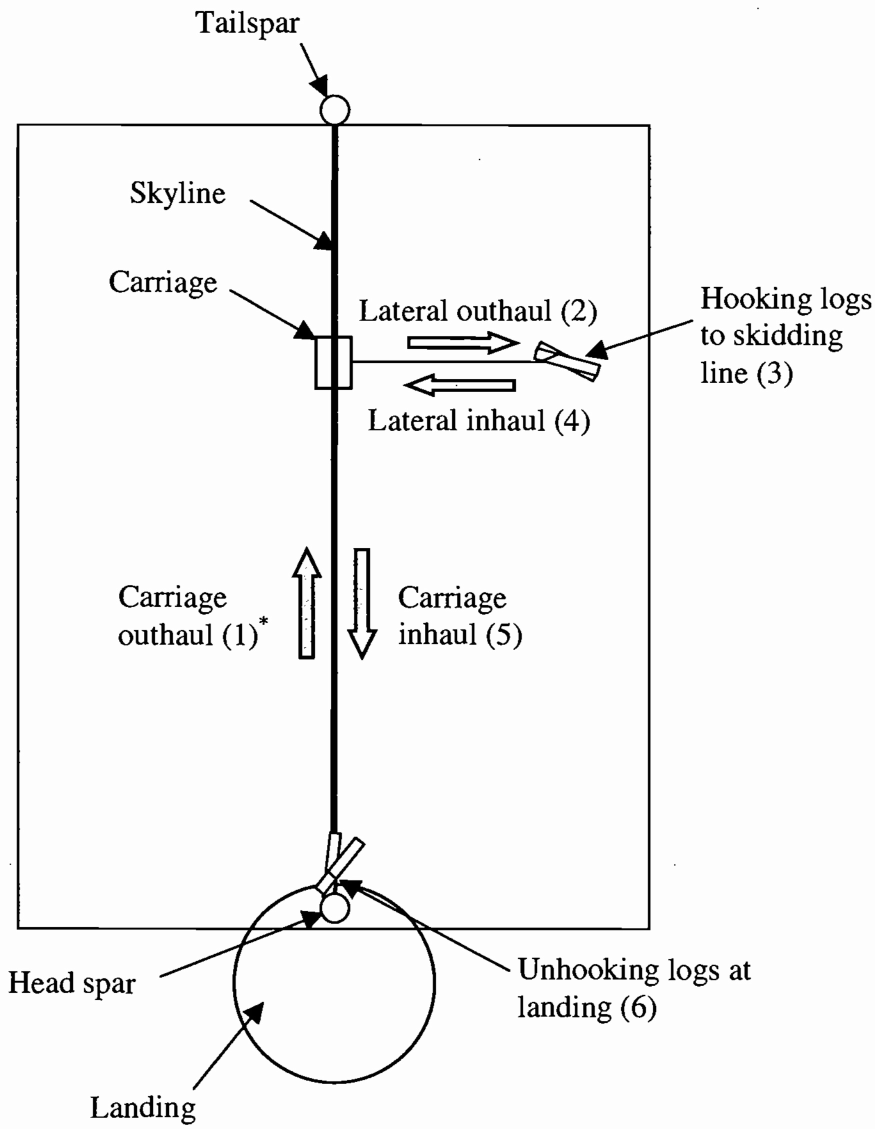
$$\text{Delay free yarding cycle time} = \text{Outhaul time} + \text{Lateral outhaul time} + \text{Hook time} + \text{Lateral inhaul time} + \text{Inhaul time} + \text{Unhook time} \qquad 19.$$

In order to estimate more reasonable yarding costs, yarding delays are considered in the analysis. Delay time for each cable equipment is determined exogenously and entered into the cost analysis module by the planner as a percentage of total operating time of each cable equipment. The module calculates yarding cycle time considering delays as follows:

$$\text{Yarding cycle time} = \text{Delay free yarding cycle time} \times \left(1 + \frac{\text{Delay time (\%)}}{100}\right) \qquad 20.$$

Dykstra (1976a) used a linear equation to estimate a yarding cycle time in his methodology, assuming that the equation could be used for any timber parcel and any cable road alternative. He estimated regression coefficients exogenously for each yarding system alternative. In application, however, using linear regressions may have several limitations. First of all, it is difficult to estimate the regression coefficient values that may vary with logging equipment, silvicultural prescriptions, stand structure, and other site specifications. The range of values for independent variables is also confined for a valid use of regression equations. Starnes (1984) pointed out that the linear equations have inherent limitations such as an application range of each independent variable and an inaccuracy due to a strong nonlinear relationship between production and independent variables.

The cost analysis module developed in this methodology uses a different approach to estimate a cycle time from that of Dykstra (1976a). Instead of using a linear regression equation, the module splits yarding cycle time into six time components of yarding activities and separately estimates time consumed for each activity. The planners can easily input or change the parameters required for estimating time for each component based on their field experience or existing time studies. Each time component is assumed to be independent of others and thus the change of parameters for one time component does not influence others in the module.



*numbers represent the order of each activity occurs during a yarding cycle.

Figure 18. Typical time components of a yarding cycle.

Lateral outhaul and lateral inhaul time

In many time studies (Hochrein and Kellogg 1988, Edwards 1992, and Kellogg et al. 1996b), lateral yarding distance is included as an independent variable in the linear equations that were derived to predict yarding cycle time. Lateral yarding time can vary with lateral yarding distance, uphill or downhill ground slope, carriage height, and many other factors. Dykstra (1976b) developed separate regression equations for lateral outhaul time and lateral inhaul time. His regression model showed that lateral outhaul time is significantly affected by average side slope of ground, brush and slash conditions at the hook point, yarding distance, and lateral yarding distance. In case of lateral inhaul time, his regression model showed that the time is associated with yarding distance, lateral yarding distance, and gross volume in the turn.

To simplify the problem the cost analysis module in this methodology assumes that the lateral yarding time (lateral inhaul plus outhaul time) depends on only lateral yarding distance. The lateral yarding distance here is defined as a slope distance from log pickup point to the point intersection of the cable road and a line drawn perpendicular to it from the log pickup point. The module uniquely applies discrete linear equations to estimate lateral yarding time in order to cover a non-linear relationship between the lateral yarding distance and time (Figure 19). Sessions and Li (1987) introduced a non-linear equation for estimating skidding costs with various skidding distances. Except for their study, not many studies included the non-linear relationship into their models.

Based on his field experiences, Edwards (2002) mentioned that the difficulties in pulling and dragging the skidding line over the ground (lateral outhaul) and in dragging logs along the ground (lateral inhaul) may exponentially increase total lateral yarding time as lateral yarding distance increases. The discrete linear equations are also useful to penalize extremely long lateral yarding distance. By applying a very slow lateral yarding speed, logs yarded from beyond the "reasonable" lateral yarding distance will quickly increase yarding costs and will be excluded from the final solution. In this case, the discrete linear equation is used to generate penalties on extremely long lateral yarding distance instead of estimating actual lateral yarding time.

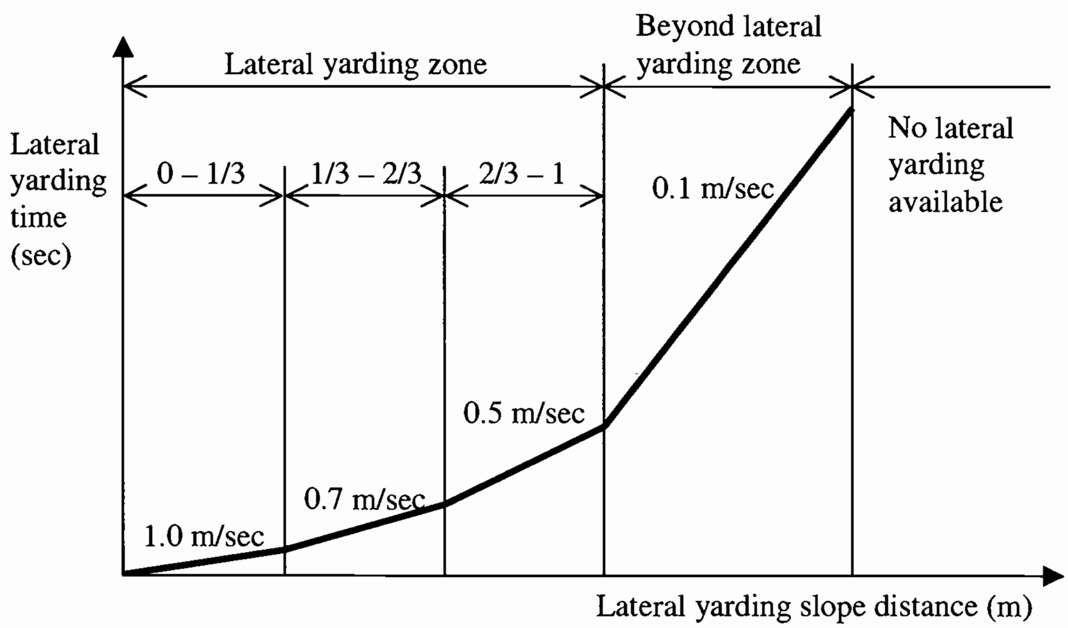


Figure 19. An example of the discrete linear relationship between lateral yarding distance and time.

Outhaul and inhaul time

Yarding distance significantly affects both outhaul and inhaul time (Dykstra 1976b). The cost analysis module in this methodology estimates outhaul and inhaul time separately. The module estimates outhaul time assuming that outhaul time is a function of the user-defined average outhaul speed of each yarding system and slope yarding distance (Equation 21).

$$\text{Outhaul Time (sec)} = \frac{\text{Slope yarding distance (m)}}{\text{Average outhaul speed (m/sec)}} \qquad 21.$$

During uphill yarding, inhaul time is estimated by measuring power required for increasing the potential energy of carriage and log load from the elevation at the log pickup point to the elevation of the landing. The yarder engine is the only power source to increase the potential energy. This approach assumes that yarder is coupled to a transmission that can keep the engine within a reasonable operating range so that power at the mainline drum is constant.

Using this approach, the cost analysis module estimates inhaul time by dividing potential energy increase (Joule) by available power (Watt or Joule/sec) from the engine. For full suspension, the energy required to elevate the height of carriage is calculated by multiplying total weight including carriage, mainline and log load by the elevation difference (Equation 22). For partial suspension, the energy required for increasing the potential energy of the load additionally includes work created by the friction between the log and the ground (Equation 23).

$$\text{Inhaul time when full suspension (sec)} = \frac{(W + W_C + MNL \cdot \omega) \times G \times h_1}{P \times \frac{E}{100}} \qquad 22.$$

$$\text{Inhaul time when partial suspension (sec)} = \frac{(W + W_C + MNL \cdot \omega) \times G \times h_1 + \sum_{i=1}^{n} \mu \cdot N_i \cdot G \cdot SD_i}{P \times \frac{E}{100}} \qquad 23.$$

where, W = log load (kg)
W_C = weight of carriage (kg)
MNL = length of the mainline (m)
ω = unit weight of the mainline (kg/m)
h_1 = elevation difference between headspar and carriage (m)
P = engine power (watts)
E = power converter efficiency (%)
N_i = normal force between log and ground at terrain point *i* (kg)
SD_i = slope distance between terrain point *i* and *i*-1 (m)
n = terrain point where the carriage is clamped to pick up logs
μ = coefficient of friction between log and ground
G = acceleration of gravity (= 9.81 m/sec^2)

In order to avoid unreasonably short inhaul time estimates that may result from this approach, the inhaul time is also calculated using the user-defined maximum drum line speed. After comparing the two estimates, the cost analysis module will take the larger estimate for inhaul time.

<u>Hook and unhook time</u>

Hook time is known to be associated with various factors such as ground slope, brush conditions, and the number of logs yarded for each turn as well as timber volume (Dykstra 1976b). To simplify the problem, this methodology assumes that hook and unhook time is only affected by timber volume in each turn. The cost analysis module estimates hook time and unhook time for a turn of logs using the user-defined average hook and unhook time per unit volume as follows:

$$\text{Hook time (sec)} = \text{Log volume}(m^3) \times \text{Average hook time per unit volume}(\text{sec}/m^3) \qquad 24.$$

$$\text{Unhook time (sec)} = \text{Log volume}(m^3) \times \text{Average unhook time per unit volume}(\text{sec}/m^3) \qquad 25.$$

Estimating yarding cost for a timber parcel

The load building simulator determines the location of each timber parcel, log pick up point, timber volume to be yarded, and the number of turns (T) required to yard each parcel as described in the beginning part of this section. Then, the cost analysis module estimates a yarding cycle time (YCT) from each log pickup point through one of the alternative paths. Once the number of turns required to yard a timber parcel and yarding cycle time are estimated, total yarding time for the parcel is obtained by multiplying cycle time by the number of turns required (T × YCT). The yarding time varies with different cable roads, yarding equipment, and landing locations because the number of turns is a function of the maximum payload of the yarding system at the log pickup point and the yarding cycle time is a function of yarding distance and lateral yarding distance. The cost analysis module is applied to all possible alternative paths for each timber parcel and estimates yarding time and costs for each alternative path. Thus, the total yarding time (TYT) and costs (TC), which is required to yard timber parcel *i* over cable road *j* by means of yarding system *k* to landing *l* are estimated as follows:

$$TYT_{ijkl} = T_{ijkl} \times YCT_{ijkl} \qquad 26.$$

where TYT_{ijkl} = total yarding time (sec), which is required to yard parcel *i* over cable road *j* by means of yarding system *k* to landing *l*

T_{ijkl} = the number of turns required to yard parcel *i* over cable road *j* by means of yarding system *k* to landing *l*

YCT_{ijkl} = yarding cycle time (sec), which is required to yard parcel *i* over cable road *j* by means of yarding system *k* to landing *l*

$$TC_{ijkl} = \frac{TYT_{ijkl}}{3600} \times C_k \qquad 27.$$

where TC_{ijkl} = yarding costs required to yard parcel *i* over cable road *j* by means of yarding system *k* to landing *l*

C_k = hourly costs of yarding system *k*, in $/hr, including both equipment and labor costs

Fixed costs

The cost analysis module also considers fixed costs that occur during yarding. Fixed costs for cable logging operations include costs for landing construction, yarding system move-in, initial yarder setup, and cable road emplacement.

Although Van Winkle (1976) found that cable road emplacement cost varies with the distance from the landing to the tailspar, the cost analysis module in this study assumes that the fixed costs for yarding move-in, initial setup, and cable road emplacement depend only on yarding equipment. Each landing is allowed to have a unique cost for its construction, which is estimated exogenously by the user. This landing cost may vary with different yarding equipment since a larger yarder may require a larger landing. If more than one yarder is evaluated for the same landing location, the user can either specify one landing cost for all yarders and have them share the cost or a different landing cost for each yarder that can be specified assumes each yarder is "virtually" located on a different landing. For the latter case, if more than one yarder is selected for the same landing, the landing cost should be adjusted by manually subtracting the landing cost for the smaller yarder after the final solution is found.

Yarding equipment move-in costs may include lowboy transport costs to move logging equipment to a landing. Initial yarder setup costs are one-time costs that occur whenever yarding equipment moves into a different landing. Cable road emplacement costs occur when cable road is changed while the yarder stays at the same landing. Both initial yarder setup costs and cable road emplacement costs are calculated by the user-specified working hours required for each activity multiplied by the hourly cost of each yarding system.

If a cable road requires intermediate supports, the support tree rigging costs are added to the cable road emplacement costs as a part of fixed costs. The rigging costs are calculated from the user-defined unit costs ($/tree) multiplied by the number of intermediate support trees required for a specified cable road. Initial yarder setup costs and cable road emplacement costs are calculated as follows:

$$ISC_k = ISH_k \times C_k$$
$$CRC_{ik} = CRH_k \times C_k + NIS_{ik} \times RC_k \qquad 28.$$

where ISC_k = initial equipment setup costs ($) for yarding system *k*
ISH_k = time required to initially set up equipment for yarding system *k* (hours)
C_k = houly cost of yarding system *k*
CRC_{ik} = cable road change costs ($) for cable road *i* of yarding system *k*
CRH_k = time required to change cable road of yarding system *k* (hours)
NIS_{ik} = the number of intermediate support trees required for cable road *i* of yarding system *k*
RC_k = costs for rigging an intermediate support tree ($/tree) for yarding system *k*

Transportation costs

The cost analysis module estimates transportation costs necessary for moving timber from the landing to the mill or other specified destination.

Transportation costs in the module include road construction and hauling costs. Each landing must be accessed from at least one road in order to move-in logging equipment and transport logs to the mill. If an access road does not exist, a road must be built with an appropriate design standard.

The cost analysis module can apply different road construction costs to each road segment to be built as a function of ground slope. The module also is able to restrict the maximum allowable ground slope for road construction in order to avoid extreme amounts of earthwork and unstable cut and fill slopes.

In this study, a road segment is defined as a link connecting two consecutive grid cells on a DTM. Two ground slopes can be obtained from the DTM. One is the ground slope in the direction of a road and the other is the side ground slope that is perpendicular to the direction of the road. Road cost increases with the increase of ground slopes assuming that building road on a steep ground requires more earthwork and higher costs. In the cost analysis module, road construction costs are estimated using the construction cost per unit distance and the user-defined multipliers. The road cost per unit distance is determined exogenously based on the road standards such as road width, turnouts, surface treatment, road grade, and other design factors. In order to reflect the cost increase caused by the increase of earthwork when a road is built on a steep ground, the user-defined multipliers are applied to the unit cost. If a road goes across a stream, total road costs may increase since an additional bridge construction or placing stream culverts may be necessary. The module applies the user-defined stream-crossing multiplier to road segments located on any stream buffers. The cost multipliers in the module can be used for estimating road costs and for penalizing road segments that are located on steep ground or cross streams so as to avoid such road locations.

Total road cost for building a road segment is estimated as follows:

$$RC_{ij} = \frac{URC}{1000} \times Dist_{ij} \times Mult_1 \times Mult_2 \times \left(1 + SB_{ij} \times \left(Mult_3 - 1\right)\right) \qquad 29.$$

where RC_{ij} = total road costs ($) for a road segment from grid cell *i* to grid cell *j*

URC = road cost per unit distance ($/km)

$Dist_{ij}$ = distance (m) from grid cell *i* to grid cell *j*

$Mult_1$ = multiplier for ground slope in the direction of road segment *ij*

$Mult_2$ = multiplier for side ground slope of road segment *ij*

SB_{ij} = indicator for stream crossing, if road segment *ij* is on any stream buffer, SB_{ij} is 1, otherwise 0

$Mult_3$ = multiplier for stream crossing, for example, multiplier of 2 increase road costs by 100%.

If either the ground slope in the direction of the road or the side slope exceeds its limit, the road segment becomes infeasible and is excluded from the analysis.

Hauling cost over each road segment is assumed to be proportional to timber volume and hauling distance. Hauling cost for unit volume per unit distance is determined exogenously and entered into the module by the user. Loading cost at the landing is included in yarding system costs, but truck time during loading and unloading cost at the mill are not included in the analysis. Hauling costs for volume that is transported over a road segment from grid cell *i* to grid cell *j* is estimated as follows:

$$HC_{ij} = \frac{UHC}{1000} \times Volume_{ij} \times Dist_{ij} \qquad 30.$$

where HC_{ij} = hauling costs ($) from grid cell *i* to grid cell *j*
UHC = hauling cost for unit volume per unit distance ($\$/m^3 \cdot km$)
$Volume_{ij}$ = timber volume to be transported from grid cell *i* to grid cell *j* (m^3)
$Dist_{ij}$ = distance from grid cell *i* to grid cell *j* (m)

PROBLEM FORMULATION AND SOLUTION TECHNIQUES

The previous chapter introduced the logging feasibility and cost analysis modules developed for this study. The logging feasibility module identifies feasible cable road candidates. The cost analysis module estimates logging and transportation costs to move each turn of logs from the stump to the destination via an alternative path that includes a cable road, a landing, and a series of road segments. This chapter presents a procedure for identifying a "good" timber path from each timber parcel based on the information provided by the feasibility and cost analysis modules.

The network assembler developed for this methodology builds a cost minimization network problem based on possible paths from each timber parcel to the destination. Then, the methodology solves the network problem using the network heuristic algorithm which is an approximation network programming technique developed by Sessions (1985). The algorithm cannot be guaranteed to give optimal solutions for larger network problems but it is computationally feasible. The problem formulation and solution techniques used in this study are described in the following sections.

