# INCORPORATING OPERATIONAL ROAD PLANNING CONSTRAINTS INTO AN INTEGRATED TACTICAL LEVEL HARVEST-SCHEDULING AND ROAD-PLANNING MODEL

by

Melika Rouhafza

A Thesis Submitted in
Partial Fulfillment of the Requirements for the
Degree of Master of Science in Forestry

Faculty of Natural Resources Management
Lakehead University
Thunder Bay, Ontario
Canada

July, 2015

# LIBRARY AND ARCHIVES CANADA
# LIBRARY RIGHTS STATEMENT

In presenting this thesis in partial fulfillment of the requirements for the M.Sc.F. degree at Lakehead University in Thunder Bay, I agree that the University will make it freely available for inspection.

This thesis is made available by my authority solely for the purpose of private study and research and may not be copied or reproduced in whole or in part (except as permitted by the Copyright Laws) without my written authority.

Signature: ________________________________
Date: ________________________________

# A CAUTION TO THE READER

This M.Sc.F. thesis has been through a formal process of review and comment by at least three faculty members and an external examiner. It is made available for loan by the Faculty of Natural Resources Management for the purpose of advancing the practice of professional and scientific forestry.

The reader should be aware that opinions and conclusions expressed in this document are those of the student and do not necessarily reflect the opinions of the thesis supervisor, the faculty or Lakehead University.

# ABSTRACT

Rouhafza, M. 2015. Incorporating operational road planning constraints into a tactical level harvest-scheduling and road-planning model. 65pp.

Keywords: harvest-scheduling, operational road planning, simulated annealing.

At the operational scale of forest planning, the location of roads, in a complex terrain, is a decision of major economic importance. The objective is to locate a network of roads connecting pre-selected cut-blocks, at minimal cost, subject to a host of feasibility constraints. The location of the pre-selected cut-blocks is a made at the tactical level of planning, and the decision is made with relative indifference to the cost of the connecting these blocks at the operational scale of planning. The objective of this thesis is to design and evaluate an optimization model by which the location of an operationally feasible road-network can be made simultaneously with the selection of cut-block locations. The underlying assumption of this undertaking is that the optimal locations of both cut-blocks and operational roads are interdependent

Our methods are summarized in three steps: first, an exhaustive library of candidate roads is generated, using an operational-scale, road location model; second, a subset of these roads is selected in a tactical planning model which optimally schedules the harvest of cut-blocks and location and construction of roads simultaneously; and third, the tactical solution is mapped, enabling inspection of road-locations at the scale of 50m X 50m.

This innovative approach was tested on a portion of the Kenogami Forest, in Ontario, and the results demonstrate its feasibility and ability to reduce road-construction costs. We conclude that the approach is useful for three reasons: first, it can reduce the total cost of constructing a road-network; second, it facilitates innovation in tactical planning by making operational road-location planning methods relevant to tactical level modeling; and finally, it can be practiced on large forests.

## CONTENTS

# TABLES

# FIGURES

# 1. Problem Defined

Over the last 15 years, many innovations in planning roads at the operational level have occurred in the field of computerized optimization techniques. Increasingly sophisticated models, search algorithms, and remotely sensed data, have been used to produce road-network plans that satisfy more realistic horizontal and vertical constraints on road allocations (see Akay et al., 2013, for a complete review of these innovations).

Comparable progress has not occurred in planning roads at the tactical level. Our Review of the Literature (below) on tactical planning model supports this statement. This lack of progress in the improvement of models used to plan for roads at the tactical scale has resulted, in part, from the computational challenge inherent in searching for solutions to the integrated harvest-scheduling and road building model; for, the spatially explicit harvest-scheduling model requires binary decision-variables, and is categorized as NP-hard; i.e., the computing time required to solve this model increases exponentially with the increases in the number of decision variables (Murray and Church 1995). This property of the model entails that the search space, for even medium-sized problems, is huge; and that an efficient search for an optimal solution cannot afford to be slowed by iteratively computing operationally feasible roads constrained by complex vertical and horizontal constraints.

The challenge to incorporating optimal road locations into a tactical planning model, has presented the planner with two alternatives:

A. Use a small set of candidate roads whose costs and operational feasibility have been empirically verified. This alternative sacrifices optimality for feasibility; for a large set of candidate roads is needed in order to optimize a selected road-network location (Stuckelberger *et al*. 2007). In addition, this alternative is often too expensive for very large forests.

B. Use a set of roads whose costs and operational feasibility are approximations. This alternative poses two risks: first, approximations risk misrepresenting the costs of roads; and second, the locations of cut-blocks themselves can be located sub-optimally in relation to a feasible road-network. Both risks can occur when the approximations of road costs do not adequately represent variation of road costs resulting from a complex topography.

In evaluating the above two alternatives, it should be borne in mind that***: the optimal locations of both cut-blocks and roads are interdependent***. Given this interdependence, the quality of the entire tactical solution is dependent on the quality of the road data used.

## 2. Objectives

In this thesis, we propose a third alternative to the problem of searching for optimal road locations in a tactical planning model. Our objective is to design and test a new tactical level planning approach that will allow for the simultaneous and optimal selection of both: a) cut block locations and b) road network locations that satisfy operational-scale modeling constraints.

The approach is divided into three steps.

1. First, a large library of roads connecting all pairs of candidate cut-blocks is generated using a shortest-path algorithm modified such that the path connecting any pair of cut-blocks is subject to vertical and horizontal constraints measured at a scale commonly found in operational level planning. This pre-processed library of roads contains two parts: i) the cost of each road between all pairs of candidate cut-blocks; and ii) the actual path, *i.e.*, set of road-links (or arcs) connecting all pairs of candidate cut-blocks.
2. Second, a tactical level planning model of the integrated harvest-scheduling and road-building model will be formulated and built. In such a model, the objective function is to maximize harvest revenue minus road-building costs. The road-building costs are input into this model from the pre-processed library; *i.e.*, the cost of each road between all pairs of candidate cut-blocks. The model is then solved.

3. Third, the solution is assembled. This entails mapping the set of cut-blocks and road-links selected in the optimal solution. The detail and operational feasibility of the mapped roads are selected from the pre-processed library.

In this way, the tactical model can select highly detailed operational roads without slowing its search for an optimal solution, by iteratively generating these roads. The result is a tactical planning solution where a schedule of cut-blocks is joined by a road-network designed to be feasible by operational planning standards. In addition, since the tactical model draws from a large library of candidate roads, the problem of optimal road network location is also solved; for the optimal location of a road network is possible only when an exhaustive set of candidate roads is evaluated in an optimization model.

## 3. Significance

This thesis is significant for several reasons:

1. First, this work is **innovative**. The literature review shows that no other published work has used this proposed approach to tactical planning. In section **4.3** of this thesis, entitled, **Summary of Literature** (see below) the nature of this innovation will be reviewed in detail.
2. The second reason for the significance of my work is **economic**. Bjorndal *et al*. (2012) estimated that road-constructions costs comprise 40% of the total cost of forest operations. Hence, a tactical planning approach that facilitates an improvement in the optimal location of cut-blocks, with regard to minimizing their construction costs at the operational scale, can lead to the reduction of a major cost in forest operations.
3. A third reason for the significance of this work is that it is **practical**, *i.e.*, it can be used on large forests managed in the real world. Since many of the commercial software packages used to solve real-world tactical planning problems use meta- heuristic search algorithms (e.g., Patchworks®, Woostock-Stanley®) the approach developed in this thesis will also employ a meta-heuristic search algorithm. Hence, our innovation will not be restricted to impractical, small-sized problems.
4. A final reason for the significance of my proposed work is that it provides the **foundation for innovation** in tactical planning. The proposed planning

approach can draw from the best operational road building models that have been developed over the last 15 years, thus facilitating a wealth of future refinements in the integrated harvest-scheduling and tactical planning model.

# 4. Literature Review

The literature review has been divided into two parts. The first part is a review of the road-building models used at the operational scale of forest planning. The second part is a review tactical optimization models that have integrated both the harvest-scheduling and road-building problem.

## 4.1 Part I: Road Location Models at Operational Scale

The literature on forest road planning can be divided into three areas of study: location, design, and construction (Tan 1992). In this thesis, we are concerned with the problem of road location, and therefore confine our review to this topic.

Road location is concerned with finding the least cost route for a road, or road network, subject to a set of design constraints. Design constraints are generally divided into two groups: geometric and environmental (Akay *et al*, 2013). The geometric constraints may include maximum road grade, minimum curve dimensions for both vertical and horizontal curves, and minimally safe stopping distance. The environmental constraints include minimum road-grade for drainage, optimal stream-crossing angle, and maximum cut and fill slope-ratio for stability (Akay *et al*. 2013, Kramer 2001). In order to satisfy vertical constraints, contour maps or digital elevation models are used, and the set of candidate road-links must be short-enough to avoid crossing multiple contours. Hence, optimizing the road location problem requires that a large number of alternatives be examined at a spatial scale suitable to operational feasibility (Stuckelberger *et al*. 2007). Computer-aided analysis has proven to be highly useful in serving this end (Akay *et al*. 2013).

Computer-aided analysis of operational road location dates back to the 1970's when shortest path algorithms were first combined with digital elevation models to locate individual roads (Turner 1978). Research using computer optimization techniques to solve the road location problem has since expanded, owing to advances in computing hardware, optimization algorithms, and remote sensing technologies (Shirasawa 2014). Many optimization techniques have been used over the last few decades, and the review of this research will be divided by the type of optimization technique used.

### 4.1.1 Integer Programming

The forest road location problem has been modeled as a binary integer programming model by Murray (1998). A graph containing 64 nodes was used, and a subset of these nodes was used to represent harvest blocks on a planar surface. A minimal cost Steiner tree was constructed to connect terminal nodes to a road network and a point of entry in the forest. The Steiner tree problem is a variant of the minimum spanning tree problem; i.e., given an undirected graph, G = (N, A) of nodes and arcs, a subset of nodes (called terminal nodes) must be connected forming a minimal cost tree. The difference between the minimum spanning tree and the Steiner tree is that, optionally, some nodes that are not terminal nodes may also be selected as part of the Steiner tree, should their inclusion lead to a lower cost tree than is possible with the strict minimum spanning tree. The major disadvantage of using a Steiner tree model that it can be solved exactly on only small problems, since the Steiner tree problem is NP hard.

Najafi and Richards (2013) presented a more complex integer programming formulation of the road location problem. They too constrained the road network to be a Steiner tree, and their objective function was to minimize the total cost of road building, skidding, transportation and maintenance over one period. They used a real dataset in Iran containing 252 harvesting sites, 883 potential skidding spurs, 440 road segments, and incorporated slope values into road segment cost. Using the branch and bound algorithm, their model yielded good results in reasonable computing time.

### 4.1.2 Dynamic Programming

Tan (2000) developed a dynamic programming procedure, integrated with a spatial database and transport network models, which was designed to assist planners in determining the *optimal* location for a forest road and an entire road network. The procedure was tested using data from a practical road planning project, on a gridded forest comprised of 2,196 cells. Tan (2000) concluded that excessive computing time using the dynamic programming method on large problems is a limit on its practicability.

### 4.1.3 Meta-heuristics

Meta-heuristics are iterative search algorithms which do not guarantee finding an optimal solution. The usefulness of meta-heuristic algorithms has been in finding good solutions to large integer programming problem instances. Chung and Sessions (2001) used both a genetic algorithm and simulated annealing to locate a forest road network. Locations were based on road standards, timber harvesting and transportation costs, and topographic conditions. In their approach, the main access road was located first (and built to a high standard) and then single stand access roads (built to lower standards) were located as branches. Optimization of main access roads was accomplished using a genetic algorithm; and the optimization of single access roads was performed by simulated annealing. The model was tested on a small area (625 ha), using 25m x 25m grid cells.

Akay (2004) integrated simulated annealing with linear programming to optimize the location of a single forest road. Simulated annealing was used to search for a path of optimal vertical alignment while linear programming was used to balancing the path's cut and fill. This method was developed to provide a road planner with a rapid evaluation of alternatives to designing a single road.

Meignan *et al*. (2012) used a greedy randomized adaptive search procedure (GRASP) to select a set of road locations to minimize harvesting and construction costs. The problem was modeled as a P-Forest problem; *i.e.*, a type of facility location problem. They examined the trade-off between road-building versus harvesting costs; *i.e.*, they quantified how much the density of a road network reduces harvesting costs but increases the road building costs.

### 4.1.4 Heuristics

Heuristic techniques are repetitive search procedures where an improved solution is derived from the current solution by executing a “rule of thumb” procedure based on experience or empirical rules. Heuristics have been used extensively in solving the forest road location problem.

