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USING OPTIMIZATION TECHNIQUES IN DESIGNING FOREST ROADS AND ROAD NETWORKS

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ABSTRACT

There has been an increasing interest in using modern optimization techniques in forest road design due to advancements in computer hardware, optimization algorithms, and remote sensing technologies. These techniques allow one to automate many of the time consuming tasks involved in road design process and improve the efficiency of road design managers in identifying road alignment alternatives. This paper presents the main road design stages to indicate the possibilities of using optimization techniques in forest road design and provides background information on many of the optimization techniques used in road design and road network management problems. The current advances in forest road design and network optimization procedures are presented and recommendations are suggested for future studies.
Key words: Road engineering, forest road design, optimum route selection, road cost

1. Introduction

Forest roads provide access for timber harvests, recreation, fire protection, and other administrative needs (Weintraub *et al* 2000a). Designing forest roads and road networks is a complex engineering problem involving social, economic, and environmental considerations. Route location is critical in steep terrain, where ground slope, geology, and machine limitations (e.g., maximum road grade, minimum turning radius) affect road layout and design. On relatively flat terrain, soil properties and quality of the substratum may also influence the road location and seasonal road strength (O'Mahony *et al* 2000). Due to the inherent trade-offs involved, decisions regarding road building, maintenance, or decommissioning are very complex (Lugo and Gucinski 2000). Road managers often aim for the best path with the lowest total cost, while protecting soil and water resources. Therefore, they have to examine a sufficient number of alternatives to ensure that road networks are cost effective with minimum environmental damage.

Planning of road location and construction is an integral part of harvest planning. Barreto *et al* (1998) compared the economics of planned and unplanned harvesting units in Brazil. The results indicated that with proper road planning, the time spent on locating roads and landings was reduced by 37%, and the density of forest roads was reduced by 33%. Furthermore, Gullison and Hardner (1993) have reported that poor road planning and construction could cause excessive damage to residual stands, reduce the value of future harvests, and diminish the role that the residual stands may play in maintaining non-timber species. Thus, effective planning of forest roads is essential from both economic and environmental perspectives.

Road management problems have become too complex to be solved using traditional road location methods, which basically consist of aerial photograph interpretation and field reconnaissance. Bailenson *et al* (1998)

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indicated that selecting a route between two known points based on a designer experience may not necessarily provide the shortest or the most efficient road alignment. Computer-aided analysis of road location have become highly desirable since it could reduce the time spent on road planning and provide a designer with quick evaluation of alternatives, considering economic and environmental constraints.

Application of computer-aided road location methods dates back to the late 1960's when shortest path algorithms were first combined with Digital Elevation Models (DEMs) (Turner 1978). Currently, there are several computer-aided systems (e.g., Pegger&RoadView WA; Lumberjack WA; RoadEng OR) that have been widely used in forest road design. These systems automate some of the tasks in locating forest road alignment; however, they do not have capability of generating large number of alternative routes, minimizing the total road cost, or considering the least environmental impact. By means of using advanced microcomputer technology (i.e., speed and memory), modern optimization techniques, and advanced Geographical Information Systems (GIS), forest road design systems using mathematical optimization techniques can be utilized to solve complex road design problems. Optimization techniques systematically search for the desired or "best" solution among the acceptable solutions at reasonable computational cost (Beasley *et al* 1993).

The objective of this study is to present the progress and opportunities of using optimization techniques in designing forest roads and road networks. In order to achieve this objective, major road design stages are identified and many of the commonly used optimization techniques and their applications in forest road design and network optimization problems are presented. It is expected that this review article will draw attentions of researchers, transportation engineers, land managers, and other practitioners to the capabilities of using optimization techniques in designing forest roads and road networks. Readers will be provided with an assessment of the current state of road design and road network optimization in forestry applications, as well as associated efforts in road design provided by the transportation sciences. This work will add to the literature a synthesis of optimization techniques used across disciplines, yet focused on applications within forest land management.