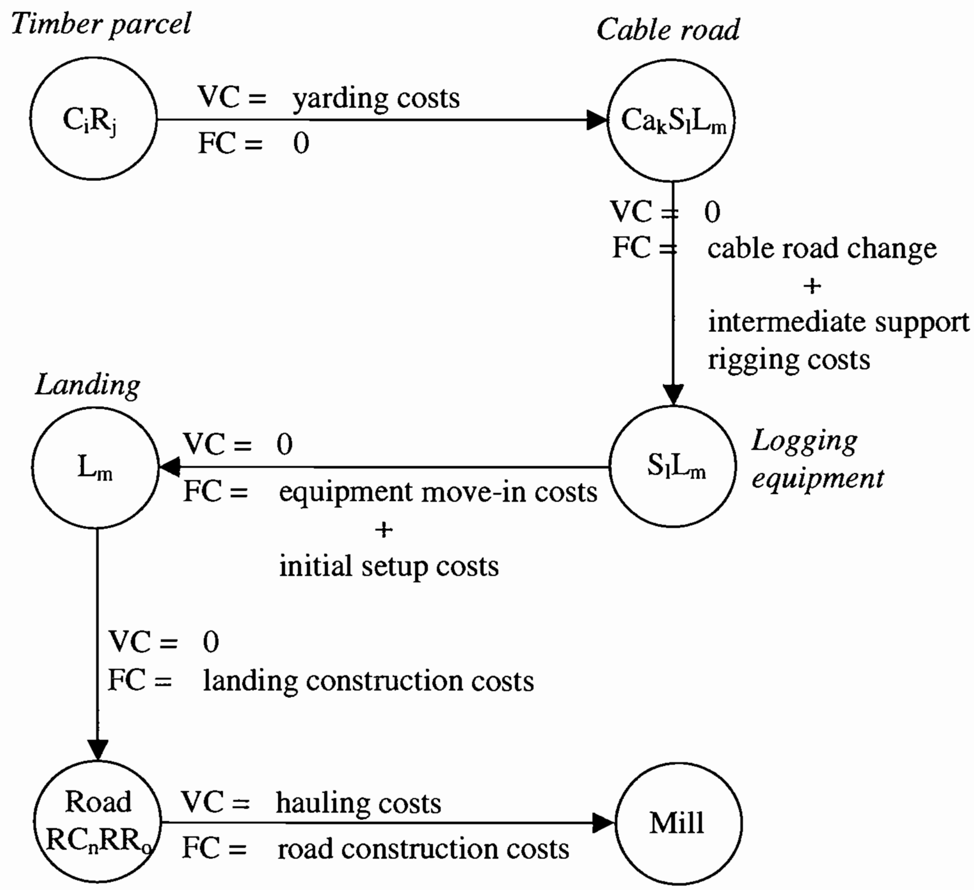
Problem formulation

To examine all possible paths from each timber parcel to the destination, the network assembler builds an entire network that implicitly considers all alternative timber paths. Each timber parcel location is identified as an individual entry node of the network. Mill locations or specified timber exit locations are identified as single or multiple destinations of the network. Then, each origin must be connected to one of the destinations through alternative paths representing alternative cable roads, harvesting equipment, landing locations, and road segments. Each path consists of a series of links representing logging activities and incurring variable costs (yarding and hauling costs) and fixed costs (landing and road construction costs) corresponding to each activity. Fixed costs are the costs that occur only once when the link is opened, while variable costs are proportional to the timber volume transported over the link.

Figure 20 illustrates an example of a path from a timber parcel to the mill via one of the appropriate landings. Each link in the figure represents variable and fixed costs associated with corresponding harvesting activity. The path starts from the location of a timber parcel, and then moves to a landing over a cable road using a yarding system. When a cable road is newly emplaced, cable road emplacement costs occur including intermediate support rigging costs if necessary. Establishing a new landing triggers its construction costs. Whenever a yarding system is newly used in a landing, equipment move-in costs and initial yarder setup costs are added to the total yarding costs.

The network assembler generates alternative road segments on a DTM and builds an entire network in which each road segment plays a role as a link. The assembler develops eight links from each grid cell on the DTM to connect it with its neighboring grid cells (Figure 21). Each link represents corresponding hauling and road construction costs estimated by the cost analysis module. If the ground slope between two consecutive grid cells exceeds the user-defined limit, the link becomes infeasible and is excluded from the network.

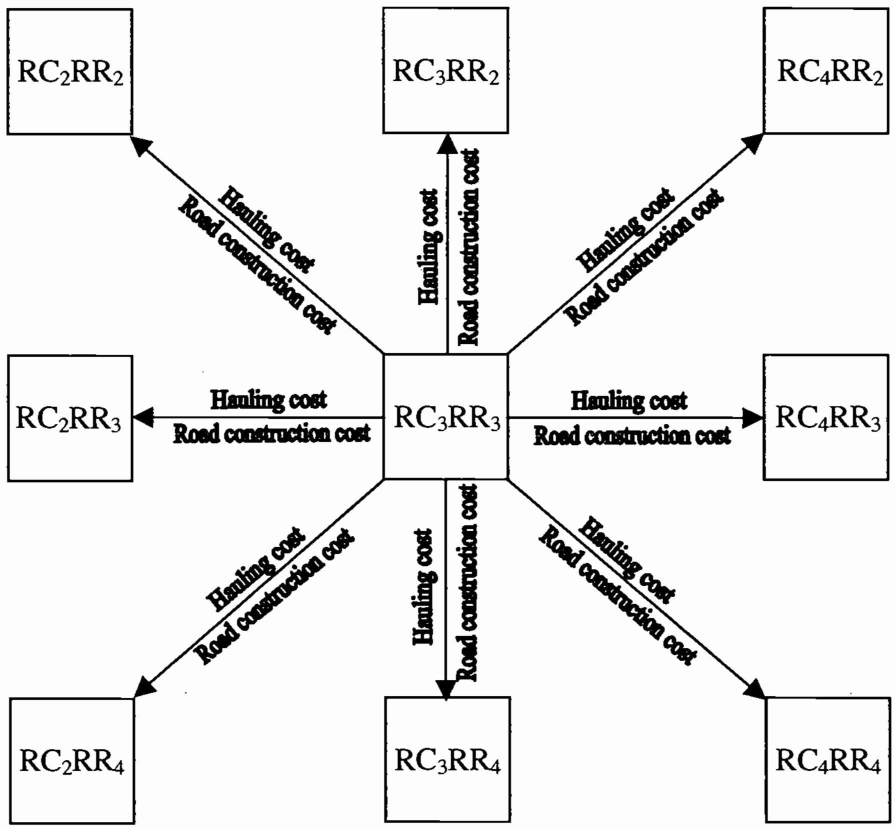
The possible candidate paths from each timber parcel to the destination via alternative cable roads, landings, and road segments form an entire network (Figure 22). Once the network is established, a "feasible" and "good" path from each timber parcel to the destination can be found by solving the cost minimization network problem. The following section introduces the problem solution techniques used in this methodology.



Nomenclature:

VC	= variable costs over the link
FC	= fixed costs over the link
C_iR_j	= node name representing a timber parcel located in column *i* and row *j* on a DTM
$Ca_kS_lL_m$	= node name representing cable road *k* associated with yarding equipment *l* located in landing *m*
S_lL_m	= node name representing logging equipment *l* located in landing *m*
L_m	= node name representing landing *m*
RC_nRR_o	= node name representing a road segment located in column *n* and row *o* on the DTM

Figure 20. An example of a path from a timber parcel to the mill. Each link represents corresponding logging activity with variable and fixed costs for the activity.



RC_iRR_j = node name representing a grid cell located in column *i* and row *j* on a DTM

Figure 21. Developing eight links representing road segments which connect a grid cell to its neighbor cells on a DTM.

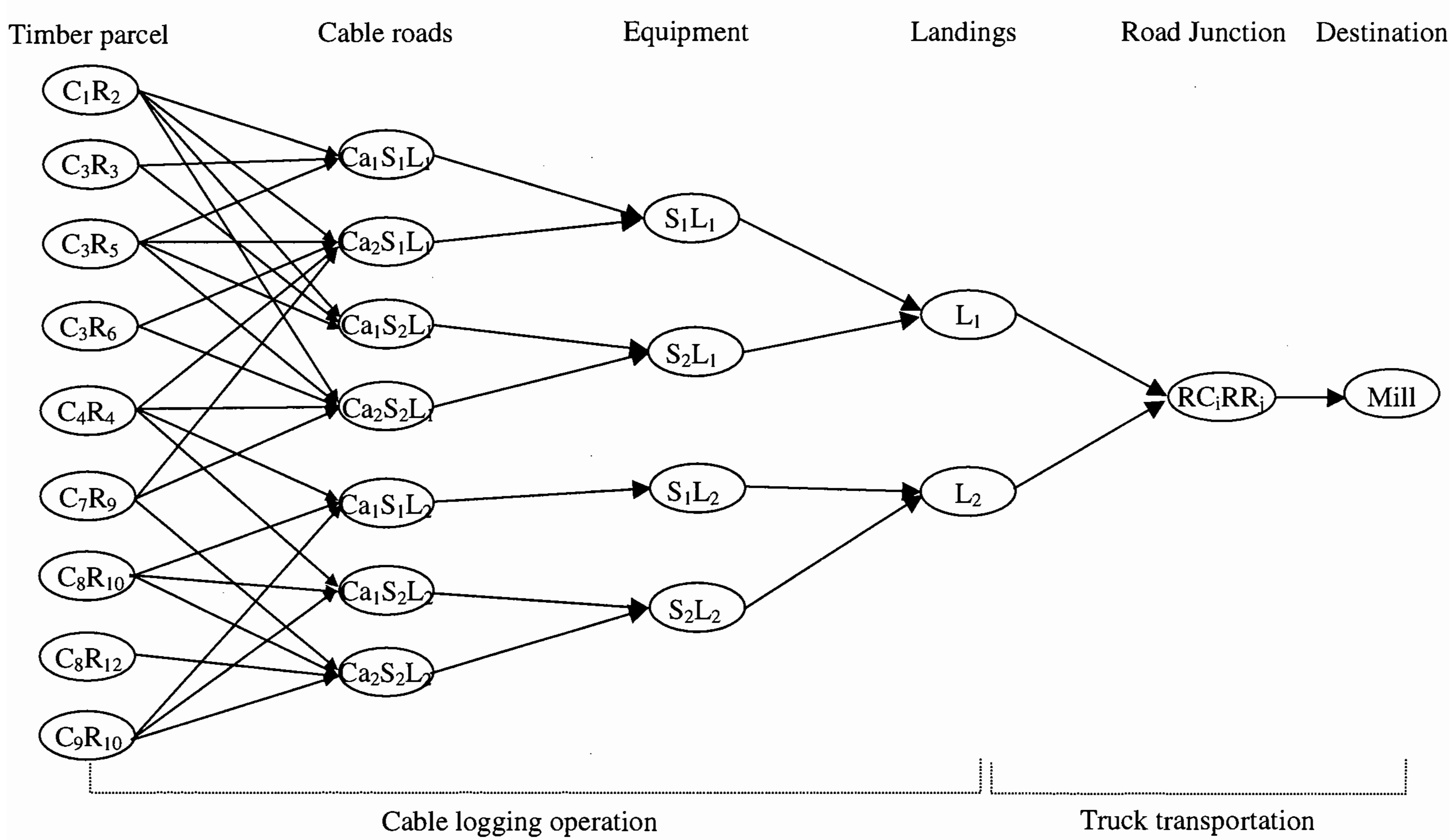


Figure 22. A network showing alternative paths from timber parcels to the mill (see Figure 20 for variable definitions).

Problem solution techniques

Once the networks for cable logging operation and truck transportation are set up, a network programming technique implemented in this methodology solves the cost minimization network problem and finds the least cost path from each timber parcel to one of destinations while simultaneously selecting cable road, cable equipment, landing location, and road segments in the path. In this study, the heuristic network algorithm developed by Sessions (1985) is used as an optimization technique. The algorithm was discussed in the literature review section in the first chapter.

In order to solve a cost minimization network problem, the algorithm requires two different data sets. One is a link data set that includes the information of each link such as from-node, to-node, variable cost, and fixed cost. The other is a sale data set that contains information on entry nodes, timber volume from each entry, and destination nodes. The solution time of the heuristic network algorithm increases as the size of problem increases while being affected by two factors: the number of sales in a network problem and the number of links involved in each candidate path.

Since cable logging layout and road location problems engage many entry nodes (timber parcels) and links (road segments), they usually produce large network problems. In this methodology, to increase the efficiency of problem solving, the large network is decomposed into two sub-parts. One is the cable logging operation (from stump to landing) and the other is truck transportation (from landing to mill). The network representing the cable logging operation planning problem requires a large number of entry nodes (timber parcels) but only few links representing cable road, yarding system, and landing are involved in each alternative path. On the contrary, a network problem for truck transportation planning involves few entry nodes (candidate landings) but an alternative path in the network consists of large number of links since each grid cell in the path should be connected to one of the eight neighboring cells by a link until the path arrives at a user-defined destination.

In this methodology, the cable logging operation part of the network is solved first in order to select cable roads, cable systems, and landing locations without considering truck transportation (Figure 23). Then, total timber volume arriving at each landing is calculated based on the results of the optimization procedure and sent to the truck transportation part as being entry volume to the 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. If several landings share the same road links, the road costs on the links will be 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. Thus, in this approach, the output of one part becomes input (feedback) for the other part.

The feedback mechanism of the methodology eventually adds road costs to the landing that are selected at the cable logging operation part of the solution. This causes the high cost landings not to be selected again in the following iteration, which may give more opportunities to explore the solution space by selecting landings which were not included in the last solution.

A number of iterations of this process are required to get to a steady state where the results from each part remain the same as the previous iteration and the algorithm stops. Depending on the problem, the repetition of this process might not merge to a steady state but keep bouncing around within a range. Setting stopping criteria such as limiting the number of repetitions would be necessary to terminate the algorithm in a reasonable time. The best overall solution is kept over the iteration process.

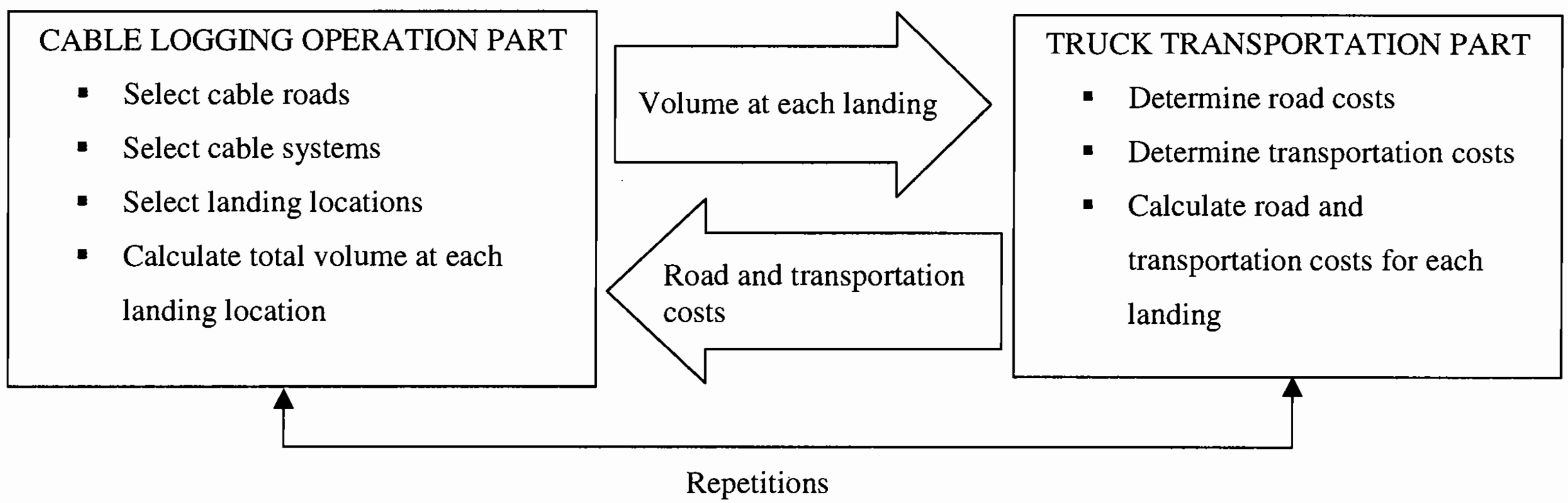


Figure 23. A feedback mechanism between two separated network problems.

DECISION SUPPORT SYSTEM

In order to implement the methodology presented in this study, a computerized model was developed as a decision support tool to assist the forest planners in designing cable logging unit layouts. The procedures for the methodology have been programmed in Microsoft Visual C++. Using the graphic user interface (GUI), the model requires the Microsoft Windows operating system to run.

The model begins with reading input data from GIS layers and then allows the users to enter candidate landing locations and the user-defined information on yarding equipment, operating costs, road costs, and other parameters (Figure 24). Next, the model conducts the logging feasibility analysis to identify physically feasible cable roads based on topographic conditions and yarding equipment capability. The logging feasibility analysis is followed by the cost analysis in order to estimate yarding costs and transportation costs for each alternative. The network assembler follows to develop a series of links with corresponding fixed and variable costs representing alternative timber paths. Two sets of networks with their link and sale data files are produced by the network assembler. One is the cable logging operation network in which timber parcels become entry nodes and candidate landings become destinations. The other is the transportation network in which candidate landings and mill become entry nodes and destination, respectively.

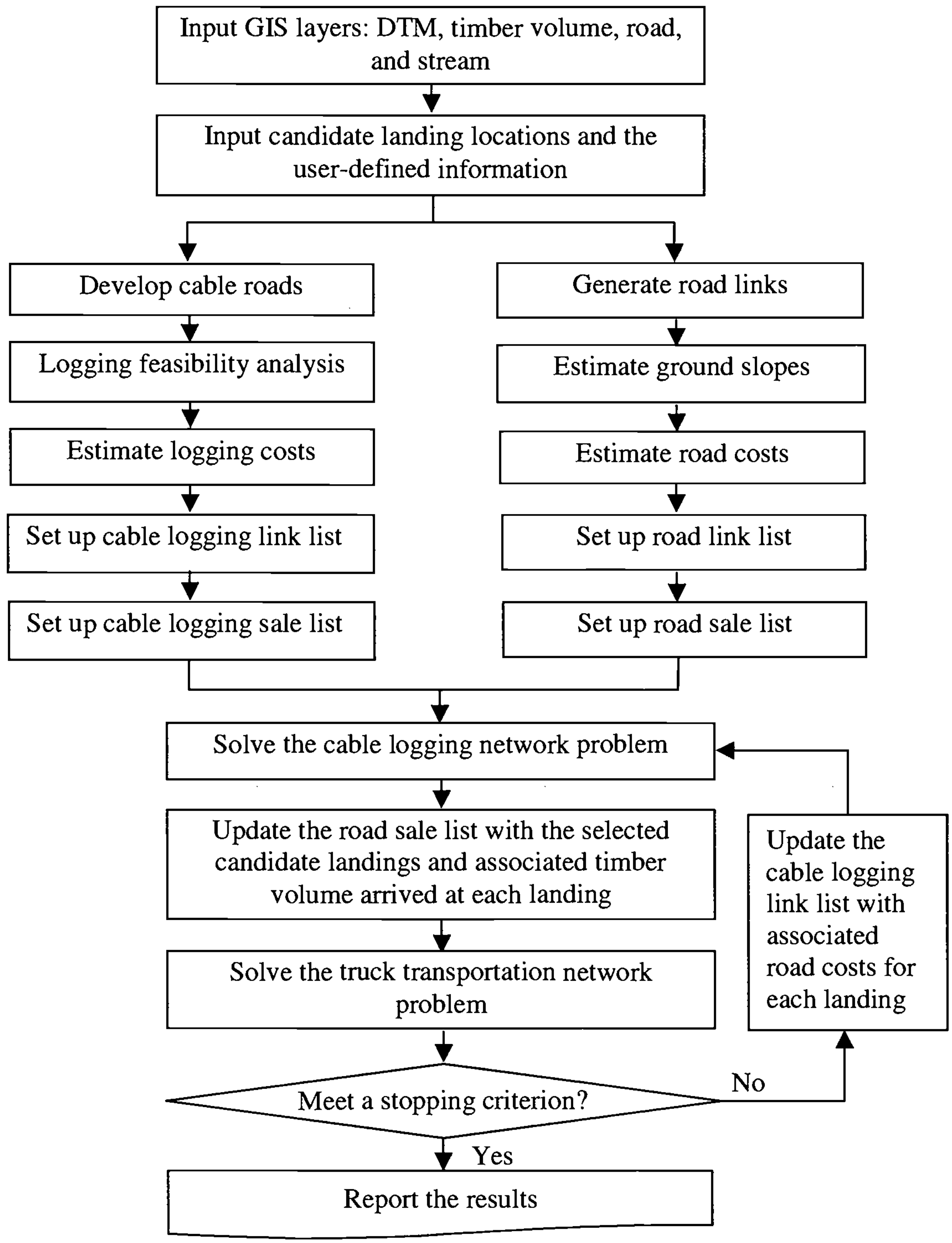


Figure 24. A flowchart of the computerized model.

Based on these two network problems, the heuristic network algorithm implemented in the model begins to solve the cable logging operation planning problem in order to find out the least cost timber path from each timber parcel to one of candidate landings. Once all timber parcels are allocated to one of candidate landings via alternative paths, the model calculates the total timber volume that arrives at each candidate landing. These candidate landings and their timber volume are passed to the second network problem which is designed to seek the least cost routes from each landing to one of the mill locations or other proposed timber destination. The model solves this transportation planning network problem and finishes the first iteration by estimating the total hauling and road costs required to transport timber from each landing as the results. The second iteration begins with adding the hauling and road costs, which are obtained from the previous iteration and assigned to each candidate landing, to the links representing each corresponding landing in the cable logging operation network problem. Then the model resolves the network problem to find out alternative paths that incurs the least cost for moving timber to the landing. This routine repeats until either the solution remains the same as the previous one or the number of iteration exceeds the user-defined limit.

