# PROCEDURES FOR PROJECTING AND EVALUATING FOREST ROAD NETWORKS IN STRATEGIC PLANS

By

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#### Abstract

Road networks have received limited attention in strategic planning primarily because generating these networks has been a significant barrier. This thesis develops computer algorithms to create and analyze the financial aspects of alternate road networks for strategic planning. The thesis is presented in three chapters. The objective of the first chapter is to develop and test a new computer method of projecting road networks. My method mimics the process professionals use when manually projecting roads using topography and road design standards. The result is a vector-based network defined by road nodes and links. The testing identified two main shortcomings of the road projection algorithm: 1) randomness associated with inputs creates variation in the proposed road networks, and 2) input parameters require considerable manipulation to yield desirable road networks. However, this automated process can create road networks much faster than manual methods and with further research, could be used to develop preliminary road networks for tactical or operational planning.

The objective addressed in the second chapter is to create and test a method of determining the optimal mix of road classes within the network. High road classes have high construction costs (\$/km) and low hauling costs (\$/m<sup>3</sup>/km) while low road classes have low construction costs and high hauling costs. Therefore, the volume of timber to be hauled is a critical factor in determining which class of road to construct. To determine the optimal road class, I use a strategic harvest schedule to determine the haul volumes over each link within the network. These haul volumes along with construction, maintenance, hauling and deactivation/reactivation costs are used by a dynamic programming algorithm to determine the optimal road class for each unique section of

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road in the network. The optimal road classes, deactivation strategies and resulting costs can then be used to help evaluate strategic harvest policies and/or road network designs. Sensitivity analysis of the input costs and haul volume determine the robustness of road networks to changes or uncertainties. The optimal road class model provides a useful tool to aid managers in the evaluation of harvesting systems, silviculture systems and transportation networks.

Because the harvest schedule is an important determinant of the optimal road class decision, chapter three combines the algorithms developed in the first two chapters with a strategic harvest scheduling algorithm. Six strategic harvest scenarios are used with thirteen road networks to examine road network quality. The harvest scenarios differ in the timing of harvests, the spatial distributions of harvesting, and the block size. Also, the road networks differ in the location/number of landings and when the networks are projected, relative to the harvest schedule. It was found that increased block size reduces the amount of active road under even flow harvest policies. Also, projecting road networks in each period when harvest blocks are selected reduces the length of active road and the amount of early road construction. However, this method created networks with long total lengths and long average haul distances, and poor flow concentration. The total cost of the network was mainly dependent on the total volume harvested, not the harvest policy.

The methods developed in the thesis are tested on a small forest of approximately 7,500ha. Computing times to generate and assess these networks (average of 219km) ranged between 6.5 to 10.7min per scenario. Subsequent work with the road projection model has been conducted on large estates (1.5 million ha). This has led to modifications

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whereby the network is projected in stages (beginning with mainlines, then branch roads and finally spur roads), which generally provides more control over road location and road class, plus it offers some computational efficiency. Further development of the road projection model combined with feedback from professionals could greatly improve its utility in operational and tactical planning, plus other strategic applications including non-timber impacts of forest roads.

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# Introduction

Strategic harvest schedules are now regularly created using spatial constrained computer models to assess the impacts and uncertainties of management policy over long time horizons (multiple rotations). Almost all forest activities scheduled in a strategic plan are related to the transportation system. Forest roads affect profitability and other forest values such as recreation, hydrology, wildlife, and forest protection. However, roads are rarely included in strategic planning, and when they are, generally only one road network option is analysed. The main reason why roads are not included in most strategic plans is because manual road projection methods are inordinately time consuming. Computer algorithms have been developed to project road networks but they are either limited to small areas or they do not use topography and/or road standards as inputs, which produces unacceptable results, especially in mountainous terrain. Because roads are an integral part of the forest landscape, they need to be incorporated into strategic plans. To create these networks, improved road projection algorithms need to be developed, along with the necessary procedures to evaluate them over long time horizons.

Road network requirements are different depending on the level of hierarchical planning. The level of planning dictates the spatial and temporal scale, policy, objectives and the amount of uncertainty surrounding the road network. There are three levels in the planning hierarchy: operational, tactical and strategic.

Operational planning uses short time frames (1-3 years) along with detailed objectives and constraints to identify the harvest areas, road locations and timing of construction. The planner requires confidence that roads meet current policy, are correctly engineered, access the harvest areas properly and that the associated costs are accurate. The level of

accuracy and detail requires that these roads be manually located in the field. Other activities, such as deactivation, reactivation and upgrades can be expensive and risky, so they are also carefully checked in the field.

Tactical plans identify the longer-term (20-30 year) effects of operational strategies. These plans have less detail and use larger landscape units. Tactical planners use maps and aerial photos or computer algorithms to identify possible road locations and activities. Tactical plans may be field checked for feasibility; however, these plans rarely match the roadwork actually implemented. Map and photo uncertainties and changes to block location, logging systems, policies and objectives all contribute to changes in the proposed road network. However, they permit rational assessment of alternatives.

Strategic plans use long time horizons (multiple rotations) and the entire forest estate to forecast harvest levels and road network activity. Strategic road networks will almost never be implemented exactly as planned because of the long time horizons and uncertainty associated with these plans. However, strategic plans are valuable for guiding long-term access management, identifying optimal road classes and assessing the impacts that roads have on other forest values, such as wildlife populations and hydrology.

The large estate size associated with most strategic plans has been a limiting factor in developing proposed road networks. Without the ability to develop proposed road networks, the effects of management policies cannot be accurately determined. This thesis focuses on the development and testing methods for creating and analysing strategic level road plans. First, a computerized method for projecting detailed vector-based road networks is presented and tested. Second, a dynamic programming approach to determine the optimal road class and deactivation strategies is presented and tested.

Finally, the road projection tools and the optimal road class/deactivation strategy methods are used in conjunction with a harvest scheduler to test methods of linking road network projection, harvest scheduling and optimal network decisions.

Chapter 1 of my thesis develops and tests a method of projecting road networks using road standards and topography. The objective is to develop and test a process to create road networks based on topography and road standards, which can create road networks for strategic planning. Although computerized road network generation has been the focus of research for years, most research of detailed road network generators deal with tactical or operational planning. The large forests covered in strategic planning make these methods infeasible. Also, the road projection methods developed for strategic planning rarely consider topography and road standards. In chapter 1, I develop and test a method based on a shortest path algorithm, digital terrain and topography information, and input parameters that control the road standards.

At the base of the road projection algorithm are nodes. The nodes are generated to cover the entire forested area, and are identified by horizontal and vertical coordinates. Connecting these nodes are carefully chosen links, which are limited by a predetermined grade and length. Some of these links represent existing roads, and the remaining links create a network of routes (paths) that are candidates for projected roads. First, some of the nodes are selected to be landings. Next, one landing is chosen from the set of landings, and then the shortest path algorithm is used to connect the landing to the existing road network through the set of candidate routes. Once the road is connected, it is added to the existing road network, and another landing is selected and then connected to the new network. This process continues until all the landings are connected.

The sensitivities of the road projection algorithm to input control parameters and the node density are tested using Hardwicke Island. The node density influences the processing time and the quality of the resulting road network. Most road standard input/control parameters behave as expected, and create trade-offs between network indicators. For example, increasing a penalty for adverse grade usually decreases the average adverse grade of the network, but increases the total length of the network and the average haul distance. However, randomness associated with the nodes and the topography often create unexpected results. It was found that considerable manipulation of the input parameters is required to produce desired road networks. Despite these limitations, the algorithm can produce road networks much faster than manual methods, and it can be used on larger areas and include more detail than other previous computer road network generation methods.

Once I was able to project road networks, I needed a method to incorporate and analyse road networks within strategic harvest plans. The main objective of including road networks in strategic plans is to determine the effects of long-term forest policy on the periodic road network values such as; road costs, length of road construction and length of active road. The road class and deactivation strategy influences these costs, so I embarked on finding a method for determining the road class and deactivation strategies. In the second chapter, a dynamic programming (DP) approach for solving the optimal road class problem, which includes optimal deactivation strategies is developed and tested. This DP is a backwards recursive network algorithm similar to that is used for equipment replacement problems. This algorithm is capable of simultaneously determining the optimal road class and deactivation level over the planning horizon. The

road network, road costs, and haul volume derived from a strategic harvest schedule are necessary inputs.

The DP algorithm is tested at three scales; 1) single road segment, 2) interaction between road segments, and 3) the entire road network. Testing showed that this DP is useful for determining the optimal road budget and the sensitivity of the solution to changing inputs. It was also found that the road class information was useful for determining timber flow concentration. When a road network has many high class roads and few low class roads, there is good timber flow concentration, while many low class roads and few high class roads indicates poor timber flow concentration. The length of the time horizon and the discount rate are important variables that influence these solutions.

With the ability to project road networks and evaluate them relative to a specified harvest schedule, my next step was to explore how sensitive these are to strategic harvest plans. My third chapter integrates the procedures developed in the first two chapters with a harvest scheduling model to test the effects of block size and harvest flow policy on the total costs and other network indicators such as haul distance, length of active road, and flow concentration. Using the same case study, road networks are developed using 6 harvest scheduling/road projection techniques: 1) prepositioned roads, 2) dynamic harvest scheduling/road projection, and 3) road projection after harvest scheduling. Projecting roads during each period of the harvest schedule (dynamic harvest scheduling/road projection) reduced the amount of active road and the length of initial road construction. However, this method created networks with relatively longer total lengths and haul distances, and with relatively poorer flow concentration. It was also found that smaller harvest blocks with an even flow harvest policy result in more active

road. However, there were no apparent block size trends in the amount of active road under pass system harvest policies.

Although harvest policy results are presented, the main benefit of Chapter 3 is the exploration of the processes involved in 1) creating road networks, 2) linking road networks to spatial plans, and 3) analysing road networks. The lessons learned about creating and analysing road networks are presented in a general discussion around the study limitations and potential for future development. I finish the thesis with conclusions and recommendations for further research.

# Chapter 1: Projecting Vector Based Road Networks with a Shortest Path Algorithm

# Abstract

Manually designing road networks for planning purposes is labour-intensive. As an alternative, I have developed computer algorithm to quickly generate road networks under a variety of assumptions related to road design standards. This method does not create an optimized road network, but rather mimics the procedure an engineer would use when projecting roads by hand. Because there are many feasible road networks for forest estates, sensitivity analysis is required to analyse and choose the best ones. Road networks for large areas can be created relatively quickly, which gives forest planners additional information to assess the long-term consequences of road density and road standards common in forest management decisions. The procedures used to create road networks are presented along with the sensitivity analyses of the input parameters and the level of spatial detail (node density). These procedures require the manipulation of many input parameters to create the desired road network and variation between outputs is a concern. Despite these limitations the method still is a considerable improvement over manual methods, especially for applications in strategic planning. The road network generation algorithm is suitable for all types of topography and road standards.

# **1.0 Introduction**

Roads are a significant investment and they affect many forest attributes such as wildlife. recreation and hydrology. Many forests estates are not completely roaded, and therefore require road networks to be projected so environmental and economical impacts can be estimated. Strategic road plans need to deal with entire forest estates, long time frames (multiple rotations), and large uncertainties surrounding economics, technology, environmental protection and policy. Engineers usually develop strategic road networks using paper map projections, but this process is very time consuming. When forest policies and regulations change, future road networks need to be redesigned. However, generating road networks for a large area is so tedious and time consuming that we do little designing and analysing of road network options at the strategic level. As a result, we know little about the strategic effects of road standards (grade and alignment), road densities, access requirements, and road location on economics and the environment. This limited understanding of strategic road plans shows the need to develop better and faster methods for projecting and analysing strategic road networks. This chapter develops and tests an automated process to generate road networks that is similar to the manual process used by forest engineers.

The design and implementation of networks has been the focus of research for decades (Clark et al. 2000). Engineers project roads using contour and thematic maps (Lui and Sessions 1993), however, this process is time consuming, subjective, expensive and usually non-repeatable. Dean (1997) called the problem of connecting a road network containing more than one timber supply area or target, the multiple target access problem (MTAP). Using raster GIS data, Dean (1997) developed and compared three heuristic

solutions and one non-heuristic method. The problems solved ranged from a 49 rasters (7x7 grid) to 14641 rasters (121x121 grid). Lui and Sessions (1993) solved a 24x24 grid problem using a network solution. Murray (1998) presented a mathematical formulation to MTAP suitable for small theoretical problems, solving a grid containing 64 rasters. Later, Clark, et al (2000) used a minimum spanning tree algorithm to develop simple road networks during harvest scheduling. This minimum spanning tree was applied to another academic size problem consisting of 225 stands in the form of a 25x25 16.2 ha grid.

Another type of road network problem is the single target access problem (STAP), which is a simplified version of the MTAP, where there is only one timber supply area. Rasters or simple node/link networks and small areas have been used for most of the road location algorithms. The method developed in this chapter uses node/link sets that allows for more detail to be modeled. In particular, the horizontal alignment (turning radius of curve) and vertical alignment (grade change) are addressed.

This chapter first develops the automated process of generating road networks, which includes the data requirements and the road network generation procedures. Second, the sensitivity to landing selection, spatial detail, and input parameters is tested. Finally, a discussion of improvements and alternate uses of the algorithm is presented.

#### 2.0 Methods

In this chapter, the road network generation algorithm is independent of the harvest schedule. Only topography, stream crossings and road design parameters are considered. Removing harvest scheduling from the road location algorithm makes the road networks independent of time and traffic, which simplifies the process and helps interpret the sensitivity analysis. In subsequent chapters road networks and harvest schedules are

examined simultaneously. The methods are presented in two sections: 1) a description of the algorithm, and 2) the methods used to test algorithm sensitivity.

#### 2.1 Algorithm Description

The algorithm requires two types of inputs: 1) node and link data, and 2) user defined parameters. Generating the node and link data is explained in the section "Generating Node and Link Data". The design and operation of the algorithm is explained in the section "STAP and MTAP Solutions". Finally the user defined parameters are explained in the section "Link Value".

#### 2.1.1 Generating Node and Link Data

My method requires a set of nodes and links along with their associated costs to generate vector road networks. Other researchers convert raster information to node/link sets to accommodate network algorithms (Liu and Sessions 1993, Dean 1997, and Murray et al. 1998). For my method, a node can be one of three types, 1) road, 2) landing or 3) extra. The road nodes are used to represent the actual road network. The landing nodes represent points where timber is to enter the network. Ideally the completed road network should include all landing nodes<sup>1</sup>. Extra nodes are placed across the forest estate to provide potential paths (roads) for the algorithm to connect the landing nodes to the road network. The placement of extra nodes is crucial for road projections in steep and broken topography. The extra node density, spatial randomness of the extra nodes and accuracy of elevation data all affect road projections. Initially, the road nodes represent only the existing roads. As the algorithm progresses and the road network expands, selected landing and extra nodes are changed to road nodes. There are four steps in creating

<sup>&</sup>lt;sup>1</sup> The sensitivity analysis explores reasons why landings do not always connect to a road network.

node/link sets. First, the horizontal coordinates (x and y) of the extra nodes are created. Second, the road nodes, landing nodes and extra nodes are combined to create the complete node/link set. Third, the elevation (z) of the nodes is estimated using contour information. Finally, the set of links connecting the nodes is created.

#### Horizontal Coordinates and Spatial Randomness of Extra Nodes

Initially, extra nodes are placed on the landscape in the form of a grid (Figure 1a). With a grid, the angles between links are often too limiting, restricting the horizontal and vertical alignment and making it difficult to locate roads. Introducing spatial randomness into the extra nodes allows for a wider range of angles and therefore better horizontal and vertical alignment. With node randomness, roads are better able to follow the topography in steep terrain.

The first step is to create a grid of nodes using a specified node density (Figure 1a shows a grid density of 25 nodes per hectare). The nodes are then moved a random distance in the x and y direction resulting in a new set of nodes (Figure 1b). The maximum distance that nodes can be adjusted is important. Too great a distance results in areas with too many nodes and others areas with too few nodes. Too small a distance does not achieve enough spatial randomness. The sensitivity of results to spatial randomness is explored later in this chapter.



Figure 1. A 16ha area of Hardwicke Island showing the process for creating nodes and links: a) 25 nodes/hectare grid b) 25 nodes/hectare with spatial randomness c) triangulation of 20m contour points, and d) links for the 25 nodes/hectare (75m length, 22% grade and a 20 link per node limit).

#### Combining Road, Landing and Extra Nodes

Once the extra nodes are determined, they are added to the landing nodes and the road nodes. Duplicate nodes (nodes with the same horizontal coordinates) are removed. If there are duplicate nodes, the type of node determines which will be retained. To insure that the existing road network stays intact, road nodes are always retained, and landings nodes have precedence over extra nodes.

#### Determining Node Elevation

Four steps are required to determine the elevation of the nodes. First, a triangulation of known contour points is created. Figure 1c shows a set of nodes, 20 metre contour lines and the associated triangles. Second, each node is assigned to a triangle with a point polygon test. Third, the plane equation of each triangle is determined. Finally, the node elevation is calculated using its x and y coordinates and the plane equation.

