IMPROVING AUTOMATIC GRID CELL BASED ROAD ROUTE LOCATION PROCEDURES

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Abstract: *Automatic road route location procedures have emerged since digital elevation models have become available and since computer power has been enabling the solution of large combinatorial problems. The most common approach consists of the following solution procedure: (1) identify all possible road segments, which are physically feasible, and (2) to find the combination of road segments, which minimizes cost. This approach has two shortcomings. First, it assumes road-building cost to be route -- independent. Second, the combination of road segments does not result in a traverse, which fulfills the minimum geometric requirements of the road centerline.*

The paper aims (1) to refine the road link identification procedure for each grid cell, and (2) to allocate route-dependent road construction costs that consider local slope, geology, cross-section geometry, and pavement structure design. It compares alternative road segment identification procedures and route – dependent construction costs estimation with the standard procedure described above.

1. Introduction

Computer-aided engineering CAE is an emerging field that has been developing since the 1970's. It aims at imitating or at least supporting problem solving activities of engineering experts. The layout of road networks is a complex location problem (Church et al., 1998), which is extremely demanding, especially in steep terrain. Availability of digital elevation models has improved tremendously, while the power of computers has been increasing continuously. Computer-aided engineering approaches for forest road networks first appeared in the 1970's (Kirby, 1973; Mandt, 1973; Dykstra, 1976), but initially were limited by computing power. They have been improving continuously, resulting in software packages such as PLANS (Twito et al., 1987) or PLANEX (Epstein et al., 1994; Epstein et al., 1999; Epstein et al., 2001). However, even the most sophisticated approaches have two shortcomings: (1) they assume road building cost to be route-independent and (2) they limit the number of possible links from a specific network node to its adjacent nodes.

The paper aims to investigate two possible improvements, (1) a refinement of the link pattern from a specific node to its adjacent nodes, and (2) the consideration of route-dependent construction costs. We assumed that considering route-dependent cost has a big effect on road location, especially in steep terrain, where cost may vary by a factor of about four, depending on slope and geological formation of the bedrock. The paper first develops improved procedures for an automatic road location procedure, and then tests them in a specific steep slope area.

2. Automatic Road Location Procedure

2.1 Framework

Automatic road route location procedures consist of five components: (1) a numerical representation of topography, (2) discretization of road segments, (3) road geometry constraints, (4) a model to estimate road construction costs, and (5) an algorithm to find the minimum cost road network (figure 1).