By interpreting the least cost path from each timber parcel to the destination, the model is able to identify the "best" combination of cable road, equipment, landing, and road segments among the alternatives for each timber parcel.

To run the model, the user has to provide information for both logging feasibility and cost analysis such as yarding equipment specifications, yarding operation information, landing costs, hauling costs, and road costs (Tables 2).

Table 2. Required information to run the computerized model.

Cable equipment specifications	
Maximum external yarding distance (EYD)	m
Maximum lateral yarding distance (LYD)	m
Head spar height	m
Intermediate tree height	m
Tailspar tree height	m
Maximum allowable skyline tension	kg
Skyline unit weight	kg/m
Maximum allowable mainline tension	kg
Mainline unit weight	kg/m
Carriage depth	m
Carriage weight	kg
Engine power of yarder	watt
Choker length	M
Log information	
Log length	m
Log diameter	m
Minimum log-to-ground angle	degree
Wood density	kg/m^3
Yarding operations	
Average hook time per unit volume	sec/m^3
Average unhook time per unit volume	sec/m^3
Intermediate support rigging costs	$/tree
Felling costs	$\$/m^3$
Hourly costs of yarding system (yarding and loading to truck)	$/hour
Delay factor	%
Yarder move-in costs	$
Time required for initial yarder set up	hour
Time required for cable road emplacement	hour

Table 2 (Continued)

Design payload for one turn of logs	kg
Maximum inhaul speed with partial suspension	m/sec
Maximum inhaul speed with full suspension	m/sec
Average outhaul speed	m/sec
Lateral yarding speed including lateral outhaul and inhaul	m/sec
▪ Multiplier for 0-1/3 of LYD	-
▪ Multiplier for 1/3-2/3 of LYD	-
▪ Multiplier for 2/3-3/3 of LYD	-
▪ Multiplier for beyond LYD	-
Landing costs	
Landing construction costs	
▪ New landing	$/landing
▪ Reconstructing existing landing	$/landing
▪ Landing along the roads	$/landing
Transportation costs	
Construction costs	$/km
Hauling costs	$/m3-km
Ground slope limit in the direction of road	%
Multipliers applied to different ground slope in the direction of road	
▪ 0% - 5%	-
▪ 5% - 10%	-
▪ 10% - 15%	-
▪ 15% - 20%	-
▪ 20% - 25%	-
▪ 25% - 30%	-
Ground side slope limit	%
Multipliers applied to different ground side slope	
▪ 0% - 15%	-
▪ 15% - 30%	-
▪ 30% - 45%	-
▪ 45% - 60%	-
▪ 60% - 75%	-
▪ 75% - 90%	-
Multiplier for stream-crossings	-

Equipped with the graphic user interface (Figure 25), the model developed in this study provides dialog boxes to facilitate data input from the users (Figures 26-27). Figure 28 presents several screens from the model showing user-defined candidate landing sites and projected cable roads (Figure 28(a)), an example of the ground profile analysis for a projected cable road (Figure 28(b)), feasible cable road alternatives after the logging feasibility analysis is conducted (Figure 28(c)), and an example of the selected cable landing locations, cable systems, cable roads, and access road network found by the problem solving techniques implemented in the model (Figure 28(d)).

The details of the computerized model regarding to data input and solution will be described with an example of the application in the following chapter.

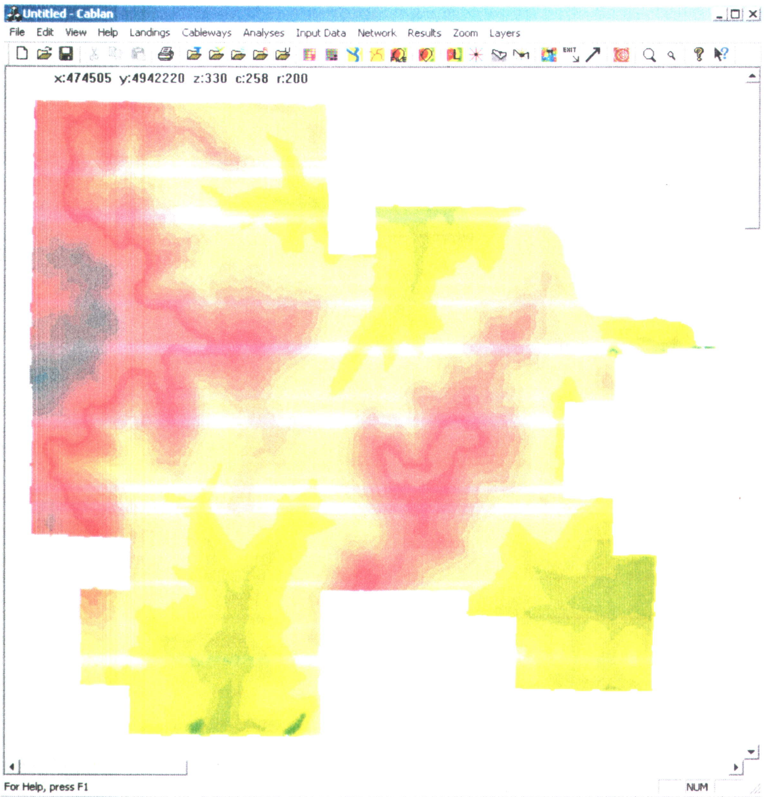


Figure 25. The computerized model programmed in the Microsoft Visual C++ 6.0 is equipped with the graphic user interface.

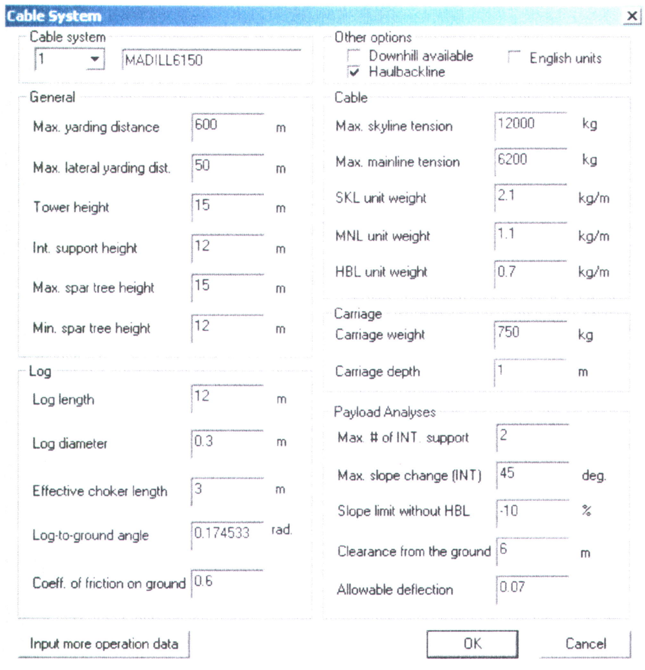


Figure 26. A dialog box for entering yarding system information

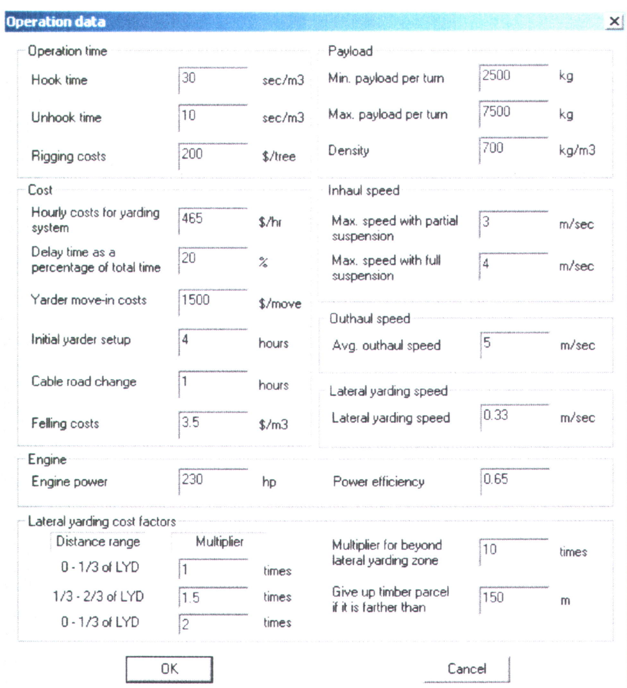


Figure 27. A dialog box of the computerized model for entering information on yarding operations.

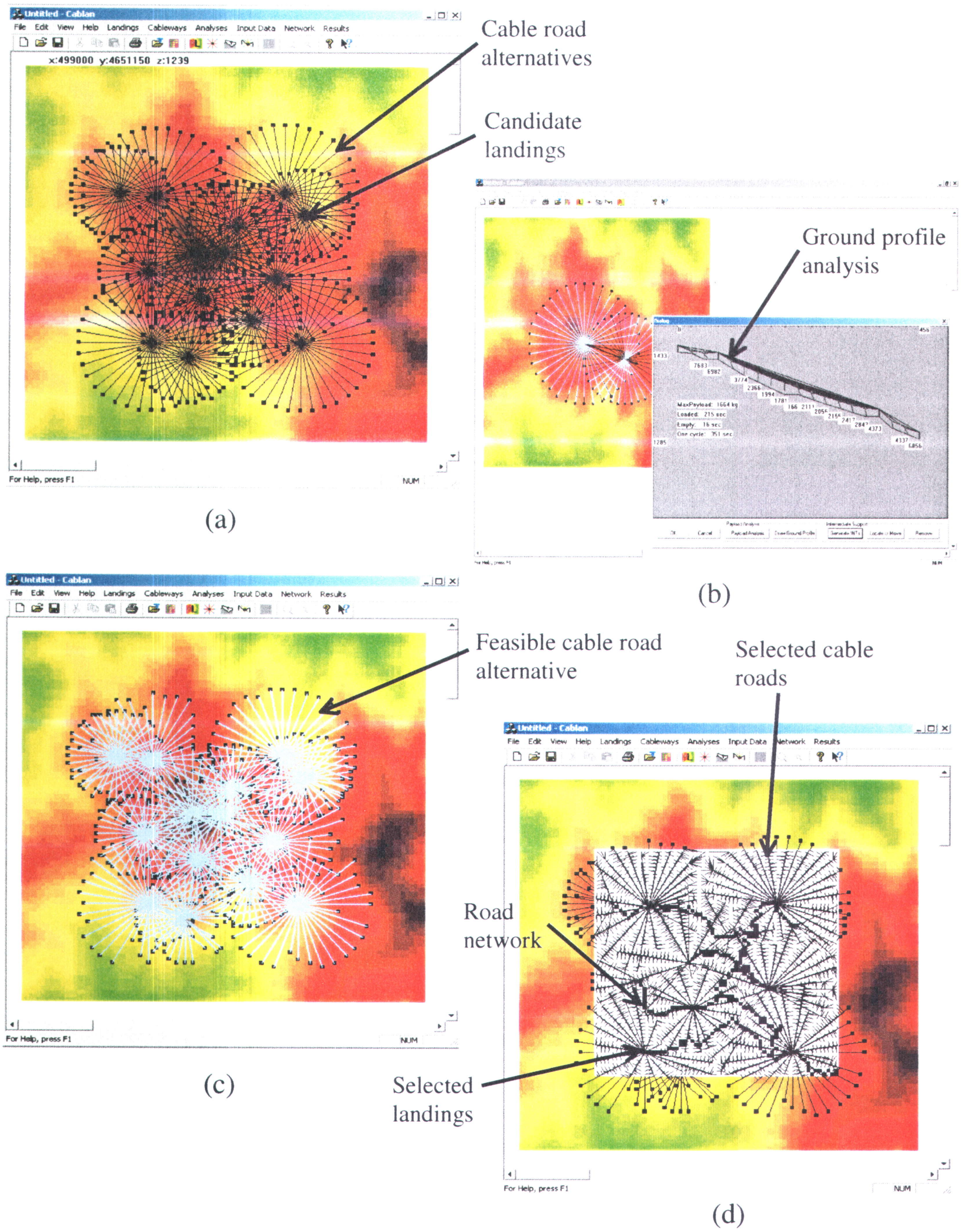


Figure 28. The computerized model showing landing candidates and cable road alternatives (a), an example of ground profile analysis (b), feasible cable road alternatives (c), and an example of the final solution to the cable logging and transportation planning problem (d).

APPLICATION OF THE METHODOLOGY

In order to address the capabilities and limitations of the methodology developed for this study the methodology was applied to an actual planning area. A harvest unit located in the McDonald-Dunn Forest (Oregon State University (OSU) Research Forests) was selected (Figure 29).

The McDonald-Dunn Research Forest is approximately 4,700 hectares of predominantly forested land on the western edge of the Willamette Valley in Oregon. The Forest is in Townships 10 and 11 South, and Range 5 West, Willamette Meridian. It lies west of U.S. Highway 99 just to the north of Corvallis, Oregon (OSU College of Forestry 2002a). The forest is managed under the McDonald-Dunn Research Forest Plan (OSU College of Forestry 2002b), recently developed by the College of Forestry and the Research Forest Staff at OSU. The plan divides the forest into three management zones; North, Central, and South. The planning area selected for this application is located in tract 8 (Soap Creek) in the South Zone of the forest. The silvicultural goal for the South Zone is to develop the structural conditions of mid-to late-successional forests of the Coast Range using primarily uneven-aged silviculture (Emmingham et al. 2002). According to the management plan of the forest, the planning area is scheduled to be harvested during year 2002 - 2003. A thinning operation will be applied to the planning area. The area was selected because the Research Forest staff has currently been developing the operational plan on the area and GIS database required for the methodology was already well established.

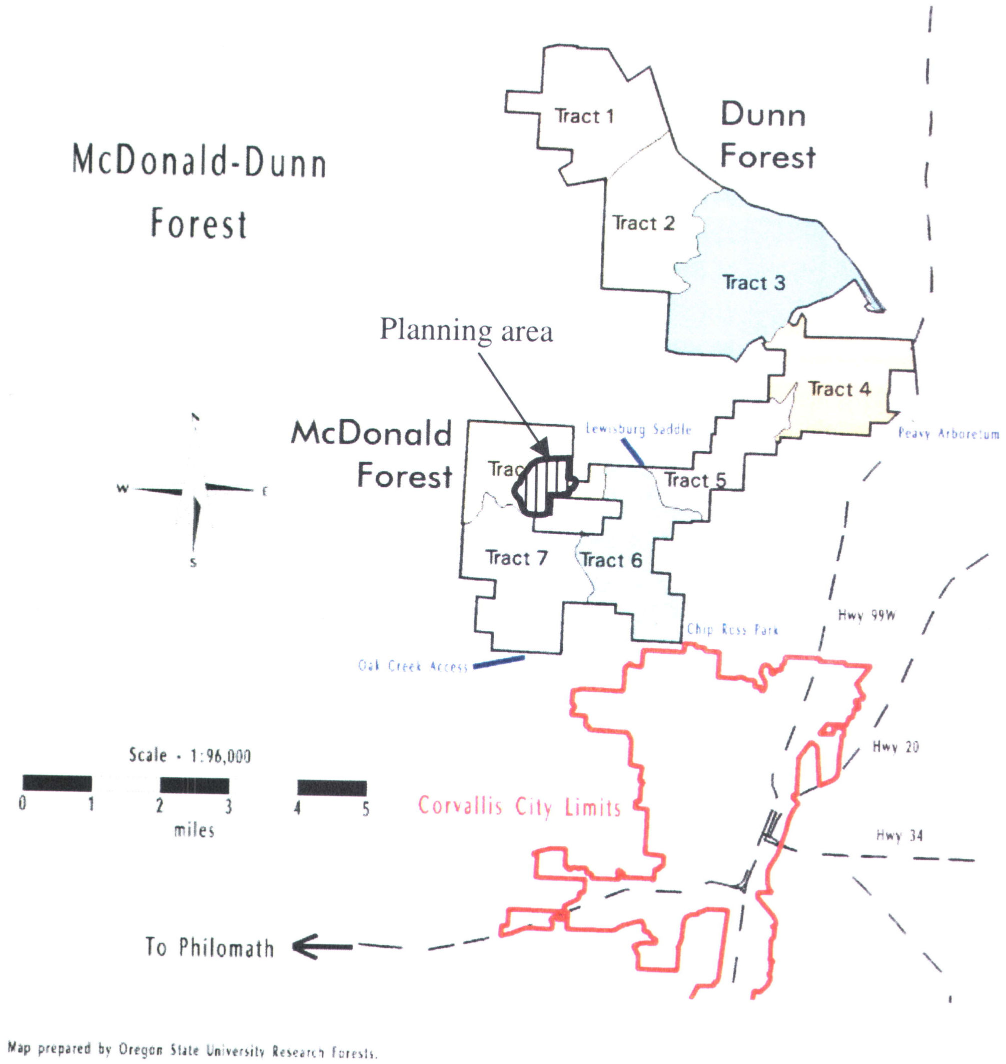
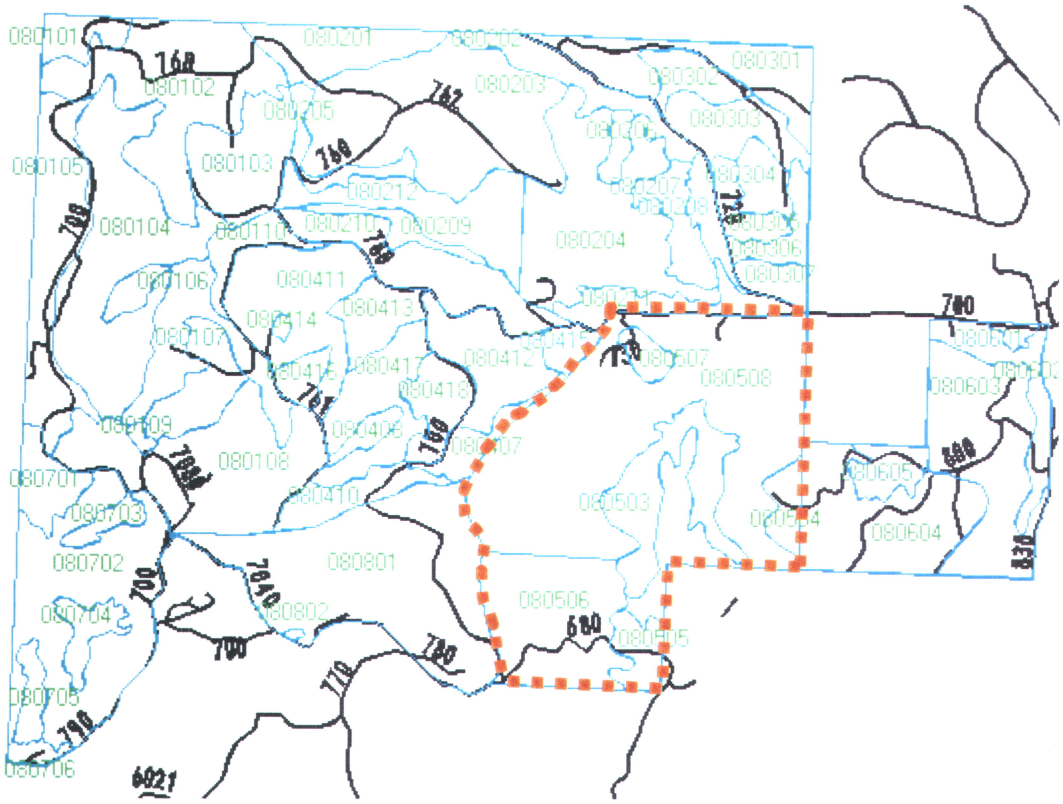


Figure 29. Location of the planning area in the McDonald-Dunn OSU Research Forest.

For this application, a DTM with a 10m by 10m resolution was developed from LIDAR data. Timber inventory was obtained by ground sampling and current inventory was projected using the Northwest Oregon version of ORGANON (Hann et al. 1997), which is an individual tree growth model widely used for the major tree species in the western Oregon. Existing roads and stream layers were also obtained from the Research Forest GIS database (Johnson 2002). The following sections describe the application of the methodology for the planning area in detail.

SITE DESCRIPTION

The planning area includes five stands (080503, 080504, 080505, 080506, and 080508) located in the Soap Creek watershed region of the South Zone (Figure 30). Access to these areas, which is about 93 ha in size, is via the Sulphur Springs and Soap Creek county roads and forest roads number 680, 682, 700 and 800. These stands were harvested by Caffall Brothers Logging Co. in 1945 except for stand 080506 and purchased by the College from the same company in 1948. Second-growth Douglas-fir (*Pseudotsuga menziesii*) is the dominant species in the area with the average age of 45-60 years. There are some grand fir (A*bies grandis*) and white oak (*Quercus garryana*) growing in the area. Average height and diameter of the trees in each stand vary from 15m to 30m and from 15 cm to 40 cm, respectively.



Boundary of planning area

080508 Stand number

700 Road number

Figure 30. Forest stands in the planning area.