2. Road Design Stages

In order to understand how optimization techniques can be used in forest road design, it is necessary to identify the major road design stages of a single forest road. Computer-aided analysis of route selection using optimization techniques generates a large number of alternatives, subject to road design constraints. Some of the route alternatives may be eliminated during the process as they do not satisfy one or more design constraints. Design constraints are generally divided into two groups; geometric specifications and environmental requirements. The geometric specifications may include maximum road grade for logging vehicles, minimum curve dimensions for both vertical and horizontal curves, and minimum safe stopping distance. The environmental requirements may include minimum road grade for drainage, optimal stream-crossing angle for stream protection, and maximum cut and fill slope ratio for slope stability. The average values for some of the design constraints used in North America are listed in Table 1 (AASHTO 1990; Kramer 1993; Kramer 2001). Optimization techniques require design constraints that can be represented quantitatively. And, the complexity of the optimization techniques increases as the number of constraints increases.

Table 1. The typical values for some of the road design constraints.

Constraints	Value
Max. adverse road grade on rock-surfaced roads	16 %
Max. favorable road grade on rock-surfaced roads	-12 %
Min. radius of a horizontal curve	18 m
Min. length of a vertical curve	15 m
Min. road grade	± 2 %
Min. safe stopping distance on gravel-surfaced roads	35 m
Optimal stream-crossing angle	90 °
Max. cut and fill slope ratios on common soil	1:1 and 1.5:1

2.1 Horizontal and Vertical Alignment of a Road

Determining the location of horizontal and vertical alignment is a time-consuming process (Erdas 1997). Computer-aided analysis of route location using optimization techniques may lead to considerable time savings by providing the designers with quick evaluation of alternative alignments, while satisfying the design constraints (Akay 2006). In the computer-aided road design optimization process, an initial horizontal alignment consisting of a set of tangents and circular curves is specified, and then the vertical alignment consisting of a set of straight lines and parabolic curves along the generated horizontal alignment is established (Figure 1). Once the horizontal alignment is fixed, vertical alignment alternatives can be generated by systematically altering the road elevations on intersection points using optimization techniques. The optimum solution for locating a single forest road can be also determined by simultaneously optimizing both horizontal and vertical alignments, at the expense of computer processing time. In a recent study, it was found that simultaneous optimization of horizontal and vertical alignments provided the best road alignment with minimum total cost, subject to specified road design constraints (*Aruga et al* 2004).