Dean (1997) introduced three different heuristics for forest road location problem. They compared the results of three heuristics to the optimal result obtained by complete enumeration. The heuristics were not constrained by vertical road design constraints. Chung *et al*. (2008) designed a specialized heuristic for locating a road network subject to a standard set of vertical and horizontal constraints. The model was applied to a forest of 4,760 ha and evaluated by comparing its solution with a manually developed road network. Shirasawa (2014) exhaustively reviewed 14 different heuristics for locating a forest road network. Many of these heuristics were originally designed to solve the minimum Steiner tree problem. These heuristics were tested on 1,120 problem instances and evaluated by the criteria of execution time and solution quality.

The shortest path algorithm is a heuristic used to find the shortest cost path between two points on a weighted graph of vertices and edges. Its execution time is relatively fast (*i.e*., execution time increases linearly with problem size) and its use guarantees a mathematically optimal solution. The shortest path algorithm was developed by Dijkstra (1959) and has been used extensively to locate individual forest roads since the 1970’s (Turner 1978).

More recently the shortest path algorithm has been used extensively to locate multiple roads for the purpose of designing a least network of forest roads. Liu and

Sessions (1993) used the shortest path algorithm for this purpose, and their approach was comprised of four steps. First, all candidate road- links which had undesirable slopes, or were passing through undesirable areas, were eliminated from the study area; second, the costs of eligible road-links were estimated as a function of road building, maintenance, and transportation costs. Third, a road network was assembled using: i) a shortest path algorithm to locate individual roads, and ii) a road-network algorithm to connect individual roads into a least cost road network. The two algorithms were combined into a software package called NETWORK II (Session 1987). In the last step, results were illustrated on the map. The model was tested on a small area (480 ha) divided into 25m x25m grid cells.

Tan (1999) also used the shortest path algorithm to design a network of roads. A specialized heuristic algorithm was designed to minimize the total cost of road construction, wood extraction, and wood transport in a forest road network connecting a set of pre-selected cut-blocks. In this approach, the specialized heuristic constructed the road network from a set of individual forest roads whose locations and costs had been pre-processed using a shortest path algorithm.

Anderson and Nelson (2004) enhanced the flexibility of using the shortest path algorithm in locating a network of forest roads by adding a set of penalty weights to the search algorithm in order to satisfy vertical and horizontal constraints on road alignment. Their shortest path algorithm was used on a 50m X 50m grid to connect a set of landing points in a 7,500 ha forest in British Columbia. Extensive sensitivity analysis was performed to demonstrate how multiple planning alternatives can be explored using a shortest path algorithm directed by multiple penalty functions.

Stuckelberger *et al.* (2007) used a shortest path algorithm with penalty functions to satisfy vertical and horizontal road constraints in a manner similar to Anderson and Nelson (2004). They also explored the effects of using the minimum spanning tree and Steiner tree heuristics in: a) connecting a set of pre-selected cut-blocks, using b) roads generated with the shortest path algorithm, to form c) a least cost network of forest roads.

## 4.2 Part II: Integrated Tactical Planning Models in Forest Management

During our literature review, over 50 papers describing tactical forest planning models, published since the year 2000, were found. Most of the papers, however, did not present models that integrated road-building with spatial harvest-scheduling. Instead, these models were formulated to schedule only cut-blocks. Since they did not describe integrated models, they are excluded from the literature review.

The review of literature on the integrated harvest-scheduling and road-building models is divided into two parts: i) models producing exact solutions to the integrated model; and ii) models producing approximate solutions through the use heuristic algorithms.

### 4.2.1 Part I: Exact Approaches

The original formulations of the integrated model used a mixed integer linear programming approach. Weintraub and Navon (1976) formulated the problem as a mixed integer programming model in which continuous variables were used to represent the volume harvested from forest strata, and binary variables were used to represent the construction of roads. Flow constraints were also used at each node in the road network to measure and minimize the cost of transporting harvested wood through the constructed road network over time. The model was tested on a hypothetical forest containing 256 decision variables, 24 of which represented binary road variables. The authors compared their integrated approach with a sequential approach and found that the integrated approach yielded an improved objective function value by 7%. Kirby *et al*. (1986) also formulated the integrated model as a mixed integer programming model in a manner similar to Weintraub and Navon (1976), but with additional refinements on modeling the road network. They applied their model to a problem in northern California and observed a 21% decrease in road-building costs compared to the sequential approach. Weintraub *et al*. (1994) later developed an LP-based heuristic to solve the integrated problem modeled as a mixed integer programming model. Error bounds in relation to the LP relaxation varied from 5.5% to 27%. An extension of this heuristic was further developed by Weintraub *et al*. (1995) to include adjacency constraints.

Nelson and Brodie (1990) were the first to formulate a spatially explicit integrated model in which both road and cut-block variables were constrained to be binary. This approach enabled the addition of adjacency constraints to the model. Guignard *et al*.

(1998) applied innovative techniques to improve the efficiency of solving the spatially explicit integrated model. They improved the efficiency of the search for an optimal solution by adding logical inequalities, lifting inequalities, and prioritizing the variables for branching based on contracting properties. Andalaft *et al*. (2003) formulated a spatially explicit integrated model and used several strategies to improve upon the computational time needed to arrive at good solutions. These strategies included strengthening the model, lifting constraints, and Lagrangian relaxation. Andalaft *et al*. (2003) were able to solve problems containing up to 1,700 binary variables to within 2.3% of the optimal.

### 4.2.2 Part II: Metaheuristic Approaches

Significant advances have also been made in modeling the road-building portion of the integrated problem using purely heuristic or meta-heuristic approaches. Exact formulations of the integrated model had simplified the road network location problem by using broad branching structures and a restricted subset of candidate routes for each cut-block. Clarke *et al*. (2000) improved upon this by modeling the road-building problem as a minimum spanning tree and integrating it with a multi period harvest-scheduling model using a three-stage heuristic. Similarly, Richards and Gunn (2000, 2003) modeled the road-building problem as a minimum Steiner tree and integrated it with a tabu search meta-heuristic for solving the integrated model.

The modeling approaches of both Clarke *et al*. (2000) and Richards and Gunn (2000, 2003) allowed for a dense network of candidate roads, from which to select a road network which is also tree, i.e., a minimal cost graph connecting all cut-blocks. These two approaches also nested road-building heuristics within the iterative search for an optimal harvest-schedule. That is, at each iteration: i) a new candidate solution, *i.e.*, a harvest-schedule, was produced; ii) a road network was then built to service this schedule of harvests; and iii) the objective function value the candidate solution was calculated as the harvest-revenue minus its road-building costs). In order for the iterative search algorithm to sample the solution space adequately, many iterations are required. Hence, the road building heuristics must execute quickly. Since the execution time of a highly detailed road location model, used at the operational scale, is too slow for the iterative search algorithms used in tactical planning models, therefore operational scale road location models have not been incorporated in the iterative search models used at the tactical scale.

### 4.3 Summary of Literature Review

In our review of road location models used at the operational planning scale, we have observed that an optimal road network is selected:

a) from a large set of candidates road-links;

b) at an operationally feasible spatial scale;

c) in order to meet a set of vertical and horizontal constraints.

In the review of the integrated tactical planning models we have observed that neither the exact nor the iterative heuristic approaches have been able locate roads with the same level of detail. Exact approaches are constrained from doing so because of the number of binary decision variables required; and iterative heuristic approaches are constrained from doing so because the computing time required to produce an operational road network, at each iteration, would slow the search and therefore reduce its effectiveness.

Hence, this review of the literature not only reveals the innovation of our proposed approach, but also, its justification. For, by pre-processing the candidate roads, a heuristic road construction algorithm need not be nested within the tactical model's meta-heuristic search. Pre-processing candidate road locations thus allows for computationally feasible solutions to be found in problem instances of the integrated harvest-scheduling and road-building model—where the selected road network is:

a) optimally located in relation to the harvest-schedule; and

b) planned at a level of detail comparable to that produced by operational-scale road location models.

# 5. Methods

Our proposed approach is divided into three parts (see Objectives, above). We shall now review each part of this approach in detail.

## 5.1 Part I: Generating a Library of Candidate Roads

The approach to generating a library of roads is based on the operational scale planning approach developed by Anderson and Nelson (2004) and Stuckelberger *et al.* (2007). To generate this library, we first constructed a map comprised of three layers. The first layer represents water bodies and forest polygons. Each forest polygon contains a particular stand type, age, and yield curve. The second layer is a digital elevation model of the forest. The third layer is a graph comprised of a set of vertices and edges, where each edge represents a candidate road link.

The graph will be built in three steps. First, a squared grid with a 50m x 50m resolution is constructed. At the centre of each of the cells within this grid we locate one vertex. The edges emanating from each vertex and connected to neighbouring vertices represent candidate road-links. The number of edges increases the flexibility of designing a road network. In this work, we use sixteen edges to emanate from each vertex and connect to the sixteen nearest adjacent vertices (see Figure 1 below). The approach to designing a set of candidate forest road-links, illustrated in Figure 1, has been used by Epstein *et al.* (2006) and Stuckelberger *et al.* (2007).

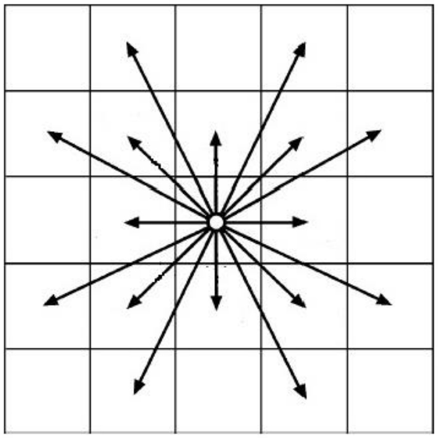

**Figure 1**: Network representation of sixteen candidate road-links emanating from each vertex on a 50m X 50 m grid.

The second step taken in constructing the graph was to remove some of the edges. All of the edges that cross lakes, rocks, or other infeasible areas for roads were eliminated. Next, we identified one vertex within each forest polygon that would serve as the landing. That vertex is used to represent a landing was that found on the largest, flattest terrain within a forest polygon.

The final step taken in constructing the graph is to assign costs, or weights, to each edge. The cost assigned to each edge is a function of: a) distance; b) slope; and c) type of area covered (e.g., stream, soil type). Having completed these steps, a directed graph with non-negative weights was prepared for generating a library of shortest paths.

Dykstra's (1959) shortest path algorithm was then used to find all pairs of shortest paths. This search algorithm was subject to a set of constraints and penalties designed to maintain the following road standards:

1. **Favourable grade:** limit and penalize steeper grades (maximum of 15%).
2. **Abrupt grade change**: limits and penalizes abrupt changes in grade (% grade change per horizontal distance).
3. **Radius of curve**: limits and penalizes abrupt changes in horizontal alignment. See Anderson and Nelson (2004) for details on this road standard.
4. **Minimal stream-crossings**: penalizes links that cross streams
5. **Minimal switchbacks**: penalizes switchbacks.

The search algorithm is adapted to satisfy road building standards by the determination of the weights assigned to each edge. First, any edge which violates the above-listed "limits" on road standards are simply removed from the graph before the search algorithm is executed. Second, any edges which did not violate limits, but deviated from a target value, have their weight incremented by a penalty value linearly proportional to the deviation from the target value. For example, suppose edge A has a cost of $100 (based on distance) and that it violated a flat slope by 5 degrees. If the penalty function used to adjust an edge's weight for violating a slope constraint were 0.1 for every degree of violation, then penalized weight of edge A becomes 5*0.1 ($100) + $100 = $150. The use of multiple weights in this modeling approach is designed to assist the model's user in satisfying multiple road design objectives that may conflict and to allow fine-tuning of the actual cost estimates of roads.

## 5.2 Part II: Tactical Planning Model

Having built the library of candidate roads, we then formulated and built an integrated harvest-scheduling and road building model. The model formulation is presented below:

### Indices and Sets

*k, K* = *indices and set of blocks*

*i, j, I* = *indices and set of nodes*

*A* = *set of terminal nodes*

*t, T* = *indices and set of time periods*

$B_t$ = *set of blocks not eligible (by age) for harvest in period t*

$M_k$ = *set of existing terminal nodes in the road network when connecting block k to the road network*

$N_k$ = *set of terminal nodes inside block k*

$O_{kt}$ = *is the set of stands, including stand k, that are harvested during period t and are included in the same opening as stand k (i.e., contiguously connected to stand k)*

$P_t$ = *set of existing periods equal to or less than t*

### Parameters

$APC_t$ = *allowable periodic cut in period t* ($m^3$).

$v_{kt}$ = *volume harvestable from block, k, period t* ($m^3$) .