Table 3 shows the stands with their average timber volume and volume to be harvested by the thinning treatment. Timber volume to be harvested was determined to be 50% of the current timber volume but not more than 110m^3/ha (Edwards 2002). Since individual tree locations and volume were not collected for this application, timber on the planning area is assumed to be homogeneous and equally distributed over the area. Thus, each grid cell of the GIS volume raster, which is 10m x 10m in size, is assumed to contain one hundredth of the average volume per hectare in each stand (Table 3).

Table 3. Forest stands and timber volume to be harvested in the planning area.

Stands	Area (ha)	Average timber volume (m^3/ha)*	Timber volume to be harvested	
			Average (m^3/ha)**	In each grid cell (m^3/cell)
080503	11.1	140	70	0.7
080504	2.7	170	85	0.9
080505	3.3	200	100	1.0
080506	17.3	380	110	1.1
080508	58.2	250	110	1.1

*total scribner volume (32 ft. logs, 6 in. top)
**timber volume was originally in bf/ac and converted to m^3/ha using the following equation: 1 mbf/ac × 5.7 m^3/mbf × 2.47 ac/ha =14.08 m^3/ha

The GIS layers required for this methodology were prepared and entered to the computerized model. These include a DTM (Figure 31) over the planning area, the boundary of the planning area (Figure 31), existing roads (Figure 32), and stream buffers (Figure 32). All streams in the planning areas are assumed to be classified as medium Type D, thus 15 meter buffers on each side of the stream were established for this application. Full suspension is required over these stream buffers and timber within the buffers is not to be harvested.

The timber volume layer was also entered into the model (Figure 33). The load building simulator in the computerized model put adjacent grid cells together until the minimum design payload was met. Figure 34 presents timber parcel locations found by the simulator using the design payload of 2,500 kg and the effective maximum distance between logs of 20m. Log pickup locations were determined at the same time by the simulator (Figure 35). A total of 1,926 log pick up points were identified from a total of 9,523 grid cells within the area. The total timber volume to be harvested from the area is 8,064 m^3.

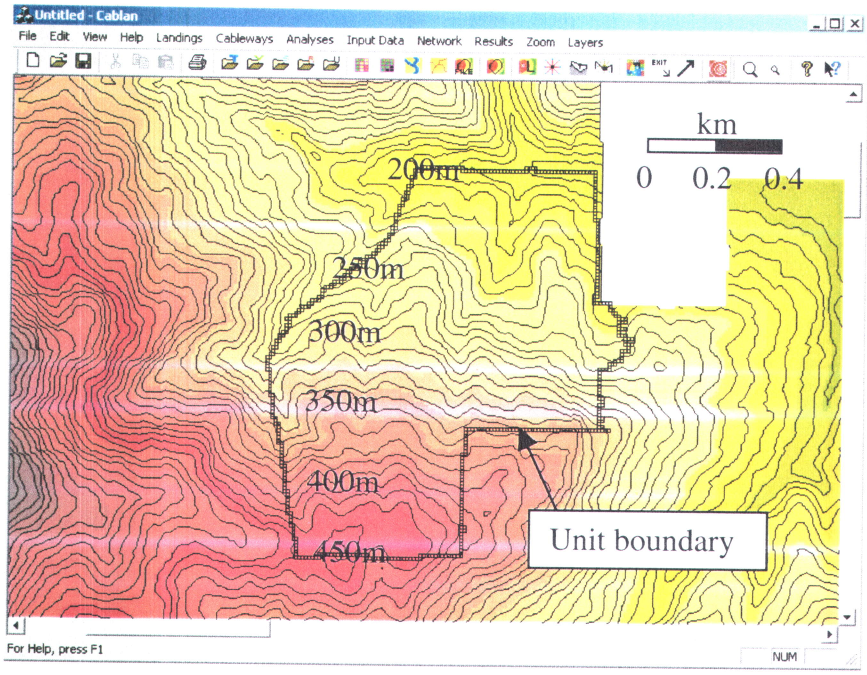


Figure 31. Computerized model showing the planning area on the DTM with contour lines.

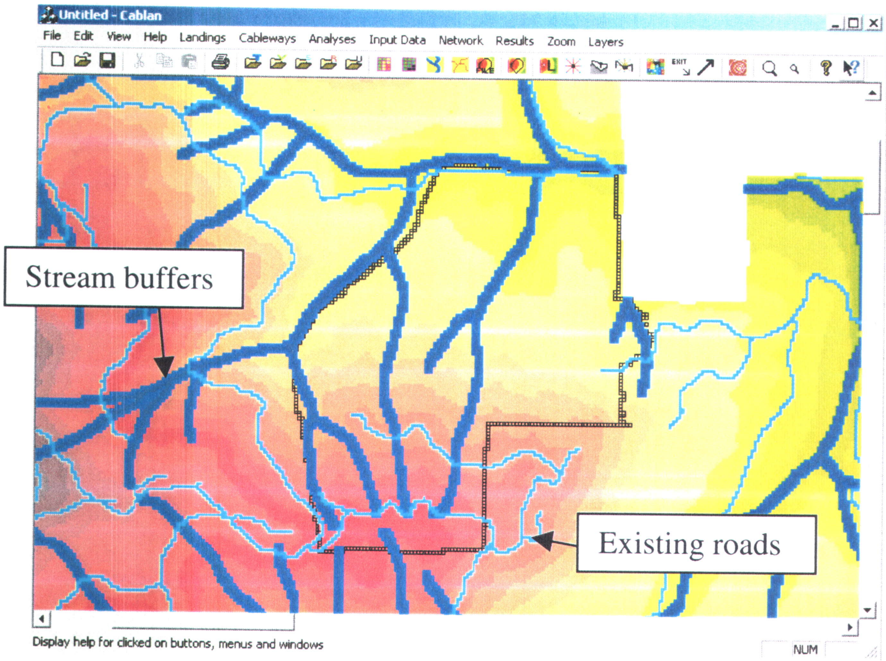


Figure 32. Existing roads and 15-meter stream buffers (each side of stream).

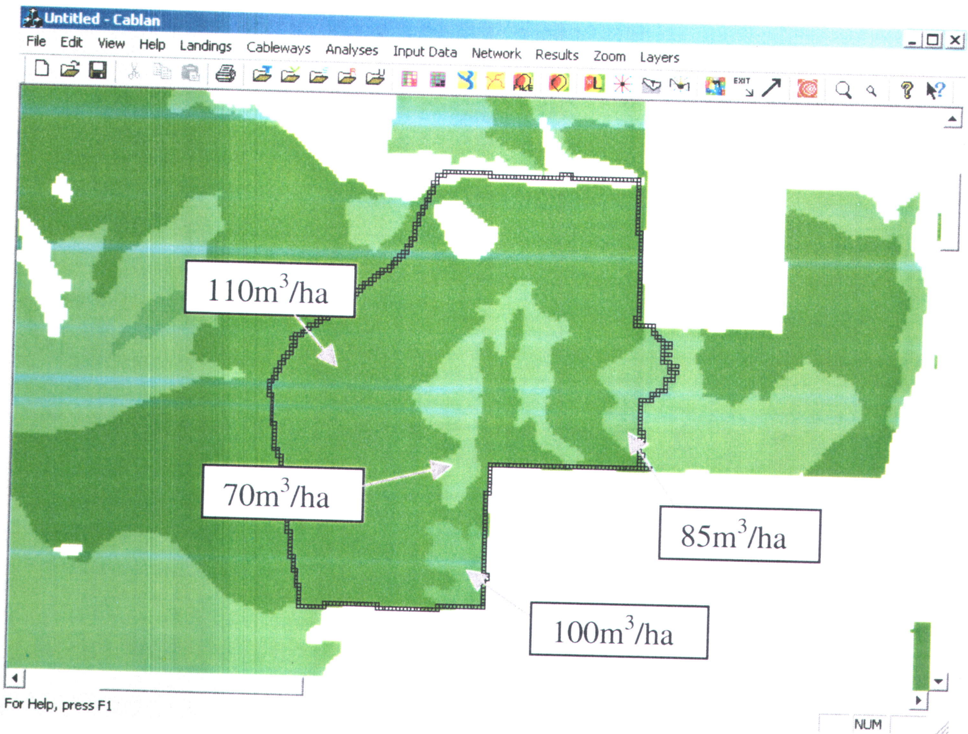


Figure 33. Timber volume layer superimposed on the planning area.

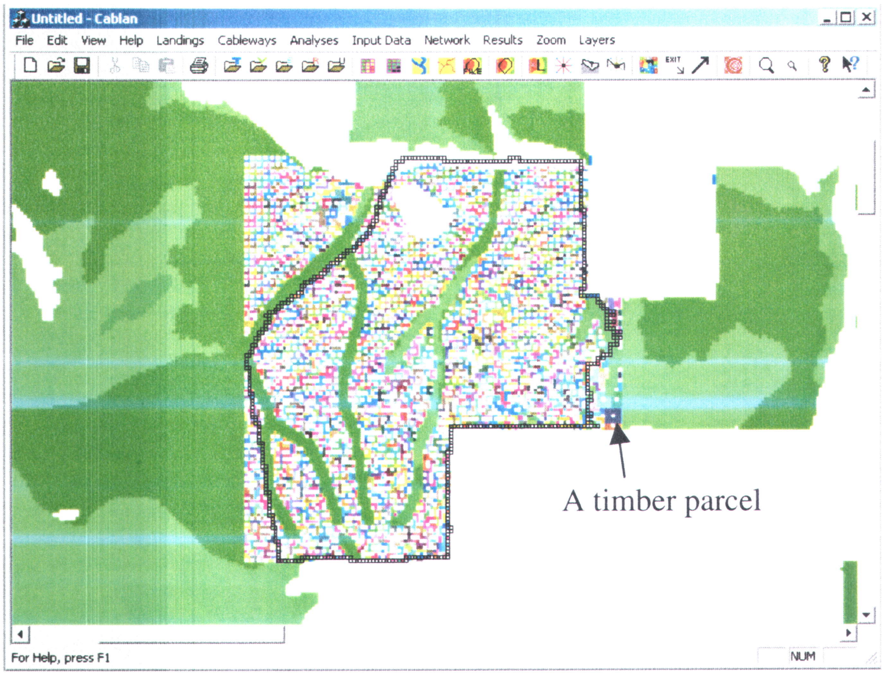


Figure 34. Identifying timber parcel locations.

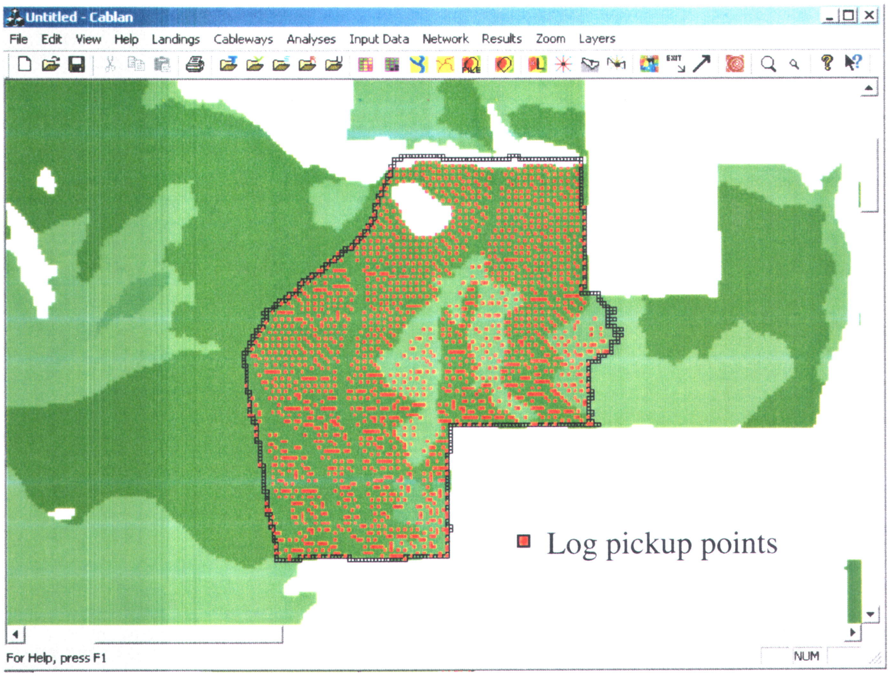


Figure 35. Locations of log pick up points.

YARDING SYSTEM ALTERNATIVES

Two yarding systems were considered in this application:

1. Koller K-300 trailer-mount three drum yarder
    - Koller carriage (SK1)
    - Kubota M110 4WD tractor
    - John Deer 540G skidder
2. Madill-6150
    - ACME 15 slack pulling carriage
    - Madill 2800 loader
    - Cat 322C monoboom stroke delimber

These systems were selected for the purpose of comparing two yarding systems. The Koller K-300 is classified as a small sized yarder which has shorter skyline length and less payload capacity, while the Madill-6150 is classified as a medium sized yarder equipped with a relatively higher tower. The Koller K-300 has been operated by the OSU student logging crew and is usually used for thinning operations on the McDonald-Dunn OSU Research Forest. The Madill-6150 has also been used for timber harvesting in the Research Forest by several logging contractors. In this application, both yarders were analyzed on an uphill standing skyline configuration. The specifications of both yarder systems required for the logging feasibility analysis are presented in Table 4.

Table 4. Cable equipment specifications.

Items		Madill-6150	Koller K-300
Maximum external yarding distance		600 m (2000 ft)	300 m (1000 ft)
Maximum lateral yarding distance		50 m (150 ft)	30 m (100 ft)
Tower height		15 m (50 ft)	7 m (23 ft)
Intermediate tree height		12 m (40 ft)	8 m (26 ft)
Tailspar tree height		12 m (40 ft)	12 m (40 ft)
Maximum tailspar tree height		15 m (50 ft)	15 m (50 ft)
Skyline	Diameter	22.2 mm (0.875 in.)	14.3 mm (0.625 in.)
	Maximum allowable tension	12,000 kg (26,450 lbs)	5,000 kg (11,200 lbs)
	Unit weight	2.1 kg/m (1.4 lb/ft)	0.9 kg/m (0.72 lb/ft)
Mainline	Diameter	15.9 mm (0.625 in.)	9.5 mm (0.375 in)
	Maximum allowable tension	6,200 kg (13,650 lbs)	2,200 kg (4,850 lbs)
	Unit weight	1.1 kg/m (0.72 lb/ft)	0.4 kg/m (0.26 lb/ft)
Carriage depth		1 m (3 ft)	0.7 m (2 ft)
Carriage weight		750 kg (1,650 lbs)	150 kg (330 lbs)
Yarder engine power		230 hp	65 hp
Engine efficiency		0.65	0.65
Design payload for one turn		2,500 kg (5,500 lbs)	1,000 kg (2,200 lbs)
Maximum allowable payload		7,500kg (16,500 lbs)	3,000 kg (6,600 lbs)
Wood density		700 kg/m^3	700 kg/m^3
Effective choker length		3 m (10 ft)	2.5 m (8 ft)

Design payload is used as a minimum load requirement for one turn, while the maximum allowable payload is the maximum load for one turn that the carriage is allowed to carry along the cable road. Thus, the load for a turn will fall in between the design payload and the maximum allowable payload by the load building simulator. Wood density is used for converting timber volume to timber weight. Effective choker length is used for measuring log clearance for full suspension or log-to-ground angle in partial suspension.

Information required for estimating cycle time of a turn of logs (Table 5) was obtained from personal communications with individuals who have experience with the yarding equipment and its operations (Starnes 2002, Edwards 2002, Stringham 2002). The information was compared with the field study conducted by Dykstra (1976b), although the comparison may not be appropriate since the data were collected from a different site with a different yarding system (a Skagit GT-3 running skyline grapple yarder was used in Dykstra's field study (1976b)). The mean value of each time component observed by Dykstra (1976b) is presented in Table 6. Hook and unhook time per unit volume is calculated by dividing the mean value of the time component by the average turn volume (1.78 m^3). To calculate average lateral yarding speed, the average lateral yarding distance (6.19 m) is divided by the average time consumed for lateral inhaul and outhaul (0.5 min). The average inhaul and outhaul speeds are calculated by dividing the average slope yarding distance (83.2 m) by the average time consumed for inhaul and outhaul. Except for the estimate of hook time, the comparisons (Tables 5-6) show that the estimates of most time elements in this application are similar to those in Dykstra's field study (1976b).

Table 5. Information for cycle time estimation in the application.

Time components		Madill-6150	Koller K-300
Hook time		0.5 min/m^3	0.5 min/m^3
Unhook time		0.17 min/m^3	0.17 min/m^3
Lateral yarding speed		20 m/min	10 m/min
Multipliers for lateral yarding time	0-1/3 of LYD	1.0	1.0
	1/3-2/3 of LYD	1.5	1.5
	2/3-3/3 of LYD	2.0	2.0
	Beyond LYD	10.0	10.0
Maximum inhaul speed	Partial suspension	180 m/min	60 m/ min
	Full suspension	240 m/min	120 m/ min
Average outhaul speed		300 m/min	180 m/min

Table 6. Mean value of each yarding time component in Dykstra's field study (1976b).

Time components	Skagit GT-3 yarder in a partial cutting area
Hook time	0.34 min/m^3
Unhook time	0.17 min/m^3
Lateral yarding speed	12.4 m/min
Inhaul speed	104 m/min
Outhaul speed	208 m/min

In this application, the hourly yarding system costs for the Koller K-300 and the Madill-6150 were estimated \$160.70 and \$464.21 respectively (Tables 7-8). It is assumed that the Koller K-300 is operated by the OSU student logging crew whose labor cost is lower than regular workers. Student labor is calculated based on \$15.4/hour including 40% benefits. For the same reason, rigging cost for intermediate supports with the Koller K-300 yarding system is lower than that with the Madill-6150 system (Table 9). Felling cost is also lower with the Koller K-300 system than that with the Madill-6150 system, but felling cost for the Koller K-300 system includes delimbing and bucking cost at the stump, while felling cost for the Madill-6150 excludes delimbing and bucking which is done at the landing. Except for the Koller K-300, initial costs of other equipment used in the analysis were derived from LOGCOST4.0 (USDA Forest Service 2002). LOGCOST is a software program to calculate stump-to-truck costs for various logging systems. Initial cost for the Koller K-300 was from the fiscal year 2000 cost guide for appraisal developed by Forest Service (USDA Forest Service 2000).

Table 7. Calculation of Koller K-300 hourly yarding system costs.

Items		Yarder	Tractor	Skidder
Model		Koller K-300	Kubota M110 4WD	John Deer 540G
Machine costs	Initial costs	$106,000	$48,000	$160,000
	Salvage %	20%	20%	30%
	Salvage value	$21,200	$9,600	$48,000
	Depreciation period in years	8	8	7
	Scheduled hours per year	1,600	1,600	1,600
	Utilized hours per year	1,600	1,600	1,600
	Average annual investment	$68,900	$31,200	$112,000
	Depreciation per year	$10,600	$4,800	$16,000
	T.I.I [1)](%)	9.5%	9.5%	9.5%
	T.I.I. per year [2)]	$6,546	$2,964	$10,640
	Total hourly owning costs [3)]	$10.72	$4.85	$20.49
	Tire initial cost	-	$2,000	$10,000
	Estimated life in hours	-	3,000	3,000

Table 7 (continued)

	Tire cost per hour	-	$0.67	$3.33
	Price of fuel per gallon	$1.45	$1.45	$1.45
	Fuel consumption (gal/hr)[4]	0	4.04[5]	4.63[6]
	Fuel cost per hour	$0.00	$5.86	$6.71
	Lubricant cost per hour[7]	$0.00	$0.41	$0.47
	% of depreciation for repair and maintenance.	50%	50%	50%
	Hourly costs for repair and maintenance[8]	$5.36	$2.43	$10.25
	Total operating costs	$5.36	$9.36	$20.76
	Total owning and operating costs	$16.07	$14.21	$41.26
	Sub total	$71.54		
Misc.	Wire rope and rigging material costs ($/hr)	$5.00		
	Radio hourly costs	$2.16		
	Crew vehicle hourly costs	$5.00		
	Sub total	$12.16		
Labor[9]	Five student crew	$77.00		
	Sub total	$77.00		
Total system costs per hour		$160.70		

[1] taxes, insurance, and interest in percentage

[2] T.I.I. per year = average annual investment × T.I.I. percentage

[3] total hourly owning costs = (depreciation per year + T.I.I. per year) / operating hour per year

[4] (0.4 × engine efficiency × engine horsepower) / 7.08

[5] engine horsepower of 110 and engine efficiency of 65% were used

[6] engine horsepower of 126 and engine efficiency of 65% were used

[7] 7% of fuel costs

[8] total hourly owning costs × percentage of depreciation

[9] labor costs include 40% fringe benefits

Table 8. Calculation of Madill-6150 hourly yarding system costs.