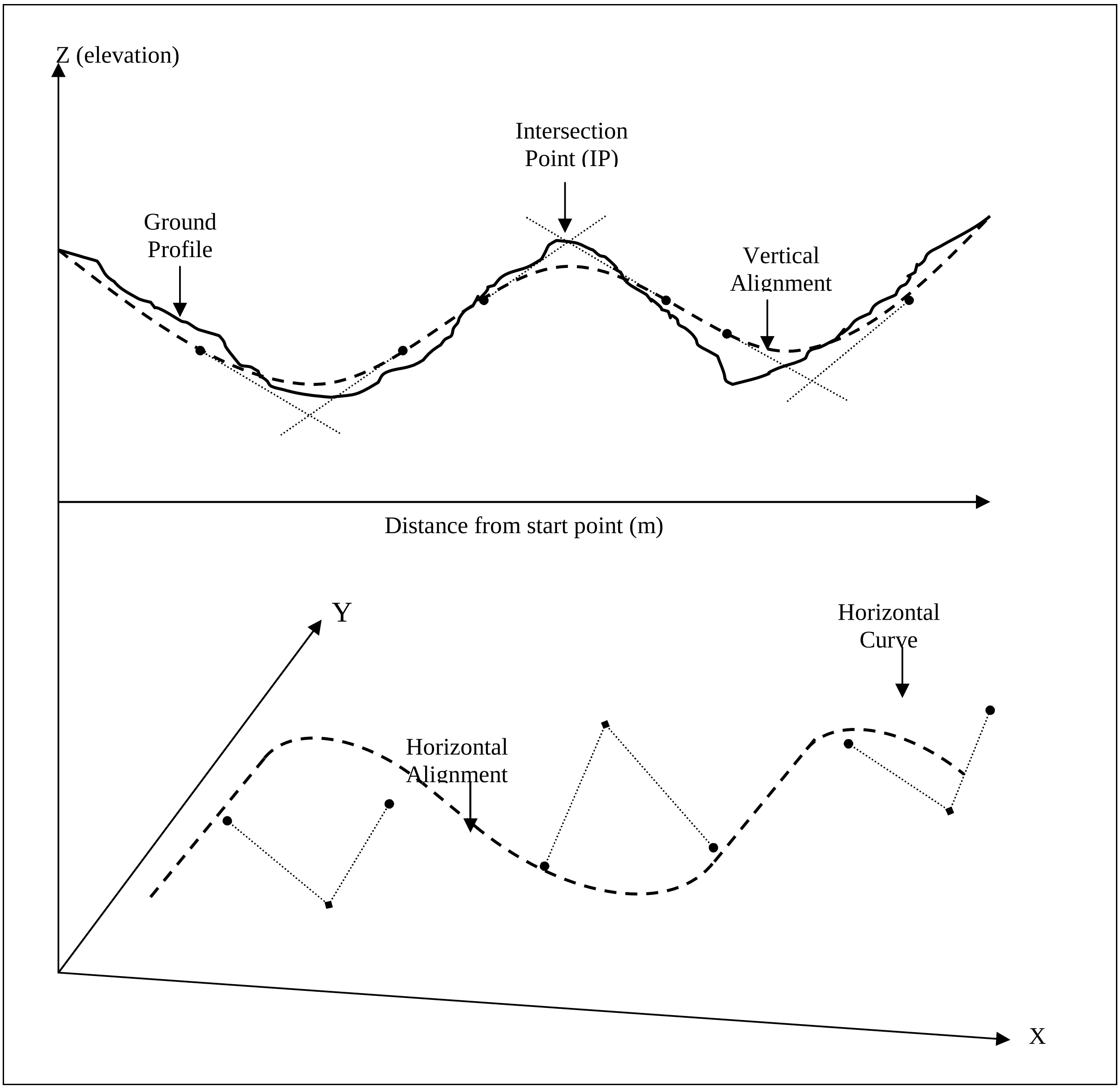

Figure 1. Horizontal and vertical alignments of a sample road section.

2.2 Earthwork Allocation of a Road

Earthwork allocation involves three major activities including excavation and loading, hauling and unloading, and compaction (Erdas 1997). This work may amount to a significant portion of the total cost of forest road construction. Determining the least-cost alternative for distribution of earthwork from cut sections and borrow areas to fill sections and landfill areas is an important design activity (Figure 2). Typically, a road designer estimates the amount of material required at each cut and fill section, soil characteristic along the roadway, location and capacities of borrow and fill areas, and the unit costs for excavation, haul, and fill and compaction activities. With this information, it is also possible to formulate earthwork allocation as an optimization problem.

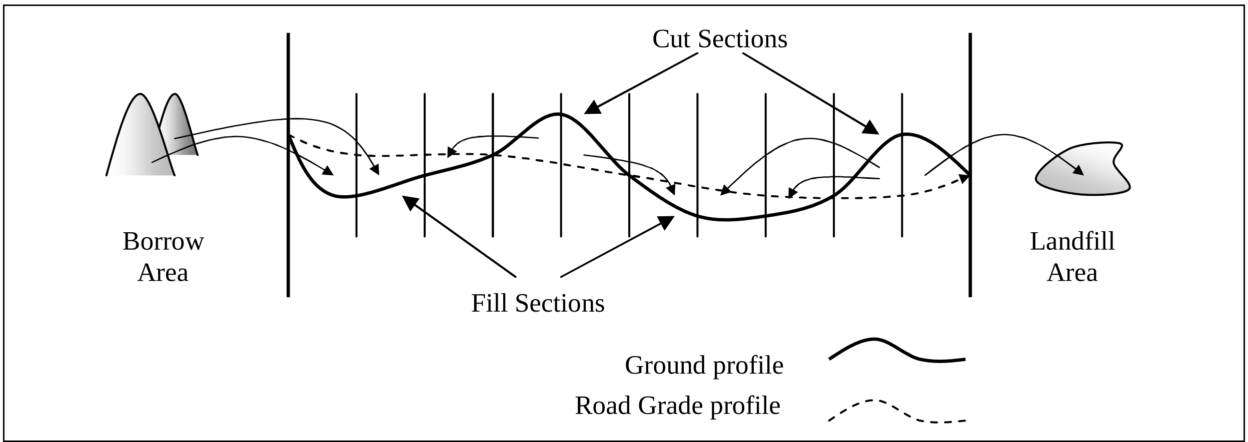

Figure 2. Sample solution for an earthwork allocation problem

In several current road design systems (Lumberjack WA and RoadEng OR), the mass diagram (Oglesby and Hicks 1982) has been used to balance the required quantities of cut and fill materials. However, the capability of the mass diagram is limited where soil characteristics vary along the roadway (Akay and Sessions 2005). Optimization techniques have been used to overcome the limitations of the mass diagram in earthwork allocation problems (Mayer and Stark 1981; Christian and Caldera 1988; Easa 1988).