$c_{ijt}$ = *discounted cost of building a path from node i to node j in period t ($)*

$r_{kt}$ = *discounted revenue from harvesting block k in period t ($).*

$a_k$ = *area of stand k (ha)*

$O_{max}$ = *the maximum opening area for harvest blocks (ha)*

**Decision Variables**

$x_{kt}$ = *1 if block k is harvested in period t, 0 otherwise*

$y_{ijt}$ = *1 if path from node i to node j is built in period t, 0 otherwise*

$H_t$ = *total volume harvested in period t* $(m^3)$

Objective function:

Maximize net present value (discounted revenue – discounted cost)

$$[1] \qquad Maximize \qquad \sum_{k \in K} \sum_{t \in T} r_{kt}\, x_{kt} - \sum_{i,j \in A} \sum_{t \in T} c_{ijt}\, y_{ijt}$$

Subject to:

Each block may be harvested once during the planning period:

$$[2] \qquad \sum_{t \in T} x_{kt} \leq 1 \qquad \forall\, k \in K$$

Defining the blocks which are not eligible for harvesting (by age) in each time period:

$$[3] \qquad x_{kt} = 0 \qquad \forall\ t \in T, k \in B_t$$

The opening size in each period should not exceed the maximum opening size:

$$[4] \qquad \sum_{k \in O_{kt}} x_{kt}\, a_k \leq O_{max} \qquad \forall\, k \in K, t \in T$$

Accounting variable defining the total volume harvested in each time period:

[5] $$H_t = \sum_{k \in K} x_{kt} \, v_{kt} \qquad \forall \; t \in T$$

Volume harvested in each period should not exceed the target volume for that period:

[6] $$H_t \leq APC_t \qquad \forall \; t \in T$$

If a block is harvested in period t, a path connecting this block to an existing terminal node in the road network should be built:

[7] $$\sum_{i \in N_k} \sum_{j \in M_k} y_{ijt} \geq x_{kt} \qquad \forall k \in K, t \in T$$

Road building and harvest scheduling variables are binary:

[8] $$x_{kt} \in \{0,1\} \qquad \forall \; k \in K \;, t \in T$$

[9] $$y_{ijt} \in \{0,1\} \qquad \forall \; i, j \in A, t \in T$$

Volume harvested in each time period is greater than zero:

[10] $$H_t \geq 0 \qquad \forall \; t \in T$$

## Solving the Integrated Model

We used a meta-heuristic algorithm, simulated annealing (Kirkpatrick 1984), to find an optimal solution to the integrated harvest-scheduling and road building model. This search algorithm has been used extensively in solving the harvest-scheduling model

(Bettinger and Chung 2004) since its first application to the problem in 1993 (Lockewood and Moore 1993). We adapted the algorithm to the tactical planning model in order that it execute as follows:

```
1. Generate and initial feasible solution, $S$, which represents a set of polygons to be
   harvested over multiple periods. (Note: $S$ does not include any decision-variables
   representing road-links).
2. Calculate the objective function $f(S)$ by: use a road building heuristic to generate
   a minimal cost road network required by $S$, and subtracting the cost of this road
   network from the revenue of $S$.
3. Get an initial temperature, $T$, and a reduction factor, $r$, with $0 < r < 1$.
4. While $T$ is not frozen:
   i) perform the following loop nrep times:
         a. pick a random neighbour, $S'$ of $S$
         b. if $S'$ is feasible, let $delta = f(S') - f(S)$
         c. if $delta > 0$, set $S = S'$
         d. if $delta < 0$, set $S = S'$ with probability $e^{-\text{delta....T}}$
   ii) set $T = rt$.
```

We defined a neighbour of S to be any solution arising from the following operation:

i. Randomly select any binary decision variable $x_{ij}$ from the current solution, S.

ii. If $x_{ij} = 0$, let $x_{ij} = 1$; and

iii. If $x_{ij} = 1$, let $x_{ij} = 0$.

Note that the simulated annealing algorithm does not search directly for a least-cost road network; it searches directly for an optimal set of polygons to harvest over time, S. The road-network required by S is found using a deterministic heuristic algorithm. Since the objective function, f(S), equals the revenue from the harvest minus the cost of the road-network, the road network: a) directly affects the objective function value; and therefore, b) indirectly affects the search for an optimal solution to the model.

Since the heuristic algorithm used for building a road-network is nested within the simulated annealing search algorithm, it is required that its execution-time be fast, in order that the solution space for tactical problems be sufficiently explored. In this paper, we therefore experimented with two heuristic algorithms to build the road network:

i. the minimum spanning tree algorithm (Prim 1957), which connects all scheduled cut-blocks, along with the forest’s point of entry, at minimal cost; and

ii. the shortest path with origin heuristic (SPOH) (Takahashi and Matsuyama 1980), which constructs a tree that consists of shortest paths from the forest’s point of entry to all other terminal nodes, *i.e.*, scheduled cut-block landings.

## Repairing the Road-Network

We originally wanted to build the road network as a Steiner tree, but could not find a heuristic to do this with sufficient speed of execution. We experimented with a Steiner tree heuristic called shortest path heuristic (SPH) (Takahashi and Matsuyama 1980, Winter and Smith 1992), but concluded (perhaps prematurely) that its execution time would be impracticably slow on large, realistic problem instances. Nonetheless, given the objective of minimizing road-building costs, we remained interested in representing the road network as a Steiner tree; and therefore added a fifth step to our algorithm for solving the tactical planning model:

5. After T is frozen:
    a. Set the forest's point of entry, and all nodes representing the landings of polygons selected for harvest in S, as terminal nodes.
    b. Using data from the pre-processed library, connect all terminal nodes, to form a minimal cost Steiner tree using the shortest path heuristic. The expansion of the tree will be periodic, i.e., each polygon scheduled for harvest must be connected to this tree within the period of its harvest.

### 5.3 Case Study: Kenogomi Forest

Our modeling approach was tested on portion of the Kenogomi Forest, located in the boreal forest of Ontario, Canada (see map in Appendix I). The area used in our model was 22,500 ha, divided into 500 polygons, ranging in size from 20 to 60 ha. Each polygon contained one of six different yield curves, and ranged in age from 14 to 210 years. The forest contains several rivers and small lakes; and the terrain is uneven, with elevations of merchantable wood ranging from 190 to 580 metres above sea level.

The minimum rotation age for each stand was set at 70 years. Revenues varied as a function of log diameter: \$75 *per* m$^3$ (ages 70 to 120 years), \$90 *per* m$^3$ (ages 121 to 180 years), and \$110 *per* m$^3$ (ages greater than 180). Unadjusted road-building costs began at \$30,000 *per* km. Adjacent cut-blocks were defined as blocks sharing a common boundary, and the maximum allowable area of a cut-block was limited to 260 ha.

The model was written in the JAVA programming language and executed using an Intel® Xeon X5650 hex-core processor (2.66 Ghz), 96 gigabytes of RAM, and a CentOS 5.5 operating system.

# 6. Results

### Results from Pre-Processing Candidate Roads using Shortest Path Algorithm

The first set of results concerns the first step of our approach: pre-processing a library of roads. For a forest of 500 cut-blocks and one entry-point, 125, 250 candidate road-links were constructed. The mean number of nodes *per* road was 19, and the total number of nodes used in all roads was 27,209,554.

The shortest path algorithm used to generate the library of candidate roads was tested by examining its output to ensure that it followed the vertical and horizontal constraints listed in the Methods. For example, in Figure 2 we observe one road generated by the shortest path algorithm. Here, we observe the 50m X 50 m resolution (represented by the gridded dots) and the shortest path between two landings (on separate green polygons). Observe also that the road:

a) does not violate a gradient constraint of 15% (given the contour interval is 10m);
b) avoids the penalty-cost of crossing a stream; and
c) does not violate the radius of the curve constraint.

In Figure 2, one can also observe that the pre-selected landing points are not in ideal locations; *i.e.*, on large and flat areas. In practice, a forest-engineer would pre-select these locations.

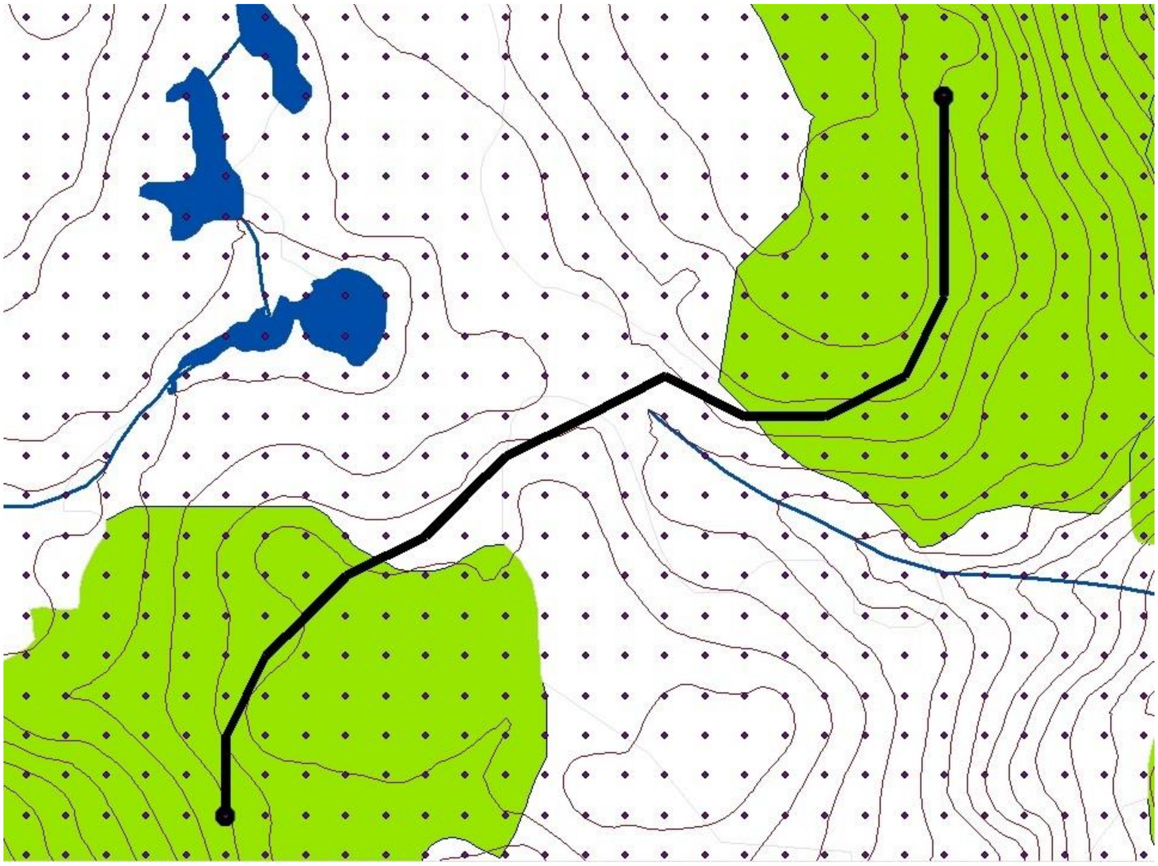

**Figure 2**: Example of pre-processed road generated using shortest path heuristic. The shortest road connecting two candidate landings is subject to horizontal and vertical constraints. This is a sample drawn from the 125,250 roads generated for the library of candidate roads.

### Results from Tactical Planning Model

The next results are from the tactical planning model. Figure 3 illustrates the progress of the simulated annealing algorithm's search for an optimal solution, over time, when it had the minimum spanning tree (MST) roading heuristic nested within it.

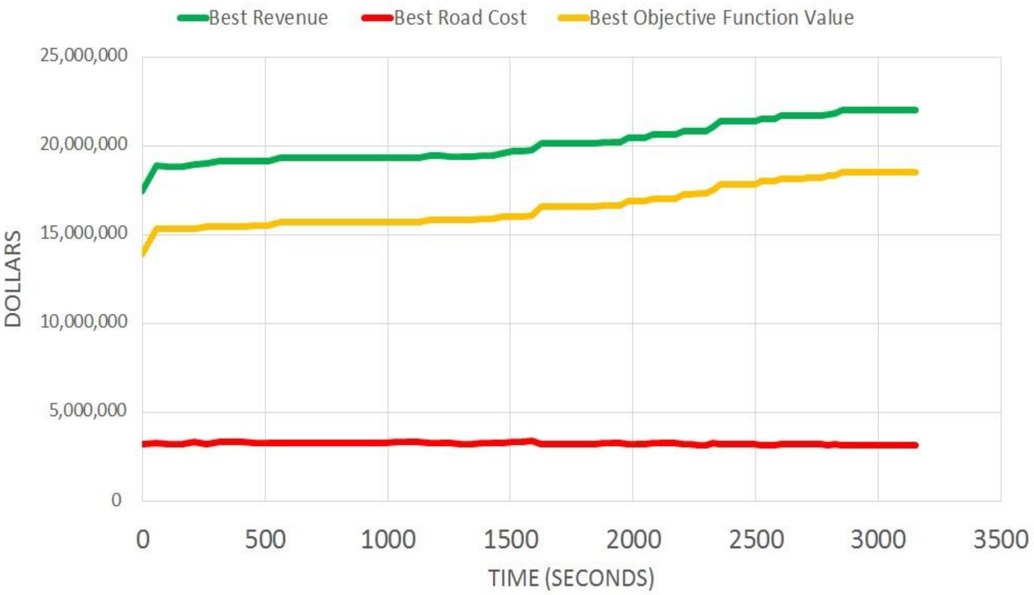

**Figure 3**: Progress of simulated annealing search algorithm with minimum spanning tree heuristic nested within it.

Figure 3 reveals that most of the progress in maximizing the objective function was made through increasing revenue, and that relatively little progress was made in minimizing road costs. One can also observe that the total computing time slightly exceeded 3,000 seconds and the average number of solution permutations evaluated per minute was 1.3 million.