Items		Yarder	Carriage	Loader	Delimber
Model		Madill-6150	Acme 15	Madill 2800	Cat 322C monoboom
Machine costs	Initial costs	$400,000	$39,500	$315,000	$468,000
	Salvage %	20%	10%	20%	30%
	Salvage value	$80,000	$3,950	$63,000	$140,400
	Depreciation period in years	8	4	8	7
	Scheduled hours per year	1,600	1,600	1,600	1,530
	Utilized hours per year	1,600	1,600	1,600	1,300
	Average annual investment	$260,000	$26,169	$204,750	$327,600
	Depreciation per year	$40,000	$8,888	$31,500	$46,800
	T.I.I (%)	9.5%	9.5%	9.5%	9.5%
	T.I.I. per year	$24,700	$2,486	$19,451	$31,122
	Total hourly owning costs	$40.44	$7.11	$31.84	$59.94
	Price of fuel per gallon	$1.45	$1.45	$1.45	$1.45
	Fuel consumption (gal/hr)	9.36	0.61	8.45	7.08
	Fuel cost per hour	$13.57	$0.88	$12.25	$10.27
	Lubricant cost per hr.	$0.95	$0.06	$0.86	$0.72
	% of depreciation for repair and maintenance.	50%	50%	50%	50%
	Hourly costs for repair and maintenance	$20.22	$3.55	$15.92	$29.97
	Total operating costs	$34.74	$4.50	$29.03	$40.95
	Total owning and operating costs	$75.18	$11.61	$60.88	$100.89
	Sub total	$248.56			
Misc.	Wire rope and rigging material costs ($/hr)	$5.00			
	Radio hourly costs	$2.16			
	Crew vehicle hourly costs	$5.00			
	Sub total	$12.16			

Table 8 (Continued)

Labor	Yarder engineer	$26.45
	One loader operator	$27.12
	One delimber operator	$27.19
	One chaser	$23.72
	Two choker setters	$45.47
	One rigging slinger	$25.52
	One hook tender	$28.03
	Sub total	$203.49
Total system costs per hour		$464.21

Other operating costs for the yarding systems used in this application are presented in Table 9. Yarder move-in costs include the costs for rigging down at previous location and moving yarding system to new location. The costs were estimated by the OSU Research Forest staff (Starnes 2002, Edwards 2002). The move-in costs for the Madill-6150 include one hour rigging down and lowboy rental costs to move the system. The move-in costs for the Koller K-300 is estimated based on one hour rigging down time and the labor costs for 5 people with two hours. Yarding installation cost is not included in yarder move-in costs but is separately estimated using hours required for the equipment installation.

The size of logs is assumed to be homogeneous over the planning area. Logs have a cylindrical shape with length of 12m and diameter of 0.3m (Table 10). The log-to-ground angle is the minimum angle between log and the ground while the log drags along the ground.

Table 9. Other operating costs.

Items	Madill-6150	Koller K-300
Rigging costs ($/tree)	$200/tree	$60/tree
Felling costs	$3.5/m^3	$3.5/m^{3*}
Yarding system hourly costs ($/hr) (yarding and loading to truck)	$465/hour	$160/hour
Delay percentage of total yarding time	20%	20%
Yarder move-in costs ($)	$1,500	$310
Initial yarder set up hour (hr)	4 hours	1 hour
Skyline road change hour (hr)	1 hour	1 hour

*Felling cost for the Koller K-300 system includes delimbing cost.

Table 10. Log information.

Items	Value
Log length	12 m (36 ft)
Log diameter	0.3 m (10 ft)
Log-to-ground angle	10 degrees
Log-to-ground friction coefficient	0.6

The parameters required for the automated method to place intermediate supports along a cable road are skyline clearance, skyline deflection, maximum allowable chord slope change, and maximum number of intermediate supports. The definitions and the usage of these parameters were described in the previous chapter (Figure 9). The maximum number of intermediate supports along a cable road was limited to 2 in this application (Table 11).

Table 11. User defined parameters for locating intermediate supports.

Items	Parameters
Skyline clearance from the ground	6 m (18 ft)
Skyline deflection	7 %
Maximum allowable chord slope change	45 degree*
Maximum number of INT supports	2

*Chord slope change of 45 degrees in this example may not be appropriate in practices. The maximum allowable chord slope change usually used in practices is about 45% (Kellogg 2002).

Landing costs were also estimated by the OSU Research Forest staff (Starnes 2002, Edwards 2002). Landings are assumed to be located along forest roads. Building a new landing is assumed to cost approximately $5,000 for leveling the ground and putting gravel on the surface. If landings on existing roads are used, the cost drops to $1,000 (Table 12).

Table 12. Landing cost.

Items	Costs
New landings	$5,000
Landings on existing roads	$1,000

Transportation costs include hauling and road construction costs. The road construction cost used in this application is $30,000/km (Table 13). All access roads to be built are assumed to be single lane roads with gravel surface. The standard road cost was estimated from the average cost of new road construction in three timber sales in the OSU Research Forests (Edwards 2002). In order to adjust road costs affected by ground slope, the user-defined multipliers are applied to the standard road cost. This application assumes the standard road cost is calculated from an area where the average ground slope in the direction of road is 5% - 10% and the average side slope is 30%-45%. If a road segment passes an area with different ground slope from the standard, multipliers will be applied to adjust road costs (Table 13). In addition, for the purpose of reducing the excessive earthwork and environmental impacts, road building is not allowed if either the ground slope in the direction of road is greater than 30% or side slope is greater than 90%. When a candidate road segment passes across any of stream buffers, the stream crossing multiplier (Table 13) is applied to the standard road cost to reflect cost increase resulted from constructing bridges or placing culverts. These user-defined multipliers can be used to estimate road costs as well as to penalize candidate road segments that are located on undesirable areas by increasing road costs.

The hauling costs per unit volume per unit distance, $0.08/m^3-km, was estimated from the average hauling costs for the timber sales in the OSU Research Forests (Edwards 2002).

In this application, mill locations were not specified. Instead, any grid cells on the existing roads around the harvesting area were set as the potential destinations for timber exits. Since the mill is not the final destination, the unloading cost at the mill is not included in the total harvesting costs in this application.

Table 13. Transportation cost.

Items		Costs
Construction cost		$30,000/km
Multipliers	Ground slope in the direction of road	
	0% - 5%	0.9
	5% - 10%	1.0
	10% - 15%	1.5
	15% - 20%	2.5
	20% - 25%	5.0
	25% - 30%	10.0
Multipliers	Ground side slope	
	0% - 15%	0.8
	15% - 30%	0.9
	30% - 45%	1.0
	45% - 60%	1.5
	60% - 75%	2.5
	75% - 90%	5.0
Limit ground slope in the direction of road		30 %
Limit ground side slope		90 %
Multiplier for stream crossing road segments		3.0
Hauling cost		$0.08/m^3-km
Timber exit		Any point on existing roads

LANDING LOCATIONS

Since it is difficult for the users to designate an exact tower location on the DTM, a semi-automated method was developed to help the users place landings over the planning area. Using the contour lines that the model provides, the users first identify an area (a group of grid cells) in which landings would most likely fit. Then, the computer program implementing the semi-automated method identifies all grid cells within the area and projects 36 cable roads from each grid cell (candidate tower location). The program conducts the logging feasibility analysis to identify feasible cable roads. The total area to be covered by the feasible cable roads projected from each grid cell (candidate tower location) is measured and the one grid cell covering the largest area is selected as the "best" tower location from the candidate group the user identified.

For the application, a total of 40 candidate landing areas were selected over the planning area. Then, the semi-automated method found the "best" grid cell for tower location in each landing area. The selected tower locations are assumed to represent landing locations as well as ending points of access road in this application (Figure 36).

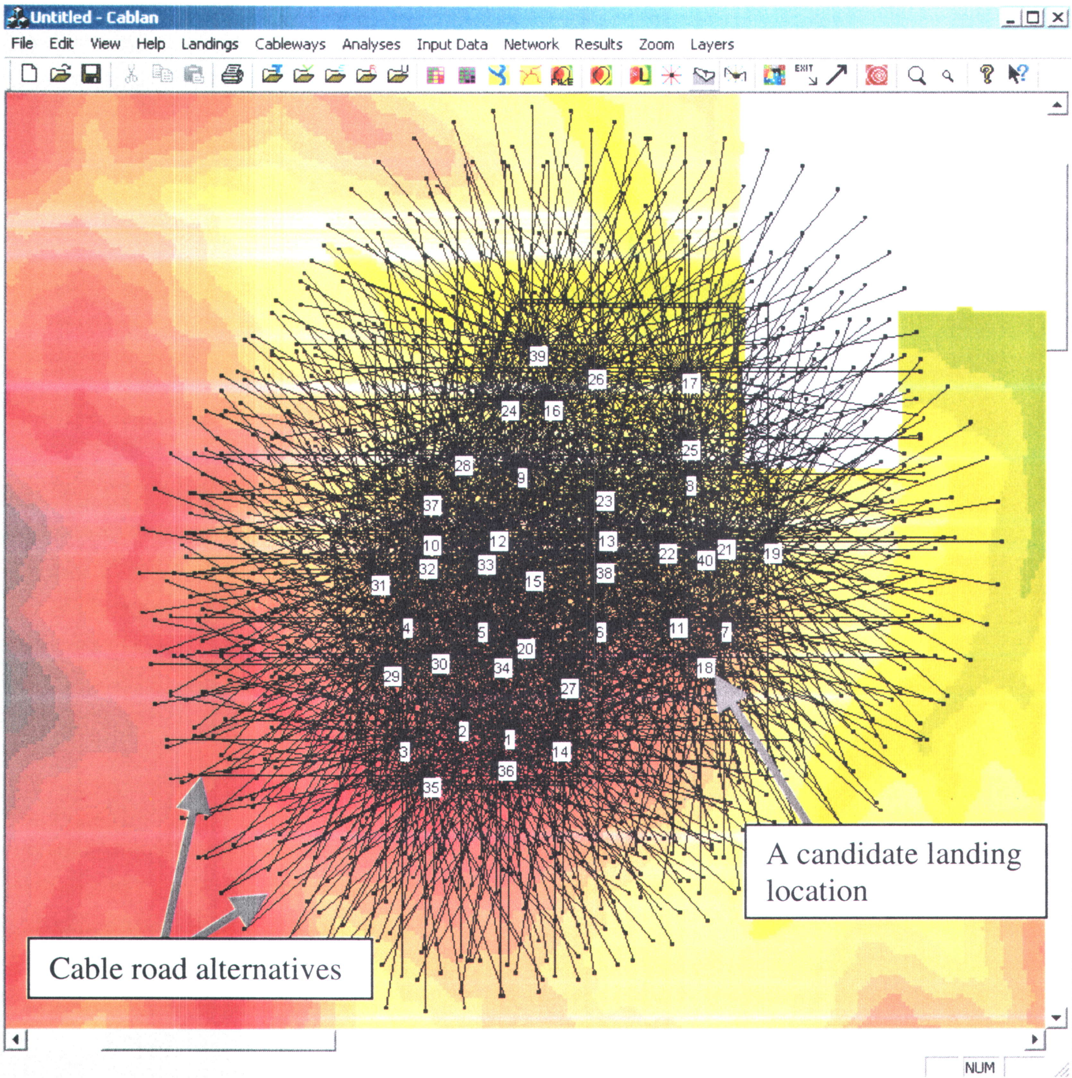


Figure 36. The 40 candidate landing locations and 36 cable road alternatives projected from each candidate landing with the Madill-6150.

LOGGING FEASIBILITY AND COST ANALYSIS

Thirty-six cable road alternatives were projected from each candidate landing location with a ten-degree interval (Figure 36). The user-defined maximum skyline length was used to set an initial cable road length. The logging feasibility analysis module of the computerized model conducted the ground profile analysis on each cable road alternative to identify the feasible cable road length, locate intermediate supports if necessary, and determine the tailspar height (Figure 37). Cable road length in this application is defined as a horizontal distance between the tower and the tailspar.

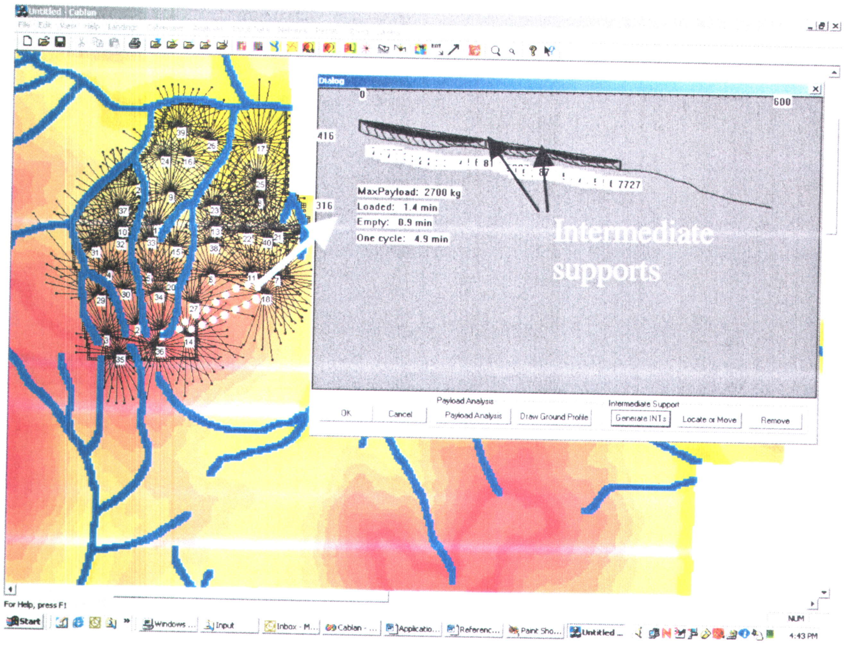
Among total 1,440 cable roads with the Madill-6150 yarding system tested, the analysis proved 959 cable roads to be physically feasible with the appropriate cable road lengths (Figure 38(a)). If the horizontal distance of a cable road length is shorter than 50 m, the cable road is assumed to be infeasible in this application.

Although the yarding system is able to reach up to 600m in horizontal distance from the tower location, no feasible cable road with 400m or longer was found (Table 14). The average horizontal length of 959 cable roads is 164 m.

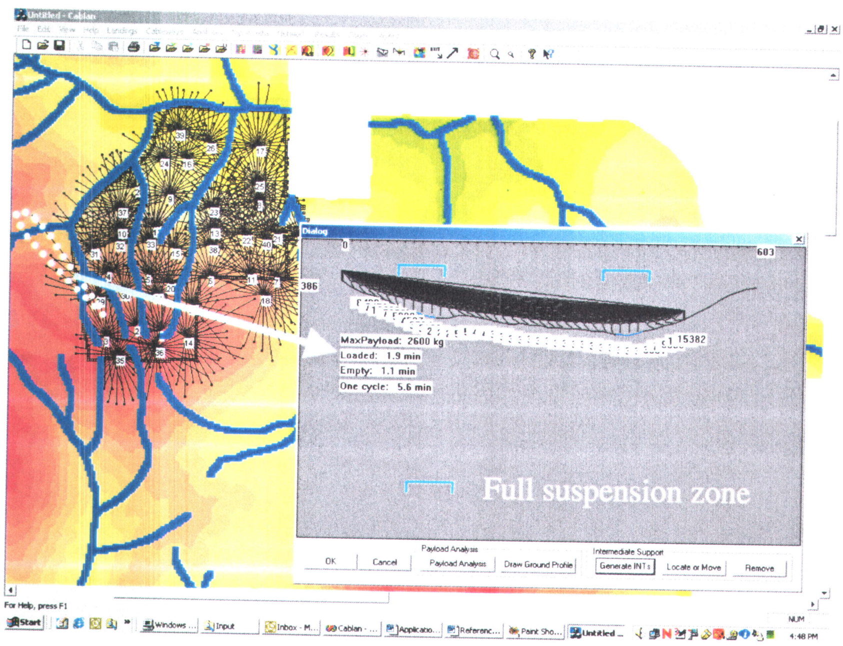
The logging feasibility analysis was also conducted without the full suspension requirement over stream buffers to show the impacts of the full suspension requirement on the logging feasibility of cable roads (Figure 38(b)). More feasible cable roads were found and the average of cable road length was higher when the requirement was not considered (Table 14).

Table 14. Distribution of the feasible cable road length.

Cable road length categories	The number of cable roads	
	With the full suspension requirement	Without the full suspension requirement
60m-100m	265	87
101m-200m	424	427
201m-300m	235	450
301m-400m	35	78
401m-500m	0	5
501m-600m	0	4
Total	959	1,051
Average length	164 m	209 m

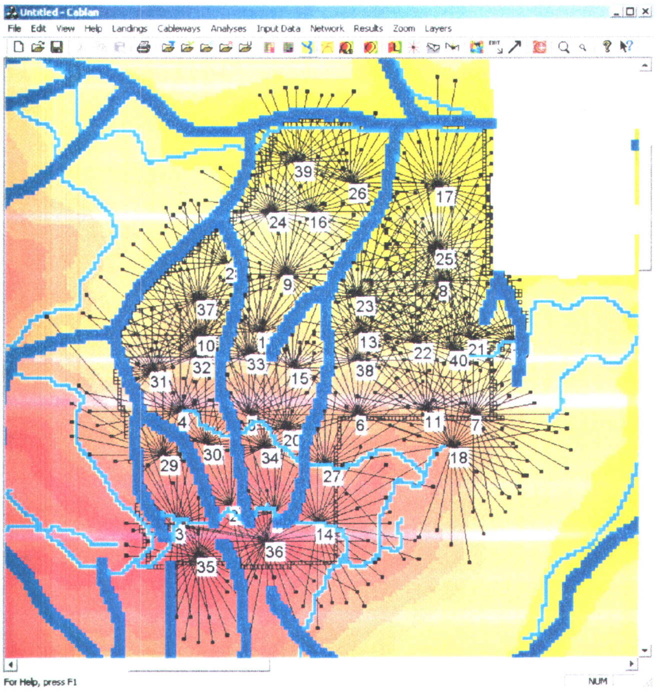


(a) Two intermediate supports were located by the computerized model.

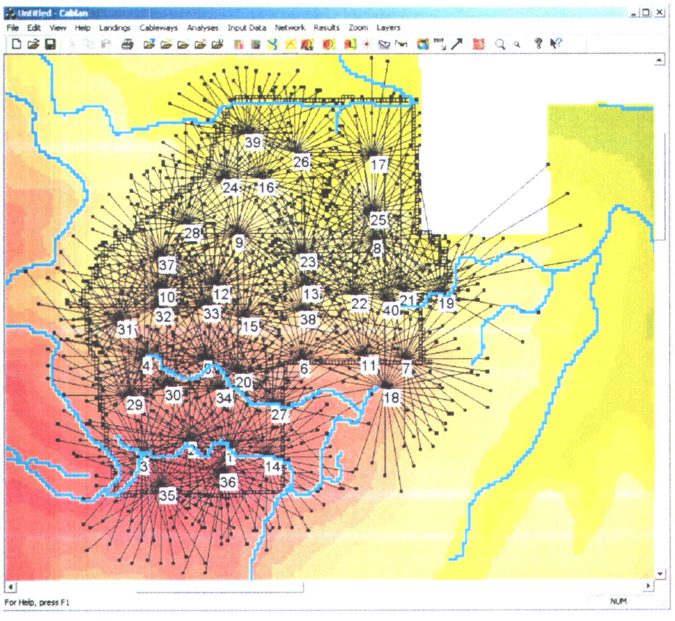


(b) The profile analysis for a cable road passing across a stream buffer.

Figure 37. Ground profile analysis examples for selected cable roads.



(a) with the full suspension requirement over the stream buffers



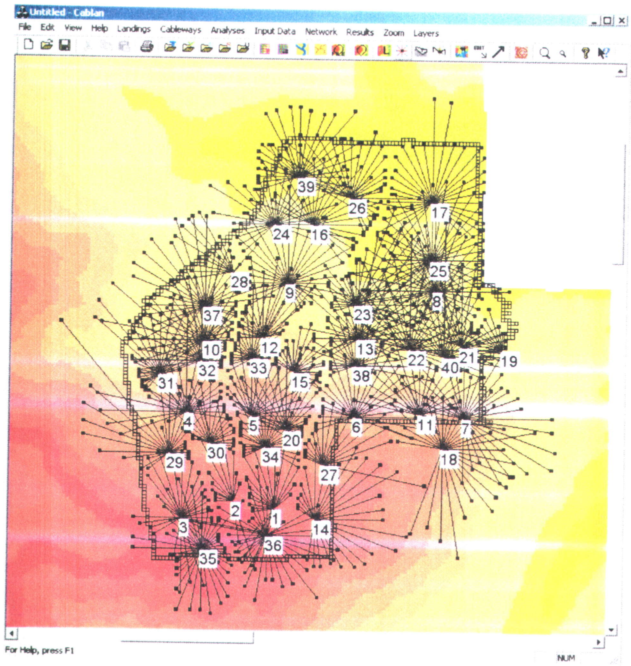
(b) without the full suspension requirement over the stream buffers

Figure 38. Feasible cable road alternatives with the Madill-6150 yarding system.