2.3 Calculating Total Road Management Cost

The main cost factors involved in managing a road network include construction, maintenance, and transportation costs (Akay 2006). Cost components analyzed with optimization techniques should be represented with a mathematical problem formulation. The “unit cost approach”, where estimated unit costs are multiplied by the quantity of design parameters (e.g. m^3, m^2, m, etc.), is often used in computer-aided road design systems. For low volume forest roads in mountainous terrain, construction and maintenance costs are the largest cost components (Pearce 1974). The road construction activities may include the construction staking, clearing and grubbing, earthwork allocation, drainage, surfacing, and seeding and mulching. Road maintenance activities generally consist of replacing the aggregate to preserve structural integrity and travel quality, performing blade maintenance activities, maintaining culverts, and cleaning ditches. Removing brush from both cut and fill slopes is also considered to maintain visibility. Transportation costs, although a minor component of the total cost computation, will vary with vehicle performance, equipment costs, and gradient and curvature. It is easy to incorporate these factors into optimization techniques using mathematical functions.

The major cost components of a single-lane forest road section in mountainous terrain were investigated by Akay (2004). In this study, two road examples were presented, considering different specifications for the surfacing material (Kramer 2001). In Example A, good quality rock for base course and surface rock (finer surface rock if road grade is less than 16%) for traction surface were used. In Example B, good quality rock (pit run if road grade is less than 10%) for base course and surface rock (no surface rock if road grade is less than 10%) for traction surface were used. The relative weightings of cost components for both road examples were indicated in Table2.

Table 2. The relative weightings of cost components for a single-lane forest road section.

Cost Components	Relative Weightings (%) Example A	Example B
Construction Costs	70.1	73.7
Earthwork allocation cost	12.5	25.7
Construction staking cost	0.8	1.3
Clearing and grubbing cost	4.5	7.7
Drainage cost	2.0	3.0
Seeding and mulching cost	2.3	4.0
Surfacing cost	48.0	32.0
Maintenance Costs	22.6	14.3
Rock replacement cost	15.9	3.5
Blade maintenance cost	0.5	0.8
Culvert, ditch, and brush costs	6.2	10.0
Transportation Costs	7.3	12.0

3. Optimization Techniques and Applications in Forest Road and Network Design

Road building, maintenance, and decommissioning problems are combinatorial in nature, and require integer decision variables. As a consequence, the resulting mathematical statements of these problems may be quite large and difficult to be solved (Church *et al* 1998). In order to find the best solution for any combinatorial optimization problem, one might first assume that complete enumeration of the feasible solutions can be generated, and their objective functions can be evaluated to determine the solution with the best result. However, this approach is not effective in practice when there are a large number of alternative solutions - either for a single road or for a network of roads. Therefore, optimization techniques are useful tools in finding the near-optimal solutions in an acceptable time frame. The following section briefly describes several optimization techniques, from exact algorithms (Linear Programming) to inexact algorithms (Dynamic Programming and Heuristics) and presents forest road design systems that utilize these techniques. The exact algorithms have an advantage of guaranteeing the optimal solutions for the problem being solved.

3.1 Linear Programming

Linear Programming (LP) is an optimization method that allows one to minimize or maximize a specified objective function while satisfying the various constraints (Bowman and Fetter 1967). In order to use LP, the objective function and the constraints need to be formulated as linear equations with non-negative variables. A general LP algorithm such as Simplex Method (Bowman and Fetter 1967) can be used to solve all LP problems. The decision variables are usually represented by continuous numbers, whereas some road design or network problems require a binary (yes/no) representation. LP has the capacity of generating the exact solution to a problem; however computer computation time can limit problem size. Some of the basic problems that can be solved by LP include production scheduling, transportation problem, and capacity allocation problems.

LP has been used in several forest road optimization models (Akay 2006; Aruga *et al* 2004 and 2005) to design roads and minimize the costs of the earthmoving activities. These models generated ground profile, intersection points, and cross sections using a high resolution DEM. The results indicated that LP overcame the limitations of the mass diagram by considering various soil characteristic and possible borrow and landfill locations along the roadway. In these models, an increase in the number of intersection points reduced the construction cost since the road profile became closer to the ground profile. However, increasing the number of intersection points significantly increases the computational time in solving earthwork allocation problem.