Figure 4 illustrates the progress of the simulated annealing algorithm's search for an optimal solution, over time, when it had the SPOH roading heuristic nested within it.

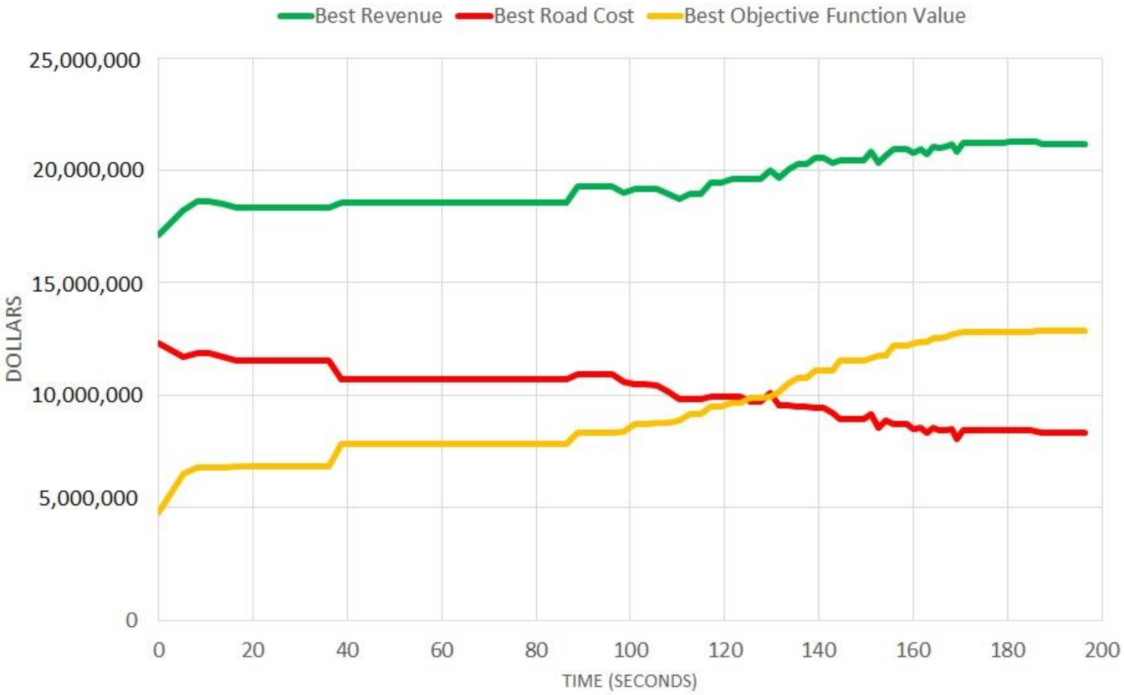

**Figure 4**: Progress of simulated annealing with the SPOH roading heuristic nested within it.

In Figure 4, one can observe that, with the SPOH algorithm nested within the tactical model's search algorithm, much greater progress was made in reducing road costs as the search for an optimal solution progressed over time. One can also observe that the execution time of the tactical model with the SPOH roading algorithm concluded after 200 seconds and was able to evaluate, on average, 14 million permutations per minute. In other words, the SPOH roading algorithm executed almost 11 times faster than the MST roading algorithm.

## Results from Algorithm used to Repair the Road Network

After the tactical model was run, we executed an SPH heuristic connecting all of the cut-blocks scheduled for harvest into a **Steiner tree**. The SPH algorithm can improve upon the results of the MST and SPOH algorithms in minimizing road network construction costs because:

a) The SPOH and MST algorithms can construct a road network only by connecting roads to existing landing points;

b) The SPH algorithm has greater flexibility in building a road network because it is not constrained to connect a road only to an existing cut-block, but can also connect a road to any node on an existing road.

An example of the output from our SPH algorithm is illustrated in Figure 5.

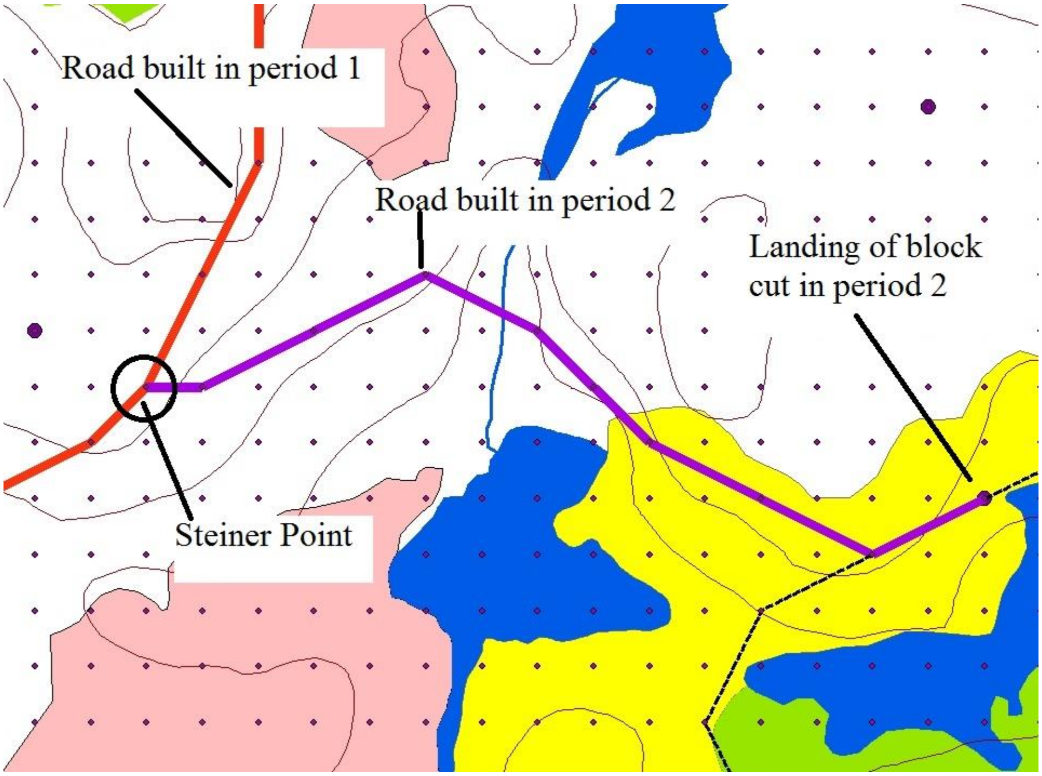

**Figure 5:** An example of the road-building resulting from the SPH algorithm.

In Figure 5, one can observe how a block scheduled for harvest in period 2 was connected to a road built in period 1. Unlike the roading algorithms MST and SPOH, where new roads can only be connected to scheduled landings, the SPH algorithm allows a new road to be connected to any point along an existing road. This point of connection is referred to as a Steiner point. The overall effect of using the SPH algorithm on the solution generated by the tactical planning model is a reduction in total road network costs (see Table 1).

**Table 1**: The reduction in road construction costs from repairing the road-networks generated using the SPOH and MST heuristics, respectively.

| | **SPOH** | **MST** |
|---|---|---|
| Road Cost Before Repair ($) | 3,249,769 | 3,378,133 |
| Road Cost After Repair ($) | 1,752,866 | 2,943,888 |
| Cost Saving (%) | -46.06% | -12.85% |

### Results from Comparing Sequential versus Simultaneous Approach

We also compared the simultaneous *versus* sequential approach to scheduling cut-blocks and roads in tactical planning. In the simultaneous approach, the scheduling and locations of cut-blocks and roads is optimized simultaneously in a model's objective function. In the sequential approach, the schedule and locations of cut-blocks are first optimized; and then, given a fixed location and timing of cut-blocks, an optimal road network is designed. Given that the optimal location and scheduling of cut-blocks is not independent of the optimal location of a road network, we know, *a priori*, that the sequential approach is inferior to the simultaneous approach. In our results, we would, therefore, like to quantify this difference.

Table 1 summarizes the solution values generated using different roading heuristics (i.e., SPOH and MST) in a model that simultaneously schedules blocks and roads *versus* a sequential approach to scheduling--where simulated annealing was first used to schedule blocks and then SPH was used to design a least-cost road network.

**Table 2**: A comparison of solution values generated using different roading heuristics within the tactical planning model.

| **Roading Heuristic** | **Discounted Revenue ($)** | **Discounted Road Cost ($)** | **Objective Function Value ($)** |
|---|---|---|---|
| MST | 21,973,262 | 2,943,888 | 19,029,373 |
| SPOH | 20,795,286 | 1,752,866 | 19,042,419 |
| Sequential | 22,308,003 | 3,885,261 | 18,422,742 |

Table 2 provides several interesting observations. First, we observe that the objective function values of the solutions found using SPOH *versus* MST differ very little; but, when I looked at the components of the objective function values, namely, revenue and road cost, I observed two very different strategies used in arriving at the same objective function value: the MST solution had a higher road cost than SPOH (40% higher) and it had a higher revenue than SPOH (5.4% higher). A second observation we could draw from Table 2 is that the sequential approach produced a solution with the highest revenue. This is not surprising because the search for an optimal set of revenue-generating cut-blocks to schedule was not constrained by road-building costs. The road-building costs incurred by the sequential approach's schedule of harvests were 24% and 55% higher than the road-costs of solutions found using MST and SPOH respectively. This relatively high road-cost incurred by the solution generated using the sequential approach caused it to have a lower objective function value than solutions generated using SPOH and MST (more than 3% lower).

### Results from Mapping the Solutions

The next set of results come from step 3 of my approach: assembling the solution on a map. The two-dimensional maps for solutions generated using the MST, SPOH, and sequential approaches are presented in Figures 6, 7, and 8, respectively.

