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Computer-Assisted Map Analysis for Planning Forest Road Network[1]

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컴퓨터 地圖分析을 利用한 林道計劃[1]

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ABSTRACT

Route projection of forest road involves several constraints ranging from construction cost to environmental impacts. This study is designed to assess the capability of computer-assisted map analysis techniques for deriving several alternatives of forest road planning. Three cartographic models are presented to address the limit of slope, soil erosion, and aesthetic value in designing forest roads over a relatively small size of mountainous forest. Primary spatial analysis techniques used are distance measurements and connectivity analysis. The fundamental approach used was to generate a set of friction maps in which each friction map represents a combined restriction for a forest road projection. Products of the spatial analysis are compared by both qualitative and quantitative methods. The results demonstrate that computer- assisted map analysis has a potential to solve rather complex problems of forest road planning by providing several alternatives effectively.

Key words : Forest road planning, GIS, map analysis.

要 約

經營的 요소에서부터 環境保護 측면까지 林道 路線의 選定에서는 여러가지 고려되어야 할 사항들이 많다. 이 研究에서는 다각적인 狀況下에서 林道路線網 計劃過程을 컴퓨터 지도분석을 통하여 보다 效果的으로 접근해보려 한다. 소규모의 林道設定區劃을 대상으로 路線計劃에 필요한 세가지 假定 狀況을 부여하였다. 첫번째의 임도계획은 단지 傾斜度만을 고려하였고, 두번째의 계획은 경사도와 함께 土壤浸蝕을 축소하는 방향으로 시도되었으며, 세번째의 계획은 경사도, 최소한의 토양침식, 그리고 山林景觀保護를 다함께 고려하는 관점에서 접근하였다. 연구지역의 地形圖, 林小班 區劃圖, 地籍圖등을 컴퓨터로 처리하기 위하여 디지탈 資料化한후, 連結分析(connectivity analysis)을 주축으로하는 여러가지 컴퓨터 지도분석 技法들을 적용하였다. 분석 결과는 삼차원 도면을 이용한 시각적 방법과 계획임도上 지형의 橫斷側面을 통한 傾斜度 및 全長 등의 비교를 바탕으로 검토되었다. 컴퓨터를 이용한 지도분석기법은 여러가지 복합적인 사항을 동시에 고려해야 하는 임도계획과정을 보다 효과적으로 遂行할 수 있다는 潛在力을 보여주고 있다.

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INTRODUCTION

Construction of a forest road network has been one of the primary tasks in timber harvesting operation. In an area where intensive forest management is required, the design of forest roads should be based on a wide range of management activities involving plantation, silviculture, and harvesting. Moreover, growing concerns of multiple uses in forest management demand extensive functions of forest roads, which can serve for managing non-timber resources as well as timber resources.

Since forest roads require large capital investments of construction and maintenance, the importance of planning has been well addressed (FAO, 1977 ; Stenzel et al., 1985 ; Woo, 1987). Route projection of forest roads has been mainly conducted by manual drawing on topographic maps along with field surveying and aerial photo interpretation. Such approaches, however, may be cumbersome and ineffective under the circumstance in which several different criteria should be considered. This is particularly true for a forest road project that must be accomplished under the restrictions of minimizing environmental hazards or aesthetic impacts.

Considering the capabilities of handling various types of digital map data, geographic information systems (GIS) can be a useful tool to derive several alternatives in preliminary stages of a forest road planning. With its flexible functions of storing, analyzing, and displaying several layers of map data, GIS has proved as a very powerful technology to assist various fields of natural resource management, such as timber inventory and harvest planning (Wightman and Ratchinsky, 1990), wildlife habitat management (Mead et al., 1988), pest control (Lee, 1989), forest fire control (Chou et al., 1990), and recreational management (Waggoner, 1991). Recently, there have been a few attempts of applying GIS technology in harvest planning and forest road construction (Nuutinen, 1990 ; Ottitsch, 1990).

The objective of this study is to demonstrate the functional capabilities of computer-assisted map analysis for the preliminary planning of forest road projects. Even though the types of data and the outcome of the spatial analysis may not represent the accuracy that is often required for actual road design, they still can be very useful to compare several alternatives at the planning stage (Moon, 1989).