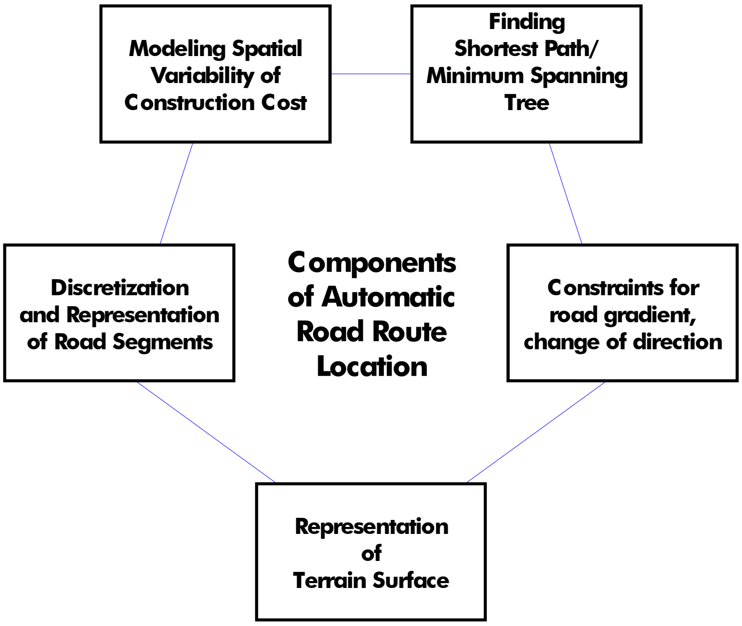
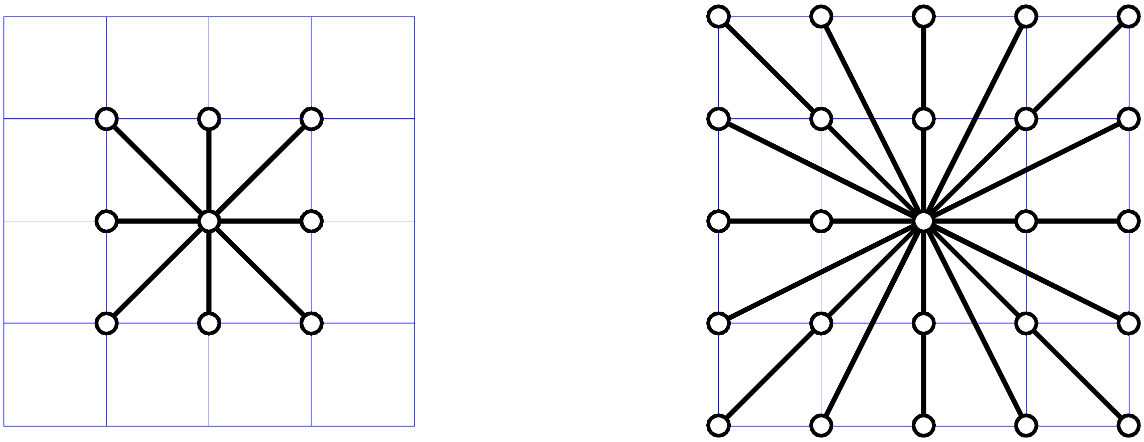


Figure 1: Components of an automatic road route location procedure.

Digital elevation models DEMs form the backbone of numerical terrain surface representation. During the last years, they have become widely available and their accuracy has been increasing. Resolution of DEMs is a measure of accuracy, which is quantified by the distance between adjacent grid cells. Commercially available DEMs are usually based on a grid cell width of 50 meters, or 25 meters respectively. Nowadays, models with a grid cell width of 10 meters have become in use, which increase accuracy, but also increase problem complexity. Discretization aims to identify a finite set of road segments, which can be used as elements of a combinatorial problem. The third component, road geometry constraints, considers maximum road gradient and maximum curvature of changes of direction. The fourth component, construction cost estimation, is usually based on experience and assumed to be constant for the whole project area. The fifth component, algorithms to find a minimum cost road network, uses knowledge of graph theory, which offers a variety of algorithms.

2.2 Discretization of Road Segments

The formulation of the road route layout problem as a combinatorial optimization problem requires a finite set of parts of a solution. Discretization of both, terrain surface and road segments is the approach to achieve this. Identifying terrain surface units of 10m x 10m results in a discrete set of grid cells. Limiting the number of segments from each grid node to the neighborhood nodes (figure 2) produces a discrete set of road segments. A road segment identification procedure, which is documented in the literature (Liu and Sessions, 1993; Epstein et al., 2001; Chung et al., 2003), usually consists of eight links per node to its adjacent nodes (figure 2). Limitation to eight links per node results in a small subset of all possible road segments. Assuming a slope gradient of 50%, a grid cell width of 10 meters and eight road segments links as shown in figure 2 results in the following limitations. Road segments can only take gradients of 0%, 35%, 50%, and -35%, from which only two links, those with a gradient of 0%, are operationally feasible. However, in reality there is a continuum of road gradients between -15% and +15%, which is feasible. An eight-link representation clearly limits the solution space. This limitation increases with increasing slope gradient. To overcome this problem we enlarged the link pattern to 24 links, 8 to the nearest and 16 to the second nearest neighbor nodes (figure 2, right side). Assuming the same slope gradient and grid cell width as above and using the 24-link pattern enlarges the solution space by adding road gradients of +22%, +45%, -22%, and -45%. We assume, that the 24 link pattern will improve the quality of road route location.