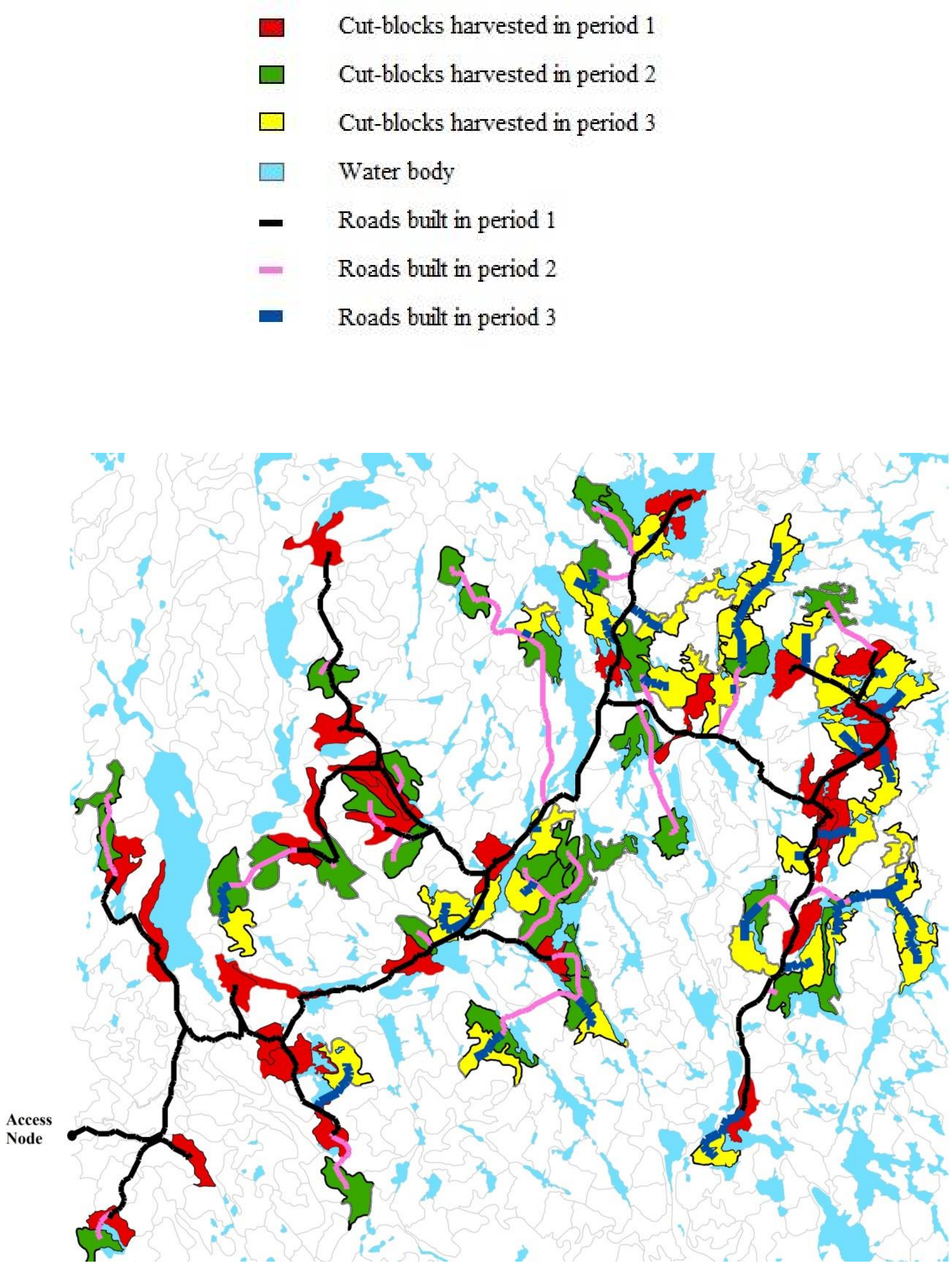

**Figure 6**: Map of solution generated using MST heuristic within tactical model

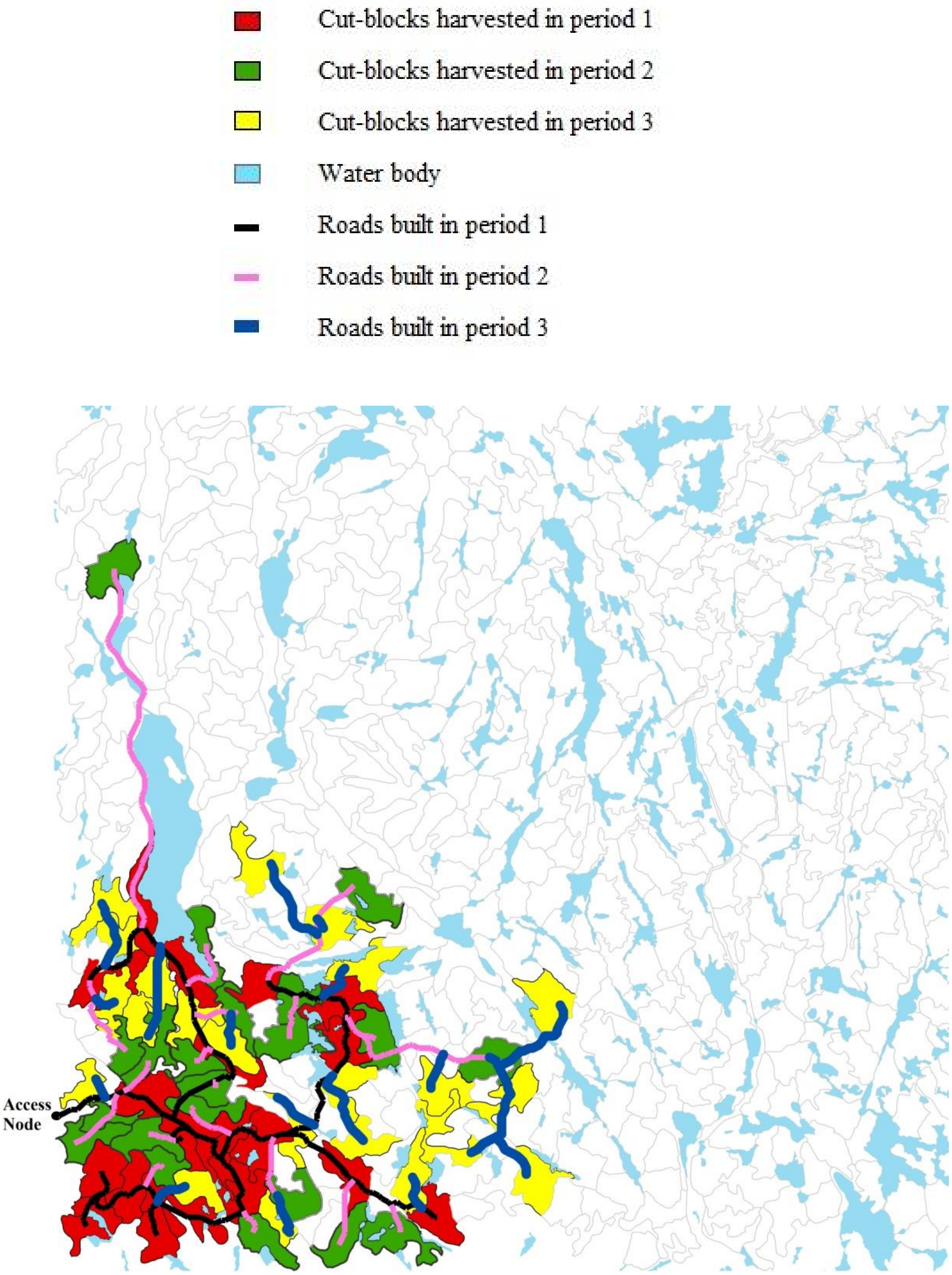

**Figure 7**: Map of solution generated using SPOH heuristic within the tactical model.

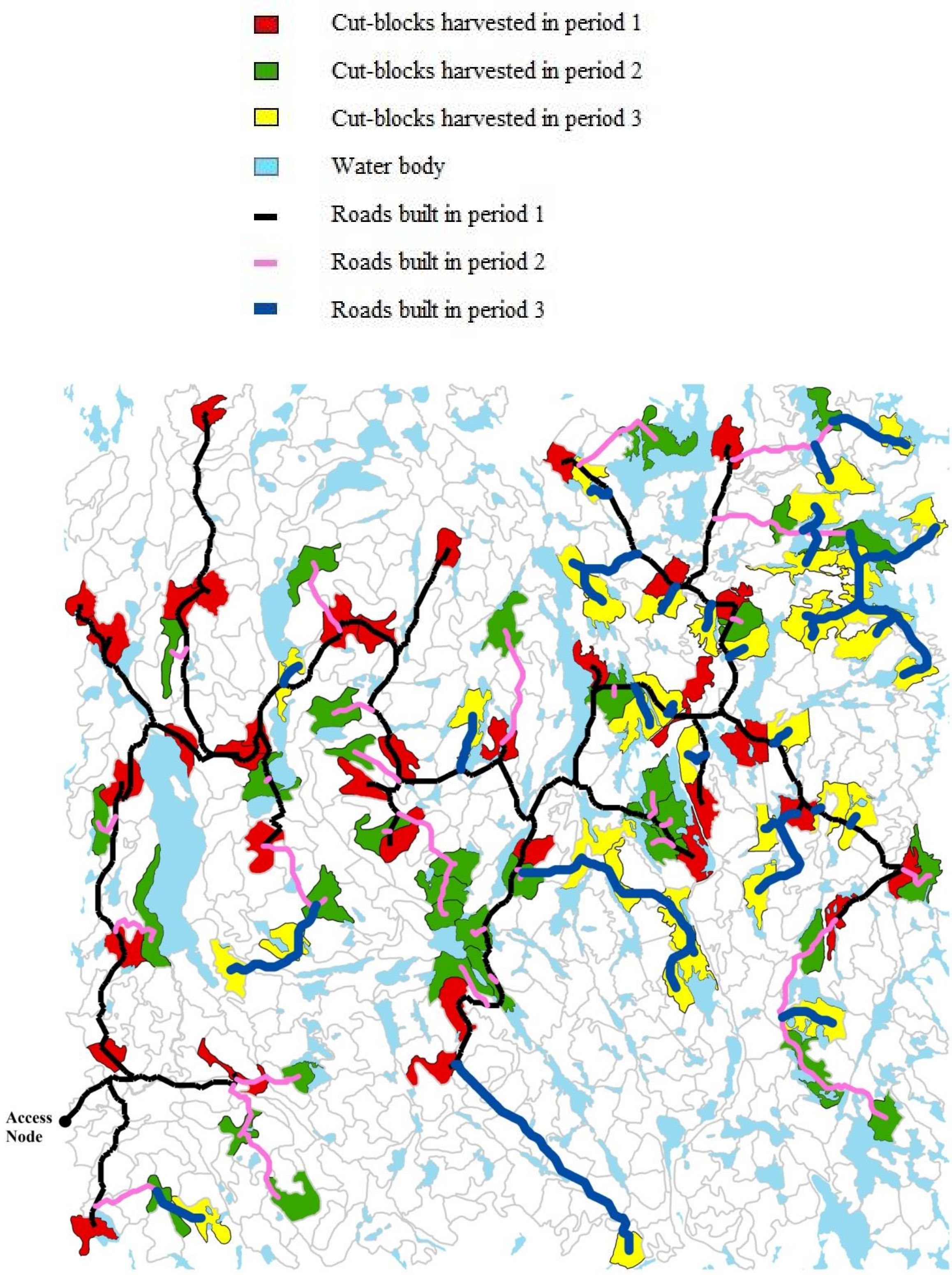

**Figure 8**: Map of solution generated using sequential approach.

We have several observations from Figures 6 through 8. The first observation is that the solutions do not appear to violate any spatial constraints (observable in two-dimensions). For example, in each of the maps:

a) the road network is a tree (i.e., a connected graph containing no cycles);
b) the road network is a Steiner tree (i.e., selected roads connect to nodes other than terminal nodes, i.e., landing-nodes);
c) the cut-block opening limit of 260 ha is not violated;
d) the road network does not to cross streams with indifference to penalties; and
e) the roads do not violate horizontal constraints (except at the conjunction of two roads which was not constrained).

A second observation we could make from Figures 6 through 8 is that the solution generated using the SPOH heuristic was much more compact than the solutions generated using the MST heuristic and the sequential approach. The dispersal of the scheduled blocks resulting from the sequential approach is not surprising; for the selection of block locations is not constrained by road-costs. The dispersal of the blocks resulting from the use of the MST heuristic appears to have arisen from the tactical model's search making much progress on maximizing revenue and little progress on minimizing road-costs (recall Figure 3, above). The compactness of the solution arising from the use of the SPOH heuristic arises from the nature of its search—to construct a tree that consists of shortest paths from the forest's point of entry to all other terminal nodes, i.e., scheduled cut-block landings.

## Results from Transportation Costs

A third observation we could make, from Figures 6 through 8, is that the dispersal of the scheduled cut-blocks had important implications not only for road-construction costs, but also for transportation costs. Using the parameter of \$0.30 *per* m$^3$ *per* km, we calculated the different transportation costs implicit in the solutions generated using the MST and SPOH heuristics (see Table 2).

**Table 3**: Transportation costs implicit in solutions generated using the SPOH versus the MST heuristics in the tactical model (at \$0.30 per m$^3$ per km).

| | MST | SPOH | Sequential |
|---|---|---|---|
| Discounted Transportation Cost (\$) | 1,282,618 | 559,501 | 1,693,121 |

Table 3 reveals that the transportation costs implicit in the solution generated using the MST heuristic are 216% greater than the transportations costs implicit in the solution generated using the SPOH heuristic. Although the minimization of transportations costs is not included in the tactical model, the results in Table 3 indicate that the SPOH, because of the nature of its search, indirectly reduces transportation costs; whereas the MST heuristic, being indifferent to the location of the forest's point of entry, is not equally effective in minimizing transportation costs.

## Results from Three-Dimensional Mapping

Our final set of results also concerns the mapping of the solutions. Since the road network of each solution was constrained by both horizontal and vertical constraints, useful inspection of the solution could occur through three-dimensional mapping of the solution generated using standard G.I.S. software. For example, Figures 9 and 10 illustrate, using three-dimensional mapping, the solutions generated using the MST and SPOH algorithms, respectively.