Mixed-integer formulations have been devised to develop road maintenance and network management plans where the locations of current and proposed roads are known. In these algorithms, the goal is not to assess the environment and determine where to place a road, but to assess the environment and decide what to do with planned or current roads (i.e., road locations are not defined *a priori*). Conservation of flow constraints between nodes (end points of road sections) are common in these mixed LP formulations as well as integer decision variables since some choices (i.e., whether to build a road) are binary (yes/no). Kirby et al. (1986) were among the first to describe a mixed integer formulation for forest road management, creating the IRPM model. Olsson and Lohmander (2005a) and Olsson (2005b) described road investment scenarios in Sweden where mixed integer formulations are used to assist decision-makers in developing tactical plans. In these cases, the road system has been defined *a priori*, and the task is to decide which route logging trucks should travel.

3.2 Dynamic Programming

Road design and road network problems can be solved by using Dynamic Programming (DP) in which optimum solution is reached in a multistage process (Beasley *et al* 1993). DP applies recursion to solve all possible small problems and then combine them to obtain solutions for larger problems. In this process, size of the optimum solution set is reduced into smaller subsets which are much easier to solve. Therefore, the optimal solution to the problem contains the optimal solution of the subsets. The subset space (stages and states) should be sufficiently small so that the same solution can be applied a number of times to obtain the solution for the main problem. Unlike LP, there is no specific DP algorithm that can be used to solve all DP problems. However, it has the ability to solve non-linear problems. DP is often used in practice for solving problems in transportation, harvest scheduling, and manufacturing. Teasley (2002) found dynamic programming to be an effective tool for developing a road removal plan, yet noted several areas of improvement necessary for the algorithm to perform as well as a heuristic.

Tan (2000) developed a procedure where DP was used to help road managers in determining the optimum location for a forest road section. Costing and routing of road construction, extraction, and transportation were predetermined in a separate module using microcomputer-based spatial database and heuristic procedure using shortest path (Tan 1999). In this DP procedure, the road planning area was divided into zones (stages) of equal width. Zone boundaries were assumed to be parallel to the existing road. Therefore, the nodes on a specific boundary of a zone have the same distance to the existing road. The DP algorithm searches for the best route between two boundaries for every node, while considering minimum construction costs. The best route between boundary nodes of adjacent zones was located by minimizing the construction costs of a road starting with the boundary nearest to the road and ending with the boundary farthest from the road.

3.3 Heuristics

The heuristic techniques are repetitive search procedure where an improved solution relative to the current one is determined based on experience and empirical rules (Tan 1999). There are numerous heuristic techniques that can be used to provide an optimization (or pseudo-optimization) approach to the design of forest roads or road networks. Many of these techniques come from fields outside of forestry. For example, Pérez de la Cruz *et al* (1995) describe an artificial intelligence approach to the design of highways, which takes into account environmental variables and other complexities.

Richard *et al* (2004) described the use of the Hooke and Jeeves search method for optimizing vector-network techniques in the design of mechanical systems. Elnagar and Hussein (2000) indicated the use of matrix methods for smooth paths in three dimensions (3D) given assumptions on machine velocity. And, Gipps *et al* (2001) presented the Quantum model, a heuristic for generating sets of low-cost alternatives for proposed highways, using databases describing the environment and economic assumptions.

In the field of forestry, Gullison and Hardner (1993) described a rule-based simulation model designed to examine options for reducing the total length of forest roads. Tan (1999) used a heuristic procedure to select road development choices from a set of network links where the shortest paths were first determined using Dijkstra'a algorithm. Peters (1978) provided a description of a direct method for determining optimal in-woods harvest system road spacing (i.e., primary transportation) and landing options, which could be extended to unroaded areas for determining low-cost secondary transportation options.

Clark et al. (2000) also used a heuristic for access road development where roads are not defined *a priori*. Finally, Weintraub *et al* (2000b) described two models: OPTIMED, which used an LP-based heuristic to decide amongst road building options that are stated *a priori*, and PLANEX, which used raster GIS databases and other information along with a heuristic to locate access roads for timber harvesting operations. Early development of this work can be found in Weintraub et al. (1994 and 1995).

In the following section, commonly used modern heuristic techniques (Simulated Annealing, Genetic Algorithm, Tabu Search, and Shortest Path Algorithm) are briefly described and their usefulness in forest road or network design have been investigated. The algorithms for these techniques are fairly easy to program and one general code can be used to solve many different optimization problem.