8 links to nearest neighbors

24 links to nearest and 2nd nearest neighbors

Figure 2: Identification of possible road links between adjacent nodes. Standard procedure identifies 8 links to nearest neighbor nodes; modified procedure identifies 24 links to nearest and 2nd nearest neighbors.

2.3 Construction Cost Estimation

Available road route location procedures (Epstein et al., 2001; Chung et al., 2003) assume construction cost being constant within a specific planning area. Practical experience has been demonstrating that road construction cost varies highly due to spatial variability of terrain conditions. A model, which predicts construction cost as a function of slope gradient, geological formation, and specifications of the cross-sectional road geometry makes it possible to calculate roading cost for each grid cell.

The present approach is based on the „cost classification by elements CCE“ framework (CRB, 1991), which is a hierarchical system consisting of macro elements, element groups, and elements. Four element groups are relevant for cost estimation of roads: (1) embankment structures, (2) retaining and supporting structures, (3) drainage structures, and (4) pavement structures. Element groups (2), (3), and (4) may be estimated per unit of road length whereas element group (1) „embankment“ highly depends on ground slope and on geology.

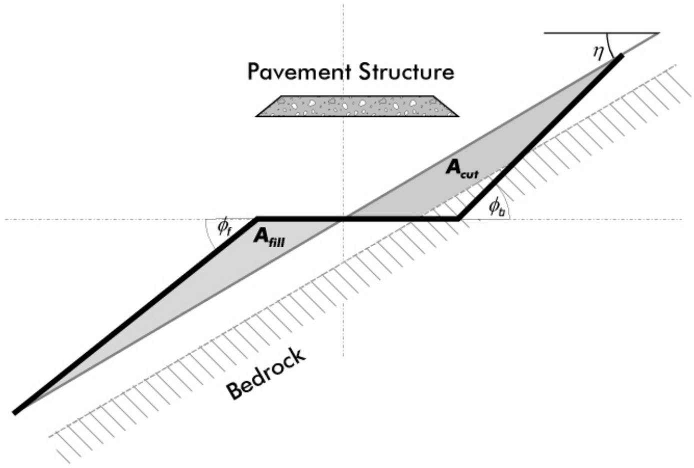


Figure 3: Element Groups for Cost Estimation: (1) Embankment structure, consisting of earth excavation and rock excavation; (2) retaining and supporting structures, (3) drainage structures, (4) pavement structures.

An analytical approach (Heinimann, 1998) models the embankment cut area A_{cut} as a function of slope and of specifications of the road cross section geometry (figure 3). (Inaba et al., 2001) developed a model to estimate rock occurrence in a cross section as a function of slope, geological formation, and crown width. Combining the two models results in [1] for embankment cost estimation.

$$C_{emb} = A_{cut} \cdot c_{soil} + A_{cut} \cdot p_{rock} \cdot c_{rock} \qquad [1]$$

where C_{emb} = embankment cost
A_{cut} = cut area
c_{soil} = soil excavation cost
c_{rock} = cost of drainage structures
p_{rock} = share of rock in total cut area

Since slope, geological formation and the specifications of the road cross section geometry are known for each grid cell, road construction costs can be predicted for each grid cell, too.

2.4 Feasibility Constraints

Roads have to fulfill technical requirements, especially (1) a gradient lower than the maximum allowable gradient for safe truck traffic and (2) allowable changes of direction along the road centerline. Calculation of the gradient of a single road segment can be done easily by dividing altitude difference by horizontal distance. Checking the allowable changes of direction along the road centerline is much more complicated. The PLANEX software package has a procedure, which considers feasible incoming and outgoing turns related to a specific node (Epstein et al., 2001; Chung et al., 2003). Numerical representation of those constraints requires each physical node to be split into several virtual nodes and therefore increases the problem size.