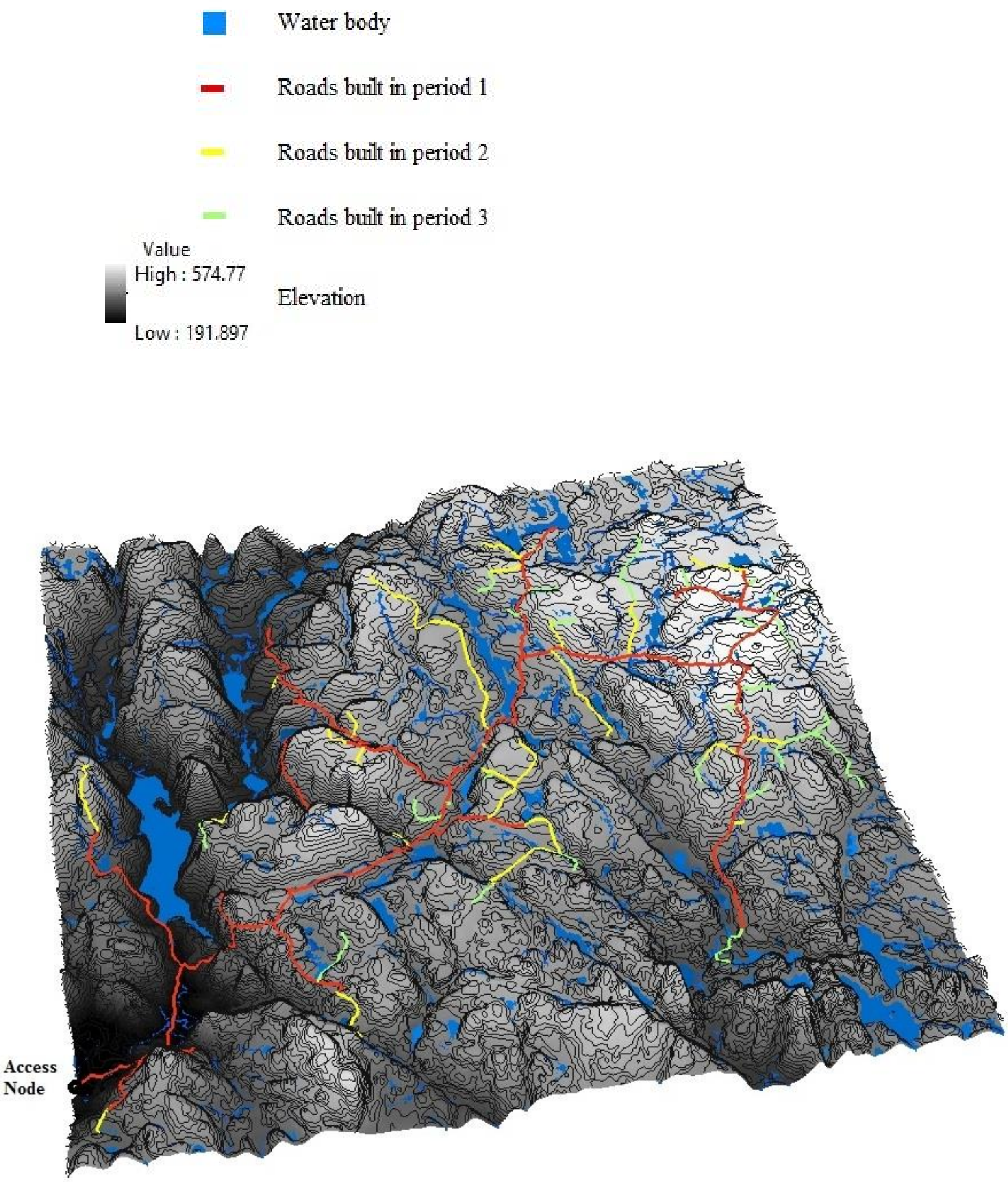

**Figure 9**: Road network generated using the MST heuristic in the tactical model.

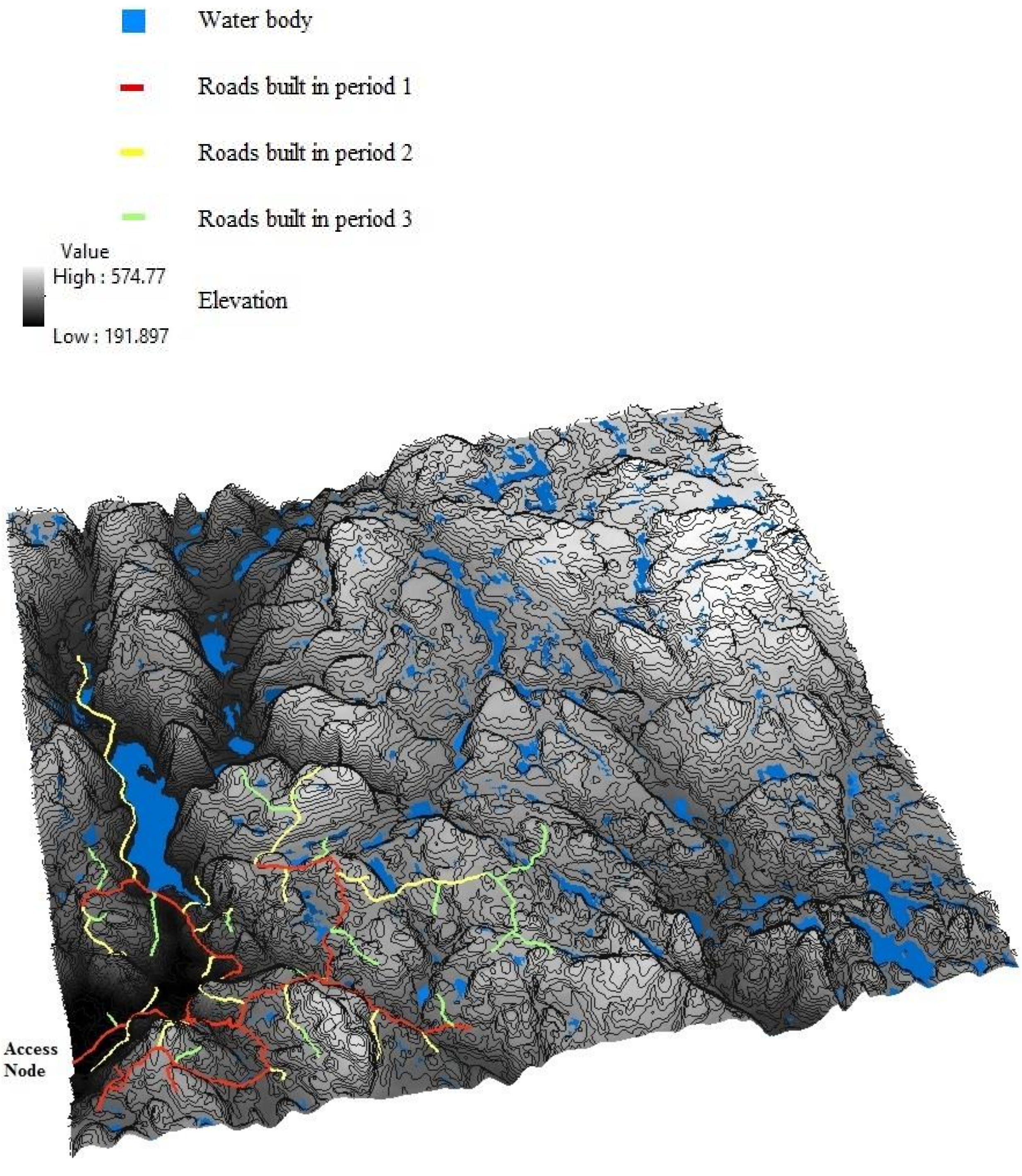

**Figure 10**: Road network generated using the SPOH heuristic in the tactical model.

Figures 9 and 10 do not adequately represent the level of detail with which one could inspect the solutions generated using the tactical model; for, in practice, the solutions mapped in three dimensions would be inspected using G.I.S. software, which allowe one to zoom into an area of interest and examine it from more than one angle.

The inspection of detailed road-planning in tactical solutions, thus facilitated by our approach, was designed to bring tactical plans closer to operational feasibility. Operational planners would thus be required to participate in evaluating alternative tactical solutions.

## Mapped Results from using Penalty Weights on Road Attributes

Given the set of penalty weights in the shortest path algorithm, used to generate the library of candidate roads (in step 1), it was possible to "fine-tune" road-network solutions by altering the penalty weights assigned to vertical and horizontal constraints. For example, Figures 11 and 12 illustrate the effects upon a tactical plan's road network of increasing the penalty function assigned to each road-link's deviation from a slope of zero.