#### Determining the Links

The links are vectors that connect nodes. To reduce disk space and processing time, the links are restricted to a maximum grade and length. If the links are too short, not enough nodes are connected. If the links are too long, they can cross several contour lines creating the opportunity for roads to span valleys or cut through ridge tops. Figure 1d shows a node/link set for the sample area. On gentle slopes, there are more links in all directions, while on steep slopes there are fewer links that tend to follow the contours. The required disk space and process time increases as the number of links per node increases, so the number of links per node needs to be limited. If more links that the maximum number of links allowed per node meet the grade and length requirements, the shortest links are retained. The maximum length of links and the maximum number of links that cross lakes, sensitive soil areas, rock or other undesirable areas are removed. Links are also assigned attributes, such as a stream crossing identifier.

#### 2.1.2 STAP and MTAP Solutions

To project a road network, the problem is broken down into STAP's. One landing is selected, and Dijkstra's shortest path algorithm (Dijkstra 1959) is used to project one road from the landing back to the existing network subject to constraints. Once the new road is

connected it is put into the road network. Then the next landing is connected and the procedure is repeated until all landings are connected. This method does not find the shortest path from the landing to the exit point of the network, but rather from the landing to the existing road network. By sequentially connecting every projected STAP road to the network, the entire process determines a solution to the MTAP.

Figure 2 is a flow diagram of the procedure used to determine the shortest route from a landing to an existing road and Figure 3 is a simple example used to explain the procedure. The landing or start node is A and the target node is B. Nodes 1 through 5 represent the extra nodes located using the spatial randomness method previously described. Table 1 shows the steps required to solve the problem in Figure 3. The algorithm starts at the landing and progressively determines routes and route costs from the landing to each node. A node can be in one of three states. The first state represents nodes that have no route cost calculated. The second state (in queue) represents nodes that have a route cost calculated and are put into a queue ranked on the route cost. Finally, when a node is removed from the queue the shortest<sup>2</sup> route from that node to the landing has been determined, so its state is "in the network" and no other node can connect to it.

To start the example, Node A (landing) is set in the network. The cost to each node connected to node A (1 and 2) is calculated, and nodes 1 and 2 are inserted in the queue. The cheapest node (node 1) is removed from the queue and designated as in the network. The costs are then calculated for all nodes connected to node 1. Node A is in the network so no cost is calculated for it. The cost to get to node 3 is the cost to get to node 1 plus the

 $<sup>^{2}</sup>$  Explained later. The node cost depends on the proceeding links so the route may not always be the shortest.

cost from node 1 to node 3. The remaining steps are outlined in Table 1. Note that there is a horizontal alignment penalty of 2 when moving from node 3 through to node B. This penalty results in different costs for link 5-B depending on the proceeding node. Figure 2 shows the two ways the algorithm will stop. First, if the queue becomes empty prior to reaching the destination node, no feasible solution can be found. Second, when the destination node is removed from the queue a feasible (usually optimal) solution has been found.

Table 1. The steps required to find a solution	on to
the example network in Figure 3.	

Action	In Network	Queue - (cost)
Set "A" In Network	A	(Carl)
Calculate Link Values	А	1 – (3)
and Insert Nodes into		2 – (4)
Queue		
Remove 1 From	A, 1	2-(4)
Queue		
Calculate Link Values	A, 1	2 – (4)
and Insert Nodes into		3 - (6)
Queue	· · · · · · · · · · · · · · · · · · ·	
Remove 2 from Queue	A, 1, 2	3-(6)
Calculate Link Values	A, 1, 2	3 – (6)
and Insert Nodes into		4 – (7)
Queue	······	
Remove 3 from Queue	A, 1, 2, 3	4-(7)
Calculate Link Values	A, 1, 2, 3	4 – (7)
and Insert Nodes into		5 - (9)
Queue		
Remove 4 from Queue	A, 1, 2, 3, 4	5 = (9)
Calculate Link Values	A, 1, 2, 3, 4	5 - (9)
and Insert Nodes into		
Queue		
Remove 5 from Queue	A, 1, 2, 3, 4, 5	
Calculate Link Values	A, 1, 2, 3, 4, 5	B – (14)
and Insert Nodes into		
Queue	······································	
Remove B from Queue	A, 1, 2, 3, 4, 5, B	
Done Solution		
A-1-3-5-B		



Figure 2. Flow chart of Dijkstra's shortest path algorithm applied to a STAP.



/ 3-5-B = 5 (includes horizontal aligment penalty of 2)
4-5-B = 3 (no horizontal alignment penalty)



The example in Figure 3 and Table 1 also shows that the algorithm will not always find the optimal solution to the STAP. The solution the algorithm found is A-1-3-5-B with a total cost of 14, but A-2-4-5-B has a value of 13. In the extreme case, the angle between 3-5-B might be greater than the acceptable horizontal alignment and no solution would be found. This happens because the cost associated with a link may be dependent on the previous link. This can be overcome by adding nodes, for example node 5 could be replaced by  $5_3$  (connected to node 3) and  $5_4$  (connected to node 4). However, as the number of nodes and links increases the required processing time and memory increases so using multiple nodes becomes impractical for entire forest estates. With the addition of the nodes, methods presented by Liu and Sessions (1993), Dean (1997), and Murray et al. (1998) can be used, but application will be limited to smaller areas.

#### Haul Distance and Junction Angle

To reduce the haul distance<sup>3</sup> the algorithm continues after initially connecting to the existing road network. This allows many connection points to be compared so that the algorithm can select a destination that reduces the haul distance for that landing. When the projected road from the landing connects to the road network there is a road junction. The angle between the projected road and the existing road network is the junction angle. Junction angles can also be controlled similar to the haul distance. Figure 4 is an example showing three junctions (connection points). Junction 1 has a large junction angle and the longest hauling distance. Junction 3 has the shortest hauling distance while Junction 2 has the smallest junction angle. There is a trade-off between haul distance, length of new road projected, and the junction angle. The algorithm parameters determine which

<sup>&</sup>lt;sup>3</sup> The haul distance is defined as the distance from the landing to the exit point of the road network (or the total length of road accessing the landing).

route from the landing to the existing road network is chosen. Sensitivity analyses of these parameters are presented later in this chapter.

Continuing to search for an improved solution after initially connecting to the existing road network adds considerable processing time because 1) the



Figure 4. Diagram used to show how the haul distance and junction angle can be controlled.

additional links have to be checked to ensure that roads do not cross, and 2) more nodes have to be searched before a solution is accepted.

#### 2.1.3 Link Values

Road standards such as horizontal/vertical alignment can be controlled using parameters.

Parameters determine the link value and limit the number of feasible links. The

parameters are broken into three groups: 1) limits, 2) penalties, and 3) thresholds. Limits

establish strict bounds on links and thereby determine the feasible network (Table 2).

Table 2. Parameters used to limit the network.

Limit	Description		
Grade	Limits the maximum favourable and adverse grades		
Vertical alignment	Limits the percent of grade change over a horizontal distance of		
	road. For example, 2% change per 10m.		
Horizontal alignment	Limits the maximum radius of curve allowed for corners and		
	switchbacks.		
Distance between Switchbacks	Limits the distance between switchbacks.		
Junction angle	Limits the junction angle where the projected road meets the		
u luite die Sternik de Kriefen	existing road network.		

Penalties and thresholds work together to add extra cost to road links. For example, if a road grade is greater than a threshold value, a penalty is applied. The base cost for a link

is the link length (m), so if no penalties are incurred, the cost for a link will be its length. When penalties are encountered they add costs so the link cost will exceed the actual link length. There are two types of penalties: fixed and variable.

Fixed penalties are used to control switchbacks and stream crossings. If a stream is crossed or a switchback assigned, the penalty is added to the link cost regardless of the link length. The penalty represents the length of road that we are willing to build to avoid incurring the penalty. For example, a stream crossing penalty of 100m means that we are indifferent to crossing a stream or building an additional 100m to avoid the stream crossing.

Variable penalties (Table 3) are used to reduce the amount of road with undesirable characteristics. The penalty value is multiplied by a multiplier (link length or haul distance) and added to the link cost. The variable link penalties have the same intent as the fixed penalties, but are more sensitive to the link length. The penalty value is a linear function of the attribute value (radius of curve, grade change, or grade). The penalty value is 0 at the threshold and the penalty value maximum at the limit. Using the favourable grade penalty as an example, a maximum penalty value of 2, threshold of 5% and a limit of 15% will combine to create a penalty value of 0 at 5%, 1 at 10% and 2 at 15%. In this case a 30m 5%- link (30 + 30\*0) a 15m 10%-link (15 + 15\*1), and a 10m 15%-link (10+10\*2) all have a link value of 30.

The haul distance penalty works in a similar way, except there is no threshold and the penalty value is constant. For example, if the penalty value is 0.5 we are willing to construct 0.5m to reduce the haul distance by 1.0m. No threshold is required because the

penalty value is added to all links that connect the projected road to the existing road network.

Penalty	Description	Multiplier
Link Grade	The favourable and adverse grade.	Link length
Vertical Alignment	Rate of change in grade per horizontal distance.	Link length
Horizontal Alignment	Radius of curve.	Link length
Haul distance	The total distance from the landing to the exit point of	Haul distance
	the road network.	

Table 3. Variable penalties used to control the shape and road standards of the road network.

# 2.2 Sensitivity of the Road Location Algorithm to Input Parameters and Assumptions

Hardwicke Island is used as the study area. Hardwicke Island is located on the west coast of British Columbia between Vancouver Island and the mainland. Figure 5 shows the topography, with gentle slopes (less than 40%) on the west side and steeper slopes on the east side. The varying topography is suitable for testing the ability of the algorithm to project roads in both steep and gentle topography. This area was chosen because it is only 7,500ha, which makes it possible to run multiple scenarios quickly and makes

interpreting results relatively easy.



Figure 5. Map of Hardwicke Island (20m contour lines).

To test the sensitivity of the algorithm, an initial set of inputs (base set) is established. The base set contains 189 landings, 10 node/link sets (30 nodes/ha) and one log dump is used as the exit point for the network. The 10 node/link sets are used to quantify spatial randomness<sup>4</sup> and are used in other sensitivity analyses. The parameters used to test algorithm sensitivity are summarized in Table 4. The base set has no penalties, and does not consider haul distance or stream crossings. The 189 landings are at least 500m apart and 300m from lakes or the edge of the island. There are no existing roads in the base set, only the destination log dump (Figure 5).

<sup>&</sup>lt;sup>4</sup> Randomness in output values resulting from using different node/link sets of the same density.

Parameter	Base Set Value
Node density	30 nodes/ha
Maximum spatial randomness adjustment distance	4.56m
Maximum link length	75m
Maximum favourable grade	18%
Maximum adverse grade	10%
Maximum change in slope	2% change/10m
Minimum curve radius	50m
Maximum junction angle	90°
Landing order <sup>1</sup>	Closest to the network first.
Maximum number of links per node	20

Table 4. Base set of parameters used to test the sensitivity of the road location algorithm.

Maximum number of links per node | 20 <sup>1</sup> The landing order is the order in which landings are connected to the network. The landings order is ranked based on the straight distance to the existing network.

Next, parameters are added to the base set or adjusted within the base set to examine five inputs to the road location algorithm: 1) landing order, 2) landings density and randomness, 3) node spatial randomness, 4) node density, and 5) penalty and limit values.

## Network Indicators

Indicators are used to determine the effect of the inputs on road network attributes (Table

5). Road standards and network quality are two distinct types of road network attributes.

Road standards are indicators of individual roads attributes, such as horizontal/vertical

alignment, road grade, and number of switchbacks. The network quality indicators refer

to attributes of the entire road network and include the number of stream crossings, the

total length of road network, the haul distance and the number of landings accessed.

Table 5. Road network attributes and indicators used to determine the sensitivity of the road network algorithm.

	Attribute	Indicator
	Horizontal Alignment	Average corner angle (degrees)
d ard	Vertical Alignment	Average grade change (%change /10m)
oa nd	Favourable Road Grade	Average favourable road grade (%)
R Sta	Adverse Road Grade	Average adverse road grade (%)
	Number of Switchbacks	Average number of switchbacks per km
	Total Network Length	Total length of the network (km)
ad	Haul Distance	Average haul distance (km)
etv etv	Stream Crossings	Total number of stream crossings in the network
Z	Landings Accessed	Total number of landings connected to the network

The average corner angle ( $\alpha$  in equation [1]) is used as an indicator of horizontal alignment instead of the average radius of curve because when the corner angle approaches 0° (straight road) the radius of curve approaches infinity.

$$R = \tan(\frac{180^{\circ} - \alpha}{2}) \times \frac{L}{2}$$
[1]

where: R = radius of curve (m) L = length of the shortest link  $\alpha$  = corner angle



Figure 6. Diagram of road location showing the relationship between the corner angle and the radius of curve.

#### Landing Order

The order in which the landings are connected to the road network (landing order) affects the road network indicators. To test landing order effects, 200 random and 2 ranked landing orders are used. The two ranked orders connect landings based on the straight distance from the landing to the road network. One order is ranked shortest to longest distance (closest first) and the other order is ranked longest to shortest distance (farthest first). For all other sensitivity analyses, closest first is used.

#### Landing Density and Spatial Randomness

To simplify the landing density analysis, node spatial randomness is considered for only one node/link (30nodes/ha) set. For each of five minimum distances between landings (300, 400, 500, 600, and 700m), ten random sets of landings were selected, resulting in a

total of 50 landing sets. A 300m buffer around lakes and the edge of the island is used for all landings sets.

#### Extra Node Spatial Randomness and Density

Two aspects of extra node spatial randomness are examined. The first is the maximum distance a node can be adjusted from the grid position. As previously describe, to achieve node spatial randomness, a grid is established, then nodes are moved a random distance in the x and y direction. The maximum adjustment distance is tested with 5 distances, 0.00m (grid), 2.28m, 4.56m, 6.84m, and 9.13m, or respectively 0, 1/8, 1/4, 3/8, and 1/2 of the grid spacing (18.25m). The second aspect of node spatial randomness is the location of individual nodes. Using a different starting point for the initial grid and using different random numbers to move nodes from the grid position results in different node/link sets. The randomness associated with the location of nodes is accounted for by using 10 node/links sets. So, for each of the 5 maximum adjustments distances, 10 different nodes sets were created, resulting in 50 node/link sets. The node density trials account for node spatial randomness by using ten node/link sets for each of five node densities (10, 20, 30, 40, and 50 nodes/ha), resulting in another 50 node/link sets.

#### Limits and Penalties

The effect of penalties and threshold parameters is simplified by holding the threshold values constant. Table 6 contains the penalty values and Table 7 contains the limit values tested. Each penalty is added individually to the base set and each limit value is changed independently, and then the effects on network indicators are recorded. Note, that both adverse and favourable grades are added at the same time. To test the interaction between road standard penalties, one run changes the penalties for road grades, grade change and the radius of curve simultaneously. Then all the limits are changed simultaneously.

If only one node/link set is used, node spatial randomness can make trends hard to detect, so 10 different node/links sets are used for each value in Table 6 and Table 7. For each value or combinations of values tested, the 10 different indicator values are used to determine mean values and 95% confidence intervals.

<b>Penalty Description</b>	Threshold	Penalty values			
Adverse Grade	-0%	0.5	1.0	1.5	2.0
Favourable Grade	0%	0.5	1.0	1.5	2.0
Grade Changes	0% over 10m	0.5	1.0	1.5	2.0
Radius of Curve	50m	0.5	1.0	1.5	2.0
Haul Distance	N/A	0.5	1.0	1.5	2.0
Stream Crossings	Any Stream Crossing	50m	100m	150m	200m

 Table 6. Penalty values used to test the sensitivity of the road location algorithm to changing penalty values.

Table 7. Limit values	used to test the sen	sitivity of the road	location algorithm to
changing limit values			

Limit Description	Values				
Adverse Grade (%)	16	17	18	19	20
Favourable Grade (%)	8	9	10	11	12
Grade Changes (% change/10m)	1.0	1.5	2.0	2.5	3.0
Radius of Curve (m)	30	40	50	60	70
Maximum Junction Angle (°)	50	70	90	110	130
Link Length (m)	35	45	55	65	75
Maximum Number of Links per	10	20	30	40	50
Node					

# Distance Between Switchbacks and Switchback Penalties

The switchback trial only uses one node/link set. This simplifies the analysis, but it also

limits the analysis because node

randomness affects the results.

Switchbacks allow roads to climb steep

side hills faster, thus reducing the amount

of road required to access a landing.

Figure 7 shows two roads used to access



Figure 7. Example of switchbacks on Hardwicke Island. The grey road has no switchbacks and the black road has one switchback.

a potential landing on Hardwicke Island. The black road contains a switchback and only

requires 2.4km to access the landing while the grey road has no switchbacks and requires

3.9km of road.

The switchbacks penalties and the limits on the distance between switchbacks are tested together. For this analysis a switchback is a corner with a radius of curve  $\geq$  20m and  $\leq$ 50m. Table 8 contains the 33 combinations of 11 penalties and 3 limits used to test the effect of the switchbacks on the road network.