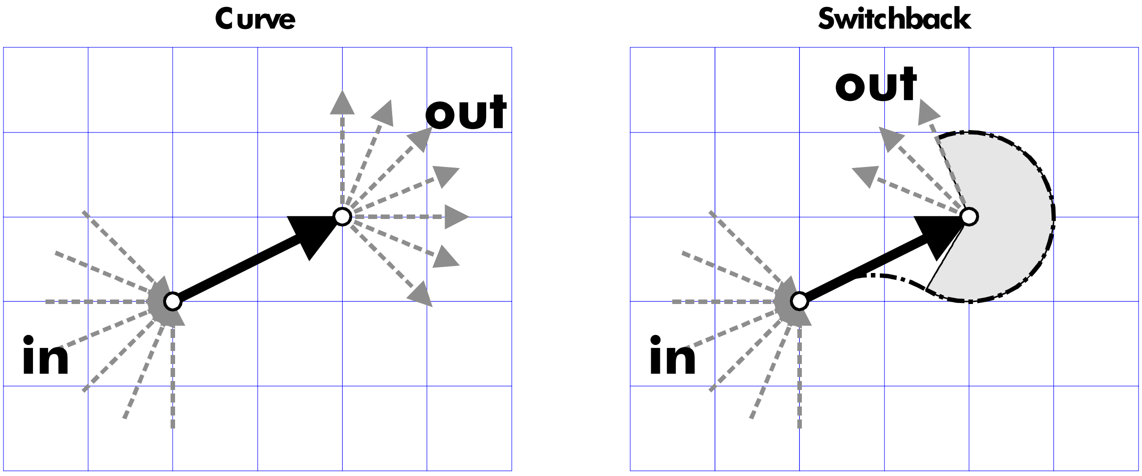


Figure 4: Direction change constraints. Single curves (left side) affect construction cost slightly; switchbacks (right side) affect construction cost considerably.

Taking up the PLANEX approach (Epstein et al., 2001), we used the following procedure (figure 4):

- Select one directed road link (figure 3),
- Check which combinations of (1) incoming and (2) outgoing directions fulfill the minimum turning circle criteria, considering 3 different cases:
    - Curve with identical turning directions (figure 3, left),
    - Curve with reverse turning directions (figure 3, left),
    - Switchback (figure 3, right),
- Choose links, which fulfill feasibility constraints
- Calculate additional road building cost, if
    - Curve radius is small and requires an increase in roadway width,
    - Switchback construction is required (figure 3, right)

2.5 Location Search Algorithms

Road route layout is a special type of a location problem, which can be treated as a network design problem. Problem representation as a network assumes (1) that a finite set of nodes and arcs represents the specific topological situation and (2) that local road construction costs are allocated as cost weights to each arc. It is quite simple to find the shortest path between two nodes within a network with Dijkstra's shortest path algorithm (Cormen et al., 1999). Finding the minimum spanning tree that links multiple nodes is a more complicated problem, which can be solved either with Kruskal’s or with Prim’s algorithm (Cormen et al., 1999). For the present study, Dijkstra's algorithm and Prim's algorithm were used.

3. Test Application

3.1 Test Layout

The test area consists of 10'000 cells, which are located within a square of 1 km to 1 km, corresponding to a grid size of 10 to 10 meters. The test layout aims to investigate the effects of two factors: (1) spatial variability of road construction cost and (2) the constraints of linking and road segments.