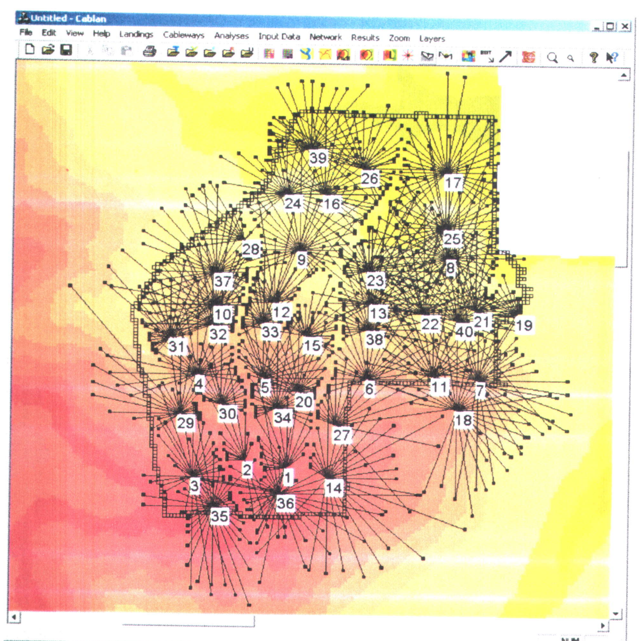
The maximum allowable number of intermediate supports also affects the feasibility of cable roads. Figure 39 illustrates the feasible cable roads when a different number of intermediate supports were allowed. The average length of feasible cable roads when three intermediate supports were allowed (Figure 39 (b)) is longer than that when only one intermediate support was allowed (Figure 39 (a)), but is not very different from the average length when two intermediate supports were allowed (Table 15). The results imply that not only the number of intermediate supports governs the logging feasibility of cable roads, but also other factors such as difficult terrain conditions or full suspension requirement affects the feasibility of cable roads.

A total of 951 cable roads were feasible when one intermediate support was allowed. Among them, 504 intermediate supports required one intermediate support (Table 16). Eight and thirteen additional cable roads became feasible when two and three intermediate supports were allowed, respectively.

Placing more intermediate supports might increase the rigging costs and difficulties in yarding operations, but it might lengthen the yarding distance, make infeasible cable roads feasible, or increase payload capability, which may result in eliminating additional road constructions or reducing number of trips of logs. The trade-offs should be analyzed and considered in the cable logging layout design for reducing total yarding costs and enhancing operational efficiency in specified terrain conditions.



(a) when one intermediate support is allowed



(b) when three intermediate supports are allowed

Figure 39. Feasible cable road alternatives with the Madill-6150 yarding system when a different number of intermediate supports are allowed.

Table 15. The average length of the feasible cable roads when the maximum number of intermediate supports is varied (when the Madill-6150 yarding system is used)

Maximum allowable number of intermediate supports	1	2	3
Average cable road length*	153 m	164 m	167 m
Total number of feasible cable roads	951	959	964

*Cable road length is defined as the horizontal distance from the tower location to the tailspar.

Table 16. Distribution of feasible cable roads with respect to the number of intermediate supports required (when the Madill-6150 yarding system is used).

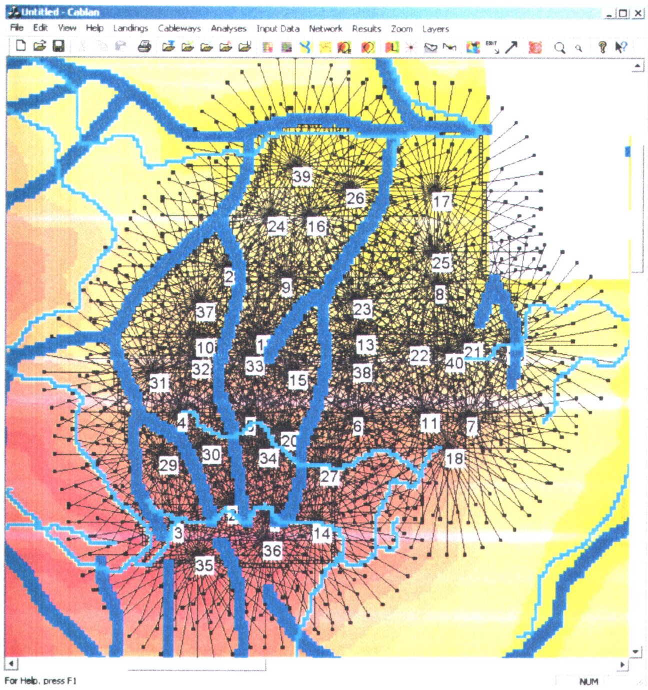
Number of intermediate supports required	Number of cable roads		
	When one intermediate support is allowed	When two intermediate supports are allowed	When three intermediate supports are allowed
0	447	446	446
1	504	317	317
2	0	196	148
3	0	0	53
Total	951	959	964

The Koller K-300 yarding system was also applied to the same landing locations (Figure 40(a)). After the logging feasibility analysis was conducted using the specifications of the yarding system (Table 4), a total 760 feasible cable roads were identified with the appropriate cable road length among 1,440 cable road candidates (Figure 40(b)). Since the Koller K-300 yarding system has a shorter skyline length and less load carrying capacity than the Madill-6150, the results show that the total number of feasible cable roads is less and the average cable road length is shorter than those with the Madill-6150 (Table17).

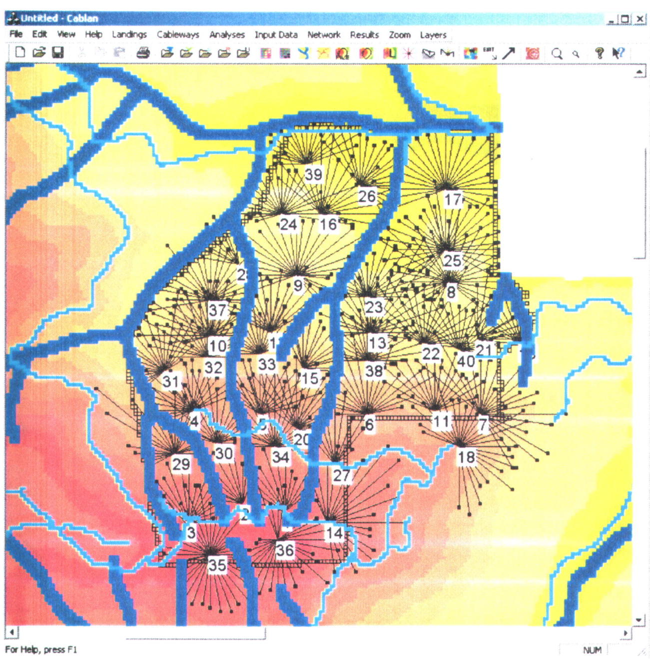
Table 17. The average length of the feasible cable roads with the Koller K-300 yarding system.

Average cable road length	130 m
Total number of feasible cable roads	760

The cost analysis program in the computerized model estimates cycle time required to move logs from the pickup point to the landing through possible alternative paths. The logging feasibility analysis program determined the maximum load capacity that can be loaded at each terrain point along a cable road for this application. Slope yarding distance of each alternative yarding path was determined by the locations of log pickup point and landing on the DTM. The cost analysis program uses the maximum load capacity and the slope yarding distance to estimate a cycle time for a given log pickup point. The details on how to estimate yarding cycle time were presented in the previous chapter.



(a) Cable road alternatives before the logging feasibility analysis is conducted.



(b) Feasible cable road alternatives found by the logging feasibility analysis

Figure 40. Cable road alternatives with the Koller K-300 yarding system.

As an example, the yarding cycle time estimated in this application for each of the 29 feasible cable roads at landing 17 with the Madill-6150 yarding system (Figure 37 (a)) is shown in Table 18. For the estimates, the log pickup point was assumed to be located at 2/3 of the chord length from the tower location and directly under the skyline. Thus, no lateral yarding was included in the cycle time. Since hook, unhook, and inhaul time are a function of log weight/volume in the turn, yarding cycle time is highly associated with log weight/volume in the turn (Figure 41).

Table 18. Estimates of cycle time for feasible cable roads at landing 17 with the Madill-6150.

Cable road no.	Slope yarding distance (m)	Log load (kg)	Cycle time (min)	Cable road no.	Slope yarding distance (m)	Log load (kg)	Cycle time (min)
1	203	2,500	4.2	16	142	6,100	7.1
2	199	2,500	4.2	17	125	7,500	8.3
3	127	3,100	4.1	18	125	2,850	3.8
4	129	4,600	5.5	19	102	2,500	3.3
5	145	3,800	4.9	20	91	3,700	4.3
6	137	6,000	7.0	21	90	5,100	5.7
7	119	2,850	3.8	22	84	4,800	5.3
8	110	2,550	3.4	23	89	5,900	6.5
9	104	4,250	5.0	24	96	4,000	4.7
10	96	4,100	4.8	25	100	5,800	6.5
11	97	3,100	3.8	26	118	6,050	6.8
12	109	2,600	3.5	27	128	4,000	4.9
13	154	3,000	4.2	28	118	2,950	3.9
14	107	7,250	7.9	29	121	5,150	6.0
15	81	7,500	7.9	Average	119	4,348	5.2

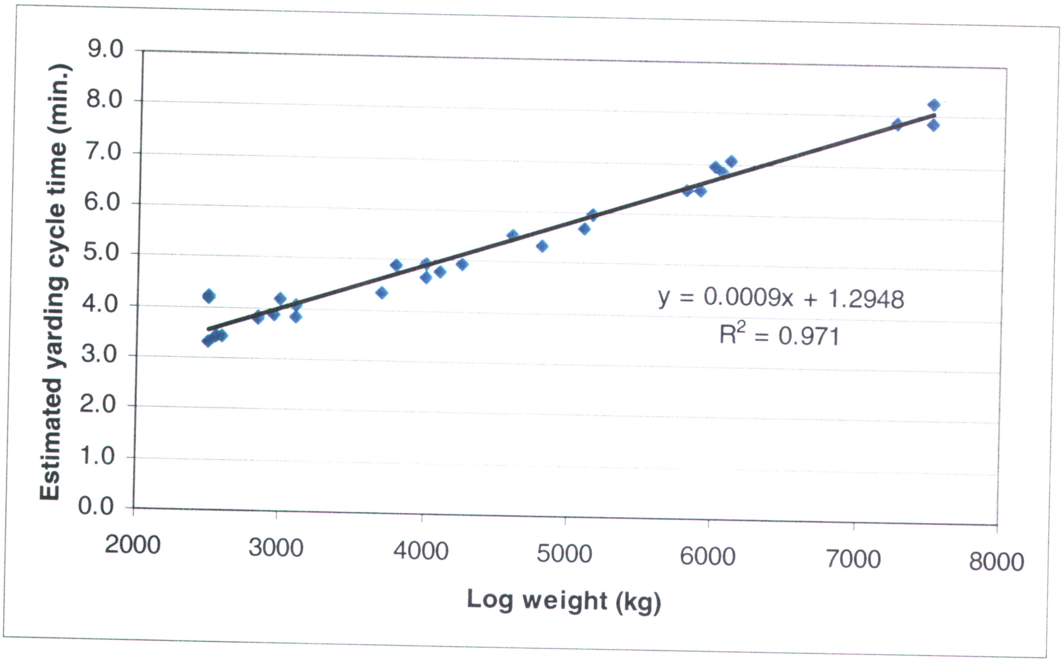


Figure 41. Scatter plot showing the relationship between log weight and yarding cycle time estimates for 29 feasible cable roads at landing 17 with the Madill-6150 yarding system. Yarding cycle time estimates do not include lateral yarding time.

The number of timber parcels that one cable road could cover is a function of cable road length and the lateral yarding capability of the individual yarding system. For this application, a total of 139,819 yarding path alternatives from 1,719 feasible cable roads, 2 yarding systems, and 40 candidate landings were evaluated for the 1,926 timber parcels on this planning area. Thus, each parcel could be yarded, on the average, by means of 73 different cable roads.

Total computer time for the feasibility and cost analysis was 3.42 hours on a Pentium III processor with 1GHz speed desktop computer. During the analysis, a total of 226,187 ground profile/intermediate support rigging combinations were conducted to identify 1,719 feasible cable roads with the appropriate cable road lengths, intermediate support locations, and tailspar height.

ASSEMBLING A NETWORK

The network assembling program in the computerized model generates two sets of networks. One is a network for cable logging alternatives and the other is for road location alternatives. Because of its size (total 9.8 Mbytes text file), the complete link and sale data for this application is not included here, but is briefly summarized:

A total of 141,139 links and 1,926 timber parcels were developed in the network problem for cable logging paths. The link data include 139,819 links representing alternative yarding paths with associated yarding costs, 1,200 links representing cable road changes and intermediate support rigging costs, 80 links representing yarding system move-in and initial setup costs, and 40 links connecting landing alternatives to a temporary destination with the associated landing construction costs (Figure 20). The load building simulator in the computerized model identified 1,926 timber parcels insuring the design payload for the Madill-6150, which is 2,500 kg. Each of 1,926 timber parcels became an individual origin and the destination could be one of the landing candidates.

In the network for solving road location problem, a total of 95,904 links were developed to connect 13,522 grid cells included in the planning area and its surrounded area. A link connecting two adjacent grid cells in the network represents the associated road construction and hauling costs between two cells. There are 498 grid cells on the existing roads that are used as the actual destinations in the network. Since the network algorithm allows only one destination, all existing road cells are connected to a "final" destination node. The number of origins in the road network problem varies depending on the number of selected landings, which is determined by solving the cable logging path network problem.

FINAL RESULTS OF THE APPLICATION

To harvest 8,064 m^3 of logs from 1,926 timber parcels in this application, a total of 19 landings were selected out of 40 alternatives and a total of 155 cable roads were selected among 1,719 feasible alternatives considered (Figure 42). As few as 2 and as many as 15 cable roads were emplaced in one landing. As a portion of the computer output for the solution, total yarding and transportation costs for timber harvest in the planning area was \$388,451. The total harvesting costs including felling cost was estimated \$416,675 (\$51.67/m^3) (Table 19). Yarding costs here include yarding equipment and operating cost as variable costs and landing construction cost, equipment move-in cost, and cable road emplacement cost as fixed costs. Transportation costs include new road construction costs as fixed costs and hauling cost over the new roads as variable costs. Percentages of yarding costs, transportation costs, and felling costs from the total estimated harvesting costs are 68%, 25%, and 7%, respectively (Table 19).

Table 19. Total cost estimation for the solution.

Costs	Yarding costs	Transportation costs*
Variable costs	$110,602	$192
Fixed costs	$172,570	$105,087
Sub total	$283,172	$105,279
Felling costs*	$28,224**	
Total harvesting costs	$416,675	
Production cost	$51.67 / m^3 ($295 / mbf)	

*Costs do not include truck time during loading or unloading.
**$3.5/m^3 \times 8{,}064m^3 = $28,224

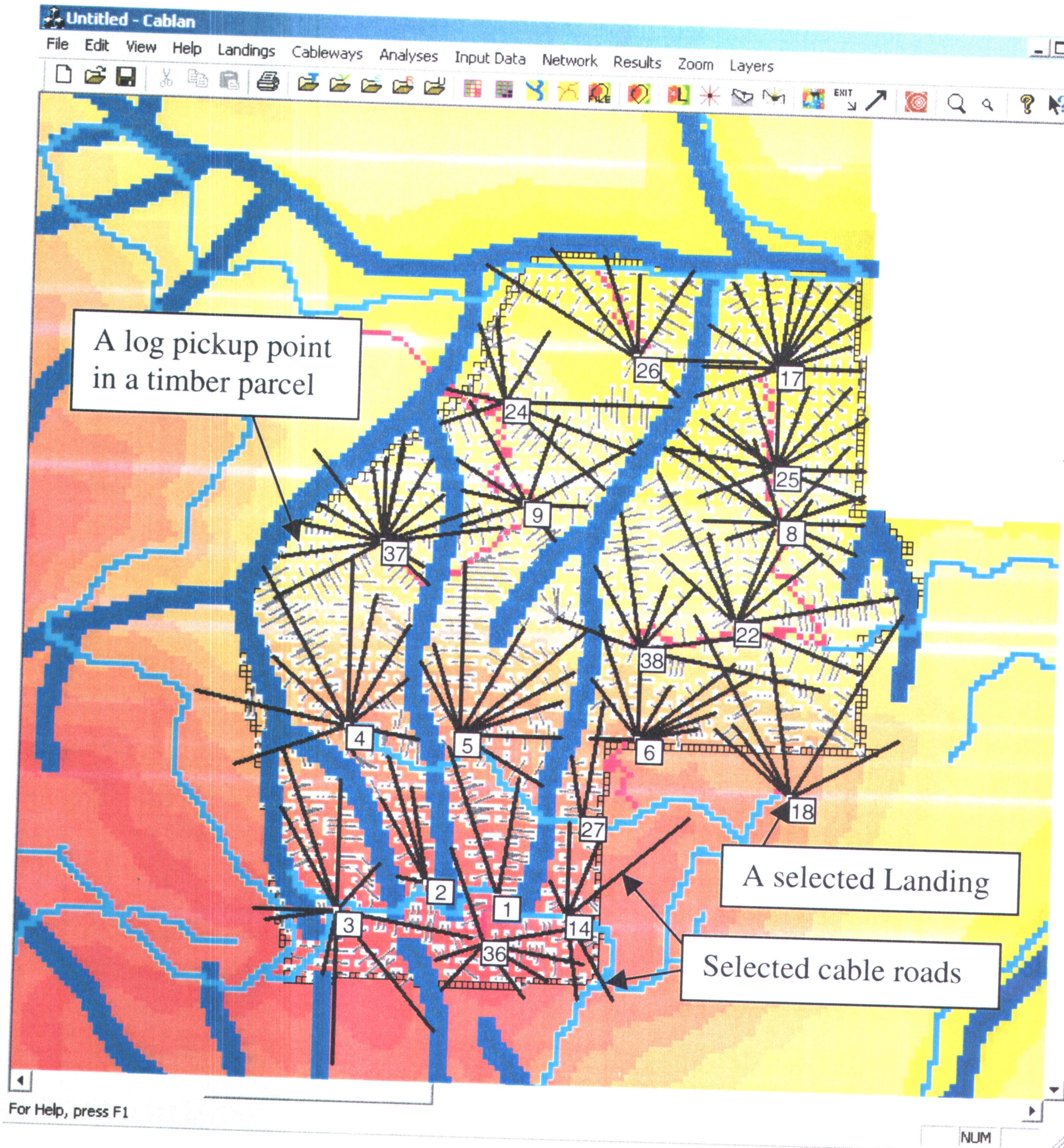


Figure 42. Landings and cable roads selected by the heuristic network algorithm for this application.

From these results, several important observations can be made:

1. Timber volume assigned to each landing varies from $105m^3$ to $776\ m^3$ (Table 20). Landing #4 where 11 cable roads were emplaced with both yarding systems is the largest landing collecting total $776\ m^3$ of logs. Landing #27 with 2 cable roads using the Koller K-300 is the smallest landing used for $105m^3$ of logs.
2. The Madill-6150 yarding system was used in 10 landings while 17 landings selected the Koller K-300 yarding system. Both yarding systems were used in 8 landings (Table 20). The Koller K-300 was used for 107 cable roads, while 48 cable roads used the Madill-6150. Except for landing #18, all landings where both yarding systems were used have cable roads that require a haulback line. The Madill-6150 system was introduced to the landings for such cable roads since the Koller K-300 does not have a haulback line. Although none of three cable roads at landing #18 requires a haulback line, the Madill-6150 system was used because the yarding system benefits from longer external yarding distance than the Koller K-300.
3. Four cases where the same skyline corridor was used by the both yarding systems in the solution were found. Since two different systems provided different external and lateral yarding distances, a shorter cable road with the Koller K-300 was used to yard logs close to the landing and a longer cable road with the Madill-6150 was used to yard logs that

cannot be reached by the shorter cable road. If the operating costs of large equipment to yard logs close to the landing overweighs the operating costs of small equipment plus its additional cable road emplacement cost, small equipment will be preferred. On the contrary, large equipment can be more economical for yarding logs far from the landing than small equipment since small equipment may require either extremely long lateral yarding operations or additional road construction. The user-defined maximum lateral yarding distance and the yarding cycle time multipliers to penalize extremely long lateral yarding distance should be considered if the case is not acceptable.

4. A total of 2.85 kilometers of new access roads were proposed as a part of the solution for this application (Figure 43). Most roads are located either on ridge top or along the contour lines since roads on steep ground slope cost more (Table 13) and were avoided when the cost minimization network problem was solved. New forest road segments in the solution were classified by ground slope categories (Table 21). Except for several road segments, most road segments were located on the gentle ground which has both ground slope in the direction of road and side slope is less than 15%. There were two stream-crossings by the proposed roads over the planning area (Figure 43).

Table 20. Cable roads, yarding system, and total timber volume to be harvested to each landing.

Landing ID Number	Number of cable roads		Number of timber parcels to be harvested to the landing	Total timber volume to be harvested to the landing (m^3)
	Madill-6150	Koller K-300		
1	2 (0)*	-	68	277
2	-	4	44	184
3	10 (5)	-	152	625
4	8 (4)	3	182	766
5	5 (1)	5	161	654
6	-	9	71	287
8	-	10	85	359
9	-	8	88	372
14	-	6	58	226
17	-	12	122	537
18	3 (0)	3	68	274
22	3 (1)	5	150	617
24	5 (3)	3	114	499
25	-	11	112	489
26	4 (3)	4	103	452
27	-	2	27	105
36	-	7	67	280
37	4 (3)	11	138	601
38	4 (2)	4	116	460
Total	155		1,926	8,064

*number in parenthesis is the number of cable roads requiring a haulback line.

Table 21. The length of road segments classified by ground slope.