		Limit on the Distance Between Switchbacks			
		100m	200m	300m	
ĸ	0m	0 \ 100	0 \ 200	0 \ 300	
enalty for One Switchbac	100m	100 \ 100	100 \ 200	100\ 300	
	200m	200 \ 100	200 \ 200	200 \ 300	
	300m	300 \ 100	300 \ 200	300 \ 300	
	400m	400 \ 100	400 \ 200	400 \ 300	
	500m	500 \ 100	500 \ 200	500 \ 300	
	600m	600 \ 100	600 \ 200	600 \ 300	
	700m	700 \ 100	700 \ 200	700 \ 300	
	800m	800 \ 100	800 \ 200	800 \ 300	
	900m	900 \ 100	900 \ 200	900 \ 300	
d,	1000m	1000 \ 100	1000 \ 200	1000 \ 300	

Table 8. The limits on the distance between
switchbacks and penalties for one switchback used to
test the sensitivity of switchbacks.

# **3.0 Results and Discussion**

Results display two types of variation. The first type variation is caused by the order in which landings are connected to the network. The algorithm determines a solution to each landing independently, and sequentially adds them to the road network. Therefore, the solutions to connected landings affects the road required to connect subsequent landings. This type of variation is referred to as "preceding road variation". The second type of variation arises from node spatial randomness. Different nodes sets with the same node density will result in different road locations. As limit and penalty values change, node spatial randomness and preceding road variation make weak trends difficult to detect. Using multiple nodes sets and calculating the mean and confidence interval for the network indicators helps quantify the node spatial randomness.

#### 3.1 Landing Order

To test the landing order, the base set is used to generate 202 road networks by connecting the landings in different orders. Figure 8 contains six graphs of road network indicators: total road network length, average corner angle, average adverse grade, average favourable grade, average haul distance, and the number of landings connected. Each graph shows the average, the range and the values of the two ranked landing orders.

a) Total Network b) Average		c) Average	d) Average	e) Average Haul	f) Number of
Length (km) Corner Angle		Adverse Grade	Favourable	Distance	Landings
	(°)	(%)	Grade (%)		Connected
185	13.5	6.25	9.5	15 -	189
180 T			-	14	188
175	13.0	6 00	9.0	13	187
170				12	
165		•	<sup>8.3</sup>	11	180
160	13.0	5.75	8.0	10	185
155				9	184
150	12.5	5.50	7.5	8	183

Error bars indicate the range of the 200 random landing orders.

• Average value of the 200 random landing orders.

× Road network created using the closest landing to the network first.

- Road network created using the farthest landing from the network first.

Figure 8. The mean and range of the network indicators for 200 random landing orders, and the indicator values for the ranked landing orders: a) total network length, b) average corner angle, c) average adverse grade, d) average favourable grade, e) average haul distance, and f) number of landings connected.

Landing order provides insight into preceding road variation. Because only the landing order is changed, all the variation in the indicators is caused by preceding road variation.

Figure 8a, shows that the total road network length has a range of 27.9km (17% of the

mean). The average haul distance has a range of 6.3km (65% of the mean, Figure 8e). The other road network indicators show less variation, and this is consistent with other trials. In fact, the haul distance parameter was added in response to wide variation in the average haul distance (a range of 20km, over twice the mean value). To reduce the variation of an indicator, the respective penalty values can be increased, but this can cause other problems. For example, increasing the haul distance penalty reduces the average haul distance variation, but it increases total network length. The large variation between the indicator values shows the need for a heuristic or exact solution method that can be completed in a reasonable time frame.

Connecting the landings based on the ranked distance from the road network is a consistent way to create road networks for comparison. Here, most indicator values are close to the mean except for the average adverse grade, the average haul distance, and the number of landings connected.

Two other important indicators associated with landing order are processing time and visual inspections of the road networks. The processing time for the closest landings is the lowest (153sec<sup>5</sup>) because shorter roads are projected, while the processing time for the farthest landings is over double this value (372sec). The road networks can look very different because roads are in different locations depending on the order in which the landings are connected. Figure 9a, shows the road network created using the farthest landing from the network first, and Figure 9b shows the road network resulting from using the closest landing to the network first. Possible road classes are included in the Figure 9a, and Figure 9b to help with the interpretation. The road classes were

<sup>&</sup>lt;sup>5</sup> All processing times are determined using an 800mhz processor.
determined using a harvest schedule, input road costs and the dynamic program presented in chapter 2.



(a) Farthest landing from the road network first.

Figure 9. Road networks developed connecting; a) farthest from the road first, b) closest to the road first.

For the network created using the farthest landings first (Figure 9a) the timber flow is concentrated into one mainline. This happens because a long road is first located through the middle of the island and other roads subsequently connect to it. The closest landing first creates many roads available for subsequent roads to connect to, resulting in less mainline and more branch and spur roads.

#### 3.2 Landing Density and Randomness

Landing selection is an important part of road design. Here landings are randomly chosen according to a minimum landing spacing distance. To test the effects of landing selection. 10 landings sets are created for each of five minimum landing spacing distances (300, 400, 500, 600, and 700m). Because the landings are randomly chosen, the number of landings for a given minimum landing spacing varies. There is a strong relationship ( $R^2 =$ 0.9664, Figure 10a) between the total network length and number of landings. This relationship is important for determining the effects of landing density. The average haul distance (Figure 10b) shows no relationship with the number of landings used. However, there is large average haul distance variation when there are similar numbers of landings. with the greatest difference being over 6km for 100-125 landings. The horizontal alignment (Figure 10c) and the vertical alignment vertical (Figure 10d) show improvement with fewer landings. This is a result of the topography and the number of roads required. With few landings, roads avoid difficult topography, but as the number of landings increase, roads are unable to avoid difficult topography and the average alignment indicators increase. With more roads in difficult topography, the average grade values are also expected to increase. However, the average grades (Figure 10e and Figure 10f) show no relationship with the number of landings. The reason is that once a road accesses a particular elevation on a hillside, subsequent roads do not require severe grades because they can connect to the first road. Therefore, additional roads tend to follow contour lines (gentle grades) at the expense of horizontal and vertical alignment.



Figure 10. Graphs of landing density results: a) total network length, b) average haul distance c) average corner angle, d) average grade change, e) average adverse grade, and f) average favourable grade.

#### 3.3 Node Spatial Randomness

For each maximum distance that nodes are shifted from the grid, 10 random node/link sets are used. This allows for means and 95% confidence intervals to be calculated. Figure 11 contains six graphs of road network indicators: total road network length, average corner angle, average grades, average haul distance, the number of landings connected, and the average grade change.



Figure 11. Node spatial randomness results: average and 95% confidence interval for a) total length, b) average corner angle, c) average grades, d) average haul distance, e) number of landings connected, and f) average grade change.

The error bars indicate variation associated with node spatial randomness, suggesting that if one node/link set were used, the result would fall between the confidence intervals 95% percent of the time. The number of landings connected (Figure 11e) and average corner angle (Figure 11b) are significantly smaller for the grids (0m). The average corner angle is smaller because there are more straight roads (0° corner angle) for a grid than for the random patterns. The average grade change (Figure 11f) is lowest at the 4.56m maximum distance because this node coverage provides the best opportunity to choose good vertical alignment. The intent of the spatial randomness is to allow for a wider range of horizontal and vertical alignments so that roads can be projected in broken topography. This is reflected in the number of landings connected to the network (Figure 11e), where on average, approximately two more landings are connected relative to the grid. The landings not connected on the grid require roads to be located in broken and steep topography, but with the limited range of horizontal alignment associated with the grid, no roads are able to connect these landings. The highest average number of landings connected is associated with a maximum distance of 4.56m (1/4 the grid spacing). The number of landings that connect to the network influences the total network length (Figure 11a) and average haul distance (Figure 11d). The road length increases as more landings are connected. The haul distance increases as more landings connect to the network because of the topography of Hardwicke Island. Most of the landings far from the dump (on east side of the island) are difficult to connect to the network because they require roads in steep and broken topography. So, as the number of landings connected decreases, the average haul distance decreases because landings far from the dump are not connected to the network because of the limited range of horizontal and vertical alignment.

#### 3.4 Node Density

Ten different node/link sets were created for each node density (10, 20, 30, 40, and 50nodes/ha). The mean value and 95% confidence intervals of six road network indicators (total road network length, average corner angle, average grades, average haul distance, the number of landings connected, and average grade change) are shown in Figure 12.



Figure 12. Node density results: average and 95% confidence interval for, a) total length, b) average corner angle, c) average grades, d) average haul distance, e) number of landings connected, and f) average grade change.

If the node density is too low (less than 30nodes/ha for Hardwicke Island) the road network is unacceptable because too few landings connect to the road network (Figure 12e). Table 9 shows that lower node densities have fewer links per node, longer average link lengths and gentler average grades. These combine to limit the horizontal and vertical alignment and make it impossible to connect the landings in steep and broken topography.

Node Density (nodes/ha)	Average <sup>1</sup> Number of nodes	Average <sup>1</sup> Number of Links	Average Links/node	Average Link Length (m)	Average Link Grade (%)	Average Processing Time (sec)
10	79,709	929,694	11.7	53.6	7.6	37
20	159,259	2,633,788	16.5	45.2	8.0	88
30	235,796	4,278,094	18.1	39.9	8.2	154
40	309,699	5,887,134	19.0	36.4	8.2	223
50	382,027	7,453,671	19.5	33.8	8.3	320

Table 9. The average number of nodes, average number of links, average links/node, average link length and average link grade for the 50 node/link sets used for the node density trials.

<sup>1</sup>Average values are required because node spatial randomness causes small variation in the number of nodes (<10 nodes) and links (<50 links) for a given node density.

The number of landings connected affects the total length of network (Figure 12a), the average haul distance (Figure 12d) and the average grades (Figure 12c). With fewer landings the total length of the road network decreases. At lower densities the landings on the east side of the island do not connect to the network and this results in a shorter average haul distance. The average favourable grade also decreases as the number of landings connected decreases because of the reduced length of extreme grades required in steep and broken topography. The node density does not affect the average adverse road grade because Hardwicke Island does not require steep adverse grades to access landings in difficult topography.

The average corner angle (Figure 12b), the total network length (Figure 12a) and the average grade change (Figure 12f) are related to the average link length. Higher node densities have smaller corner angles because the radius of curve is a function of the link length and corner angle (equation [1]). As the node density increases, the average link length decreases (Table 9) and the average corner angle is forced to decrease to stay within the limit of the radius of curve. Longer link lengths allow roads to cross ridges and gullies thereby shortening the total road length. The shorter average link lengths

associated with the high node densities create longer roads because roads are forced to follow broken topography. The average grade change (Figure 12f) is a function of the percent grade difference between the links and the length of the links. As the average length of links decreases, the average grade change per length increases.

One other important factor for node density is the processing time. The processing time increases as the node density increases (Table 9) because more nodes offer more options when connecting roads. Processing time increased by approximately one order of magnitude from the lowest density to the highest density.

#### 3.5 Limit and Penalty Values

Limits and penalties are both used to control the road standards and the network quality. Penalties add cost to undesirable links so that the algorithm will "favour" other links, and limits unacceptable links, thereby restricting the network to only the feasible links.

# Road Grade, and Horizontal/Vertical Alignment Penalties and Limits

Depending on the topography, interactions and trade-offs can occur between road grade, horizontal/vertical alignment and road length. To determine these interactions the penalty and limit values for the road standards are added to the base set, and the indicator values for road grade (average adverse and favourable grade), horizontal alignment (average corner angle), vertical alignment (average grade change), total road length and number of landings connected are recorded. Figure 13 shows the results from changing penalty values and Figure 14 shows the results form changing the limit values. Because node spatial randomness can affect these indicators, the average and 95% confidence intervals of 10 spatial random node/link sets are used.



Figure 13. Graphs of the alignment and grade penalty results: the total network length, number of landings connected, average adverse and favourable grades, average corner angle and the average grade change.



Figure 14. Graphs of the alignment and grade limit results: the total network length, number of landings connected, average adverse and favourable grades, average corner angle and the average grade change.

<sup>1</sup>Set value refers the values in Table 7 used to test the limits.

The confidence intervals in Figure 13 and Figure 14 reflect the variation associated with node spatial randomness. More than one node/link set is required to evaluate the interaction between the road grade and alignments because these trends are weak. The topography causes the interactions between the alignment and road grades (Figure 13, and Figure 14). The grade and alignment limits and penalties cause the same interaction because both are used to improve specific road standards, only using different methods. Improving the vertical alignment slightly compromises the horizontal alignment (increasing corner angle). However, the horizontal alignment penalty has the opposite effect, slightly decreasing the average grade change. This is attributed to the location and type of roads affected by the alignment penalties. Poor vertical alignment is only a consideration in steep and broken topography, so favouring better vertical alignment only affects roads located in these types of topography. Sensitive trade-offs between horizontal alignment, vertical alignment, and road grades are required to locate roads in steep and broken topography. Specific topography dictates the exact trade-offs, but here, improving the vertical alignment adversely affects the horizontal alignment and improves (lowers) average road grades. Conversely, the horizontal alignment is a factor in all types of topography, and in flat topography horizontal alignment is not limited by feasible road grades or vertical alignment. When horizontal alignment penalties are applied, roads in flat topography with good horizontal alignment are favoured, which reduces the average grades and improves average horizontal and vertical alignment. The average vertical alignment and average road grades are improved relatively little by the horizontal alignment penalty, suggesting that roads in steep and broken topography are not greatly affected by penalizing poor horizontal alignment. These alignment interactions are

consistent with the results of the road grade penalties. Steep and broken topography accounts for roads with the most extreme road grades, so road grade penalties affect roads in steep and broken topography the most. Favouring roads with gentler grades improves the vertical alignment and adversely affects horizontal alignment.

As expected, adding a penalty (Figure 13) affects the related indicator values and increasing the penalty value increases the effect. For example, adding grade penalties reduces the average favourable and adverse grades and the size of the reduction increases as the penalty value increases. If only one penalty is present at a time, adding a penalty should cause the algorithm to choose longer routes and increase the total length of the road network, but this is not always the case. This is because the preceding road variation is affecting the total network length in two ways. First, penalties favour easier links causing different road locations that affect subsequent road projections. Second, the landing order can change. The preceding roads can change which landing is closest to the network and thus the landing order. The preceding road variation also affects the number of landings connected and fewer landings can be expected to connect when higher penalties for road grade and vertical alignment are applied.

The limit values (Figure 14) affect the related indicators in a similar way as the penalty values (Figure 13). Relaxing the grade limits causes steeper average grades. However, unlike penalty values (Figure 13), the limit value has a more pronounced effect on the total length of the network. Relaxing the limits causes a shorter total road network. This trade-off between road network length and road standards is important for assessing the impact to the road budget (construction, hauling and maintenance costs) associated with road standards. Decreasing road standards will have lower construction costs but high

hauling costs. However, the length of the road network also will impact the road budget, so the road standard/road length interaction needs to be considered when planning road standards for the forest estates.

The number of landings connected is related to the limit values. More restrictive limits reduce the feasible network and the shortest path algorithm is unable to connect all landings. The vertical alignment limit is the best example; decrease the limit to 1.0% change/10m and on average 171 landings can be expected to connect to the network compared to 188-189 landings connecting for 3.0% change/10m. Even though fewer landings are connected to the network with stricter limits, the total network length increases. This is because longer, higher standard roads are required to connect the landings. Low standard spur roads would be needed to access the remaining landings. The right column in Figure 13 shows the results of adding and changing the grade and alignment penalties simultaneously. When the grade and alignment penalties are applied together the road network indicators improve less than if only one penalty is applied; however, all the road standards improve simultaneously.

The effect of changing all limits simultaneously (right column of Figure 14) can be explained by examining the interactions between alignments and grade limits. The average grades and vertical alignment change more when all limits are changed compared to changing individual limits, but the horizontal alignment has less change. Vertical alignment and road grade have positive interactions. Increasing one of the input variables causes both the grade and vertical alignment indicators to increase. However, increasing either the grade or vertical alignment parameter decreases the corner angle. Combing these relationships it follows that when all limits are changed, the grade and vertical

alignment indicators will show more affect because they compliment each other. But, changing all the limits causes less effect to the corner angle because the corner angle change is compromised by the negative relationship with the grade and vertical alignment limits.

Reducing all the limits simultaneously also has a large impact on the number of landings connected. When all limits are restricted to the lowest values (set 1) on average 118 landings can be expected to connect to the network. With individual limits, the lowest average number of landings connected was 172 for the vertical alignment. The low number of landings connected causes the large reduction in total network length (set 1).

# Haul Distance Penalty

Even though road standards such as

horizontal/vertical alignment and grades, construction materials and topography primarily determine the road location, the haul distance is an important factor for the whole network. Figure 15 shows average haul distance and total network length for road networks that access the same landings, and use the same road standard limits. These savings in haul distance could be significant to future profitability. Road networks with short hauling distance may require more road construction, but will have future savings in hauling cost. The specific hauling and construction costs of



Figure 15. Haul distance penalty results, a) total network length, b) average haul distance.

forest estates will determine if it is more economical to build less road and have higher future hauling costs or low hauling costs and high initial construction costs.

Using the haul distance penalty requires much longer processing times (6158sec or

1.71hrs versus 152sec without the haul distance parameter).

#### Stream Crossings

The stream crossing penalty has little affect on the total network length, but still decreases the number of stream crossings (Figure 16). Having the stream crossing penalty not only allows us to control the number of stream crossings but also gives us the ability to use stream crossings as an indicator for comparing road networks or harvest schedules.