3.2 Cost Modeling

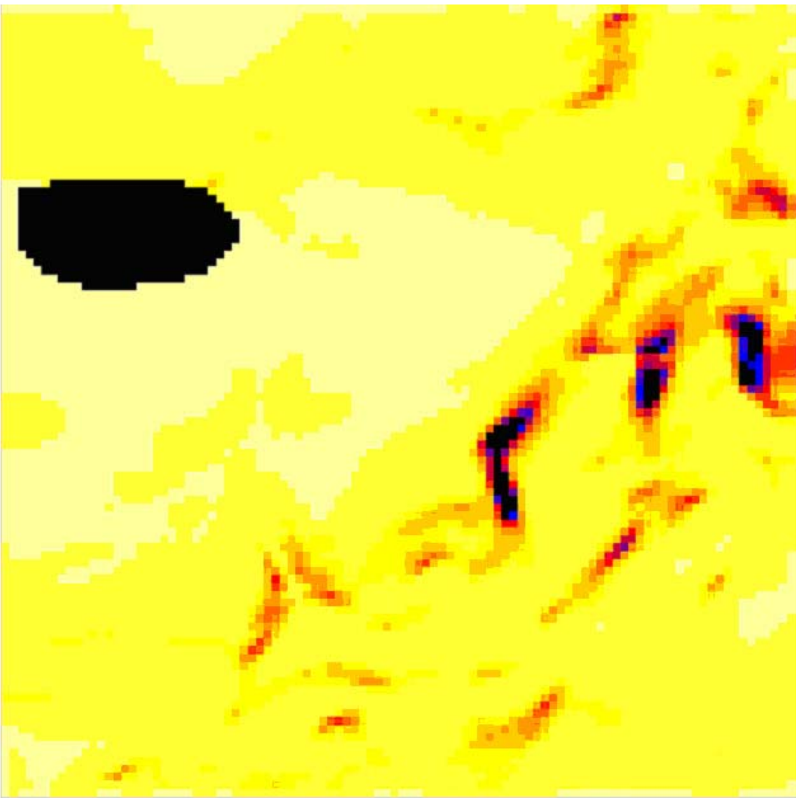


Figure 5: Spatial variability of road construction cost. Colors [white] < 100 CHF$\cdot$m^{-1}, [yellow] 150 CHF$\cdot$m^{-1}, [red] 200 CHF$\cdot$m^{-1}, [blue] 250 CHF$\cdot$m^{-1}, [black] >300 CHF$\cdot$m^{-1}

Figure 5 shows the spatial variability of road construction cost for the test area. We assume that the influence of cost variability and linking constraints show most prominently in that part of the test area in which variability is high. Cost variability is highest in the middle-right part of figure 5. The following analysis will therefore mainly focus on that part of the test area.

3.3 Effect of Refined Road Segment Identification on Road Location

Figure 6 shows the shortest path, which Dijkstra's algorithm identified for two cases. A first case allows unconstrained change of direction (Figure 6, left), whereas a second case constrains the change of direction according to the rules defined in section 2.4. The introduction of turning constraints results in a smoother layout of the road route and in an increase of road length of about 60 percent (Figure 6, right).