3.3.1 Simulated Annealing

Simulated Annealing (SA) as a solution strategy for combinatorial optimization problems dates back to the early 1980's (Beasley *et al* 1993). SA relies on a metallurgical concept, where a heated raw material is cooled back slowly-while being reheated occasionally- to produce the best material (Kirkpatrick *et al* 1983). The basis for SA was first published by Metropolis *et al* (1953), and the approach uses a local search in which a subset of solutions is explored by moving from one solution to a neighboring solution. To avoid converging and becoming stuck in local optima, the procedure allows the occasional acceptance of an inferior solution. SA has been applied in a wide variety of disciplines to solve optimization problems due to its simplicity.

In a study conducted by Akay (2004), SA was used to guide the search for the best vertical alignment that minimizes the total costs of construction, transportation, and maintenance costs for a single forest road. An initial road path is generated by establishing intersection points on the 3D image of the terrain, considering road design constraints. During the search process, 182 feasible solutions were evaluated out of 1200 automatically generated vertical alignment alternatives. For each change in the vertical alignment, the model minimized the costs of the earthmoving activities using LP. The results indicated that total road cost was reduced about 25% by using optimization techniques. The most of the computer computation time was spent on calculating earthwork allocation using LP.

3.3.2 Genetic Algorithm

To solve optimization problems, the Genetic Algorithm (GA) approach was developed by Holland (1975) and his colleagues at the University of Michigan. GA is based on biological processes of inheritance, mutation, natural selection, and the genetic crossover (Beasley *et al* 1993). First, a set of feasible solutions is randomly generated, where each solution corresponds to a chromosome. Second, two parent chromosomes are chosen based on their objective function values (fitness) to reproduce two new child chromosomes, which is called cross-over operation. In an attempt to improve the solutions over time, GA allows a random mutation when producing child chromosomes. This search process is repeated until a stopping condition (desired number of generations or improvement of the best solution) is satisfied. GA has been mostly applied to problems involving sequencing and scheduling.

In applications outside of the forestry field, Liatsis and Tawfik (1999) presented a GA approach to optimize the shape of roads in two dimensions. Jong and Schonfield (2003) developed a GA approach for optimizing highway alignment in 3D. Jha and Schonfled (2004) also developed a GA approach for optimizing highway alignment, yet within GIS, and investigated the effectiveness of the algorithm in steep terrain conditions. In each of these approaches, road locations were not specified *a priori*; the resulting road locations were a function of environmental conditions and other information.

In the field of forestry, Ichihara *et al* (1996) proposed a GA model integrating two optimization techniques to optimize forest road profiles. Once a horizontal alignment is fixed, the model identifies the optimum combinations of intersection points. Within the model, the optimum longitudinal slope with minimum construction cost was designed by using a DP method (Kanzaki 1973). The model was applied to a road section that had been previously designed using traditional methods. It was assumed that this original road profile was optimum from an economic perspective since it was designed by professionals. Then, the original profile was compared with the profile designed by GA. The results indicated that the volume of earth cutting by GA was less than that of the original profile, while the volume of earth waste by GA was larger than that of the original profile. It was assumed that the difference is due to objective function of DP where driver comfort and safety were not considered. In the model, 420 feasible profiles were evaluated in approximately 10 minutes in which one profile was calculated approximately 1.43 sec. The optimum combinations of intersection points determined by GA indicated close correspondence to those of a road profile determined using traditional methods, yet the computer computation time was significantly reduced when using GA.

3.3.3 Tabu Search

Tabu Search (TS) was first developed by Glover (1989) as a neighborhood search technique to solve discrete optimization problems. TS produces solutions by making iterative choices, considering certain choices as taboo (i.e. Tabu). In general, during the solution process, if a decision choice has been recently selected, it is rejected (Tabu). If a choise is not Tabu, or is Tabu yet its objective function value is better than the previous best solution, the choice is selected. If the solution is not better than the previous best solution, the algorithm accepts the candidate which gives the highest increase above the current the objective function value. If it is not possible to generate a candidate with increased value, the algorithm moves forward with the candidate, which provides the least decline in the objective function value. TS has been successfully applied to a number of optimization problems.