#### Junction Angle

Figure 16. Stream Crossing penalty results, a) total network length, b) number of stream crossings.

The junction angle affects the total network length

(Figure 17a) and the average haul distance (Figure 17b). More restrictive junction angles (smaller angles) cause the algorithm to create longer roads to find appropriate locations to join to the network. Restricting the junction angle decreases the average haul distance because projected roads are forced to connect closer to the log dump to stay within the junction angle limit. Figure 18 shows the interactions between the junction angle and the haul distance. Comparing the three junctions (1,2 and 3), junction 1 has a long haul

distance and a large junction angle. As the road moves from junction 1 to 2 then to 3 haul distance and junction angle decreases but the road length increases.





Figure 18. Diagram used to demonstrate the interaction between junction angle, haul distance and road length.

Figure 17. Maximum junction angle limit results, a) total network length, b) average haul distance.

Link Length and Maximum Number of Links per Node

The maximum link length affects the number of

landings connected (Figure 19). As the link length decreases there are fewer possible solutions for landings that require road located in steep and broken topography and therefore fewer landings are connected. Restricting the number of links also controls the link length. Limiting the maximum link length to 35 or reducing the maximum the number of



connected versus the maximum link length (all node/link sets have a maximum of 20 links/node).

links per node to 10 causes no landings to connect the network. This is because the topography around the log dump requires links longer than 35m to connect roads to the log dump. When the number of links/node is 20 or greater the number of landings connected to the network is 189 (100%). Figure 19 shows that the number of landings connected with a maximum number of 20 links/node and a 75m maximum length is 188. Simply limiting the number of links allows for some links to be longer than 75m, so in steep in broken topography there are more options available making it possible to connect all the landings.

Figure 20 shows the mean value and 95% confidence intervals for the total length, average corner angle, average grades, average grade change and processing time by the maximum links/node (10 random node/link sets).



Figure 20. Maximum number of links per node results: average and 95% confidence interval for a) total length, b) average corner angle, c) average grades, d) average grade change, and e) processing time.

As the number of links/node increases the total length of the network decreases (Figure 20a), average corner angle increases (Figure 20b) and the average grade change decreases (Figure 20d). As shown in the node density sensitivity analysis (Table 9), longer links result in shorter roads, larger average corner angles, and decreased average grade change. However, the road grades increase (Figure 20c) because more links are available and the algorithm shortens road length at the cost of road grade. If road grade penalties were included this would not be a concern. The processing times (Figure 20d) show a linear increase with the number of links/node and the disk space and memory required also increase. For each forest estate, determining the best maximum link length and number of

links per node will be based on specific road standards, network quality, processing time, disk storage, and memory required.

# Switchbacks Penalty and the Limit on the Distance Between Switchbacks

In total, 33 road networks were created using the combinations of 11 switchback penalties and 3 limits on the distance between switchbacks. The network indicators total network length (Figure 21a) and number of switchbacks/km (Figure 21b) are used to determine the effects of the switchback parameters. Two general trends are seen in Figure 21. First, as the allowable distance between switchbacks increases, the switchbacks/km decrease and the total network length increases. Second, increasing the penalty for one switchback will decrease the switchbacks/km and increase the total network length. However, there are exceptions to these general trends resulting from preceding road variation and/or node spatial randomness variation. For example, the 300m limit on the distance between switchbacks has a lower total road length (155.1km) than at 200m (157.9km). We would expect a shorter total road length as the limit on the restriction distance between switchbacks decreases.



Figure 21. Graphs of the a) total length of the network, and b) the number of switchbacks/km for the 33 networks produce to test the sensitivity of the limit on the distance between switchback and the penalty for a switchback.

# 4.0 Discussion

The algorithm mimics the processes an engineer uses to manually project roads. These vector roads provide a fast way to project road networks that can be used for strategic planning. Testing the sensitivity revealed that considerable manipulation of the inputs is required. While this may seem to be a limitation of my work, I see the algorithm as a significant improvement over manual methods that have the same limitations (sensitive to the assumptions and preferences of engineers). The real advantage of my approach is that it can explore the impacts and sensitivities of road densities, road standards, haul vehicle limitations, digital map quality and harvest regulations. The algorithm can be used to analyse all these factors, it can be used on any topography and is capable of generating road networks for large (>200,000ha) forest estates.

However, the variation created with different landing orders is a concern. Determining optimal road network locations for tactical or operational plans will require an exact solution or a heuristic method. The problem is an extension of the Steiner tree network problem (Murray 1998). However, corners and grade changes require information from the proceeding link to determine the feasible links and link costs. Epstein et al. (2001) tackled the corner angle problem by using raster and node information. Within each raster there are several nodes, which identify the direction of timber flow and determine the feasible corners. By doing this, they create a network of potential road links that connect the landing to an existing road network. This network contains independent link costs, which can be solved using exact or heuristic network algorithms. There have been exact solutions and other methods of optimizing the solution to the STAP and MTAP presented (Murray 1998), however they can be time consuming. Heuristics can also be applied to

the method presented here. The landing order can be optimized using hill climbing, simulated annealing or other heuristics; however, the processing time makes heuristics impractical for any large forest estate. A prototype hill-climbing algorithm was tested on Hardwicke Island to determine an order of landings that might create a better road network. This algorithm reduces the overall total penalty cost of a network by randomly swapping landings within the landing order and keeping the cheapest road network. The preliminary results are promising, but the required processing time (approximately 1day for 10 landings) makes the algorithm infeasible even for small problems such as Hardwicke Island.

Creating road networks for areas with steep and broken topography proved difficult. Roads can only be located in theses types of topography if high node densities (≥30 nodes/ha) are used and care is taken in selecting limit and penalty values. Different topography requires different node densities, so node/link sets need different node densities depending on topography. The road class is also an important consideration when creating proposed road networks. High class roads have high road standards, which may limit the acceptable location for these roads. To accurately model road networks in strategic plans, the road standard and topography associated with each road class has to be considered. Creating road networks in stages based on road class will allow the road standards and acceptable topography for each class to be controlled.

The selection of landings needs more work. In my study, landings were selected randomly to be a minimum distance apart and a minimum distance from lakes or the edge of the island. However, landing selection should be based on yarding or skidding capability, harvest block boundaries, topography and existing roads. Epstein et al. (2001)

have developed a computerized method of determining landings. Their method identifies areas to be harvested by cable and ground based systems, and then the potential landings are established using raster topography information combined with yarding capabilities. Some form of this method would help determine landings that serve as end points of the road network.

Preliminary applications of these algorithms to large forest estates have been successful. So far the best approach is to select the penalty and limit values on a small representative area ( $\pm$ 10,000ha). Once the parameters values are satisfactory, a road network can be developed for the entire forest estate. Trial runs on an section of an forest estate with an area greater than 235,000ha (Block 4 of Tree Farm License 48 managed by Canfor in Chetwynd BC), with an existing road network, has shown run times ranging from 3.5 to 4.0hrs depending on the parameters used.

This algorithm also provides a fast way to "clean" existing road network data so that it is useful for computer models. Existing data often have duplicate road segments and nodes, road segments not connected to the network, or loops in the network. All these problems can prevent road networks data from working in computer models. To clean the data, a node/link set can be generated using the road segments. Using the end points of roads as landings, the road segment lengths as link costs, and destination points (log dump, or mill yard) the algorithm will sequentially select the shortest route from the end points to the destinations. This method cleans all road segments that connect to an end point of a road. However, some road segments do not terminate at an end point rather, they connect two roads, creating loops in the road network. Loops have to be "broken" to create a hauling direction for each road segment. This algorithm can be used to break the loop based on

the shortest haul distance. Finally, links can be added to end point road segments not connected to the network, and the algorithm run once more. The result is the shortest distance to the mill from each point. For large networks the shortest distance to the highway system or to mainlines is more logical than to the final destination point. Road networks can be cleaned in stages (highways, mainlines, branch roads, etc.) and the distance to the previous road class can be used rather than the distance to the final destination point.

# **5.0 Conclusions**

This method of sequentially adding roads to a road network using the shortest path algorithm can create networks for large areas. Through input parameters, road networks with different road standards and road network quality can be quickly generated. However, the solutions are not optimal, and there is variation caused by the order of landings and spatial randomness of the node/link set. More research is required to develop heuristics that can produce better networks with less variation by changing the landing order. However, because of the low levels of certainty in strategic plans, this method is still useful for developing road networks to be used with strategic harvest scheduling models. Generating multiple road networks will determine the effect and sensitivity of forest management policies on many road network indicators.

# **Chapter 2: Determining The Optimal Road Class and Deactivation Strategies Using Dynamic Programming**

#### Abstract

Classical, minimal cost analysis can be used for single decisions such as which road standard to construct or which level of deactivation to implement. However, when construction, upgrading and deactivation strategies are determined simultaneously, the problem becomes very complex and decision support systems are needed. This chapter develops an optimal road class and optimal deactivation model using Dynamic Programming. The model is tested on road networks that were developed for Hardwicke Island using the methods presented in Chapter 1. Sensitivity of inputs such as construction costs, upgrade costs, hauling and maintenance costs, deactivation costs, length of time horizon, discount rate and haul volume are tested at three levels: 1) individual road segment, 2) multiple road segment interactions, and 3) the entire road network. Comparison of two road networks revealed that haul volume concentration, average haul distance and total road length are the most important variables that affect road class decisions and total network costs. For the case study, the road network with the lowest average hauling distance resulted in the lowest total cost (\$0.24/m<sup>3</sup> less) because the hauling costs are the largest component (46%) of the total road cost. A well-designed road network (in terms of the distribution of road classes) appears to be quite robust with respect to changes in inputs. The model could be modified to include risk associated with failures of deactivated roads and the risk of fire that is related to access to growing stock.

# **1.0 Introduction**

Thousands of kilometres of forest roads are constructed each year. At the same time, inactive roads are deactivated and may subsequently be reactivated. At the time of deactivation, there are choices related to the level of deactivation to implement. At the time of reactivation, some of these roads may be upgraded to a higher road class. These decisions are relatively simple when analysed separately, however, when considered simultaneously, there are a large number of possible combinations. We know little about how these decisions interact, especially at the strategic planning level. Because forest roads represent a significant and permanent investment, determining the optimal set of decisions related to road class is important.

This chapter develops and tests a Dynamic Programming (DP) approach for solving optimal road class and deactivation problems. First, the optimal road class and deactivation problems are explained. Second, the assumptions and data requirements of the model are explained. Third, the mathematical formulation of the DP is presented. Fourth, sensitivity of the algorithm to inputs costs, road networks, and harvest schedules is examined using a case study. Finally, the results and implications for forest management are discussed and conclusions are presented.

#### The Optimal Road Class and Deactivation Problems

Determining the optimal road class is done to minimize the total costs of road construction, maintenance and timber transportation (Walbridge 1990). The road class defines the design speed and the road standards. A high road class has gentle horizontal and vertical alignment, wide right-of-ways, good drainage systems and wide, high quality running surfaces. High class roads have high construction costs, but fast travel speeds that result in low transportation costs. The good running surfaces also require less variable maintenance and cause less damage to vehicles. In addition, there are fixed costs required to maintain the running surface, drainage systems and cut banks. High class roads have high fixed maintenance costs because they have wide surfaces, large cut banks, and large drainage structures.

Minimum total cost analysis is commonly used to determine the optimal road class. First, costs are categorized as fixed construction costs, fixed annual maintenance costs or variable hauling and maintenance costs. The timing and amount of timber volume to be transported are then estimated. Finally, total cost equations for two road classes are used to determine the break-even volume where the total costs are equal. If the expected volume is greater than the break even volume, the higher road class is constructed, and if the expected volume is less than the break even volume, the lower road class is constructed (Figure 22).



Estimated Volume (m<sup>3</sup>)



Roads with high volumes are assigned a high road class because the added construction and fixed maintenance costs are offset by lower variable maintenance and hauling costs. Conversely, roads with the least traffic are assigned to a low class.

A heuristic network algorithm has been used to determine the optimal road class within a road network (Sessions and Sessions, 1988). Each road segment in the road network is assigned multiple links, where each link represents a road class. The appropriate fixed costs and variable costs are assigned to each link and then the network algorithm determines the best route for volume to travel from supply nodes to a destination node. This solution identifies the optimal road class for each segment in the road network. In addition to construction, inactive roads are deactivated and reactivated as necessary. This cycle adds deactivation and reactivation costs that need to be incorporated into the analysis. Many factors determine the level of deactivation, including; the length of time the road is inactive, the level of access required during the deactivation period, the cost of the deactivation, environmental risks associated with drainage structure or road prism failures, and reactivation costs. In some jurisdictions, legislation dictates the level of deactivation (Moore 1994). Upgrades are also a consideration when determining the optimal road class strategy. Upgrades can further complicate the system because many upgrades occur in conjunction with reactivation.

Strategic harvest scheduling forecasts harvest rates and silviculture systems used across the landscape, which in turn determines the haul volumes and when they occur. Haul volumes in combination with road costs can then be used to estimate road classes, construction and maintenance schedules, road budgets, and potential impacts on other forest values.

The objectives of this chapter are: 1) to develop and test a dynamic programming model that will determine optimal road construction and deactivation strategies, 2) to identify interactions between inputs, and 3) to identify which inputs are most sensitive with respect to model outputs.

# 2.0 Methods

The methodology is presented in two sections. First, a description of the data requirements, assumptions, and mathematical formulation of the algorithm are presented. Second, the sensitivity analysis of input variables is explained. The sensitivity analysis is presented for three levels; 1) at the road segment, 2) multiple road segment interactions, and 3) the entire road network.

#### 2.1 Mathematical Formulation of the Dynamic Program

#### Assumptions

Two assumptions are made to simplify road class and road location interactions. First, I assume that the road location allows for any road class to be constructed at its respective cost. Second, I assume that costs represent the road class on average topography and soil types.

#### Data Requirements

Roads are broken into straight segments with unique features (grade, alignment, soil type, and haul volume) and are generally 10 to 75m in length. The road segment is identified by its end points, which have x, y and z coordinates. To determine the optimal road class for each segment, the algorithm requires three inputs during each time period; 1) length of the time period (years), 2) volume of timber moving across the segment ( $m^3$ ), and 3)

the initial state of the road segment (proposed, constructed, or deactivated). The final information required is the cost associated with each road class, as shown in Table 10.

Cost	Description
Construction	The cost to construct one km of road (\$/km).
Deactivation	The cost to deactivate one km of road for each deactivation level (\$/km).
Reactivation	The cost to reactivate one km of road (\$/km).
Upgrade	The cost to upgrade one km of road to a higher road class (\$/km)
Reactivate and upgrade	The cost to reactivate and upgrade one km of road to another road class (\$/km)
Variable maintenance and	The variable maintenance cost and the hauling cost (\$/m <sup>3</sup> /km)
hauling	
Fixed maintenance	The fixed cost of maintaining a road in each road state (\$/km/yr)

Table 10. Road costs required for each road class.

#### Mathematical Formulation of the Optimal Road Class Algorithm

For clarity, the algorithm is first explained without considering deactivation strategies. After the basic road class algorithm has been described, deactivation is introduced to complete the formulation.

The optimal road class problem is similar to a classical equipment replacement problem and can be formulated as a dynamic program. The DP uses a backwards recursive network as shown in Figure 23. Three road classes are used to explain the algorithm (class 1 is the best and class 3 is the worst). In this example class 1 roads are also referred to as mainlines, class 2 roads are branch roads and class 3 roads are spur roads.

In each time period, there is at least one node, which represents a decision point. The first node is the construction period, where there are three decisions possible: 1) build class 1, 2) build class 2, or 3) build class 3. Each of these decisions connects to another node. The class 1 node has no further decisions; it is a class 1 road for the remainder of the planning horizon. The class 2 node has two decisions, upgrade to class 1 or stay with class 2. If the road is upgraded to class 1, the node in the next time period has no further decisions. If

the road stays as class 2, the same decision applies in next time period. The class 3 node has three choices; it can remain as class 3 or it can be upgraded to class 1 or class 2. The nodes are connected with links, which have the associated cost for each decision. A collection of links and nodes that stretch from a time period to the end of the planning horizon is called a branch.



Figure 23. Sample network for the optimal road class problem (without deactivation options).

The level of deactivation can be incorporated in two ways. First it can be incorporated by using predetermined times based on the length of inactivity. For example, if a road is inactive for less than 10 years, deactivation level 1 is used, and if the road will be inactive for greater than 10 years, deactivation level 2 is used. The second way to address the deactivation level is to incorporate it as a decision variable within the DP. The algorithm will then determine both the optimal road class strategy and the road deactivation strategy. To incorporate the level of deactivation as a decision variable, nodes and links are added to the network. Figure 24 shows an example of a class 2 branch road when it is deactivated at the end of time period 1 and reactivated at the start of time period 4. The example shows options for 3 levels of deactivation plus the additional option of not deactivating the road.



Figure 24. Example of nodes and links required to determine the optimal deactivation level.

The steps for solving the DP are the same whether the deactivation strategy is incorporated or not. Determining the minimum path from the construction node to the end of the network determines the optimal road class and deactivation strategy for each time period. There are three steps used to calculate the solution.