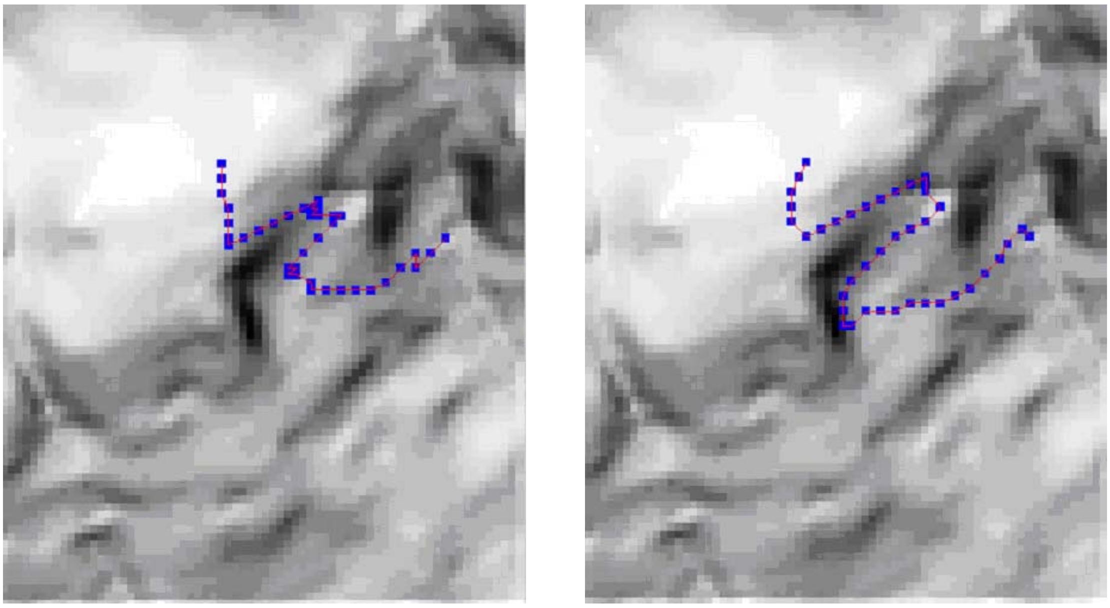


Figure 6: Shortest path between two terrain points for [a] unconstrained change of direction on the left, and [b] constrained change of direction of the right. One pixel equals a terrain unit of 10m to 10 m. Grey shading: bright -> flat, dark -> steep. Road length [a] 726 m, [b] 1147 m.

3.4 Effect of Cost Variability on Road Location

The next step of analysis introduced spatial variability of road construction cost (figure 7). Figure 7, left side, shows the road route, which resulted from turning constraints and from constant costs per unit of road length. Figure 7, right side, shows the road route, which resulted by considering spatial variability of road construction cost. Although road length increased by about 3 percent, total construction cost decreased by about 28 percent. This finding clearly supports our assumption, that allocation of route-dependent construction cost improves the effectiveness of the layout procedures.

Figure 8 shows a minimum spanning tree example. The first case is based on the following assumptions: (1) 8 possible links per node (figure 2), (2) no turning constraints, and (3) constant road construction cost for the whole area. The second case used the following assumptions: (1) 24 possible links per node, (2) turning constraints according to section 2.4, and (3) route-dependent road construction cost (figure 5). The difference of the two approaches is obvious. Improving the link pattern to 24 links per node and considering the spatial variability of cost results in a reduction of road length of 36 percent and of cost of 23 percent.