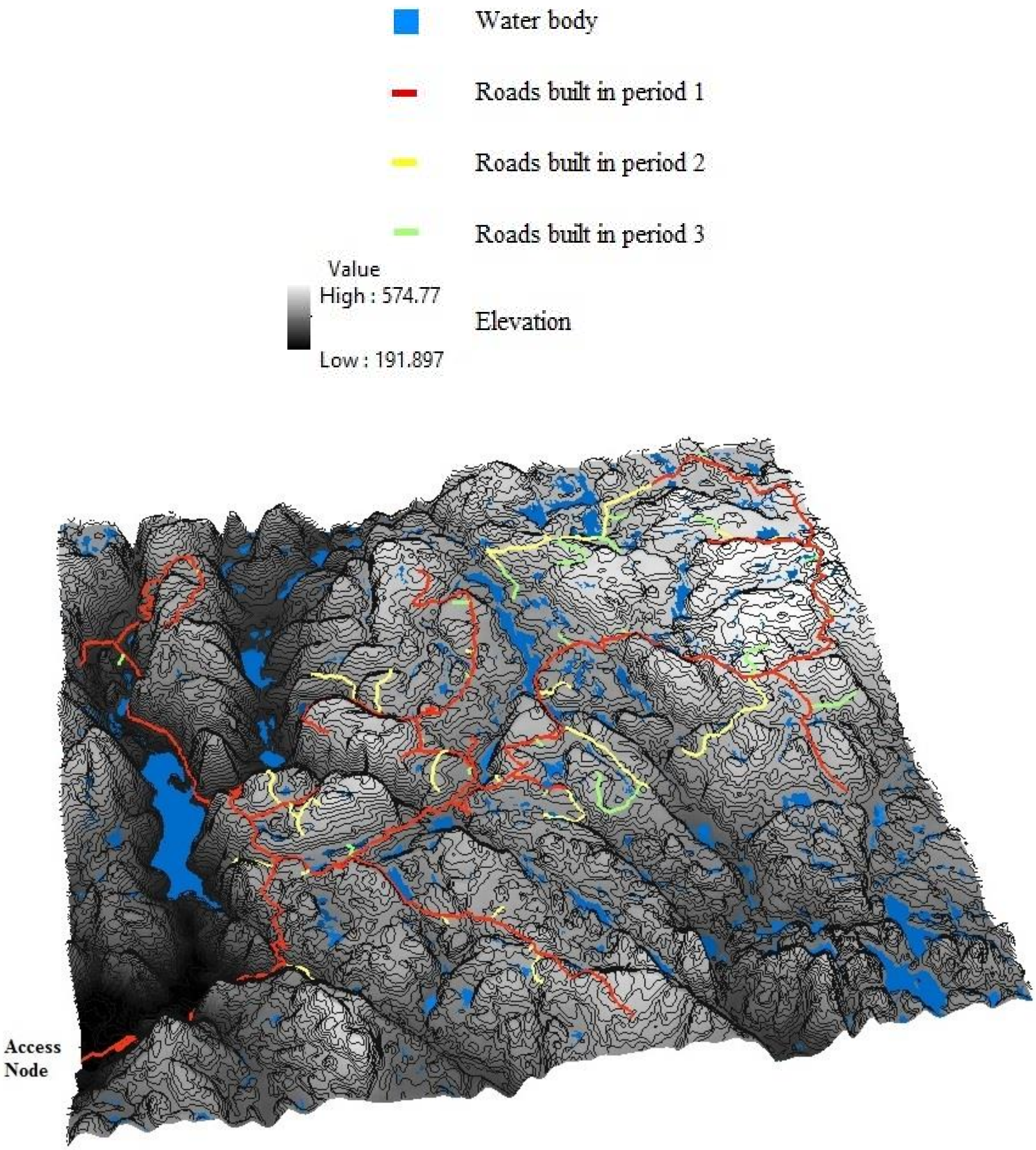

**Figure 11**: Solution generated using the MST algorithm with increased penalty weight on slope deviations.

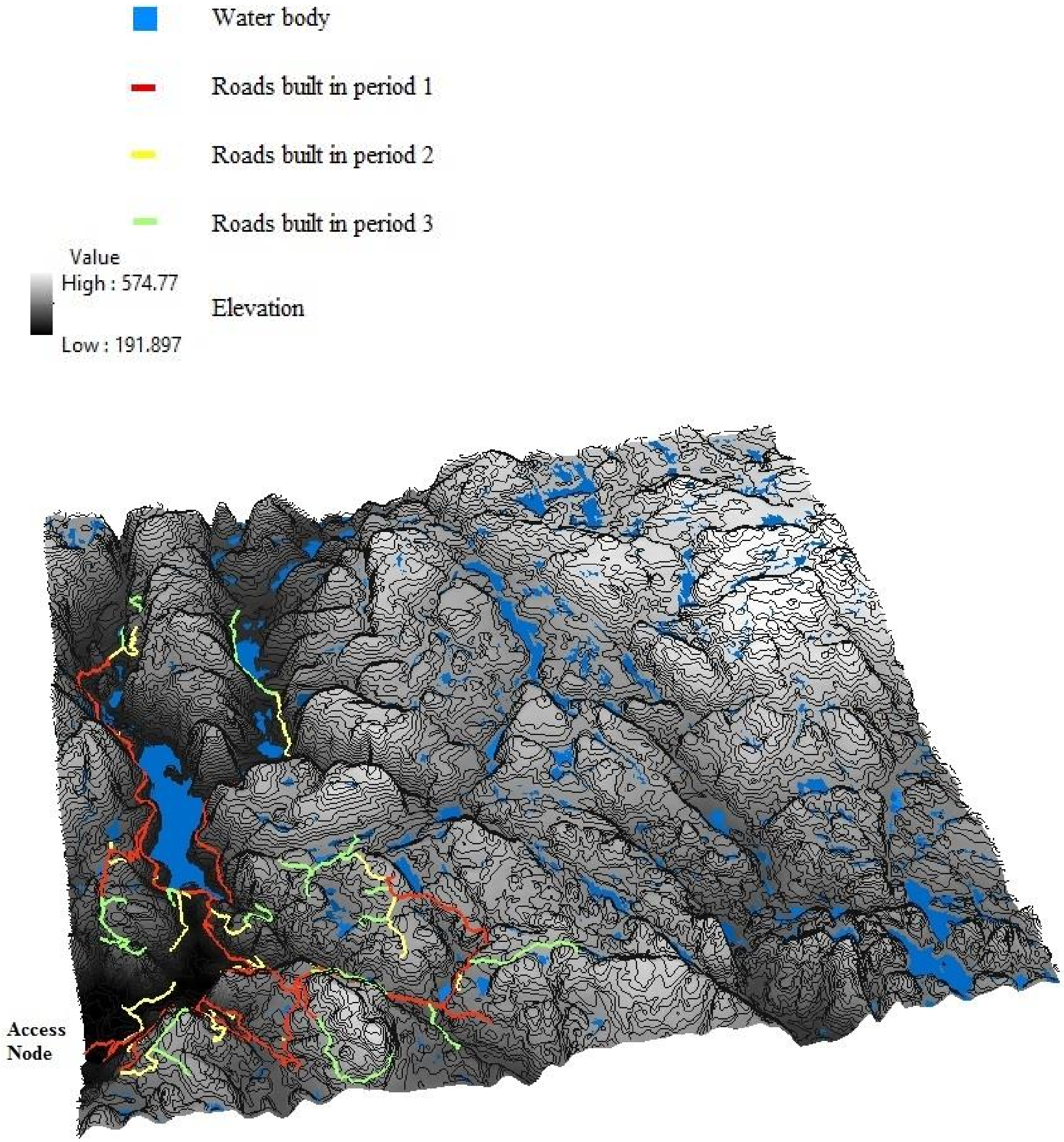

**Figure 12**: Solution generated using the SPOH algorithm with increased penalty weight on slope deviations.

In Figures 11 and 12 one can observe the effects of penalizing roads with higher slopes by comparison with un-penalized road-networks, illustrated in Figures 9 and 10. Through this comparison, one can observe the effect of the penalty to be:

a) increased road-construction at lower elevations; and

b) when road construction occurs at higher elevations, it persists at higher elevations with fewer dips into areas of lower elevations.

Figures 9 through 12, therefore, illustrate one of the main objectives of this thesis: to design a decision support framework that more closely integrates tactical planning with operational planning of road-networks.

# 7. Discussion

In the Introduction to this thesis we observed the principle that the optimal locations of both cut-blocks and roads are interdependent. In addition, we also observed that the selection of an optimal location for a forest road-network requires a large set of candidate roads. For example, Stuckelberger *et al*. (2007), in searching for an optimal road network to connect a pre-selected set of cut-blocks, generated a large set of candidate roads. This set was exhaustive because it connected all pairs of candidate cut-blocks using one road for each pair of cut-blocks. The same exhaustive approach was practiced in this thesis. In the case study, there were 500 candidate blocks and we generated 125,250 candidate roads. Earlier work on the integrated harvest-scheduling and road-building model did not pursue a similarly exhaustive approach to generating candidate roads. For example, Richards and Gunn (2000) had 1,035 candidate cut-blocks in their case study and used 135 candidate roads; and Clarke *et al*. (2000) had 225 cut-blocks in their case study and generated 855 candidate roads. One can conclude from this that, in this thesis, an advance in optimal road location modeling has been successfully integrated with a harvest-scheduling model. This advance is the incorporation of an exhaustive set of candidate roads into the search for an optimal solution to the harvest-scheduling and road-building model.

Another topic of discussion concerns evaluating our method of generating a library of candidate roads, using the shortest path roading algorithm--developed by

Anderson and Nelson (2004). It was chosen as a useful method with which to test our three-step approach to incorporating operational-level road location within a tactical planning model. In hindsight, it might have been useful to include excavation costs in the shortest path roading algorithm (e.g., Tan 2000). I do not hold that Anderson and Nelson's (2004) method is the best; for I believe that different forests have different primary roading challenges. Hence, the best roading algorithm is one which best addresses the particular set of major roading challenges found in a particular forest. This reasoning is consistent with our objective in developing a three-step approach to incorporating operational road planning into tactical modeling:

a) to remain open to the wealth of literature that exists in operational road-location planning; and
b) to facilitate innovation in tactical planning by drawing from this wealth of operational level road planning (hitherto, largely ignored in tactical planning).

Another point of discussion concerns evaluating the different approaches used to generating road networks in the tactical plans presented in the results; namely:

a) the sequential approach;
b) the SPOH heuristic nested within the tactical model; and
c) the MST heuristic nested within the tactical model.

The sequential approach produced a solution with the highest revenue, highest road construction costs, and the lowest objective function value. These results confirm an *a priori* spatial principle that, when applied to forest planning, is summarized in Figure 13:

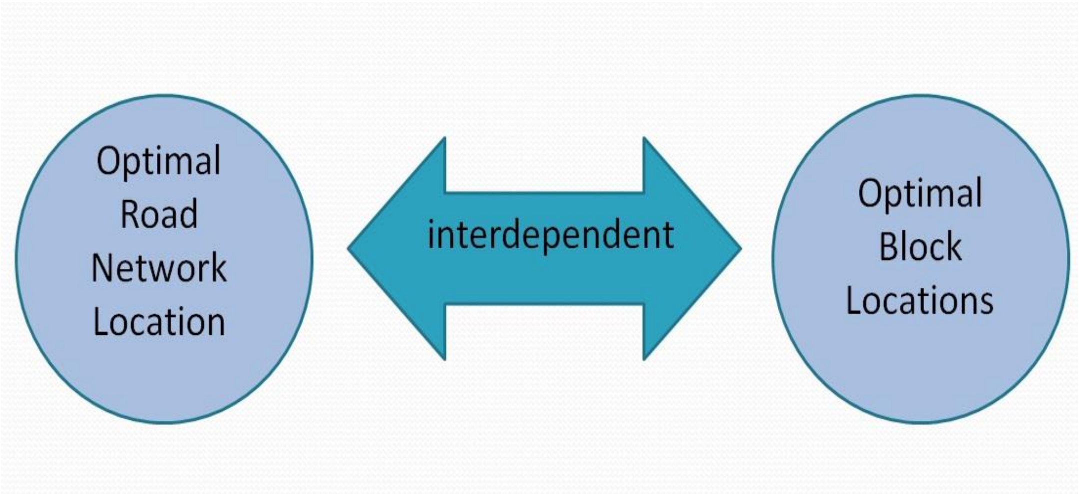

**Figure 13**: Conceptual figure on interdependence of optimal block and road locations.

Since the sequential approach selected a harvest-schedule independently of its required road network, it was not surprising that its overall objective function (as shown in Table 2) was the lowest. The results in Table 2 demonstrate the inferiority of the sequential approach *versus* the integrated approach to scheduling forest harvests and road construction. Similar results were found by earlier researchers who compared the sequential *versus* integrated approach to scheduling blocks and roads (e.g., Weintraub and Navon 1976; Kirby *et al*. 1986).

A more difficult evaluation involves the comparison of the SPOH and MST heuristics nested within the integrated tactical planning model. We perform this comparison using four criteria:

i. execution time;

ii. road costs;

iii. revenue;

iv. transportation costs; and

v. loss of forest productivity.

First, the execution time of the SPOH algorithm was 11 times faster than that of the MST algorithm. In addition to empirical experience, "Big O" notation is used in computer science to classify the complexity of an algorithm by how it responds in processing time to changes in input size. The worst case complexity of the MST and SPOH is the same (Shirasawa 2014):

$$O(E + V \log V) \qquad [11]$$

where E = the number of edges in the dataset and V = the number of vertices in the dataset. In our problem instance, the number of edges equals 124,500 candidate roads and the number of vertices equals 500 cut-blocks plus one point of entry. One can therefore conclude from equation [11] that the number of cut-blocks added to a problem instance has a greater impact on computing time than the number of roads added to a problem instance.

The question of which algorithm has superior execution time is important because, in a much larger forest (for example, with 10,000 or more blocks to connect) the faster execution time of an algorithm would make it a more practical choice for the generation of multiple alternative solutions required in planning. Based on empirical experience, we must conclude that the execution time of the SPOH algorithm is much faster than that of the MST algorithm; this judgment, however, must be qualified by the fact that it is based on only one data-set and that the worst-case complexities of the two algorithms are regarded as equal.

Second, road costs of the solution generated using the MST heuristic were 40% higher than those generated using the SPOH heuristic. The MST heuristic, by definition, connects all selected cut-blocks and the point of entry of the forest into a minimal cost tree. Hence, we were initially surprised that the MST heuristic did not induce the formation of a more compact solution. When we looked at the progress of the search of the tactical model using the MST heuristic (Figure 3), we observed that the search maximized the revenue component of the objective function and made little progress on reducing road costs. This makes sense because, as Table 2 reveals, the revenue component of the objective function is, on average, 10 times greater than the cost component of the objective function. Hence, the MST search focussed on maximizing the revenue component.

One should also observe that the solutions generated using MST need not necessarily be dispersed; for example, a penalty weight of 10 applied to the cost component of the objective function would induce the tactical model using the MST heuristic to generate more compact solutions. Hence, it would be premature to conclude that the SPOH heuristic is necessarily superior to the MST heuristic in the generating of solutions with lower construction costs.

Third, revenue in the solution generated by the MST heuristic was 5.4% higher than that produced using the SPOH heuristic. Given that a simple upper bound on allowable harvest-volume constrained both solutions, the extra revenue earned using the MST heuristic must have arisen from harvesting more valuable, *i.e.*, older, stands.

Fourth, the transportation costs in the solution generated using the MST heuristic were 229% higher than those incurred by the solution generated using the SPOH heuristic. On the one hand, as was mentioned above, it is possible to introduce a penalty function into the tactical planning model’s objective function and thereby penalize solutions with excessive construction costs generated using the MST heuristic. Hence, one can indirectly reduce the transportation costs by reducing the road-network.

On the other hand, the two algorithms have fundamental differences that will ultimately limit the efficacy of penalty functions thus used to reduce transportation costs. The fundamental difference is that the MST algorithm is indifferent to location of the forest's point of entry whereas the SPOH algorithm is not.

The fifth attribute by which I will compare the MST heuristic versus the SPOH heuristic is loss of forest productivity. Loss of forest productivity occurs due to sub-optimal timing of a stand's harvest. The optimal timing of a stand's harvest (when measured in $m^3$) occurs when the mean annual increment of the stand's volume is maximized. With the objective of minimizing the loss of forest productivity over the long-term, older, unproductive stands should be harvested before younger, more productive stands. The parameters used in the harvest-scheduling model had higher dollar values per $m^3$ assigned to older stands than to younger stands; thus there was quantifiable bias directing the model to harvest older stands before younger ones. From Tables 2 and 4, one can observe two interesting trends with regard to minimizing productivity loss:

i. The revenue was highest in the sequential approach, second highest using the MST, and lowest using the SPOH. A higher revenue indicates that more older, unproductive stands were harvested, and therefore a lower loss of long-term forest productivity.

ii. The road-cost required for harvesting was lowest using the SPOH, second lowest using MST, and highest using the sequential approach.

These trends correspond to a production possibility frontier, developed by Richards and Gunn (2000), where the trade-off between money spent on road construction *versus* loss of forest productivity was quantified. At one end of the curve, minimizing the loss of forest productivity requires the highest expenditure of road construction (this corresponds to the sequential approach); and at the other end of the curve, minimizing road expenditures entails the highest loss in forest productivity (this corresponds to results from using the SPOH heuristic).

Having reviewed the five criteria used to compare the results generated by the MST versus SPOH algorithms, we now conclude that MST is to be preferred as an algorithm nested within the harvest-scheduling model, for the following reasons:

1. The worst-case complexity of the search algorithms do not differ.
2. The objective function values of the solutions found using the two algorithms do not differ.
3. The trade-off engaged in by the MST heuristic, between investment in road-building *versus* maximizing revenue, was more favourable to long-term productivity than the trade-off engaged in by the SPOH algorithm. That is, since the MST algorithm produced a solution with higher revenue and higher road-building costs than the SPOH algorithm; and since they both yielded solutions with the same objective function value, one can conclude that the loss of productivity in the solution generated using MST was lower without any overall reduction in profit, as measured by the objective function value.
4. The higher transportation cost is of less value than the reduction in lost forest productivity resulting from solution generated by the MST algorithm.