CONSTRUCTION OF DIGITAL MAP DATA

The study area covers approximately 150 hectares of the Kon- Kun University Experimental Forest in Moogap Mountain, located about 35 km southeast of Seoul. The study area can be characterized by a steep terrain of mountainous forests within a small watershed boundary. The study area has been mainly managed for forestry-related teaching and research purposes. Three types of paper map were obtained and digitized to a computer-readable digital format : 1) 1 : 5,000 scale topographic map, 2) forest stand map showing the boundaries of management compartments and land ownership, and 3) soil survey map.

Building a spatial database is a critical step toward a successful implementation of geographic information systems and often requires a great amount of technical and monetary investments. Avoiding the technical details with respect to creating digital map data, this paper will primarily focus on the spatial analysis and leave detailed explanations of database development to other studies (Goodchild and Gopal, 1989).

Digital Elevation Model Data

On conventional topographic maps, terrain surfaces are represented by contour lines in which each line is regarded to have the same elevation value (isoline). The area between two adjacent contour lines is considered as continually varying surface from one elevation to another. In a digital map, such isoline representation of elevation is not suitable for spatial processing. Any digital representation of terrain surface is known as a digital elevation model (DEM) or digital terrain model (DTM) (Burrough, 1987).

The basic assumption to create digital elevation model data is that the terrain surface is considered as a set of rectangular grid cells and each cell has a numeric value of elevation. Since it is almost impossible to put elevation values for the entire surface, we often rely on estimation techniques, referred to spatial interpolation, to fill elevation value for every grid cell using the known elevation points. Interpolation is based upon several mathematical functions ranging from simple local averaging methods to complex techniques that use spatial statistics.

Although there are several methods of creating digital elevation model data, this study used a simple method that can be easily adopted. Every contour line, separated by 5 meter difference of elevation, on a 1 : 5, 000 scale topographic map of the study area was digitized. The sampling interval to obtain the elevation values from a contour line was approximately 2 millimeters on the map, which is equivalent to 10 meters on ground. Once all the contour lines were digitized, the next process was to estimate the elevation for the unknown grid cells by using the known elevation points obtained from the digitization. The interpolation method used was the inverse squared distance weighting average, in which the weighting factor is inversely proportional to the distance from the neighbor cells of known elevation (Burrough, 1987). The mathematical equation used for interpolation was as follows :

$$Z = \frac{\sum_{i=1}^{n} Z_i/(d_i)^2}{\sum_{i=1}^{n} 1/(d_i)^2}$$

where Z = the estimated elevation for an unknown point,
Z_i = known elevation of neighboring points,
d_i = distance, and
n = number of neighboring points.

Once the digital elevation model data are created, other types of topographic data can be derived from the elevation data. Slope (first derivative of the elevation) and aspect maps were generated using the elevation data. From the topographic map, stream lines were also digitized.

Forest Stand and Soil Maps

From the forest stand map, boundaries of management compartments and stands were digitized. In addition, the political boundary and land ownership were also incorporated into the digital map. The soil survey map available for the study site contains primitive categories of broad soil types. Each soil type is affiliated with several attributes of soil characteristics.