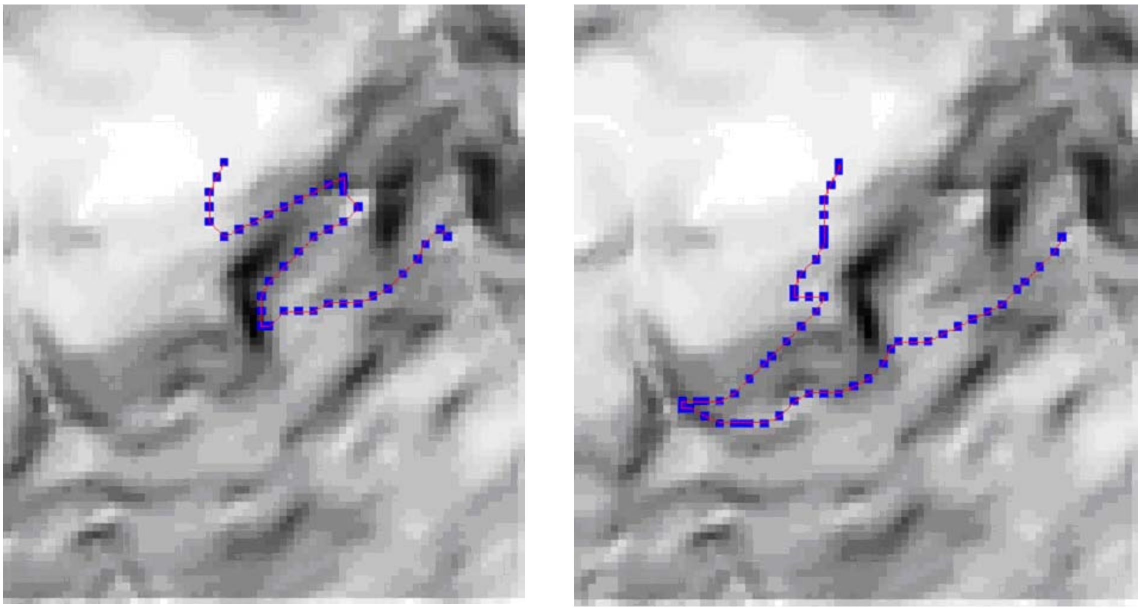


Figure 7: Shortest Path for [a] constant construction cost on the left, and for [b] spatially variable construction cost on the right. One pixel equals a terrain unit of 10m to 10 m. Grey shading: bright -> flat, dark -> steep. Road length [a] 1147 m, [b] 1186 m. Cost [a] 275000 CHF, [b] 198000 CHF.

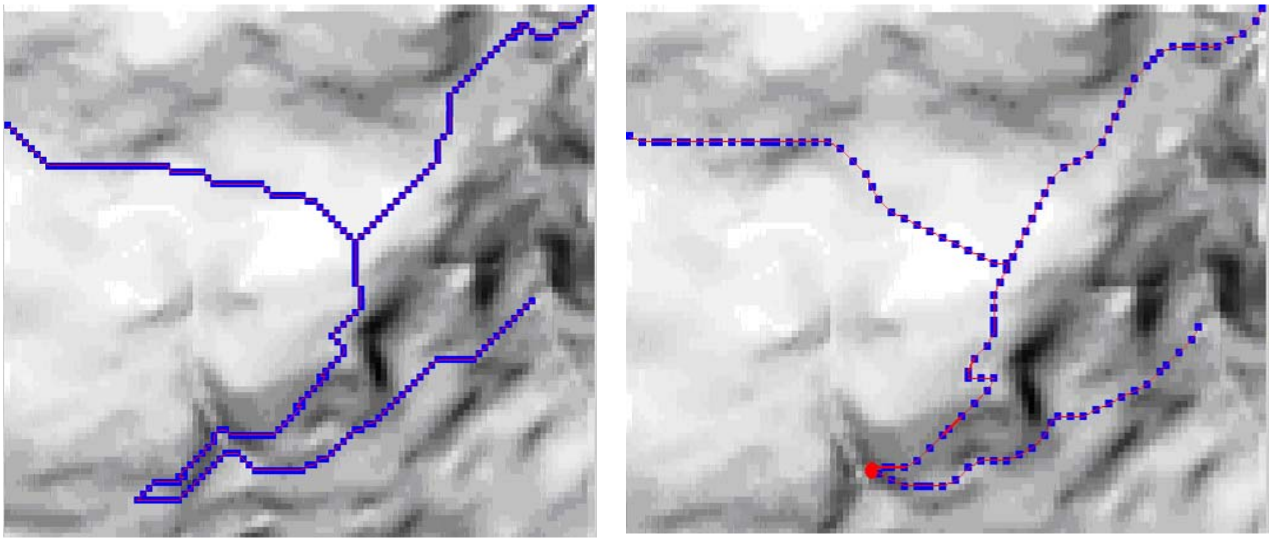


Figure 8: Minimum Spanning Tree for [a] constant construction cost, unconstrained turns and the 8-link pattern on the left, and for [b] spatially variable construction cost, constrained turns, and the 24-link pattern on the right. One pixel equals a terrain unit of 10m to 10 m. Grey shading: bright -> flat, dark -> steep. Road length [a] 3,335 m, [b] 2,455 m. Cost [a] 455,000 CHF, [b] 370,000 CHF.