Ground slope in the direction of road		Ground side slope	
Slope	Length (m)	Slope	Length (m)
0% - 5%	476	0% - 15%	2,782
5% - 10%	976	15% - 30%	65
10% - 15%	1,330	30% - 45%	0
15% - 20%	0	45% - 60%	0
20% - 25%	48	60% - 75%	0
25% - 30%	14	75% - 90%	0
Total	2,845	Total	2,845

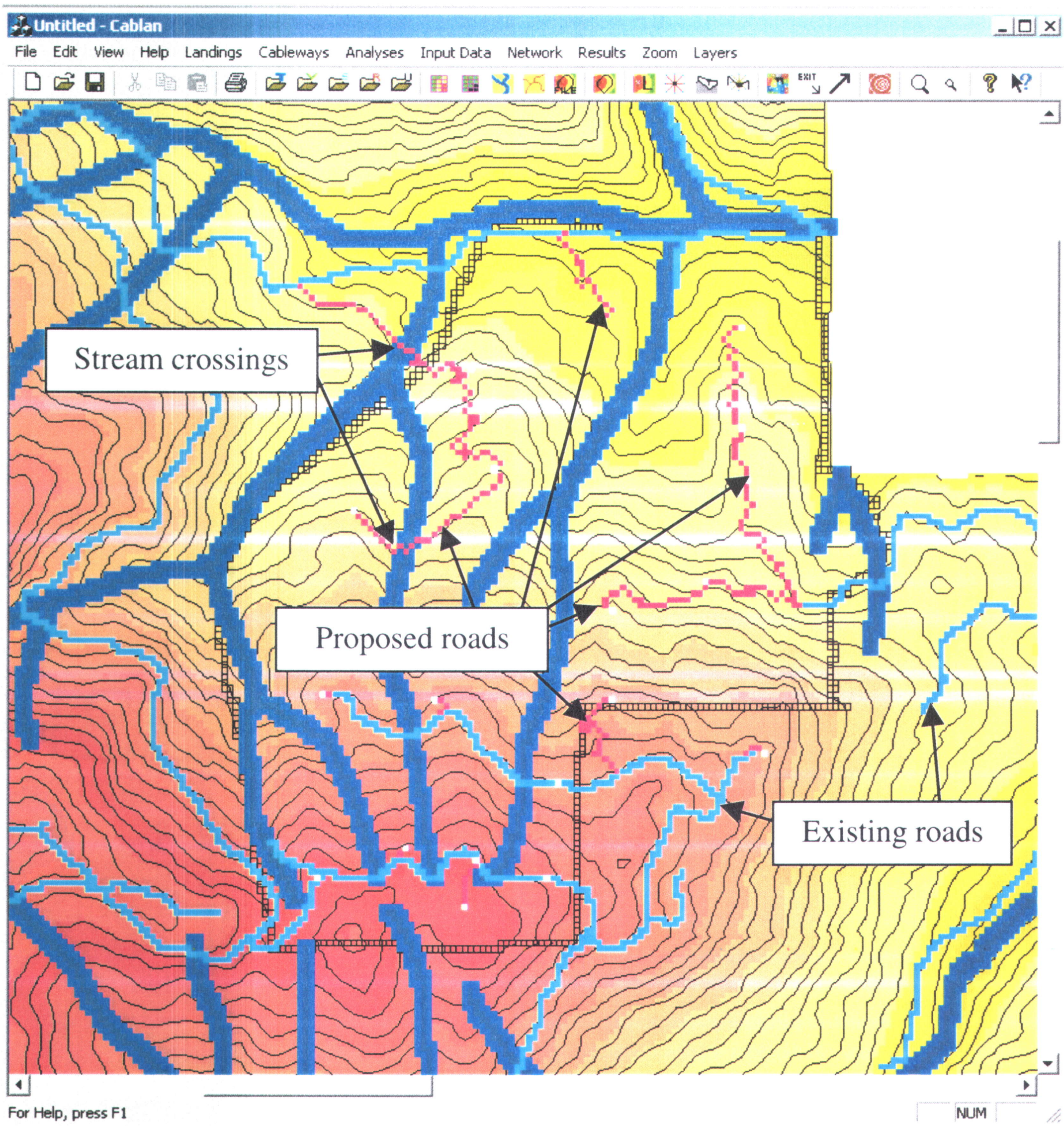


Figure 43. New access road locations on the DTM with 10 meter interval contour lines.

SENSITIVITY ANALYSIS

Different yarding equipment

Instead of applying two yarding systems at the same time, the choice was limited to using one yarding system or the other for the entire plan. Each case was solved by the heuristic network algorithm and the solutions were compared in Table 22.

Since the Koller K-300 yarding system has shorter external and lateral yarding distances (Table 4), the solution showed that the system required 30 landings and 206 cable roads to cover the whole planning area, while the Madill-6150 yarding system required only 17 landings and 90 cable roads. Although the Koller K-300 required many more landings and cable roads than the Madill-6150, the solutions showed both cases had similar yarding costs. Fixed yarding costs, in particular, are more or less the same in both cases (Table 22). This is because the yarder move-in cost, initial yarder setup, and cable road emplacement cost for the Koller K-300 is much less than those for the Madill-6150 (Table 23). The total landing construction costs with the Koller K-300, however, is much higher than the Madill-6150 because the cost increases with increasing number of selected landings regardless of the yarding system (Table 23).

Transportation costs including road construction cost from both cases were very different. The Koller K-300 required more landings, resulting in more road construction required to access to each landing from the existing roads. A total of 4.2 km of new access roads were proposed for the Koller K-300 system, whereas only 2.9 km of roads were proposed for the Madill-6150 system (Table 22).

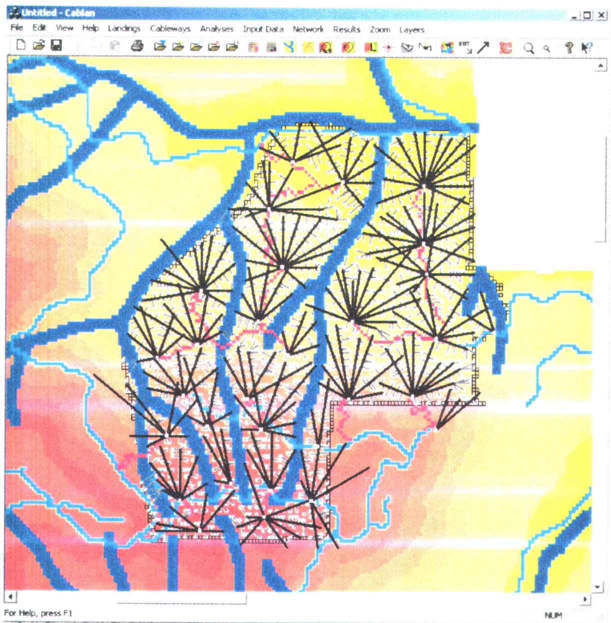
Due mainly to the landing and road construction costs, the results from this sensitivity analysis showed that skyline thinning operation with the Koller K-300 was higher than the Madill-6150, which is opposite to the results of the actual production study (Hochrein and Kellogg 1988) which did not include landing and road costs. If the landing and road costs were excluded from the results of this sensitivity analysis, the yarding costs for Koller K-300 and Madill-6150 would be \$179,242 (\$22.2/m^3) and \$222,481 (\$27.6/m^3), respectively, which shows that the yarding costs with the Madill-6150 is about 19% higher than the Koller K-300.

Table 22. Total cost estimation from the cases that only one of the two yarding systems was applied to the planning area.

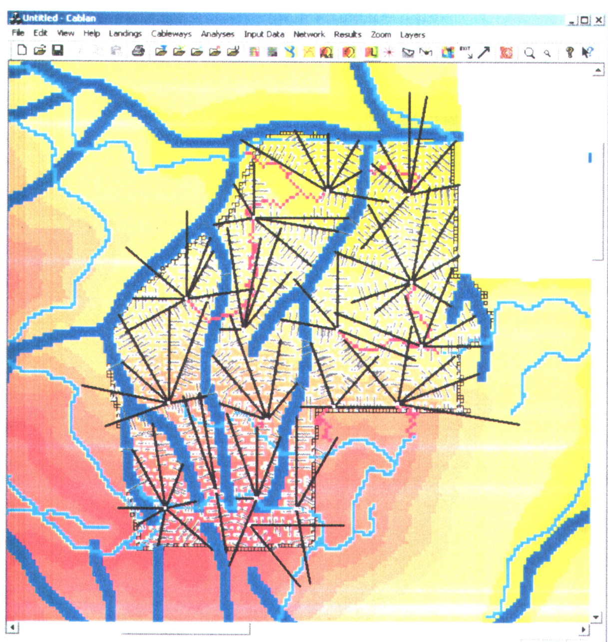
Equipment	Koller K-300 only		Madill-6150 only	
Total landings	30		17	
Total cable roads	206		90	
Total road length	4,167 m		2,905 m	
Cost items	Yarding	Transportation	Yarding	Transportation
Variable cost	\$114,842	\$286	\$106,311	\$191
Fixed cost	\$186,400	\$156,525	\$181,170	\$101,521
Sub total	\$301,242	\$156,811	\$287,481	\$101,712
Felling cost	\$28,224		\$28,224	
Total harvesting cost	\$486,277		\$417,417	
Production cost	\$60.30 / m^3		\$51.76 / m^3	

Table 23. Itemized fixed yarding cost from the cases that only one of the two yarding systems was applied to the planning area.

Cost items	Koller K-300 only	Madill-6150 only
Landing cost	$122,000	$65,000
Yarder move-in cost	$9,300	$25,500
Initial setup cost	$4,800	$31,620
Cable road emplacement cost	$50,300	$59,050
Total fixed yarding cost	$186,400	$181,170



(a) when only the Koller K-300 is applied



(b) when only the Madill-6150 is applied

Figure 44. The solutions found by the heuristic network algorithm when only one of each yarding system is applied to the planning area.

Change of landing construction and equipment move-in costs

Landing construction and equipment move-in costs may affect the number of landings selected by this methodology. In this analysis, different landing construction and yarder move-in costs were applied to the same planning area while other costs remained the same as the original application. The landing cost also varied with different yarding equipment in this analysis. The applied landing construction costs for the Madill-6150 and the Koller K-300 were $300 and $50 per landing, respectively, assuming that the landings are located in truck turnouts along the road and not much earthwork is necessary for the construction. The move-in cost for each yarding equipment was determined as one-hour machine cost (Table 24).

Table 24. The landing and move-in costs per landing for each yarding equipment applied to the sensitivity analysis.

Cost items	Koller K-300	Madill-6150
Landing cost	$50	$300
Yarder move-in cost	$160	$465

The solution showed that a total of 38 landings and 195 cable roads were selected and about 5.4 km of new roads were proposed (Table 25 and Figure 45). The Koller K-300 was selected at 37 landings for 177 cable roads, whereas the

Madill-6150 was selected at 7 landings for only 18 cable roads. Both yarders shared 6 landings.

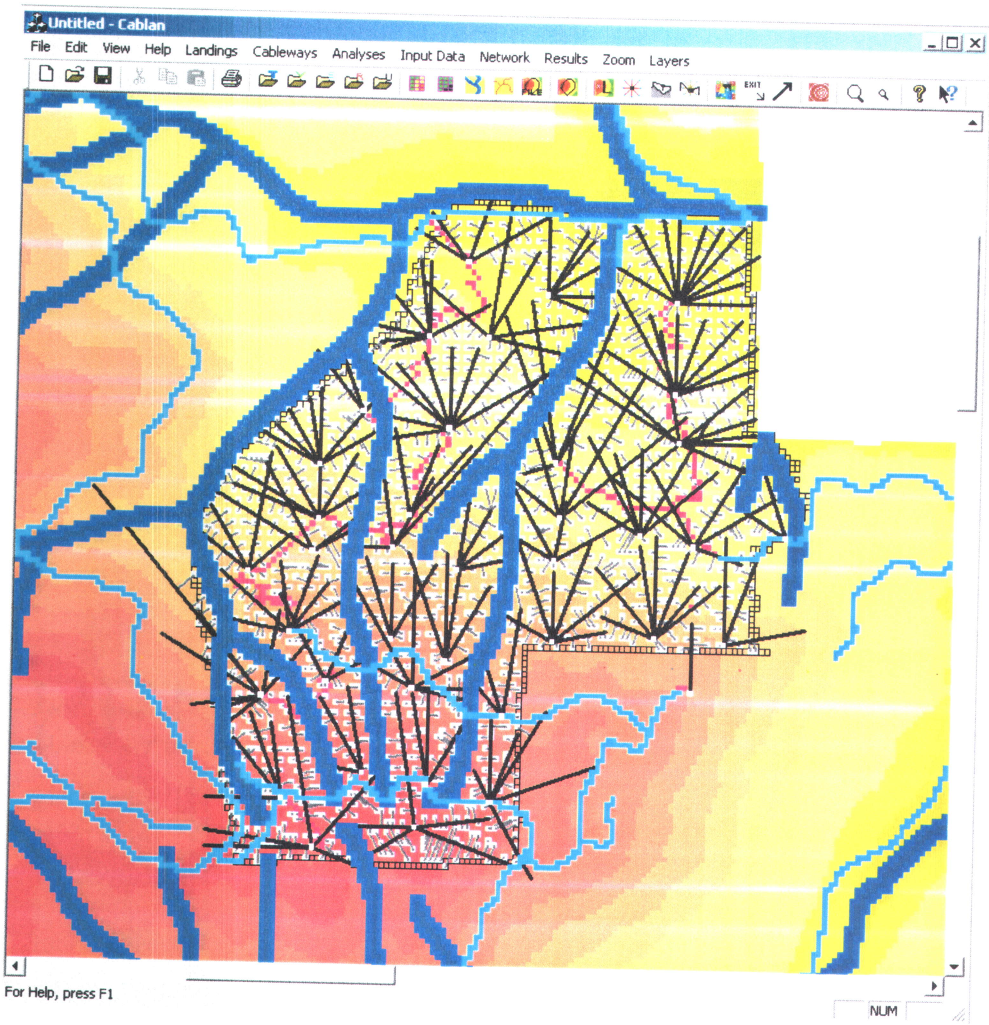


Figure 45. Landings and cable roads selected for the case where the low landing and move-in costs were applied.

Compared to the results from the original case where the high landing and equipment move-in costs were applied, the solution showed more landings were selected and the Koller K-300 was used for most cable roads. This implies that the low landing cost makes building small landings for the small yarder with fewer cable roads per landing more economical than building large landings for more cable roads per landing. The original case showed the average number of cable roads per landing was 8, whereas only 5 cable roads were emplaced per landing with low landing cost (Table 25).

Table 25. Comparisons of the solutions for the cases where low and high landing and equipment move-in costs were applied.

Items		Low landing cost	High landing cost
The number of selected landings		38	19
The number of selected cable roads		195 (177)[1)]	155 (107)[1)]
Total length of proposed roads		5.4 km	2.8 km
Yarding cost	Variable cost	$89,342	$110,602
	Fixed cost	$84,475	$172,570
	Adjusted fixed cost	$84,175	-
	Total cost	$173,517	$283,172
Hauling and road cost		$223,068	$105,279
Total yarding and road cost[2)]		$396,585	$388,451

[1)] numbers in parentheses are the number of cable roads using Koller K-300
[2)] total yarding and road cost here does not include felling cost.

Since the landing cost varies with different yarding equipment in this analysis, two different yarders located at the same landing are internally recognized as if they are located in different landings. In the case, the landing cost is counted twice for the same landing and needs to be adjusted. A total of 6 landings were shared by both Koller K-300 and Madill-6150 in the solution of this analysis. Thus, the total landing cost was adjusted by subtracting \$300 (6 landings × \$50/landing for Koller K-300) from the total fixed yarding cost (Table 25).

Although the solution was the best one found by the methodology within the limited computation time, the solution with the low landing and move-in costs is not superior to the solution with the high landing and move-in costs in terms of minimizing total yarding costs. The total yarding cost resulted from the case with the high landing cost (Table 19 and Table 25) would be smaller than that with the low landing cost if the yarding costs were recalculated on the same basis of the landing cost (Table 26). Thus, the best combination of landings, harvesting equipment, and roads for both the high and low landing cost was for the initial solution (Table 19).

This result can be explained by examining how the heuristic works. The methodology develops two parts of the network problem for solving cable logging operation planning and road network planning problems as described in the previous chapter. In the first part of the network problem, the low landing cost leads the network algorithm to select more landings rather than to select more cable roads per landing with fewer landings. The second part of the network problem develops road network to access to the landings selected in the first part of the network problem. If the algorithm selects few landings among many candidates in the first part of the network problem, it may select a different set of landings in the following repetition because the selected landings at the previous repetition already include road cost, which makes the landings more expensive than the others. If the algorithm selects most landing candidates in the previous repetition, however, the chances to select a different set of landings is limited and the algorithm may end up with a similar set of landings at the following repetitions, which may cause the algorithm to be trapped in a local optimum. This might be the reason why the quality of the solution with the low landing cost is not as good as the solution with the high landing cost. It also suggests that any solution should be accepted with caution and that a landing cost sensitivity analysis should be undertaken.

Table 26. Adjusted total costs for the cases where low and high landing and equipment move-in costs were applied after the landing costs were recalculated on the same basis.

Items		Low landing cost	High landing cost
Yarding cost	Variable cost	\$89,342	\$110,602
	Fixed cost	\$84,475	\$172,570
	Adjusted fixed cost	\$84,175	\$105,020[1)]
	Total cost	\$173,517	\$215,622
Hauling and road cost		\$223,068	\$105,279
Total yarding and road cost[2)]		\$396,585	\$320,901

[1)] \$172,570 - \$71,000 (total landing costs when the high landing cost was applied) + \$3,450 (total landing costs when the low landing cost was applied to the same set of landings) = \$105,020

[2)] total yarding and road cost here does not include felling cost.

Change of road construction costs

The balance between road cost and yarding cost is very important for determining the number of landings and their locations. In order to show how the solution changes with respect to the road cost change, two different road construction unit costs were applied to the same planning area while all other parameters remained the same. The applied road construction costs were $10,000/km (Case I) and $50,000/km (Case III). Case II is the standard case in which the road cost is $30,000/km. The results from Case II were described in the previous section.

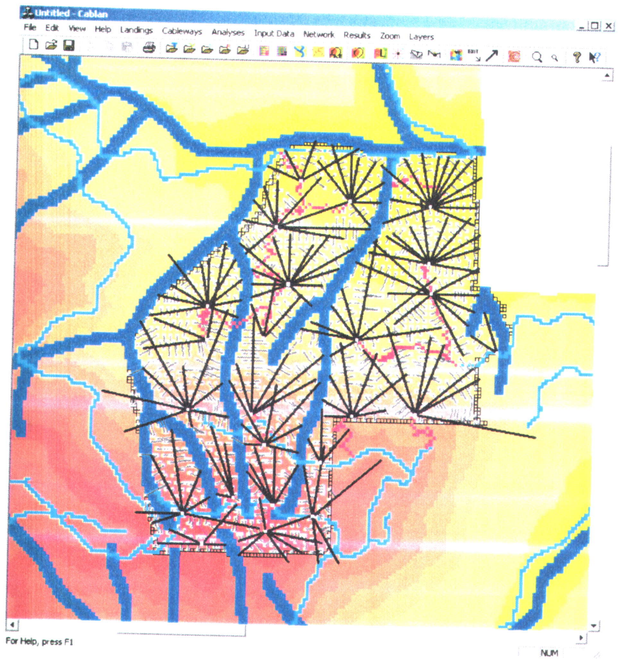
With the lowest road construction cost (Case I), the solutions showed that a total of 24 landings were selected and about 3.7km of new roads were proposed (Table 27, Figure 46(a)). The number of selected landings dropped to 18 when the road construction cost increased to $50,000 (Case III) and total proposed road length decreased to 2.8 km (Table 27, Figure 46(b)). There was a large drop in the number of landings (21%) and the proposed road length (22%) between Case I and Case II, but there were relatively small changes between Case II and Case III. Only 5% and 4% decrease in the number of landings and road length, respectively, from Case II to Case III.

Total yarding costs were separated into variable cost and fixed cost. Variable cost includes yarding equipment and operating cost calculated from yarding cycle time. Fixed cost includes landing construction cost, equipment move-in cost, equipment setup cost, and cable road emplacement cost (Table 27). Case I had the lowest variable yarding cost, which is $93,989, but had the highest fixed yarding cost, which was $188,500. This implies that using more landings may be able to reduce total cycle time because average yarding distance may decrease, but raise landing cost, equipment move-in cost, and equipment setup cost.