# Step 1: Calculate the Value of the Links

With three road classes there are six calculations at each time period. Only three equations are required to determine the link values because Boolean variables are used to represent most road activities. For example, the construction cost is only applied at the construction time period when  $Const_t = 1$ , as shown in Equation [1]. Equation [1] determines the values for links that are not upgraded by summing the necessary costs for construction, reactivation, maintenance and hauling, and deactivation. Equations [2] and [3] determine the costs for the upgrade links. If the road is currently active, Equation [2] is used to sum the upgrade cost, maintenance costs, hauling cost, and cost of deactivation. Equation [3] is used if the road is currently deactivated, and requires reactivation and upgrading.

$LV_{t,i} = Len \begin{bmatrix} Con\\ T_t \end{bmatrix}$	$nst_{i} * Cc_{i} + \text{Re} act_{i,i} * Creact_{i,i} + V_{i} * Cv_{i} + B_{i} * Cb_{i} + D_{i,i} * Cd_{i,i} + Deact_{i,i} * Cdeact_{i,i}$	[1]
$LV_{\iota,i,j} = Len[C\iota$	$u_{i,j} + V_i * Cv_j + T_i (B_i * Cb_j) + Deact_{i,l} * Cdeact_{j,l}]$	[2]
$LV_{t,i,j} = Len[Cr$	$u_{i,j,l} + V_i * Cv_j + T_i (B_i * Cb_j) + Deact_{i,l} * Cdeact_{j,l}]$	[3]
Where: $LV_{t,i}$ $LV_{t,ij}$ Len $V_t$ $T_t$	<ul> <li>the link value of class <i>i</i> at time period <i>t</i> (\$).</li> <li>the link value of upgrading from class <i>i</i> to class <i>j</i> at time period <i>t</i> (\$).</li> <li>the length of the road link (km).</li> <li>the volume traveling over the link at time period <i>t</i> (m<sup>3</sup>).</li> <li>the length in years of time period <i>t</i>.</li> </ul>	
Const <sub>t</sub> Deact <sub>t</sub> React <sub>t</sub> B <sub>t</sub> D <sub>t,1</sub>	<ul> <li>= a Boolean variable: 1 if constructed in time period t otherwise 0.</li> <li>a Boolean variables: 1 (each deactivation level l) if deactivated in time period otherwise 0.</li> <li>= a Boolean variables: 1 (each deactivation level l) if reactivated in time period otherwise 0.</li> <li>= a Boolean variable: 1 if the road is active in time period t otherwise 0.</li> <li>= a Boolean variable: 1 if deactivated in time period t (deactivation level l) otherwise 0.</li> </ul>	d <i>t</i> i <i>t</i>
Cc <sub>i</sub> Cdeac Creacu Cv <sub>i</sub> Cb <sub>i</sub> Cd <sub>i,l</sub> Cu <sub>i,j</sub>	<ul> <li>= the cost to construct road class <i>i</i> (\$/km).</li> <li><i>t<sub>i,l</sub></i> = the cost to deactivate road class <i>i</i> to level <i>l</i> (\$/km) at the end of time period t.</li> <li><i>t<sub>i,l</sub></i> = the cost to reactivate road class <i>i</i> of level <i>l</i> (\$/km).</li> <li>= the variable cost per m<sup>3</sup> for road class <i>i</i> (\$/m<sup>3</sup>/km).</li> <li>= the fixed cost to maintain active road of class <i>i</i> (\$/km/year).</li> <li>= the fix cost to maintain a deactivated road of class <i>i</i> deactivation level <i>l</i> (\$/km/year).</li> <li>= the cost to upgrade from class <i>i</i> to <i>j</i> (\$/km).</li> </ul>	

Step 2: Determine the Cheapest Branches for Each Time Period

The DP determines the cheapest branch from each time period to the end of the time horizon. At the construction node there are three branches to compare, 1) class 1 branch, 2) class 2 branch, and 3) class 3 branch. For all other time periods there are 6 branches. Class 1 nodes have one branch (Equation [4]), the class 2 nodes have two branches (Equation [5]) and the class 3 nodes have three branches (Equation [6]). Starting at the last time period, the algorithm works backwards to determine the cheapest branch using Equations [4] to [6].

$$BV_{t,3} = \min \begin{cases} LV_{t,3} + BV_{t+1,3} \\ LV_{t,3,1} + BV_{t+1,1} \\ LV_{t,3,2} + BV_{t+1,2} \end{cases}$$

$$BV_{t,2} = \min \begin{cases} LV_{t,2} + BV_{t+1,2} \\ LV_{t,2,1} + BV_{t+1,1} \end{cases}$$

$$BV_{t,1} = LV_{t,1} + BV_{t+1,1}$$

$$BV_{t,1} = LV_{t,1} + BV_{t+1,1}$$

$$BV_{t,1} = the link value of class i at time period t ($). LV_{t,ij} = the link value of upgrading from class i to class j at time period t ($). BV_{t,i} = the branch value from time t to the end of the planning horizon for road class i ($). ($).$$

# Step 3: Choose the Cheapest Branch at the Construction Node

Once the minimum values for all the branches are determined, Equation [7] is used to

choose the cheapest branch.

 $BV_{construct,\min} = \min \begin{cases} BV_{construct,3} \\ BV_{construct,2} \\ BV_{construct,1} \end{cases}$ [7]

Discounting is incorporated by multiplying each link value by a discounting factor (Equation [8]). The discount factor is added to Equations [1], [2], and [3] before the minimum branches are determined.

$$DF_{t} = \frac{1}{(1+ir)^{T-\frac{T_{t}}{2}}}$$

Where:  $DF_t$ = the discounting factor for time t.ir= the interest rate (decimal %). $T_t$ = the length of time period t (years).T= the length of time from time 0 to  $T_t$  (years).

# 2.2 Sensitivity of the Optimal Road Class Algorithm to Input Costs and Assumptions

To test the optimal road class, a base set of inputs is established. This base set contains

input costs (Table 11), one harvest schedule and two road networks. Two levels of

deactivation are considered, level 1 and level 2. The road costs were chosen to so that the

DP produced a road network with a reasonable mix of mainlines (class 1), branch roads

(class 2) and spurs (class 3). Level 2 deactivation has no fixed maintenance costs because

...

the risk of road failure is intended to be so low that maintenance is not required.

Cost	Class 1	Class 1 Class 2		
Construction	(\$/km)	\$100,000	\$70,000	\$50,000
Variable hauling and maintenance	(\$/m³/km)	\$0.32	\$0.35	\$0.80
Fixed Maintenance				
Active	(\$/km/yr)	\$900	\$700	\$500
Level 1	(\$/km/yr)	\$300	\$300	\$300
Level 2	(\$/km/yr)	\$0	\$0	\$0
Deactivation		······		
Level 1	(\$/km)	\$10,000	\$8,000	\$6,000
Level 2	(\$/km)	\$25,000	\$15,000	\$13,000
Reactivate				
Level 1	(\$/km)	\$10,000	\$8,000	\$6,000
Level 2	(\$/km)	\$25,000	\$15,000	\$13,000
Upgrade to class				
1	(\$/km)	N/A	\$30,000	\$50,000
2	(\$/km)	N/A	N/A	\$20,000

	Table	11.	Base	set	of	input	costs	for	road	classes.
--	-------	-----	------	-----	----	-------	-------	-----	------	----------

A 30,000m<sup>3</sup>/yr even-flow harvest scenario is used to determine haul volumes. Two road networks are used to compare network level sensitivities, (network 1 and network 2). The difference between the networks arises from the method used to develop them. The road projection algorithm in chapter 1 is used for both networks, however, network 1 uses the road state to reduce the amount of active road and road reactivated, while road network 2 does not.

#### Individual Road Segment Sensitivity

Predetermined times are used to set the deactivation level (< 20 years deactivated to level 1,  $\geq$ 20 years deactivated to level 2). At the road segment level, the solution to the problem is exact, so a mathematical equation of the interaction between input costs is possible. This is an extension of the classical total minimum cost analysis where the total costs equations are equated to determine the optimal road class. Three road segments from network 1 are used to illustrate; 1) a mainline without deactivation requirements (segment 98), 2) a branch road (segment 99), and 3) a spur road (segment 138) (Figure 27). The costs in Table 11 are used as inputs and the haul volume and road states are determined from the harvest schedule.

#### Road Segment Interaction Sensitivity

The interactions between road segments are examined using the harvest schedule and selected portions of the road network 1. First, three contrived situations are used to demonstrate how it is possible to have a lower class road on the destination side of a higher class road. The explanations of these three situations help to verify that the DP is properly determining the optimal road class strategy. Then, the general interactions between road classes are examined using the costs in Table 11.

#### Road Network Sensitivity

Road network 1 is used to show the sensitivity of total costs, length of road class and length of deactivation to the input costs listed in Table 11. The values in Table 11 are used as a base case and inputs are subsequently adjusted. The construction costs, upgrade costs, variable maintenance costs, and haul volume are changed individually. Other inputs have little effect on the construction strategy, deactivation strategy, and the total cost, so these inputs are changed simultaneously. These include the active fixed maintenance cost for all classes, the reactivation and deactivation costs for all classes, and the fixed maintenance costs for all classes at level 1 deactivation. Level 2 deactivation requires no maintenance, so this cost is not adjusted. All values are changed 10% at a time, over a range of 50%-150% of the base value. This results in 11 scenarios (1 base value and 10 changed values) for each of the inputs. In addition, the time horizon is changed (100 years to 300 years in 20 years increments) and the discount rate is changed (0%-10% in 1% increments).

#### Sensitivity to Different Networks

The total length of the network, average hauling distance and flow concentrations all affect costs and construction strategies. These impacts are explored by comparing costs, total length, average hauling distance and flow concentrations in Network 1 and Network 2. Figure 25 shows the two road networks, where Network 1 has higher flow concentrations than Network 2. Both Networks used the base costs in Table 11.


Figure 25. Road networks used for determining the effect of total network length, average haul distance, and concentration of haul volume on the road costs: a) Network 1, and b) Network 2.

# **3.0 Results and Discussion**

# 3.1 Single Segment Level Sensitivity

Equating two branch equations and solving for the variable of interest determines the break-even point for two road classes. Equation [9] is the difference between building class 1 and building class 2, including a discount rate, and using predetermined times for

the deactivation levels (<20 years = level 1 and  $\geq 20$  years = level 2).

$$BV_{1,1} - BV_{1,2} = Len \sum_{i=1}^{N} \left[ \begin{cases} Const_{i} * (Cc_{1} - Cc_{2}) + \operatorname{Re}act_{i,i} * (Creact_{1,i} - Creact_{2,i}) + \\ V_{i} * (Cv_{1} - Cv_{2}) + T_{i} * B_{i} * (Cb_{1} - Cb_{2}) + \\ T_{i} * D_{i} * (Cd_{1} - Cd_{2}) + Deact_{i,i} * (Cdeact_{1,i} - Cdeact_{2,i}) \end{cases} \right] \frac{1}{(1+i)^{T-\frac{T_{i}}{2}}}$$
[9]

Where: N = the total number of time periods in the planning horizon.

The roots of Equation [9] are the break-even points were the variable of interest causes the road class to change. If there are no roots to Equation [9], the variable of interest will not cause the road class to change. Since *Len* is a constant applied to every time period, Equation [9] shows that the road class determination is independent of the segment length. By incrementally changing the values in Equation [9] a graph can be produced that gives the roots of the equation and an estimation of the sensitivity of the link to the variable. Figure 26b shows the relationship between class 1 and class 2 when the total haul volume is changed. The interest rate is 0% and the planning horizon is 300 years. In this case, the root for equation [9] ( $V_t$ ) is 10,000m<sup>3</sup>/yr. A road segment expected to haul less then 10,000m<sup>3</sup>/yr should be class 2 and if the volume is more than 10,000m<sup>3</sup>/yr, it should be class 1.



b) Class 1 - class 2 cost equations



Figure 26. Minimum cost analysis for construction of class 1 or class 2 for segment 98: a) both equations and b) result of equation [9] (class 1- class 2).

Figure 26a shows the minimum cost analysis used to determine the optimal road construction class. Using this method, the break-even volume for class 2 and 3 is 593m<sup>3</sup>/yr. These break-even volumes (10,000m<sup>3</sup>/yr and 593m<sup>3</sup>/yr) are consistent with average yearly haul volumes from the harvest schedule, which are shown in Table 12. Figure 27, shows the road segments used for this analysis (98, 99, and 138). Segment 98 accesses approximately 85% of the island, segment 99 accesses approximately 2% of the island and segment 138 accesses less than 1% of the island.



Figure 27. Location of the segments used for individual road segment minimal cost analysis: segments 98, 99, and 138 in network 1.

Segment	Class	Number of Deactivations / Reactivations		Average annual volume $(m^3)$	
		Level 1	Level 2		
Segment 98	Mainline (class 1)	0 / 0	0 / 0	23,992	
Segment 99	Branch road (class 2)	2 / 1	5/5	647	
Segment 138	Spur road (class 3)	0 / 0	2/1	102	

Table 12. Summary of road segments used to test the sensitivity at the single road segment level.

If discounting is included it will weight the future hauling and maintenance costs less and thereby cause the break-even volume to be higher. For example, an interest rate of 5% increases the break-even volume for class 1 and 2 to  $55,942m^3/yr$ , which would cause segment 98 to be constructed to class 2 instead of class 1 (Table 12).

The above analysis assumes that the road is always active and the volume is evenly distributed in each period. To determine how sensitive the number of deactivations and reactivations is, Equation [9] can be solved for ( $React_t + Deact_t = constant$ ). The decision to construct a mainline road for segment 98 is not sensitive to the number of

deactivations, because it would require 9 level 2, or 256 level 1 deactivations before it would be economical to construct to class 2. However, 6 level 2 deactivations for segment 99 will change it from class 2 to class 3. Because this segment has already been deactivated to level 2 five times, it is very sensitive to an increase in the number of deactivations.

All factors in Equation [9] interact, so it is difficult to isolate which variable is causing a particular road class to change. Upgrading and determining the optimal deactivation strategy adds other decision variables and creates more equations. When only the choice between two construction classes is considered, there is only one decision (determine the optimal road class to construct) and two equations (construct class 1 and construct class 2). Upgrading is a decision to be made at all active time periods after construction, and the optimal deactivation strategy is a decision to be made at each time the road becomes inactive. Since each decision requires an equation using the minimum cost analysis, it becomes prohibitive for simultaneously determining the optimal construction strategy (including upgrading) and the optimal deactivation strategy. The DP model overcomes these problems.

### 3.2 Interaction Between Road Segments

Generally, the road segments on the destination side of a single segment are of equal or greater road class. However, it is possible to have a lower class road on the destination side of a higher class road. Three situations were contrived to demonstrate how this happens. In the first situation, segments 64, 74, 75,76 and 79 from network 1 are used to illustrate (Figure 28). Simplified diagrams of these road segments are shown in Figure 29 and are used to explain the interactions.



Segment 64, 74 and 79 are initially built to class 3 (Figure 29a(i)). In a later time period, (Figure 29a(ii)), segment 64 could be upgraded to class 2 because of timber coming from segment 74. In an even later time period (Figure 29a(iii)), timber coming through segment 79 could upgrade segment 79 from class 3 to class 1, but it may not economical to upgrade segment 64 from class 2 to 1. This leaves segment 64 a lower class (2) than the segment 79 (class 1) on the source side.



Figure 29. Road segments used to illustrate two situations where a lower class is found on the destination side of a high class road.

Ti	me period	State			Activity			Class		
		74	75	76	74	75	76	74	75	76
h.	1	Active	Proposed	Proposed	Construction	and the same		2	1944 (j. 1944)	
	2	Deactivated	Proposed	Proposed	Deactivation			2		1
e.	3	Active	Active	Active	Reactivation	Construction	Construction	2	2	2
	4	Deactivated	Deactivated	Deactivated	Deactivation	Deactivation	Deactivation	2	2	2
	5	Active	Active	Active	Reactivation	Reactivation	Reactivation	2	2	1 1
	6	Deactivated	Deactivated	Deactivated	Deactivation	Deactivation	Deactivation	2	2	1
Latinia	7	Active	Active	Deactivated	Reactivation	Reactivation	and the second	2	2	1
	8	Deactivated	Deactivated	Deactivated	Deactivation	Deactivation		2	2	1

Table 13. Road states, activities and classes per time period for the situation in shown Figure 29b.

The second situation where road segments on the destination side can be a lower class than on the source side is when roads are reactivated. For example, if segment 64 is always active, and in subsequent periods segment 74 is deactivated and then reactivated, segment 74 maybe reactivated and upgraded while segment 64 is left at class 3. In this case, the cost of upgrading segment 64 in the absence of a reactivation requirement is not worth the investment.

The final abnormality in the road classes results from the timing of the activities on the road segments. The cost to reactivate and deactivate roads can be expensive. This results in the situation shown in Figure 29b and explained in Table 13. Only 8 time periods are shown to explain the process. At the end of the 8 time periods, segments 74 and 75 are class 2 and segment 76 is class 1. Table 13 shows that segment 76 requires the least

deactivation and reactivation and segment 75 requires more deactivation and reactivation than segment 74. Segments 74 and 75 require reactivation beyond period 6 and these costs are higher than the savings in hauling and maintenance costs that result from upgrading to a higher class. Since no reactivation of segment 76 is required after period 5, the savings in hauling and maintenance costs makes upgrading economical, and segment 76 is upgraded to class 1 in period 5.