Another point of discussion concerns evaluating the role of the SPH algorithm used after the tactical scheduling is completed. Recall that the SPH algorithm repairs the final solution's road network by connecting the selected blocks into a Steiner tree. Table

1 shows that execution of the SPH heuristic decreased the costs of the road networks generated by the MST and the SPOH heuristics by 12.8% and 46%, respectively. Clearly, these reductions justify the inclusion of the SPH algorithm in our approach; but the scale of the improvements to the road network generated using the SPOH algorithm leads to the question: how was such a large improvement possible?

To answer this question, one must recall that the SPOH heuristic constructs a tree that consists of shortest paths from the forest's point of entry to all other terminal nodes, *i.e.*, scheduled cut-block landings. In other words, it does not design a very clever road network; *i.e.*, it produces multiple roads leading directly to the forest's point of entry instead of multiple roads connected to a main artery stemming from forest's point of entry. Hence, it must be borne in mind that our evaluation of the SPOH heuristic has thus far been based on its resulting solutions *after* they have been repaired by the SPH heuristic. As a stand-alone roading heuristic, the SPOH heuristic produces inferior road networks; but, when repaired by the SPH algorithm, the resulting road networks have several advantages over those produced using the MST heuristic, as discussed above.

A final point of discussion concerns evaluating the overall effectiveness of our three- step approach, aimed at incorporating operationally detailed road location planning into a tactical modeling. We evaluate the work by three criteria:

i. economic;

ii. practical; and

iii. as a platform for future innovation.

First, the economic benefits of our approach stem from the nature of hierarchical planning in forestry. At the tactical level, the locations of cut-blocks are made, along with estimates of resulting revenues. Road network locations and costs are also made and estimated at the tactical level. At the operational level, the locations of these cut-blocks do not change, but there is considerable flexibility allowed in redesigning road locations in order to minimize construction costs not foreseen at the tactical level. The traditional reason for this flexibility is that the level of detail required in operational road location planning is too great for the purposes of tactical planning. For example, two of the most widely used software tools for forest planning in North America (Patchworks®, and Woodstock-Stanley®) do not use operational design constraints on the road used in their tactical models. Nonetheless, it is at the operational scale that the true costs of the road network required to connect a set of cut-blocks, selected at the tactical level, are discovered.

Now, given our three-step approach, in which operational detail is incorporated into tactical planning, the difference between tactical estimates of road locations and costs, and the realized road locations and costs, should be *minimized* as much as is currently possible. Should this minimization occur, then one will be one step closer to the goal of achieving, on the ground, the simultaneous optimization of both road-network and cut-block locations. The economic efficiency of such planning should be obvious; and the disparities in road construction costs, found in our results, further reveals the economic relevance of our more efficient method of road location planning.

It is our conclusion, therefore, that: a) through the inclusion of greater operational road location detail, at tactical level of planning, one can move toward the realization of more economically efficient forest road construction; and b) my three-step approach successfully facilitates the inclusion of such detail.

Second, the practicality of our approach has been demonstrated in the results; but one important question is whether our approach can be implemented on much larger problem instances, found in the real world?

Let us examine this question at each of the steps in taken in our approach. In the first step, in which a large library of candidate roads is generated, there is no computational challenge: a larger library of roads will simply take more time to pre-process. In the second step, in which the tactical model is run, the execution time required to produce a solution will be much greater, but not impractical. Meta-heuristic algorithms have been used to generate tactical plans on large planning problems for many years. The SPOH roading heuristic would be more practical, on large problems, in terms of execution time, than the MST roading heuristic.

After the second step is complete, a repair of the road-network is executed using the SPH algorithm. The SPH algorithm does pose a minor practical problem: for we found that, since the SPH designs a road network as a Steiner tree, it must select links at a 50m X 50m scale; and that this requirement tested the memory limits of our available 96 gigabytes of RAM. Hence, the only practical challenge we foresee in using our approach on larger problems is the requirement of additional RAM.

In evaluating the practicality of this approach, the limitations of the planned road network should be made clear. As prior researchers on road-network optimization have observed (e.g., Nelson 2004; Stuckelberger *et al*. 2007), automated road design may not always provide ‘optimal’ road networks. Some modifications to the proposed link pattern and node spacing may be necessary for better results, depending on the road design specifications. Those results must then be field-verified before implementation.

Third, our three-step approach functions as a framework for future innovation in tactical planning for several reasons. First, the approach, as was mentioned earlier, facilitates the inclusion and relevance of the wealth of research, conducted on operational road location planning, into tactical level planning. Such inclusion will innovate and improve the practice of tactical level planners. Second, the approach will lead to innovations in the practice of tactical planning insofar as the role of the operational planning forester will become more important in evaluating alternative tactical solutions. The level of road-network detail provided in the tactical solutions requires the evaluation of an experienced forest road engineer who will, perhaps, come to play a more prominent role in the tactical planning team.

# 8. Conclusions

The purpose of this thesis was to design and evaluate a planning approach by which greater operational road-location detail can be included in tactical-level modeling. The approach consisted of three steps:

First, an exhaustive library of roads connecting all pairs of candidate cut-blocks is generated, using a shortest-path algorithm modified such that the path connecting any pair of cut-blocks is subject to vertical and horizontal constraints measured at a scale commonly found in operational level planning.

Second, the costs of these roads are input into a tactical level planning model of the integrated harvest-scheduling and road-building model. The tactical model thus avoids the computational burden of designing roads but instead selects a set of pre-designed roads, based on their costs, in forming a solution.

Third, a map of solution is generated using the highly detailed roads generated in step 1 and selected in step 2.

The approach was tested on a portion of the Kenogami Forest and the results demonstrated its feasibility. We conclude that that the approach has the potential:

a. to support more economically efficient decisions on the locations of forest road-networks and cut-blocks;

b. to be used on large, real-world data-sets; and

c. to function as a framework for innovation in tactical planning-- where the modeling innovations in road-location planning, developed in operational planning, will become relevant to tactical planning.

Future research from this thesis should be directed at quantifying the benefits of this approach by comparing its results with those from a real-world case study. For example a dataset representing a planning inventory from a phase 1 plan, that has already published, can be used to compare sequential planning results *versus* results produced using MST and SPOH. In addition, the utility of this modeling approach could be evaluated using data from a “well-roaded” fores in order to discover potential improvements in alignments and needed upgrades.

# LITERATURE CITED

Akay, A. E. 2004. A new method of designing forest roads. Turkish Journal of Agriculture and Forestry, 28(4), 273-279.

Akay, A. E., Aruga, K., Bettinger, P., & Sessions, J. 2013. Using optimization techniques in designing forest roads and road networks. Bartın Orman Fakültesi Dergisi, 15(1), 49-62.

Andalaft, N., Andalaft, P., Guignard, M., Magendzo, A., Wainer, A., and Weintraub, A. 2003. A problem of forest harvesting and road building solved through model strengthening and Lagrangean relaxation. Operations Research 51(4): 613-628.

Anderson, A.E., and Nelson, J. 2004. Projecting vector-based road networks with a shortest path algorithm. Can. J. For. Res. 34: 1444-1457.

Bettinger, P., and Chung, W. 2004. The key literature of, and trends in, forest-level management planning in North America, 1950-2001. International Forestry Review 6(1): 40-50.

Bjørndal, T., Herrero, I., Newman, A., Romero, C., & Weintraub, A. 2012. Operations research in the natural resource industry. International Transactions in operational Research, 19(1-2), 39-62.

Chung, W., Stückelberger, J., Aruga, K., and Cundy, T. W. 2008. Forest road network design using a trade-off analysis between skidding and road construction costs. Canadian Journal of Forest Research 38(3): 439-448.

Chung, W. and Sessions, J. 2001. Designing a forest road network using heuristic optimization techniques. In J. F. McNeel, editor, Appalachian Hardwood: Managing Change, Corvallis, Oregon, 2001. Council on Forest Engineering.

Clark, M.M., Meller, R.D., and McDonald, T.P. 2000. A three-stage heuristic for harvest scheduling with access road network development. For. Sci. 46: 204.

Dean, D.J. 1997. Finding optimal routes for networks of harvest site access roads using GIS-based techniques. Can. J. For. Res. 27: 11-22.

Dijkstra, E.W. 1959. A note on two problems in connection with graphs. Num. Math 1: 269–271.

Epstein, R., Weintraub, A., Sapunar, P., Nieto, E., Sessions, J. B., Sessions, J., Bustamante, F., and Musante, H. 2006. A combinatorial heuristic approach for solving real-size machinery location and road design problems in forestry planning. Operations Research 54(6): 1017-1027.

Guignard, M., Ryu, C., and Spielberg, K. 1998. Model tightening for integrated timber harvest and transportation planning. Eur. J. Oper. Res. 111: 448-460.

Kirby, M.W., Hager, W.A., and Wong, P. 1986. Simultaneous planning of wildland management and transportation alternatives. TIMS Studies in the Management Sciences 21: 371-387.

Kirkpatrick, Scott. 1984. Optimization by simulated annealing: quantitative studies. Journal of Statistical Physics 34.5-6: 975-986.

Kramer, B. W. 2001. Forest road contracting, construction, and maintenance for small forest woodland owners. Corvallis, Or.: Oregon State University, College of Forestry, Forest Research Laboratory.

Liu, K., and Sessions, J. 1993. Preliminary planning of road systems using digital terrain models. Journal of Forest Engineering 4: 27.

Lockwood, C., and Moore, T. 1993. Harvest scheduling with spatial constraints: a simulated annealing approach. *Canadian Journal of Forest Research*, *23*(3), 468-478.

Meignan, D., Frayret, J., Pesant, G., and Blouin, M. 2012. A heuristic approach to automated forest road location. Can. J. For. Res. 42: 2130-2141.

Murray, A.T., and Murray, R.L. 1995. Heuristic solution approaches to operational forest planning problems. OR-Spektrum 17: 193-203.

Murray, A.T. 1998. Route planning for harvest site access. Can. J. For. Res. 28: 1084-1087.

Najafi, A., and Richards, E.W. 2013. Designing a Forest Road Network Using Mixed Integer Programming. Croatian Journal of Forest Engineering 34: 17.

Nelson, J., and Brodie, J.D. 1990. Comparison of a random search algorithm and mixed integer programming for solving area-based forest plans. Canadian Journal of Forest Research 20: 934-942.

Prim, R. C. 1957. Shortest connection networks and some generalizations. Bell Systems Technical Journal. 36 (6): 1389–1401.

Richards, E.W., and Gunn, E.A. 2000. A model and tabu search method to optimize stand harvest and road construction schedules. For. Sci. 46: 188.

Richards, E.W., and Gunn, E.A. 2003. Tabu search design for difficult forest management optimization problems. Can. J. For. Res. 33: 1126-1133.

Sessions, J. 1987. A Heuristic Algorithm for the Solution of the Variable and Fixed Cost Transportation Problem. In Proc: The 1985 Symposium on System Analysis in Forest Resources. Univ. of Georgia, Athens, pp. 324-336.

Shirasawa. 2014. A comparative study of heuristic algorithms for the multiple target access problem. Journal of forest research 19: 437-449.

Stückelberger, J.A., Heinimann, H.R., and Woodam, C. 2007. Improved road network design models with the consideration of various link patterns and road design elements. Can. J. For. Res. 37: 2281-2298.

Takahashi, H., and Matsuyama, A. 1980. An approximate solution for the Steiner problem in graphs. Math Jap 24:573–577.

Tan, J. 1992. Planning a forest road network by a spatial data handling-network routing system. Acta Forestalia Fennica 227:5-87.

Tan, J. 1999. Locating Forest Roads by A Spatial and Heuristic Procedure Using Microcomputers.International Journal of Forest Engineering. 10 (2): 91-100.

Tan, J. 2000. Application of dynamic programming to optimum location of a forest road. Journal of Forest Engineering, 11(2), 33-42.

Turner, A. K. 1978. A Decade of Experience in Computer Aided Route Selection. Photogrammetric. Engineering And Remote Sensing. 44: 1561-1576.

Weintraub, A., and Navon, D. 1976. A forest management planning model integrating silvicultural and transportation activities. Management Science 22: 1299-1309.

Weintraub, A., Jones, G., Magendzo, A., Meacham, M., and Kirby, M. 1994. A heuristic system to solve mixed integer forest planning models. Oper. Res. 42: 1010-1024.

Weintraub, A., J.G. Jones, M.L. Meacham, A. Magendzo, A. Magendzo and D. Malchuk. 1995. Heuristic procedures for solving mixed-integer harvest scheduling-transportation planning models, Canadian Journal of Forest Research 25: 1618–1626.

Winter, P., and Smith, J. M. 1992. Path-distance heuristics for the Steiner problem in undirected networks. Algorithmica 7(1-6): 309-327.

# APPENDIX I

The Kenogami Forest is located approximately 300 kilometres northeast of Thunder Bay, in the OMNR Nipigon District. The municipalities of Terrace Bay, Schreiber, Longlac, Geraldton and Nakina are located within its boundaries.