4. Conclusions

The paper investigated how improvements of the link pattern between adjacent network nodes and how the consideration of route-dependent construction costs improve the effectiveness of algorithmic road layout. The study results in four major findings: (1) the introduction of turning constraints for the road centerline increases total road length; (2) the allocation of route-dependent construction cost to each road segment increases total road length while decreasing construction cost by about 20 percent; (3) enhancing the link pattern per node from 8 to 24 decreases road length, especially in steep terrain; (4) the standard link pattern with 8 links per node limits the solution space significantly, leading to sub optimal layout in steep terrain. Road construction costs have a share of at least about one-third in the total of life-cycle operations cost. Combining the 24-link pattern with the allocation of route dependent cost to each road segment therefore offers the possibility to life cycle operations cost by at least five percent. However, those findings are only based on the present case study. Further research is needed to test the procedures in different terrain conditions and to verify road route layout in the field.

5. References

Chung, W.; Sessions, J.; Heinimann, H. R (2003) An application of a heuristic network algorithm to cable logging layout design, Journal of Forest Engineering, 14: (forthcoming).

Church, R. L.; Murray, A. T.; Weintraub, A. (1998) Locational issues in forest management, Location Science, 6 (1-4): 137-53.

Cormen, T. H.; Leiserson, C. E.; Rivest, R. L. (1999) Introduction to Algorithms, 23rd printing Ed. The MIT Electrical Engineering and Computer Science Series. Cambridge MS, USA; London: MIT Press, McGraw-Hill. 1028 p.

CRB (1991) Elementkostengliederung EKG - Kostengliederung nach Elementen, für Hoch- und Tiefbau, mit Projektkostengliederungen. [Cost classification by elements CCE - cost classification by elements for building and civil engineering, with project cost classifications]. Swiss Research Centre for Rationalization in Building and Civil Engineering. Zurich, Swiss Standard SN 506 502. 139 p.

Dykstra, D. P. (1976) Timber harvest layout by mathematical and heuristic programming. Department of Forest Engineering, Oregon State University. Corvallis, OR. PhD dissertation. 299 p.

Epstein, R.; Morales, R.; Seron, J.; Weintraub, A. (1999) Use of OR systems in the Chilean forest industries, Interfaces, 29(1): 7-29.

Epstein, R.; Weintraub, A.; Sapunar, P. et al. (1994) PLANEX - Software for operational planning, In international seminar on forest operations under mountainous conditions, ed. J. Sessions, 52-57.

Epstein, R.; Weintraub, A.; Sessions, J. et al. (2001) PLANEX: a system to identify landing locations and access, In Proceedings, International Mountain Logging and 11th Pacific Northwest Skyline Symposium, eds. P. Schiess and F. Krogstad, 190-193. Seattle, WA, U.S.A. College of Forest Resources, University of Washington, Seattle, USA.

Harbin, P. R. (1994) Department of Forest Engineering, Oregon State University. of China, 24-27 July.

Heinimann, H. R. (1998) A computer model to differentiate skidder and cable-yarder based road network concepts on steep slopes, Journal of Forest Research (Japan), 3(1): 1-9.

Inaba, S.; Heinimann, H. R.; Shiba, M. (2001) A model to estimate rock excavation volume of forest roads in steep terrain conditions, In 112th Meeting of the Japanese Forestry Society.

Kirby, M. (1973) An example of optimal planning of forest roads and projects, In Planning and Decisionmaking As Applied to Forest Harvesting, ed. J. O'Leary, 75-83. Corvallis OR, USA. Forest Research Laboratory, School of Forestry, Oregon State University.

Liu, K. and Sessions, J. (1993) Preliminary planning of road systems using digital terrain models, Journal of Forest Engineering, 4 (2): 27-32.

Mandt, C. J. (1973) Network analysis in transportation planning, In Planning and Decisionmaking As Applied to Forest Harvesting, ed. J. O'Leary, 95-101. Corvallis OR, USA. Forest Research Laboratory, School of Forestry, Oregon State University.

Twito, R. H.; Reutebuch, S. E.; Stephen, E. et al. (1987) Preliminary logging analysis system (PLANS): overview. USDA, Forest Service, Pacific Northwest Research Station. Portland. General Technical Report, PNW-GTR-199. 24 p.