Normally the interaction between road segments is more predictable. Figure 30 shows the road classes for road network 1 using the base value inputs. Most class 3 roads are short spurs that access only one or two harvest blocks. The switch from class 3 to class 2 happens where two roads meet or where timber enters the road network. Finally, class 1 roads start where class 2 roads join and the cumulative volume crossing segments is sufficient to trigger the highest class. Class 1 roads continue from this point to the log dump.



Figure 30. Road classes for Network 1 using the base costs.

#### 3.3 Road Network Sensitivity

First, the effects of the input costs on the length of road class constructed, upgraded, deactivated, and the total road cost are examined using network 1. Second, networks 1 and 2 are used to test the effects of haul distance, total length and harvest flow concentration on the length of each class constructed and network costs (total, construction, maintenance, deactivation/reactivation and hauling).

### 3.3.1 Input Cost Sensitivity

Sensitivity analysis is important for three reasons. First, it provides the means to test whether the model is behaving as expected. Second, it determines where best to concentrate data collection. Finally, determining how sensitive a system is to its inputs will help forecast a range of future conditions. For example, an increase in the cost of fuel will increase the hauling costs, which, depending on the relative differences between road classes, might change our decision of which class to build or upgrade.

Two methods are used calculate the total network cost; 1) the solution is reoptimized with the new input value (Reoptimized), and 2) the network stays the same and the total cost is recalculated (Old). First, a practical example of rising fuel costs that increase the hauling costs is used to illustrate. It helps to consider this in the context of three questions.

#### *Question* #1

If the <u>present</u> hauling cost is used to design the optimal road network, and the future costs turn out to be higher, what will be the increase in the total cost?

#### *Question* #2

If the increase to fuel costs is expected and the road network is designed with the <u>future</u> hauling costs, what will be the increase in the total costs?

#### Question #3

What are the savings of planning the road network with the future (uncertain) hauling cost compared to present hauling cost?

The difference between the reoptimized and old network costs is affected by changes in the construction and deactivation strategies. The reoptimized cost will always be less than or equal to the old network cost. If the construction and deactivation strategies are not affected by the change in the input variable, then the old and reoptimized network costs will be equal. If the construction and deactivation strategies change, the reoptimized network cost will be lower than the old network cost. The difference between the two costs and the change to the construction and deactivation strategies combine to become indicators of how sensitive the network is to a change in the input variable.

For this analysis all inputs except the discount rate, and time horizon are linearly related to the old network cost. The slope of this linear relationship determines the sensitivity of the old network cost to the input variable. The steeper the slope, the more sensitive the total costs are to a change in the input cost.

Three indicators are used to test the sensitivity of inputs: 1) the total network costs, 2) the amount of road class constructed or upgraded, and 3) the total amount of road deactivated. Figure 31 shows the effects of changing the construction costs, Figure 32 shows the effects of changing the upgrade costs, Figure 33 shows the effects of changing the variable volume costs (hauling and maintenance costs), Figure 34 shows the effects of changing the discount rate, haul volume and time horizon, and Figure 35 shows the effects of changing the fixed maintenance and deactivation costs.



Figure 31. The effect of construction costs on the a) total costs, b) length of class constructed and upgraded, and c) total length of road deactivated. In the far right column, all construction costs are changed simultaneously.

### Construction Costs

The total costs are most sensitive to the class 2 construction costs because for the base case, the majority (46%) of the roads are class 2 (Figure 31). The class 3 roads account for 39% of the total road network and the remaining 5% are class 1. It follows that the total costs are more sensitive to changes in the class 3 construction costs than the class 1 construction costs.

Comparing the old and reoptimized total costs, the class 2 construction cost show the largest difference. When the class 2 construction cost is changed, all road classes are affected. Changing class 3 construction cost only affects class 2 and 3 roads, while the class 1 construction cost affects only class 1 and 2. The length of upgrades is also

influenced by construction costs, but to a lesser extent. Increasing the class 1 construction cost or decreasing the class 2 construction cost makes it more economical to construct class 2 roads than to upgrade them to class 1 at a later date.

The length of road deactivated is also dependent on the length of road class constructed. As the length of class 2 road decreases and class 3 road increases, the length of level 2 deactivation increases. This suggests that level 2 deactivation is the most economical for roads that are class 3 with high haul volumes (close to class 2 haul volumes). As these marginal roads switch from class 2 to class 3 (increasing class 2 or decreasing class 3 construction costs) the deactivation strategy for some of these roads changes from level 1 to level 2. However, Figure 31 shows that the deactivation strategies are generally robust with respect to changing construction costs.

When all construction costs are changed simultaneously by a fixed percentage, there are large changes in the total cost (steep slope) and large changes in the length of class 2 and class 3 roads. The net effect of a fixed percentage change is that the more expensive higher class roads become even more expensive, relative to the lower class roads. This leads to an increase in class 3 roads, at the expense of class 1 and 2 roads. Upgrades and deactivation lengths are largely unaffected by these changes.



constructed and upgraded, and c) total length of road deactivated.

### Upgrade Costs

The base set of input costs produces a strategy with no upgrades and increasing the upgrade costs has little effect on the total cost (Figure 32). Reducing the upgrade cost from class 2 to class 1 causes a modest change for more road segments to be constructed to class 2, then upgraded to class 1 later. There is a marginal improvement in total cost with the reoptimized network relative to the old network when the costs to upgrade class 2 to 1 decreases. However, this reduction in total cost is so small that is barely detectable in Figure 32. Similarly, reducing the cost for upgrading from class 3 to 1 causes class 3 roads to be upgraded to class 1 roads, thereby reducing the total cost. Figure 32 shows that the upgrade costs have no effect on the deactivation strategies.



Figure 33. The effect of variable volume costs on: a) total costs, b) length of class constructed and upgraded, and c) total length of road deactivated. In the far right column, all variable costs are changed simultaneously.

## Variable Volume Costs

The class 1 variable volume cost (hauling and variable maintenance costs) affects the total cost the most, followed by class 2 and by then class 3 (steepest slopes in Figure 33). Larger differences between the reoptimized network cost and the old network cost are observed with the variable volume costs. Because of the long planning horizon (300 years), future volume costs are a significant component (46%) of the total costs, which makes it worthwhile to reoptimize the network when variable volume costs change. Changing the class 2 variable volume cost affects the lengths of all road classes. Changing the class 3 variable volume cost only affects the class 2 and class 3 lengths and changing the class 1 variable volume cost only affects class 1 and class 2 lengths. The

length of deactivated road behaves the same way to the variable volume costs as it does to the construction costs. Increasing the amount of class 3 road creates more level 2 deactivation.

When all variable volume costs are changed simultaneously by a fixed percentage, there are large changes in the total cost (steep slope) and large changes in the length of class 2 and class 3 roads. The net effect of a fixed percentage change is that the more expensive lower class roads become even more expensive, relative to the higher class roads. This leads to an increase in class 1 and 2 roads, at the expense of class 3 roads. As the length of higher class roads increases, there is a trend towards more level 1 deactivation and less level 2 deactivation. Upgrade lengths show virtually no change when the variable volume costs change.



Figure 34. The effect of the time horizon, discount rate, and haul volume on: a) the total costs, b) the length of class constructed and upgraded, and c) the total length of road deactivated.

### Time Horizon

Unlike the other inputs, changing the time horizon changes the total length of road constructed and the total length roads deactivated. As time progresses, more roads are deactivated, however the relative proportions of each level of deactivation show little change (Figure 34). However, the total costs and construction strategy do change considerably with time. The length of class 2 roads stays relatively constant over the time horizon, but less class 1 and class 3 roads are required for the shorter time horizons. There are less class 1 roads with short time horizons (<180 years) because there is not enough volume to justify constructing class 1 roads. There are less class 3 roads with

shorter time horizons because not all the roads in the network are constructed. Year 180 also corresponds with a decrease in the total annual network costs. The 140-180 year period is significant because this is when final construction of most the road network is completed. Following year 180, only a few class 3 roads are constructed. Before year 140 the total yearly network costs are lower because there is a low cumulative haul volume, and after year 180 the annual costs fall because of reduced construction. The rate of decline in the total yearly costs slows around year 240. This trend in total yearly cost is important because before the "plateau" (<140 years), not enough roads are constructed and not enough cumulative haul volume has been transported to accurately model the system. After the plateau (>180 years), the variable volume, maintenance and deactivation/reactivation costs dominate the system. Therefore, testing costs and construction strategies should be done with time horizons that correspond with this plateau (years 140-180). When sample cost sensitivities were tested at 100 and 300 years, it was found that the variable volume costs were still the most sensitive in both cases, however, the relative sensitivity of construction costs was higher at 100 years than at 300 years.

#### Discount Rate

Higher discount rates favour strategies with low initial costs and high future costs. Figure 34 shows that increasing the discount rate increases the length of class 3 and decreases the length of class 2 road constructed. Class 1 roads are not constructed when the discount rate is 1% or greater. The deactivation strategy also changes as the discount rate increases, until all the roads are deactivated to level 1 when the discount reaches 5%.

## Haul Volume

As expected, an increase in haul volume creates more class 1 and class 2 roads and less class 3 roads, while decreasing the haul volume favours low class roads (Figure 34). However, even though the construction strategy changes, there is little difference between the old and reoptimized networks total costs. As expected, changing all variable volume costs (Figure 33) and the haul volume (Figure 34) produce similar results. Both these scenarios cause large difference in construction strategies and the total cost relative to the base scenario. However, reoptimizing the network provides little improvement in total costs relative to the old network.



Figure 35. The effect of fixed maintenance costs on the a) total costs, b) length of class constructed and upgraded, and c) total length of road deactivated.

#### Deactivation Costs

Figure 35 shows that increasing the level 1 deactivation cost or decreasing the level 2 deactivation cost reduces the amount of level 1 deactivation and increases the amount of level 2 deactivation. The total costs are most sensitive (steepest slope) to the level 1 deactivation costs because most roads are deactivated to level 1. However, there is not much difference between the old and reoptimized total costs so there is no advantage to reoptimizing the network in this case.

#### Fixed Maintenance Costs

Figure 35 shows that the length of road class constructed is generally insensitive to changes in the active maintenance costs. Only the total network costs are affected, not the deactivation or construction strategies. The total cost and construction strategy are insensitive to the level 2 deactivation maintenance costs. However, decreasing the level 2 deactivation maintenance costs to be deactivated to level 2.

In summary, the inputs (costs, discount rate, and haul volume) change the construction strategy and the value of the total costs, however, there is little difference between the old and reoptimized total costs. This is attributed to the specifics of the case study. These include long time horizons, relative weights of each cost component, the range that the inputs were varied and the spatial distribution and timing of harvests. Changing the individual variable volume costs creates the greatest difference between the old and reoptimizes total costs (Figure 33), while changing other costs has little effect on the difference between the total costs. This is related to the amount of savings realized when the construction or deactivation strategy changes. For example, the construction costs account for 18% of the total costs, so the total costs change according to moderately steep

slopes as the construction costs change (Figure 31). However, the difference between constructing a class 1 road and class 2 road is only \$30,000/km (Table 11) or \$100/yr/km. As the cost for constructing class 1 roads increases, marginal roads (in terms of volume) change from class 1 to class 2. In order to save \$100/yr (old - reomptimized total cost) one km of road has to shift from class 1 to class 2. As the class switches, variable volume costs increase (\$0.32/m<sup>3</sup>/km to \$0.35/m<sup>3</sup>/km), which further reduces these savings. This that means many kilometres of road have to change from class 1 to 2 before there is a significant benefit to reoptimizing the solution. Re-optimizing the network is only required for the most sensitive variables, which in this case are the variable hauling and maintenance costs.

### 3.3.2 Effects of Different Road Networks

The road network itself affects the length of road classes and the total cost. To illustrate, two road networks are used with the same harvest schedule. Table 14 shows the road costs and length of road class constructed for each road network. The two main differences are 1) haul distance, and 2) harvest flow concentration. The hauling costs account for a large portion of the total cost (46% for network 1 and 45% for network 2) and the hauling costs are directly related to the haul distance. Network 1 has an average haul distance 630m longer than network 2, which results, in part, to the \$0.14/m<sup>3</sup> increase in hauling costs. The total length of network 1 is 11.9km shorter than network 2, resulting in \$0.08/m<sup>3</sup> savings in total construction costs. When developing network 1, the active road and road reactivated was minimized, which concentrates timber flow in the network. This creates a shift to the higher road classes. The lower deactivation/reactivation costs for network 1 is also a result of flow concentration and the total road length. With higher

flow concentration, more timber moves over the same roads during the whole time horizon, which means more roads remain active, which in turn reduces the amount of deactivation and reactivation. The fixed maintenance costs are lower for network 1 because it is shorter than network 2. Network 1 has the lower total costs because flow concentration and the shorter total network length outweigh the gains from the shorter haul distance in Network 2.

Table 14. Costs, lengths constructed and haul distance for network 1 and network 2.

Road	Cost (\$/m <sup>3</sup> )			Length Constructed (km)			Average Haul			
INCLWOIK	Total	Construction	Maintenance	Deactivation/ Reactivation	Hauling	Class 1	Class 2	Class 3	Total	(km)
1	7.36	1.30	1.39	1.29	3.38	9.2	98.3	69.4	176.8	9.76
2	7.60	1.38	1.55	1.43	3.24	6.0	111.1	71.8	188.9	9.13

In addition to monitoring the amount of each road class constructed, visual inspections of the road networks helps determine the flow pattern and concentration of haul volumes. In Figure 36, network 1 has less spur roads than network 2, which demonstrates the concentration of harvest volume. For example, in the circled area of Network 1, there are short spur roads and branch roads that concentrate the haul volume into one branch road that finally exits the area as a mainline. However, Network 2 has three parallel branch roads that exit the same area.



Figure 36. Network 1 has more flow concentration and less total length of road than Network 2, however, Network 2 has a shorter haul distance.

## 4.0 Discussion

The haul volume is affected by interactions between the roads and the spatial distribution of the harvest. This analysis revealed three important variables associated with road networks and harvest scheduling: 1) harvest flow concentration, 3) total road length, and 3) average haul distance. The most sensitive variables will differ for other areas where the cost components have different weights compared to Hardwicke Island. The timber flowing over roads is dependent on the harvest schedule and silviculture systems. Implementing silviculture systems that require multiple entries such as shelterwoods, selection systems, and commercial thinning will increase the time a road must be active. This will probably result in more high class roads. However, the spatial distribution and timing of harvests strongly affects these decisions, making it difficult to determine impacts without modeling the specific forest estate. The ability to examine the construction strategy, deactivation strategy and projected road costs make the DP approach a useful decision support system for assessing the impacts of multiple-entry silviculture systems.

Determining the optimal road class and deactivation strategy took on average 1.8sec of processing time on an 800Mhz computer (both road networks have on average of 4672 road segments, and 30 time periods).

The wrong level of road deactivation can have both environmental and economical impacts. The level of deactivation is similar to other road class decisions in that low levels of deactivation require little implementation cost but require more future maintenance costs. One other factor that has to be considered is risk. Low levels of deactivation have greater risk of road damage due to mass wasting or drainage failure. For some roads these risks increase with time causing higher maintenance and reactivation costs. In the future, such costs could be added to the DP model. Forest fire is another risk associated with road networks. When high levels of deactivation are used the ability to suppress fires by ground access is impeded. This can increase the risk of losing growing stock to fires and/or impede savage efforts. In populated areas, low levels of road deactivation allow the public easier access to the forest, and the chance of people

starting fires increases. These fire risks could be assessed and incorporated into the DP model.

Maintaining active road networks allows managers to access timber best suited for current markets. With high levels of deactivation, the roads become expensive and time consuming to reactivate, thus increasing foregone market opportunities because high valued stands can not be timely accessed. The methods presented here could incorporate a cost associated with high deactivation levels to account for lost revenue incurred by missed markets opportunities. The road model could also be used to assess how much mature timber is accessible over time, which could be used as an indicator of the firm's ability to react to markets.

The case study used a British Columbia coastal example with only three road classes. In other areas, seasonal roads complicate the procedures. Temporary winter roads commonly used in the interior of British Columbia are a case in point. These roads are used in the winter and are often only used for one year, which requires that the road be deactivated immediately following road construction. The short life of these roads may require that they be modeled at the tactical or operational level. The algorithm could be used at the tactical or operational level to address sensitivity of issues such as temporary roads or the type of haul trucks used. For example, switching from 6-axle to 7-axle trucks or using central tire inflation systems will affect the hauling and maintenance costs, which may change the road class.

The case study used road networks produced with the same set of possible road standards for each road segment. This created the need for my first assumption that the road location allows for any road standard to be constructed at its respective cost. To eliminate

this assumption, roads could be projected in stages (mainlines, branch roads, then spur roads). This allows the road standards to be different during each stage of network generation. Projecting road networks in stages should also improve the flow concentration because roads projected at the branch road stage logically connect to mainlines, and roads projected at the spur road stage logically connected to branch roads.