In a road design study conducted by Aruga *et al* (2005), GA and TS were compared to a manually designed forest road profile. Once the horizontal alignment was fixed, optimization techniques were used to generate alternative vertical alignments by adjusting the heights and the location of the intersection points. The vertical alignment was optimized considering construction and maintenance costs. LP was used to determine earthwork allocation. Both heuristic techniques found near optimum solutions within a reasonable time. TS could not find a better solution than GA, but it usually found a good solution in less time. One year later, Aruga *et al* (2004) proposed an improved road design model in which TS was used to optimize the horizontal and vertical alignment of a forest road. The model was applied to design 827-meter road section in Capitol Forest, Washington State, USA. In the model, the vertical alignment was first optimized, and then horizontal and vertical alignments were optimized simultaneously. The best road alignment found by the simultaneous optimization of both alignments reduced the total cost by 29%, compared to the case where only vertical alignment was optimized.

3.3.4 Shortest Path Algorithms

Shortest path problems are among the most fundamental problems studied in computational geography (Lanthier *et al,* 2003). In general, the shortest path is the problem of finding a series of road links connecting two nodes such that the sum of the weights on those edges is minimized. Dijkstra's algorithm is one of the most efficient algorithms for solving the shortest path problem in which all the weights are non-negative (Dijkstra, 1959). Zhan (1997) provides a discussion of the performance of several shortest path algorithms.

In the algorithm, road links are connected in the order of their weighted lengths, from the shortest to the longest paths. The weights of the links can be represented by distances, costs, or times. The algorithm stores the weighted value for each path. The essential feature of Dijkstra's algorithm is road link relaxation (Cormen *et al* 1990). When there is an edge from node A to node B, the shortest path from node C to node A can be extended to a path from node C to node B by adding link (A, B) at the end. If the weight of this path is less than the previous weight, the current best weight is replaced with the new weight. In the algorithm, each road link (A, B) can be relaxed only once, when the weight of the path has reached its final value.

In the field of forestry, shortest path algorithms have been used to develop near-optimal transportation networks. Sessions and Sessions (1991) implement a shortest path algorithm for secondary harvest transport in forest operations. Bettinger *et al* (1998) integrated road maintenance and obliteration choices with a harvest scheduling model (TS) in an effort to develop forest plans where sediment concerns were important. Dijkstra's algorithm was used to determine the shortest paths from each management unit to a mill given the roads available.

Anderson and Nelson (2004) developed a computer algorithm that quickly generated road networks for strategic road planning. In this study, Dijkstra's shortest path algorithm was used to project a road link that minimized the distance between a landing and the current road network, considering specified road design constraints. In order to present the capabilities of the model, it was applied to a forest on Hardwicke Island, Canada. A sensitivity analysis was conducted to provide road managers with extra information on long-term effects of various variables (total length of road network, percentage of landings connected, and road gradient). The order in which the landings were connected to the road network was also tested. The results indicated that reducing the maximum road gradient constraint increased the total length of the road network and decreased the percentage of landings connected. That produced longer roads in gentler grounds and fewer roads in steep and broken grounds. The number of landings connected and total length of the road network decreased as the landing spacing increased. The network generated using closest landings first resulted in a longer network, steeper road gradient, sharper curves, more landings, and shorter processing time than that of using farthest landings first.

Dijkstra's algorithm was a practical tool for quickly projecting road networks in strategic planning. However, it caused a considerable variation due to landing order in which the landings were connected. To improve the landing order, Tan (1999) suggested a heuristic procedure where each possible landing was connected by using a shortest path algorithm. In this procedure, each road link between two nodes was associated with the cost which was equal to road length times the average cost per unit distance. To reduce processing time, the shortest route of extraction, transport, and road construction between every two nodes were predetermined by the procedure. This procedure integrated spatial database and shortest path algorithm to assist road managers for quickly generating and assessing road network alternatives.

Since the processing involved with shortest path algorithms is computationally intensive, Lanthier *et al* (2003) suggested using a parallel processing approach to the implementation of shortest paths through a triangular irregular network, one form of a DEM. This currently requires, however, a number of personal computers to be interconnected, creating a cluster, as well as shared-memory architecture. This type of computer network design is atypical of most natural resource management organizations.

4. Results and Discussion

Computer-aided processes for optimizing the design of single roads or road networks improve the efficiency of managing both budgets and natural resources. When road design algorithms are integrated with optimization techniques, guidance can be provided to natural resource managers to help them wisely use the limited resources at their disposal. Forest road design systems using mathematical optimization techniques automate many of the time consuming road design tasks while implementing a decision support framework. For the design of a single road, the systems developed by Akay (2006), Aruga *et al* (2005), and others allow one to optimize the vertical alignment for a given horizontal alignment. These systems can be improved by including joint optimization of the horizontal and vertical alignments (Aruga *at al* 2004) into the optimization process.