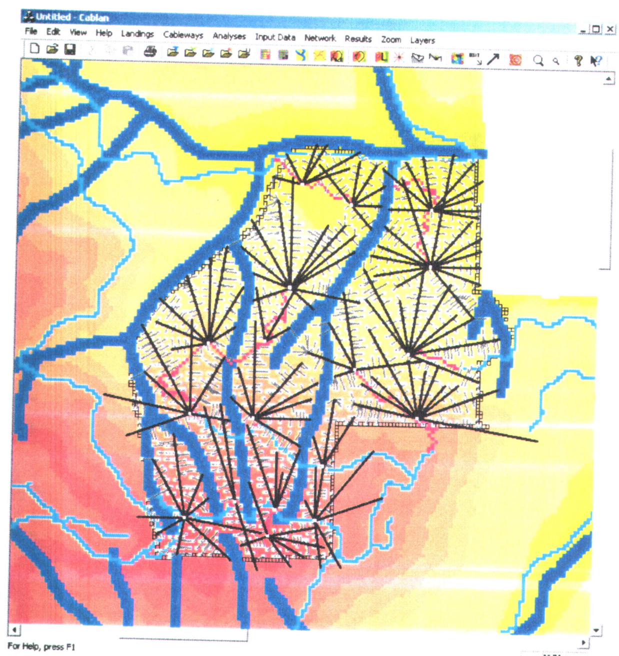
Table 27. Summary of the solutions for three cases with different road costs.

Items		Case I ($10,000/km)	Case II ($30,000/km)	Case III ($50,000/km)
The number of selected landings		24	19	18
The number of selected cable roads		162	155	130
Total length of proposed roads		3,682 m	2,883 m	2,773 m
Yarding cost	Variable	$93,989	$110,602	$108,675
	Fixed	$188,500	$172,570	$170,310
	Total	$282,489	$283,172	$278,985
Hauling and road cost		$44,731	$105,279	$171,575
Total yarding and road cost		$327,220	$388,451	$450,560

Unexpectedly both variable and fixed yarding costs with Case III were less than those with Case II, even though Case III used fewer landings than Case II. Although the difference is very slight (only 1.5% of total yarding cost), this implies the network algorithm found better yarding patterns with higher road cost and the solution with Case II is not an "optimum". Higher road cost might lead the algorithm to search for good yarding patterns while reducing the number of landings used, which resulted in a better solution in this case. As this case showed, the sensitivity analysis is essential for finding a better solution since the heuristic network algorithm used in this methodology cannot guarantee the optimal solution.



(a) with road cost of $10,000/km



(b) with road costs of $50,000/km

Figure 46. Landing and road layouts solved by the heuristic network algorithm when different road costs were applied.

PROBLEM SOLVING TECHNIQUES

After initial trials, the stopping criteria for the heuristic network algorithm for this application were determined (Figure 47). A total of 10 repetitions of problem solving were allowed unless the objective function of the current solution is close to that of the previous solution. Each repetition involves solving two network problems: cable logging path and road planning problems. As described in Chapter I (Figure 2), the heuristic network algorithm stops if the current solution is the same as the previous one. In order to reduce solution time, the total number of iterations was limited in this application. A maximum 300 iterations were allowed and the algorithm always stored the best solution found during the iterations.

Since the heuristic network algorithm applies negative value to the links that are not included in the solution after the first iteration, the objective function of the solution at the second iteration is very different from the first iteration, but the solution gradually converges as more iterations are completed (Figures 48 and 49). Table 28 presents the change of the overall costs from 10 repetitions of problem solving. The best solution was found at the 4th repetition. It took 47.2 hours to run 10 repetitions on a Pentium III 1.0 GHz processor desktop computer (Table 28).

It took only 0.67 hour to run the 7th repetition because the heuristic network algorithm stopped at the 16th iteration when it found the total costs of the current solution was the same as the previous solution in the cable logging planning problem. This early stop resulted in a poor solution because the algorithm did not have enough opportunity to explore alternative paths.

Table 28. Yarding and road costs in the best solution found at each repetition.

Repetition	Yarding cost ($)	Road cost ($)	Total cost ($)	Solution Time (hours)
1	279,685	220,728	500,413	6.63
2	285,456	221,128	506,584	3.63
3	275,534	222,978	498,512	6.34
4	283,173	105,278	388,451	4.09
5	282,010	218,366	500,376	5.16
6	281,794	222,426	504,220	6.31
7	646,819	207,807	854,626	0.67
8	273,956	207,395	481,351	3.87
9	282,448	123,754	406,202	4.37
10	276,090	218,109	494,199	6.14
Average	316,697	196,797	513,494	4.72

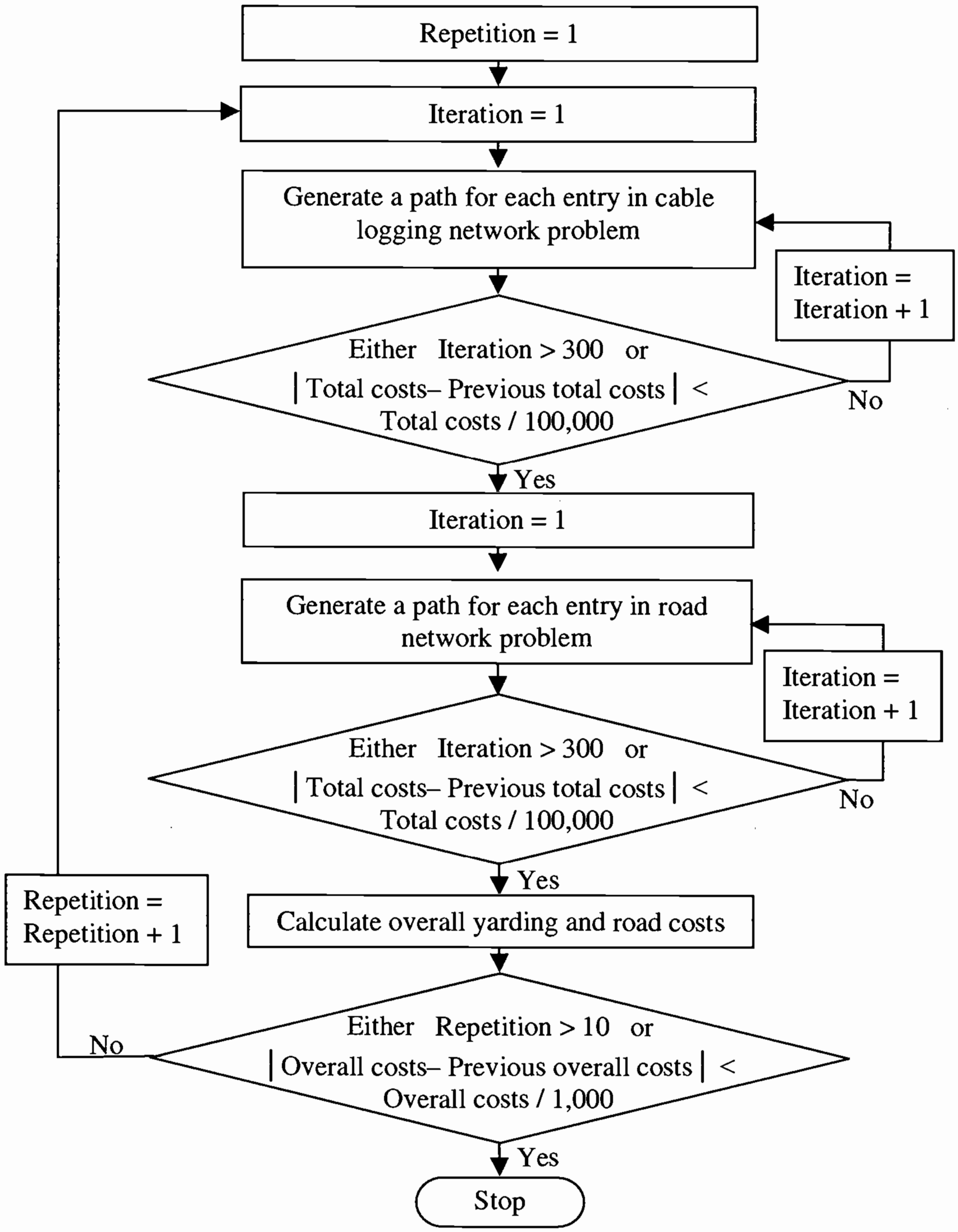


Figure 47. A flowchart showing the stopping criteria used for the problem solving algorithm in this application.

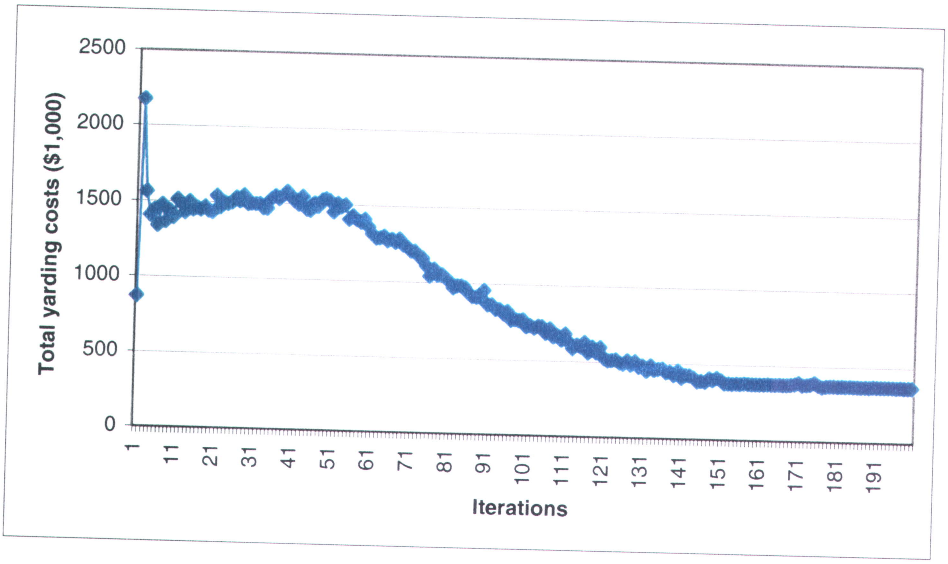


Figure 48. Changes of the solution for the cable logging network problem at the 4th repetition. The algorithm stopped at 200th iteration and the best solution found at the 177th iteration.

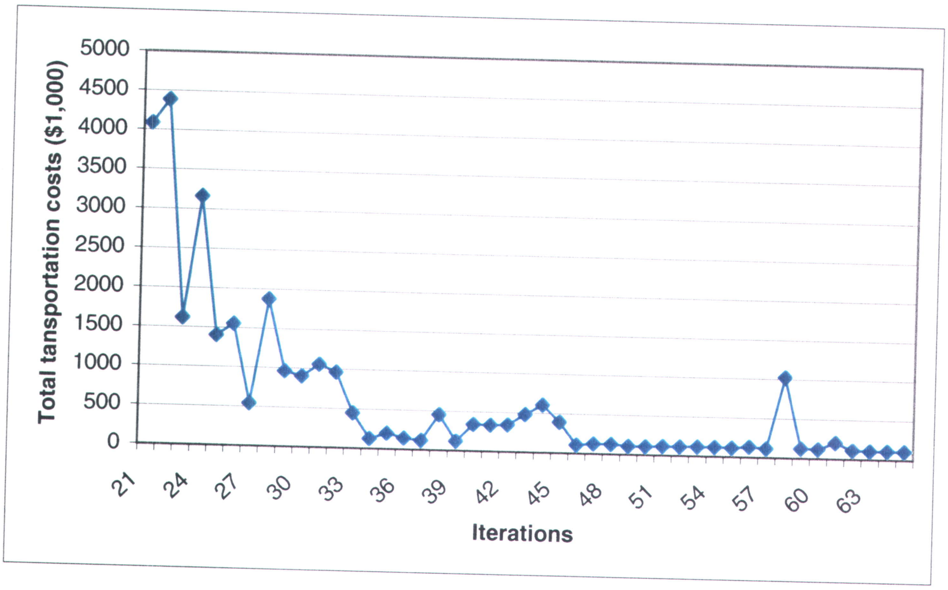


Figure 49. Changes of the solution for the truck transportation network problem at the 4th repetition. The algorithm stopped at 65th iteration and the best solution found at the 63rd iteration (first 20 iterations are not shown in this figure).

SUGGESTIONS FOR APPLICATION OF THE METHODOLOGY

The results of this methodology should be considered as a "preplan" for timber harvest in a specific area. Although the results may be close to the economic optimum, they rely on the parameters and information that the user brings into the methodology. Certainly lack of suitable data for the analysis would not produce useful and satisfactory solutions. The planners should understand the quality and the limitations of input data and appropriately interpret the outputs of the methodology.

Each parameter required in the methodology has a significant impact on the final solutions. It is necessary for the planners to know how the parameters affect decision making process within the methodology for better understanding of the solutions. The sensitivity analyses may help the planners understand how the parameters in the methodology affect the solutions. These analyses can also provide valuable alternative plans. In addition, the logging feasibility and cost analysis module in the computerized model is a useful tool to help the planners get better acquainted with the planning area and recognize challenging logging areas where careful attention needs to be paid during the actual logging operations.

It is important to understand that landing, cable road, and road network alternatives produced by this methodology may not be the "best" set of alternatives as the sensitivity analyses presented in this study showed. A different planner working with the same planning area would most likely produce a different set of alternatives. Creating several sets of alternatives and comparing the results is necessary to find a better and more reasonable plan for timber harvesting in a specific area.

Although the test application of the methodology was completed, several limitations of the methodology were observed during the application:

1. The current version of the logging feasibility analysis is limited to only cable systems with an uphill standing skyline configuration.
2. The methodology assumes that all timber within the user-defined harvest unit boundary is harvested by only cable logging systems. If a harvest unit boundary includes areas to be harvested using tractor system or helicopter, the boundary should be redefined to exclude those areas.
3. The methodology projects the cable roads, assuming tailspars are available anywhere it is necessary. In actual timber harvesting operations, however, tailspars become often a limiting factor in locating a skyline corridor and determining the length of the corridor. The outputs of the methodology must be followed by field verification or verification using large scale aerial photography to identify actual location of the tailspar on the ground.
4. The roads proposed by the methodology should be considered providing "approximate" road locations rather than "exact" locations. Since the methodology develops road routes based on a raster map and the

alignment of roads are not constrained in the methodology, the proposed road routes may include many sharp turns that are inherently produced by connecting a grid cell to one of its adjacent cells. Most these sharp turns are not feasible for actual road layout, thus it may be impossible to directly implement the proposed roads on the ground. The road should be relocated with the considerations of the specified design standards and the physical feasibility of the road alignment.

5. Finding good candidate landing locations is critical for developing a good timber harvest plan with this methodology. Besides using a contour map and the semi-automated method for identifying tower location developed for the computerized model, visits to the planning area or using aerial photography would be helpful to find appropriate landing candidates.
6. When alternative yarding systems with different design payloads are evaluated at the same time, the larger design payload should be used as the minimum design payload in the analysis. The load building simulator determines timber parcel locations and harvest volume at each timber parcel based on the larger minimum design payload. For smaller yarding equipment, the cost analysis program will assign additional turns of logs to each parcel if the parcel has more volume than its minimum design payload.

7. Since the heuristic network algorithm used in this methodology cannot guarantee the optimal solution, various sensitivity analyses are essential for exploring more alternative solutions to find a better one. Applying different road cost, landing construction cost, yarding equipment move-in cost, or machine cost to the same planning area or eliminating some of the landing candidates would be good examples of sensitivity analyses that can be easily done. Applying a large range of each cost factor may lead the algorithm to explore different solution space and generate a better layout. In the case, actual harvesting cost for the layout can be estimated by replacing the applied cost with the actual cost while the layout settings and other costs remain the same.
8. A significant amount of solution time is required for the computerized model to solve a timber harvest planning problem, especially for a large area with a high resolution DTM. The solution time exponentially increases with the increase of the number of origin-destination sets and the number of links involved in a network. Using a high resolution DTM resulting in a large number of origins-destination sets and links requires a large amount of solution time. The scale of the information should be determined considering problem size, data accuracy, solution time, and memory capacity of the computer system.
9. Solution time of the computerized model is also affected by the program structure. Cumbersome structure and frequent access to the data file in

local storage may also explain a significant amount of solution time. A good programmer certainly can improve the performance of the model and significantly reduce solution time by reprogramming or restructuring the program.

10. The performance of the heuristic network algorithm relies heavily on the stopping criteria of the algorithm. As shown in the application, sometimes the algorithm stops at the local optimum which may be far from the global optimum. It is necessary to select the appropriate stopping criteria and repeat the problem solving procedures to assure the solution quality.

CONCLUSIONS

An automated and comprehensive methodology has been developed to assist the forest planner in designing a cable logging unit layout. The methodology includes the logging feasibility and cost analysis procedures and an operations research approach to simultaneously optimize cable logging operations and road locations. The methodology combined with GIS techniques helps the forest planner evaluate a large number of alternatives paths in extracting logs from the stump to the mill using cable logging and truck transportation.

Considering many alternatives in the planning problem greatly increases the size of the problem and finding a good solution to such a large planning problem becomes a challenge. A conventional operations research approach such as Linear Programming (LP) or Integer Programming (IP) is an attractive approach to solve the planning problem since it is able to find an exact solution. However, it is almost impossible to currently solve a large problem that consists of many integer decision variables using such approaches.

The methodology presented in this study applies a heuristic network algorithm to solve a large cable logging operation and transportation planning problem. All possible alternative paths from the stump to the mill form a large network. The logging feasibility and cost analysis modules included in the methodology provide physically and environmentally feasible alternatives of timber paths and their associated costs. The heuristic network algorithm applied to solve a large network problem finds an economic layout.

The procedures of the methodology were incorporated into a computerized model. The capability of the model to use a GIS database and the graphic user interface allows the planners to develop alternative cable logging operation and road locations by evaluating various logging operation scenarios. The logging feasibility and cost analysis functions in the model provide an efficient analytic tool to analyze physical, economic, and environmental feasibility of alternative cable roads, yarding systems, landings, and road locations.

Although the methodology and the computerized model developed in this study provides a new approach to solving forest operational planning problems, most of the procedures in the methodology are no more than applications of existing knowledge. The most important new developments in this study are to apply a network programming technique to cable logging unit layout design problems and to develop a decision support system incorporating complete procedures of existing knowledge necessary for designing cable logging layout.

It is important to understand that the computerized model implementing the methodology was not intended to be a decision maker but a decision support tool. The outputs of the methodology are supposed to be used as a "preliminary" harvest operation plan. Since it is impossible to completely model an actual planning problem in mathematical terms, the outputs of the methodology may not be appropriate to directly implement on the ground and thus should be followed by field verification and revisions based on the planner's decisions.

The methodology was applied to an actual cable logging harvest area in the McDonald-Dunn OSU research forest to verify its performance, although the verification of the solution is limited since no tool has been developed that is able to find the optimal solution to a large operational planning problem. Several sensitivity analyses were conducted to explore alternative plans. Through the application and the sensitivity analyses, several limitations on practical usage of the outputs from the methodology were found. As the results of the sensitivity analyses showed, the current network algorithm applied in this methodology cannot guarantee to find the "optimal" solution to each specific problem. Various cost factors may affect the quality of the solutions, and the sensitivity analysis is an essential process to find a good solution with the current algorithm. Additional considerations should be included in the analysis in order to develop more practicable cable logging layouts. For example, tailspars may not be available in some areas within the planning unit or outside the boundaries. Some areas may be restricted from road construction due to the high probability of landslides. These additional considerations in the analysis may be able to eliminate "impractical" aspects of the solution developed by the methodology.

Further studies to improve the algorithm and the solution techniques should be taken based on the verification of the presented methodology. The algorithm may get improved by adding a series of rules internally changing link costs, hoping the algorithm to explore additional parts of the solution space. Combining two separated parts of the network problem into a large network problem may be an alternative solution technique to find a better solution. Besides, the methodology and the computerized model should also be improved in order to bring additional considerations such as tailspar availability and road construction restricted areas into the analysis. Developing specific GIS layers containing the additional spatial information and providing information to the system through the GIS layers may be a possible way to include the additional considerations in the analysis. At the same time, the applications of the methodology should be further tested with actual cable logging areas. In a future study, the outputs from this methodology can be compared with a cable logging paper plan done by the conventional manual method for the same area. The efficiency of the methodology in terms of time required to develop a harvesting unit layout can also be compared with that of the conventional method. The computational experience with the applications will help to improve the performance of the methodology in the future.

Further study should also include the improvement of the method to formulate the network problem. The resolution of a DTM directly affects the problem size for the network analysis. High resolution would provide topographic details but exponentially increases problem size resulting in increasing solution time and demand for a large memory capacity. Methods to reduce problem size with a high resolution DTM may need to be explored to shorten solution time and lessen memory requirement. Since different types of analyses may require different scales of information, changing the resolution and scale of data with respect to the type of the analysis might be an alternative way to reduce problem size without losing information quality.

The applications of this methodology can be expanded to harvesting unit design for ground-based systems with further study. It may require ground slope analysis to redefine unit boundaries complying with the capability of different harvesting methods. The location of designated skid trails and economic skidding routes can be determined through the optimization procedure of the methodology.

The methodology and the computerized model developed for this study cannot perfectly represent an actual timber harvest operation. They are intended to solve the planning problem only in a way it is formulated. They cannot substitute the forest planner who makes a decision for timber management, but they can provide useful information that helps him make a better decision. Hopefully, the decision support system presented in this study will provide an efficient analytic tool that can contribute to better cable logging layouts in terms of minimizing costs and environmental impacts of timber harvesting.

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* Program codes for the computerized model written in Microsoft Visual C++ 6.0 are on a CD-ROM attached to this book.