### **5.0 Conclusions**

The DP algorithm provides a fast and easy way to determine optimal road classes and deactivation strategies costs for a road network. Sensitivity analysis was used to demonstrate that the model behaves as expected. Sensitivity testing of the inputs provides useful information about costs and the distribution of road classes within a network. Sensitivity analysis can be examined at three levels; individual road segment, multiple road segment interactions and at the entire network level. Three important factors in network design are: timber flow concentration, haul distance and total network length. For Hardwicke Island, the network with the shortest total length and best flow concentration resulted in the lowest total cost. Although total cost is affected by changing input costs and total volume, cost savings associated with reoptimizing the road network are low. Contrary to intuition, the initial construction strategy appears to be sufficient even when future costs change. This suggests that a well designed network is quite robust with respect to changing input costs.

Other policies can be examined using the optimal road class procedures developed here. Future applications could determine the effect of management and silviculture policies, such as thinning or alternative silviculture systems. Other studies could estimate the risk

of fire to growing stock or indicate the level access to stands and the ability to respond to changes in market demand.

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# **Chapter 3: Incorporating Road Location and Optimal Road Class Algorithms with Strategic Harvest Schedules**

## Abstract

This chapter combines the road projection algorithm developed in chapter 1 and the DP algorithm for solving the optimal road class problem in Chapter 2 with a strategic harvest scheduler to examine the effect of block size and harvest policy (even flow and pass system) on road networks. Hardwicke Island is used as a case study, and road networks are developed using 6 harvest scenarios and 3 road projection techniques: 1) prepositioned roads, 2) dynamic harvest scheduling/road projection, and 3) road projection after harvest scheduling. Dynamically harvest scheduling/road projection reduced the amount of active road and the length of early road construction. However, this method increased the total length of road and haul distance, and created poor flow concentration. It was also found that smaller harvest blocks with an even flow harvest policy result in more active road for the pass system. The road projection, optimal road class and harvest scheduling algorithms allow many strategic road network questions to be explored. The methods developed here can be adapted for different conditions, assumptions and for large forest estates.

## **1.0 Introduction**

Forest road networks are major investments and they affect many other forest values. Like most spatial planning of forest activities, developing road plans for large areas (>100,000ha) is a difficult task. As the area increases, computer generated information becomes necessary because the amount of work required to manually develop and analyse road networks is prohibitive. Although roads are sometimes included in strategic harvest schedules, multiple road networks are rarely used to test the sensitivity of the proposed transportation system. As a result, we know little about interactions between harvest scheduling and road networks. The objective of this chapter is to explore the sensitivity of road network characteristics such as haul distance, total network length, timber flow concentration and methods used to generate road networks under a variety of harvest schedules. First, I describe road network planning within the context of strategic harvest scheduling. Second, I present the methodology used to generate road networks, determine the road network costs, and link the road networks to spatial harvest schedules. Third, the results from combining the harvest schedules with different networks in a case study are presented. Finally, the results are discussed and conclusions are presented.

#### Road Network Planning

Strategic plans use long time horizons (multiple rotations) and the entire forest estate to forecast harvest level and road network activity. It is unlikely that strategic road network plans will ever be implemented because of long time horizons and high uncertainty. However, strategic plans are valuable for guiding long-term access management, estimating the extent and location of road classes and assessing the impacts that roads have on other forest values, such as wildlife populations and hydrology.

Generally, road networks are prepositioned (projected before harvest scheduling) and typically only one road network is used. Nelson and Finn (1991) used one prepositioned road network to examine the effects of cut block size and exclusion period on harvest schedules and road network activities. Their results showed that small harvest areas and long exclusion periods increase the initial construction costs and create more active road because the harvest blocks are dispersed over the landscape. Clark et al. (2000) used a minimum spanning tree network algorithm to assess stand access during harvest scheduling, however, road access was based on grids and their road networks do not consider topography or road standards. More detailed analyses have been undertaken at a tactical level. For example, Richards and Gunn (2000) used a Tabu search heuristic with a prepositioned road network to develop a trade-off analysis of road access costs against the missed opportunities caused by not accessing stands at their optimal harvest age.

Road projections can be incorporated into harvest scheduling in three ways. Clark et al. (2000), describe two of these methods. First, prepositioned roads can be projected prior to the harvest schedule, and then these roads are triggered as the blocks are harvested. In this case, the roads are projected independent of the harvest schedule. Second, roads can be projected when the blocks are selected for harvest (e.g. simultaneous harvest scheduling and road projection). A third method, used in this chapter, is to produce an entire harvest schedule and then project all necessary roads to access each harvest block.

### 2.0 Methods

The methods are presented in three sections; 1) an overview of the procedures, 2) the procedures used to create the road networks for the strategic plans, and 3) a description of the harvest scheduling model.

#### Overview

In total, 13 road networks are created for 6 harvest scenarios. The six harvest scenarios represent combinations of 3 block sizes and 2 harvest flow policies. For each of the 6 harvest scenarios, road networks are created using; 1) prepositioned roads, 2) dynamic harvest scheduling/road projection and 3) road projection after harvest scheduling. Prepositioned roads use a common set of landings located in the centre of each forest cover polygon, so only 1 prepositioned network is used in all 6 harvest scenarios. The latter 2 methods use landings located within harvest blocks, which are aggregations of the forest cover polygons created by the harvest scheduling model. These 13 road networks and 6 harvest scenarios are used to examine the effects of block size and harvest schedule (even flow versus pass system) on the distribution of road classes, network costs and other road network characteristics.

To help create the harvest blocks<sup>6</sup>, large forest cover polygons were split into 10ha polygons. Figure 37 shows these 10ha polygons along with the initial age class distribution of Hardwicke Island. Approximately 83% of the area is  $\geq$  80 years and 52% of the area is  $\geq$  200 years. Only 5% of the area is under the minimum adjacency age of 20 years.

<sup>&</sup>lt;sup>6</sup> The blocking algorithm is explained later in the section "Harvest Scheduling Model".



Figure 37. The harvestable land base and initial spatial age class distribution of Hardwicke Island (10ha polygons).

## 2.1 Road Networks for Strategic Harvest Plans

When the roads are projected after the harvest schedule, the landings are selected within the harvest blocks. However, Chapter 1 showed that the length of road is related to the number of landings, so to standardize the number of landings between the different block sizes, more landings are located in the larger harvest blocks. To do this, landings were chosen within the harvest block to be more than 200m from the edge of a block and 500m from other landings. When projecting roads in each time period, a road network is created to access the harvest blocks for the first time period, and this network is then built on during the next time period and so on. This method mimics how forest development occurs. This periodic method is the only method that can control the length of active and reactivated road.

However, for the prepositioned roads, the harvest blocks are not known, so the landings are determined independent of the harvest blocks. To create prepositioned landings, the productive land base was aggregated into 10 to 23ha areas, and landings were selected in the centre of these areas. These areas were selected to standardise the number of landings with the larger harvest blocks. The rational for the block size and number of landings is presented later in this section after the harvest scheduling model is explained.

The road projection and road class algorithms used here are explained in Chapter 1 and 2, respectively. For consistency, all road networks were projected by connecting the landings closest to road network first and all networks use the parameters shown in Table 15. Note that the parameters for reducing the length of active and reactivated road are only used when dynamically projecting road in each time period because the road states must be known. The same road costs are used in all road networks (Table 16).

	Parameter	Value
Limits	Maximum favourable grade	22%
	Maximum adverse grade	15%
	Maximum grade change (vertical	2%/10m
	alignment)	
	Minimum radius of curve (horizontal	30m
	alignment)	
	Distance between switchbacks	200m
Fixed	Switchback penalty	200m
Penalties	Stream Crossing penalty	75m
Variable	Radius of curve	100m / 1.0
penalties	Favourable grade	10% / 1.0
(threshold /		15% / 1.0
value)	Averse grade	8 % / 1.0
		10% / 1.0
	Distance to mill	1/3 (1.0 metre of road can be added to reduce the
		distance to the mill by 3.0m)
	Amount of active road	1/3 (1.0 metre of road can be added to reduce the active road by 3.0m)
	Amount of road reactivated <sup>1</sup>	1/3 (1.0 metre of road can be added to reduce the reactivated road by 3.0m)

Table 15. Parameters used to project all road networks.

<sup>1</sup>Only used when roads are dynamically projected by period because the road state for the present and previous periods are required.

### Table 16. Road costs used for all road networks.

Cost		Class 1	Class 2	Class 3
Construction	(\$/km)	\$90,000	\$60,000	\$40,000
Variable hauling and maintenance	(\$/m³/km)	\$0.30	\$0.32	\$0.75
Fixed Maintenance			•	
Active	(\$/km/yr)	\$900	\$700	\$500
Level 1	(\$/km/yr)	\$300	\$300	\$300
Level 2	(\$/km/yr)	\$0	\$0	\$0
Deactivation				
Level 1	(\$/km)	\$10,000	\$8,000	\$6,000
Level 2	(\$/km)	\$25,000	\$15,000	\$13,000
Reactivate				
Level 1	(\$/km)	\$10,000	\$8,000	\$6,000
Level 2	(\$/km)	\$25,000	\$15,000	\$13,000
Upgrade to class			•	
1	(\$/km)	N/A	\$30,000	\$50,000
2	(\$/km)	N/A	N/A	\$20,000

#### Harvest scheduling model

To generate the harvest blocks and schedules, a harvest scheduling model that also builds blocks was created. The scheduler is a rule based simulator that creates blocks in each period, given a maximum and minimum block size. Figure 38 is a flow chart of the harvest scheduling model split into two parts, 1) the harvest scheduler, and 2) the block builder. The harvest scheduler determines the eligible polygons, harvests them according to block size rules, and stops when the target harvest volume is met. Polygons eligible for harvesting are forested, older than 80 years and at least 250m from polygons less than 20 years old. The harvest scheduler finishes scheduling a period when there are no more eligible polygons or the target harvest volume is met.



Figure 38. Flow chart of harvest scheduling model and block building model (1 period shown).

The block building algorithm aggregates the polygons into blocks. First the polygons are ranked in a queue based on a harvest priority, either by age or by distance to the log dump. All harvest scenarios use both harvest priorities. The first 4 time periods use the closest to the dump harvest priority, and in subsequent periods polygons are ranked based on the oldest first. To start the harvest block, the first polygon is removed from the queue. Neighbouring polygons are added to the initial polygon based on the number of boundary points that are shared. The shape of the block is more compact if polygons with the most

common boundary points are added first, but other criteria such as age, and species can be used. Polygons are added to the block until: 1) the maximum block area is surpassed, 2) the target volume for the time period is met, or 3) there are no more eligible polygons neighbouring the block. If the maximum area, or target volume is surpassed, the last polygon added is removed and the next in the queue is tried. This ensures that no block violates the maximum size and that the target harvest volume is never exceeded. Once a block is created, the size is checked to ensure it is larger than the minimum block size. If the size is adequate the block is harvested, and if not, block is discarded and a new block is created.

The average size of blocks and the average number of blocks harvested per period for the six scenarios are shown in Table 17. The

harvest scenarios use three block sizes (20-40ha, 40-80ha, and 80-120ha). The maximum and minimum block size restrictions were never violated.

Figure 39 shows the first time period for the six harvest scenarios. Only the blocks and landings for the first time period are shown because the harvest scheduler

 Table 17. Average block size and number of blocks

 harvested per period for the 6 harvest scenarios

Scenario	Average block size (ha)	Average number of blocks harvested per period	Total Number of Landings
Even Flow	/		•
20-40ha	36	13.5	326
40-80ha	73	6.9	329
80-120ha	111	4.6	325
Pass syste	m	· · · · ·	<b>1</b>
20-40ha	36	59.8	339
40-80ha	75	33.7	353
80-120ha	115	21.7	332
Prepositio	ned Network		337

dynamically schedules the blocks, which often results in overlapping blocks in subsequent periods. The landings within the blocks can be seen in Figure 39. There are 1 or 2 landings in the 20-40ha blocks, 2 or 3 in the 40-80ha blocks and 3 or 4 in the 80-120ha blocks. The number of landings depends on the shape of the block, but the median
number of landings is 1 for every 40ha. However, the harvest blocks from different time periods overlap, so on average, there is one landing per 21ha (not 40ha). To produce a similar number of landings for the prepositioned road network, the productive area was aggregated to blocks 10 to 23ha in size and landings were chosen to be in the centre of these blocks. This resulted in the total number of landings ranging from 325 to 353 (Table 17).



Figure 39. Time period 1 (0-10year) for the 6 harvest schedules. The harvest blocks are the grey polygons and the landings are the black points.

Figure 40 shows the harvest blocks, roads and landings for the first two periods for the three methods used to create the road networks. For each harvest scenario there are two sets of landings. The periodic method (Figure 40a) and the "all period" method (Figure

40b) have the same landings, while the prepositioned method (Figure 40c) have another set of landings. The landings for the periodic and "all period" methods (Figure 40a and b) are created from the harvest blocks. Figure 40a shows that there are no proposed roads for the periodic method because roads are not projected until they are required. The difference between the prepositioned (Figure 40c) and the "all period" (Figure 40b) is that the prepositioned landings are selected independently of the harvest polygons. Therefore unlike the periodic and "all period" road networks, the prepositioned road network is identical for all harvest scenarios.



Figure 40. Diagrams of period 1 and 2 for the three road network projection methods; a) periodic, b) "all period", and c) prepositioned. Heavy grey lines are the roads required for the first period, the black lines are roads required for the second period, and the light grey lines are proposed roads. The darker polygons are the blocks harvested in the second period.

#### 1.1 Harvest Scenarios

The harvest scenarios use three block sizes (20-40ha, 40-80ha, and 80-120ha) and two harvest flow policies; an even flow policy (30,000m<sup>3</sup>/yr), and an intermittent harvest pass system. As shown in Figure 41, the pass system harvests 1,500,000m<sup>3</sup> in the first pass followed by a 20-year green-up period, and then a second pass is made with the same target volume. The minimum harvest age is 80 years, but 100 years is left before the next pass. This results in harvest scenarios with two harvest entries 20 years apart cycling on 100 years intervals. The stands were left for 100 years to help achieve the target volume

(which is not met) and also to standardize the total target volume (30,000m<sup>3</sup>/yr or 9 million m<sup>3</sup> total) for all 6 harvest scenarios. The harvest scenarios do not attempt to harvest all the available timber, but rather test the effects of spatial harvest patterns and the timing of harvesting on road networks.

Adjacency and/or block size constraints often prevent achieving the target volumes (Figure 41). The harvest scheduling model does not allow the achieved volume to exceed the target volume, so with the larger block sizes it is difficult to achieve the target volume in each period. This causes the low volumes in years 30, 40, and 160 for the 80-120ha block size (Figure 41a). The total volume for the pass system is restricted by adjacency, not the target volume. The smaller blocks (20-40ha) disperse the harvesting, making much of the area unavailable due to adjacency (Figure 41b). This is illustrated in Figure 39 where the spatial pattern of the blocks for the 20-40ha pass system in period 1 extends over the entire forest.

a) Even Flow harvest systems



Figure 41. Target and achieved volume for the 6 harvest scenarios: a) even flow scenarios, b) multiple entry pass systems.

# **3.0 Results and Discussion**

The results are presented in two sections: 1) a comparison of average values for each harvest scenario/road projection method, and 2) periodic values for each harvest scenario/road projection method. Indicators used for comparison are active road, active stream crossings, haul distance, total network length, flow concentration and road construction.

#### 3.1 Average Values for each Harvest Scenario/Road Projection Method

# Average Active Road and Average Number of Active Stream Crossings

Figure 42 shows the average active road length and the average number of active stream crossings for the thirteen road networks and the six harvest scenarios. The average length of road per active period (TP) is used because it shows the average amount of active road required during harvesting, rather than the average amount of active road for all periods, which includes periods when there is no harvesting (i.e. pass system).



 $^{T}TP = Active time period (30 periods for even flow, 6 periods for pass system)$ Figure 42. Average active length of road and average number of streamcrossings for the three network methods.

When using the periodic method to project roads, penalties attempt to reduce the amount of active road and road reactivated (Table 15). These penalties are most effective when using the smaller blocks. With 80-120ha blocks there is no noticeable difference between the average length of active road according to the method used to create the network. With small blocks, the harvest is dispersed over the landscape so there is more opportunity to reduce the length of active road than with larger blocks. Regardless of the method used to project roads, larger blocks require less active road than the smaller blocks in the even flow scenarios. The pass system scenarios show no consistent trends in active roads according to block size. This is because the harvesting is maximized in each pass and the length of active road is similar for all block sizes.

Reducing the length of active road results in fewer active stream crossings, which is likely why the trends in stream crossings are similar to those in active roads for the even flow scenarios. However, the road projection algorithm makes no distinction between active and inactive stream crossings. When using the periodic method to project roads, the algorithm reduces the active road, but not always the number of active stream crossings. However, in general, the periodic method reduces the length of active road and the number of active stream crossings per period. No apparent trends are observed in the number of active stream crossings according to block size for the pass systems.

# Average Haul Distance and Total Length

Figure 43 shows the total length and average haul distance for the six harvest scenarios using the three road network generation methods.



Figure 43. Total length of the road network and the average haul distance for the three network generation methods.