For the design of road networks, Sessions and Sessions (1991), Weintraub *et al* (1994 and 1995), and Bettinger *et al* (1998) provide a diverse set of options. In this forest network case, current and potential road locations and specifications must be pre-defined. In the former case (optimizing the location of a single forest road), the specifications and location are not pre-defined - the optimization algorithm defines them.

There are several key researchable questions may arise from this discussion. First, the shortest path algorithm is useful in locating optimal solutions for individual forest roads. Although shortest path algorithms are designed to find paths through a pre-defined network, one could utilize them to locate the optimal solution to a single forest road design problem, if the design problem is formulated as a network of choices for the road. LP, DP, SA, GA, and TS have been used to assist with the design of single forest roads, but the possibility for using them to optimize forest road networks also presents an area of future research. Within the forest planning studies, these techniques have been used for timber management options, while shortest path algorithms have been used to optimize road networks.

The second researchable question relates to the design of optimal road networks in roadless areas. While many current "roadless areas" in North America may never be developed, areas can be found where the road network is not very dense, and the in-fill of roads is possible for timber production purposes. Here, one might apply the SA approach by Akay (2004) to an entire proposed network, where the initial road paths are generated, and vertical alignment is then optimized. Single road optimization processes could also be developed to utilize GIS techniques without any proposal of new roads, to identify the best transportation network of a given road density for a landscape. These methods could be used in conjunction with shortest path or other techniques to reduce the proposed roads to a network that is appropriate given the timber production or recreation activities proposed, or so that other environmental impacts measured at larger scales (i.e., sediment production, wildlife habitat) are minimized.

The third researchable topic is to design a smaller, more effective forest transportation network in areas where roads exist, yet new road construction will not be considered. A management goal may be to reduce the density of roads for wildlife, aquatic resource, or visual quality reasons. Bettinger *et al* (1998) provided a method to reduce the network given sediment concerns. However, a more in-depth analysis of road profiles and landscape conditions (as used in the individual road design problem) may help in the assessment of road network alternatives. Combining these processes with a forest road network optimization process would allow one to evaluate contemporary land management options.

Most of the recent advances in optimization models for single forest roads rely highly on DEMs and other GIS databases (soils, streams, etc.). The fourth researchable question relates to resolution of DEM and accuracy of the attribute data that directly affect the performance of the optimization process. Tan (1999) notes that cell sizes that are too small bog down the processing associated with network nodes, and cell sizes that are too large result in accuracy levels that may be unacceptable. Thus, the trade-offs related to the input databases require some thought. Available attribute data in forested areas may also not represent the actual conditions well; however, the quality of GIS data keeps improving as GIS technologies advance. These advances include improved data sources for generating high-resolution and accurate DEMs using the latest technology (LIDAR), highly developed GIS techniques to store, analyze, and display spatial data, and advanced features of sophisticated computer software languages to display and render high-resolution 3D images on personal computers.

The fifth researchable topic is the verification of the optimal road design systems. To improve their performances in the future, the solution obtained from these optimization systems should be further tested by comparing them with current forest road design systems for the same area. Finally, office and field road design can be better linked. Although, the optimization systems do not provide a designer with a decision tool that locates the final route alignment, they can be enhanced by integrating it with Global Positioning Systems (GPS) extensions to help the designer evaluate the model solutions on the ground.

5. Conclusions

Computer-aided road design systems, using optimization techniques, provide land managers with a decision support tool that quickly evaluate alternatives. A number of approaches have been used to optimize the placement (vertical and horizontal) of individual forest roads. Enabling the optimization of entire networks of roads across a landscape, while considering broader-scale issues such as sedimentation and wildlife habitat, remains an issue to be addressed. In addition, assessing the design of optimal transportation networks from the suite of roads currently available seems to be a fruitful area of research, particularly if the algorithms used to delineate single forest roads can be used to assess which current roads should be eliminated from the network. Optimization of entire road networks with shortest path algorithms has received considerable attention in the forestry literature. Whether heuristics or exact algorithms can improve on the efficiency of shortest path algorithms remains to be seen. However, advances in computer-aided optimal road design and road network management have provided land managers, researchers, and others the ability to make more informed management decisions.

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