Introducing penalties to reduce the length of active road affects other road network factors. Figure 43 shows that adding these penalties (periodic) increased the average haul distance and the total length of the network. The "all period" and prepositioned road networks have similar total lengths and are always considerably shorter than the periodic road networks. In general, the prepositioned road network shows a slight increase in total length as block size increases. The trend for the total network length to increase with block size is also apparent in the periodic road networks in the pass system. With smaller blocks, the total volume harvested under the pass system is reduced because of adjacency constraints. This reduction in volume harvested reduces the total length of road required. In addition, the ability for the periodic method to reduce the active road depends on the length of road projected in the first time period. When more of the road network is constructed in the first time period (decreasing block size under the pass system (Figure 39)), the periodic method is better at reducing the total network length.

The location of harvesting can affect the average haul distance. If more harvesting occurs far from the log dump the average haul distance will be longer. This is best seen with the prepositioned and "all period" road networks. The smaller harvest blocks disperse the harvesting which causes harvesting further from the log dump and results in increased average haul distance. This is particularly true in the early time periods (<50 years) when the harvest priority is closest to the dump. Because the prepositioned road network is the same for all scenarios, the haul distance is only affected by the location of harvesting. The other factor (besides the location of harvesting) affecting the average haul distance is the geometry of the road network. The input parameters, landings and the order in which the landings connect to the network all determine the geometry of the road network. Because the landings change for the "all period" method, it is difficult to determine which factor (harvest location or road network geometry) is affecting the average haul distance. However, when the periodic method is compared to the other methods, the average haul distances are generally longer. The periodic road networks favour roads

with less active road at the cost of total length, and the average haul distance. So, in most cases the average haul distance for the periodic networks is longer.

## Timber Flow Concentration

Flow concentration can be estimated by the distribution of road classes. More high class road and less low class road indicates better timber flow concentration. Although, the amount of road class is a good indicator of flow concentration, the amount of road class (certainly lower classes) is related to the total length of road in the network, so caution should be used when interpreting these results.

Figure 44 shows the kilometres of mainlines, branch roads and spur roads for the six harvest scenarios and for each road generation method.





Figure 44 shows there are no strong trends for the amount of class 1 road, regardless of the generation method, block size and harvest scenario. This is because all haul volumes are ultimately concentrated into mainlines and the total volumes are relatively similar. However, the length of class 3 roads is affected by the network generation method. Contrary to my expectations, and the findings in chapter 2, the periodic method generally reduces the amount of flow concentration. The periodic method was expected to reduce the amount of reactivated road by projecting roads that connected to active roads rather than inactive roads, which in turn would concentrate haul volumes. However, the penalty values used to reduce the length of reactivated road were too high (Table 15) causing the algorithm to create even more road by avoiding inactive roads. This additional road causes the high total road network length (Figure 43), and poor flow concentration as indicated by fewer class 2 roads and more class 3 roads in Figure 44.

Figure 45 shows the average annual costs, the total volumes and the total costs per  $m^3$  for the 6 harvest scenarios and the 13 road networks.



Figure 45. Average annual costs, total volume and total costs per cubic metre harvested for the 6 harvest scenarios.

The total target volume for all scenarios is 9 million cubic metres. Figure 45 shows the target is never met in all scenarios. This happens because the harvest scheduler will not allow the volume to be greater than the target. The even flow total volume drops slightly as the block size increases because harvest scheduler never violates the target volume or the minimum block size. With the smaller block size, the block volumes are relatively small, so the achieved volume can be closer to the target volume. The total volume for the pass system is restricted by adjacency, not the target volume. The smaller blocks disperse harvesting more than large blocks, making more area unavailable due to adjacency.

#### Average Annual Costs

Figure 45 shows the total costs expressed as average annual costs and per cubic metre costs. The total costs consist of construction, maintenance, deactivation, reactivation and hauling costs. The total volume harvested has a large influence on the hauling and maintenance costs, which make up the major portion of the total costs. It follows that the total volume harvested will have a large influence on the total costs. This can been seen in the total costs associated with the 20-40ha pass system scenarios, where the low volume causes low average total costs. As expected, the poor flow concentration, long average haul distances, and long total length associated with the periodic method consistently create road networks with high total costs.

The total costs for the even flow scenarios using the prepositioned roads are the same regardless of the block size. The road costs are similar because the total volume for each harvest scenario is similar. The average annual costs for the prepositioned road network mirrors in the pass system mirrors the corresponding harvest volumes. This suggests that over long time horizons, total road costs are relatively robust to changes in the harvest pattern and schedule, provide the volume is similar. It appears that a well designed road network will have low total road costs, and a poor designed road network will have high road costs, even when harvest policies change.

#### Total Costs per cubic metre

The haul volume mostly governs the total costs of the prepositioned road network. Because the volume is similar for all even flow scenarios, the prepositioned network costs per m<sup>3</sup> are relatively constant. However, the lower volume associated with the small blocks under the pass system causes higher costs per m<sup>3</sup> with the prepositioned roads. The costs for the periodic road network developed for the 20-40ha pass system are lower

than expected. This low cost is a result of the harvest pattern in the first time period. As shown by the coverage of the blocks in Figure 39, the first time period of the 20-40ha pass system requires the road network to access almost all of the island, which makes the periodic road network generation method similar to the "all period" and prepositioned road methods. When compared to other periodic road networks, Figure 43 shows that this network has a short total length and short haul distance, and Figure 44 shows that it also has relatively good flow concentration. These factors combine to cause low total costs, and low per m<sup>3</sup> cost.

With the exception of the periodic pass system scenarios, larger blocks under the pass system generally have lower costs per  $m^3$ . The even flow scenarios show similar trends, however, the trends are much weaker than in the pass system. In fact, there is no difference between the 40-80ha and 80-120ha block sizes and only a slight increase in cost per  $m^3$  with 20-40ha blocks. The weakness of the trend is a result of the intensity of harvesting. The intensity of the pass system scenarios is very high, removing all the available timber in every pass. Conversely, the even flow scenario has a low harvest intensity, which never harvests all the available timber in any time period. Increasing the harvest intensity pushes the system to its limits, and the negative impacts on the costs per  $m^3$  become more apparent.

#### 3.2 Periodic Indicators

Fluctuations between periods make the periodic indicators more difficult to interpret compared to average values. However, some trends not apparent in the average values can be determined. The length of road construction, length of active road and average haul distance are used as periodic indicators.

### Length of Road Construction

Figure 46 contains the length of road construction for the 6 harvest scenarios and the 13



road networks.

Figure 46. Length of road construction per period for the 6 harvest scenarios.

Figure 46 shows that for the even flow scenarios the length of road constructed decreases with time and nearly the entire road network is constructed by year 150. This corresponds with a shift from harvesting old growth to harvesting second growth stands. The large increase in road construction in period 5 is a result of the harvest priority change from the closest to the log dump first to the oldest first. The pass system scenarios follow the cycles of harvesting, and after the first 2 passes nearly all the road network is constructed. The periodic roads require the least road construction in first 50 years, however following this, the periodic networks require the most road construction per period. "All period" and prepositioned road networks have higher construction in the early periods, however this accesses many future blocks and therefore requires less road construction in the later

periods. Similarly, regardless of road projection method, smaller blocks under the pass system require more road construction in the first time period, and subsequently require less construction in future time periods.

# Length of Active Road

The length of active road for the 6 harvest scenarios and the 13 road networks are in

Figure 47.



Figure 47. Length of active road per period for the 6 harvest scenarios.

Figure 47 shows that in general, a larger block size requires slightly less active road. The smaller blocks require slightly more active road because the harvesting is more dispersed. Also, the ability of the periodic method to reduce the amount of active road is easily seen in the even flow scenarios. The pass systems show little difference between the road generation methods used because most of the island is harvested in each pass. Most roads are constructed in the first two time periods, which hinders the ability of the periodic method to reduce the amount of active road. As the block size increases, the harvesting is

more concentrated, which also limits the amount of road that the periodic method can reduce. As a result, the large blocks (80-120ha) under the even flow harvest policy shows no consistent reduction in the length of active road.

The pass system scenarios follow the harvest cycles and the length of active road is relatively constant ranging between 80km and 120km. For the even flow scenarios, the amount of active road is increasing for the first 50 years, and then levels off between approximately 30km and 80 km.

#### Average Haul Distance

The average per period haul distance for the 6 harvest scenarios and 13 road networks are shown in Figure 48.



The average haul distance fluctuates between periods for the even flow scenarios (Figure 48). These fluctuations make it difficult to identify trends, however in general, the periodic road networks have longer average haul distances. Like increasing the total

length of the network (Figure 43), the increased haul distance is a trade-off resulting from a decrease in the length of active road when creating periodic road networks. With the exception of the 20-40ha blocks, where blocks are located on the entire island in each pass, the pass system scenarios show increased average haul distances for the periodic method.

#### 4.0 Discussion

This case study showed that for even flow harvest scenarios, larger harvest blocks required less active road. When using the periodic method, there was an increase in the haul distance, total length of the network, and poor flow concentration. These factors combined to increase the total costs of the road networks. However, the periodic method reduced the amount of active road and decreased the required length of initial road construction. In hindsight the parameter values used to reduce the amount of active road were too high. Lower parameter values will reduce the negative impact to the flow concentration and reduce the total length of the networks, but will cause less of a reduction in the length of active road. This trade-off stresses the need to choose the road projection parameters carefully. In addition, the even flow policy and multiple pass system selected to test harvest flow policy were too different to make clear comparisons. In hindsight, a pass system with shorter times between passes (i.e. 20 years rather than 100 years) would have produced scenarios that were more similar and likely have led to a better assessment of block size effects.

Creating, analysing and summarizing the roads of the 13 road networks took between 6.5min and 10.7min of processing time (on an 800Mhz processor). This time includes generating the road network, linking the network to the harvest schedule, determining the

haul volumes, calculating the optimal road class and deactivation strategies, and summarizing the information for output. The prepositioned road network scenarios required the least processing time and the periodic method required the most processing time.

To standardize the number of landings required for the different harvest areas, more landings were placed in the larger harvest areas. Visual inspection of the road networks revealed that there was more active road in the larger blocks than expected. The landings within blocks were selected to be 500m apart. For some harvest blocks, the elevation difference between the two landings prevented one road connecting both landings, and two roads were required. If the landings were moved slightly, only one road would be required to connect both landings, thus lowering the amount of active road. The landings in the 20-40ha blocks were far enough apart that this was not normally a concern. There are two possible ways to fix this problem. First, only block access roads could be projected, with the understanding that more in-block roads are required later. Block access roads would use fewer landings spaced far enough apart so that the excess road problem is eliminated. The distance between the landings would be determined by trial and error. The second alternative is to first project block access roads and then project inblock roads. However, to do this properly, the harvest block boundary must be known. This level of detail for road and harvest block location is generally determined at the tactical or operational level.

# 5.0 Conclusions

This chapter integrated road projection, optimal road class determination and harvest scheduling. The main objective was to integrate and test methods of 1) generating road

networks 2) linking road networks to harvest schedules, and 3) analysing the results. Three techniques were applied to a case study where harvest flow policy harvest and harvest block size were altered. In hindsight, two aspects of this analysis could be improved. First, the parameter values used to reduce the length of active road are too high, which increased the total length of the network and haul distance, and created networks with poor flow concentration. Second, the harvest policies (even flow and pass system) were too different to yield results that could be easily compared. However despite these limitations, this chapter provides methods that can be used to integrate road networks, spatial strategic harvest plans and algorithms for determining optimal classes and road costs.

From the case study, it was determined that road networks should have short hauling distances and good flow concentration. The results suggested that a good quality prepositioned road network produces low total road costs and by extension a poor quality prepositioned road network will produce high total costs, regardless of the harvest policy. Generally, the smaller harvest blocks had more active road. Compared to the other methods tested, the periodic method produced road networks that required less road construction in the early time periods, followed by more road construction later.

The processes presented here are useful for determining the long-term effects of harvest policy on road values. It was also found that calculating optimal road classes is useful for determining flow concentration, which can be used to assess networks under a variety of block size and harvest flow policies. While the case study is a small area with simplified inputs, the methods developed here can be extended to larger estates with more complex inputs. The lessons learned about the complexities involved with generating road

networks, linking roads to harvest blocks and analysing road networks are the real value of the work in this chapter. With more complex systems the models developed here can be used to understand the interactions between road location, road state, road classes, road budgets, harvest volume, and harvest timing.

# **General Discussion**

#### Limitations of Case Study

Even though the analyses were done on a small island, with simplified inputs, the interpretation of results was difficult and in hindsight, an even simpler case study should have been chosen. Although the Hardwicke Island is small (+7,500ha) the terrain is very challenging for road projections. Specifically, the terrain on the east side of the island is steep and broken, and access on the west side to the log dump is difficult. The location of roads was strongly controlled by the terrain, which made it difficult to establish trends between input parameters (road standards) and output indicators when the road projection algorithm was tested in chapter 1. Likewise, the comparison of road networks based on road costs, physical indicators such as active road, plus block size and harvest policy in chapter 3 was complicated by the restricted road projections. Further, the even flow policy and multiple pass system selected to test harvest flow policy in chapter 3 were too different to make clear comparisons. In hindsight, a pass system with shorter times between passes (i.e. 20 years rather than 100 years) would have produced scenarios that were more similar and likely have led to clearer results. Also, the parameter values used to reduce the length of active road were too high in chapter 3. This increased the total length of the network and haul distance, and created networks with poor flow concentration.

Like many resource planning processes, projecting networks using the methods presented here requires many runs until the analyst is content with the plan. To understand and account for the landing order variation many road networks have to be created and compared. The choice of the road standard parameters is also critical in creating the

desired road networks. Considering other factors such as yarding distance and harvest block boundaries further influence the road network. Determining which factors are most important for specific forest estates will help the analyst develop better road networks. Some forest estates have high road construction costs and difficult topography. In these situations, the road location is limited by construction costs, and optimizing factors such as yarding distance, haul distance and the total road length is not practical. Other areas have low construction costs and the topography allows for many possible road locations. Here, the loss in production due to increased yarding distance or haul distance can be greater than road construction costs. Creating and comparing multiple networks based on length of road, haul distance or yarding distance for these areas would be beneficial.

#### Future Research

There are many research opportunities available by building on the methods presented in this thesis. In some cases, I have already developed improvements and applied them on other forest estates. For example, procedures for projecting the network in stages were applied to the Morice Timber Supply Area (1.5 million gross ha, 25,873 total km, which includes 16,432km of projected roads) for the Morice and Lakes Innovative Forest Practices Agreement. Developing road networks in stages allows control over the road standards during each stage, resulting in better road networks. Also, the main roads (and some branch roads) in a network make up a backbone that is most important to strategic planning. In harvest scheduling models that use roads to guide the harvesting, it is this backbone that helps direct timber harvesting. When road networks are developed in stages the user has more control over this backbone. The remaining spur roads are not as important in strategic planning, and are probably better included only in operational and tactical level planning.

Yarding distances have also been incorporated into the road projection model as part of the Morice Timber Supply Area application. Depending on the slope of the terrain, road links are assigned a yarding system. Buffers around existing roads are established based on the yarding system and its maximum favourable and adverse varding distances. Nodes are then assigned as being accessed or not, depending on whether they fall within the buffer zone. The road projection algorithm then projects roads and updates the yarding distance buffer until all the nodes are accessed. Not only are landings no longer required prior to projecting the road network, but the yarding information for each node can be used to determine harvest blocks of any size, based on access. Integrating the yarding systems, road access and block delineation in this way needs more research, but preliminary results are promising. Much of the development has concentrated on reducing the computing time required during road projection. Some pre-processing and sorted data structures plus splitting the forest into smaller areas allows the program to work more efficiently. This makes projecting road networks for large areas with detailed inputs feasible. For example, developing the 16,432km of road for the Morice Timber Supply Area was done in a little over 30hrs (800Mhz processor). Manually producing a road network for an area this size is not feasible because it would take too much time and effort.

Strategic impacts of roads on other forest values needs further research. With the ability to develop road networks, including harvest blocks for large areas, spatial harvest schedulers can now capitalize on this information. A logical example would be to investigate how road density and/or road deactivation strategies impact wildlife populations. Similarly, these factors could also be assessed in terms of recreation,

hydrology and aesthetics. Clearly, the underlying relationships between roads and the other values need to be known in order to develop meaningful models that can be used to assess the strategic impacts.

With modifications, the methods presented here are well suited to tactical planning. Road and block boundary projection is more common in tactical planning than in strategic planning. These tactical projects are generally created using manual methods, which allows the planner to control detail. Using the road projection model combined with harvest block projection will allow planners to quickly create and assess multiple scenarios, which can then be assessed, and if necessary, manually modified. The greater level of detail and smaller areas associated tactical plans make determining the economical, social, and environmental effects of roads more certain. In particular, the optimal road class and deactivation strategies are more significant at the tactical level, where the decision of which road class to construct or level of deactivation to implement have more immediate consequences.

I prioritize three areas for continued development. Future development and testing of these algorithms should first concentrate on the road projection, yarding distance and harvest block boundary projection tools. Second, the road projection algorithm should be modified to include some form of heuristic to minimize the variation associated with the landing order. Dean (1997) presented some possible methods, however, the algorithm must be able to efficiently project roads for larger areas and use the detailed road standards and parameters as described in chapter 1. Finally, methods to assess the long-term effects of roads on environmental and social forest values need to be developed and tested.

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