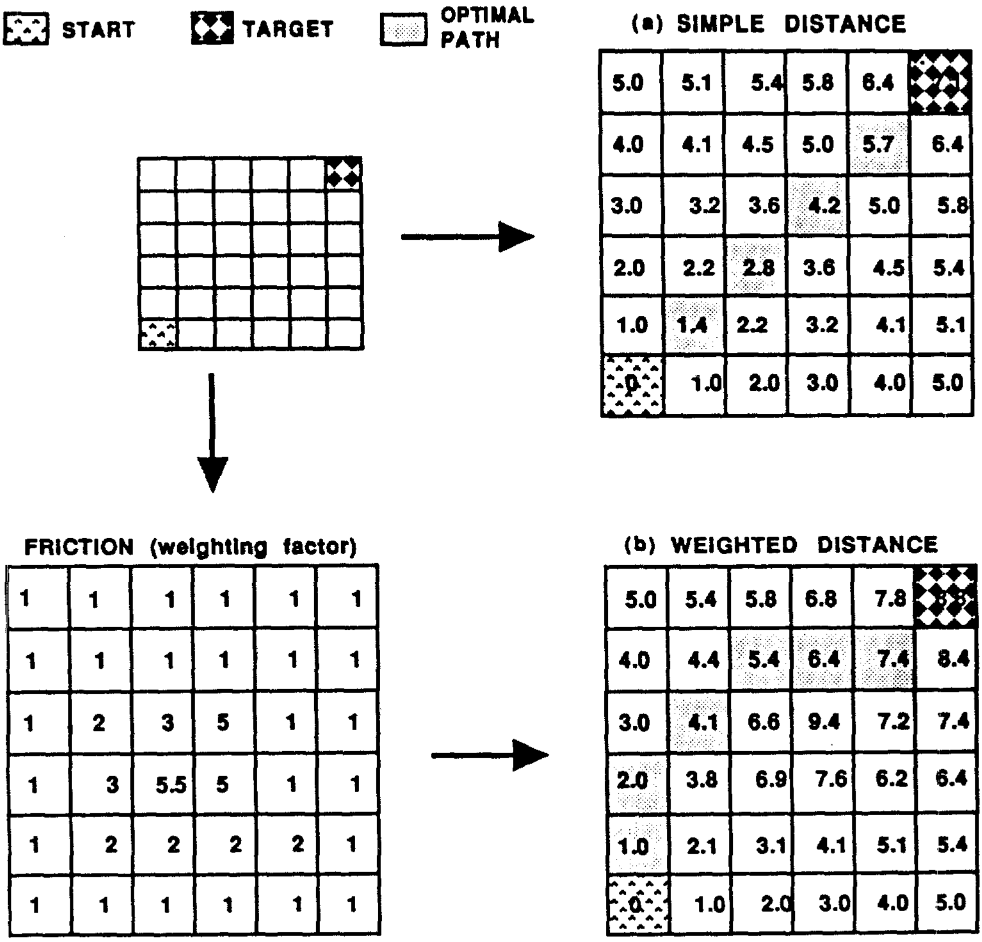
All the digital maps were registered on a common geographic coordinate system, Universal Transverse Mercator (UTM) system, with a cell size of 18 x 18 meters on ground. Since the major concern of this study was analytical process of GIS functions, the digital map data were produced on raster format that is known to be more effective for spatial analysis than vector format. In raster format, the whole surface of a map is divided into a set of grid cells having an equal size of area and each grid cell represents a certain geographic feature or characteristics. Another primary method representing spatial data is vector format, in which a spatial feature is represented by a set of point coordinates and line segments. Detailed comparison between the two data types can be found in the literature (Aronoff, 1989 ; Berry, 1987 ; Burrough, 1987).

SPATIAL ANALYSIS

Distance Measurements and Connectivity Analysis

The analytical capability of geographic data in GIS is perhaps the most distinct function as compared to other computer-based graphics, mapping, or design (CAD) systems. Spatial analysis functions in GIS involve a wide range of operations, such as reclassifying a single map, multiple map overlaying, distance measurements and connectivity analysis, and neighborhood characterization. Cartographic modelling, implying a problem solving process in a cartographic format, is a group of multiple spatial analysis operations that are organized to address a specific application (Tomlin, 1990 ; Berry, 1987).

Although this study used several different types of computer-assisted map analysis techniques, the key analytical process used was a connectivity analysis



5.0	5.1	5.4	5.8	6.4	7.1
4.0	4.1	4.5	5.0	5.7	6.4
3.0	3.2	3.6	4.2	5.0	5.8
2.0	2.2	2.8	3.6	4.5	5.4
1.0	1.4	2.2	3.2	4.1	5.1
0	1.0	2.0	3.0	4.0	5.0

1	1	1	1	1	1
1	1	1	1	1	1
1	2	3	5	1	1
1	3	5.5	5	1	1
1	2	2	2	2	1
1	1	1	1	1	1

5.0	5.4	5.8	6.8	7.8	8.8
4.0	4.4	5.4	6.4	7.4	8.4
3.0	4.1	6.6	9.4	7.2	7.4
2.0	3.8	6.9	7.6	6.2	6.4
1.0	2.1	3.1	4.1	5.1	5.4
0	1.0	2.0	3.0	4.0	5.0

Figure 3. Simplified concept of connectivity analysis over the surfaces of (a) simple distance map and (b) weighted distance map through a friction map.

to find the optimal route for forest road. Figure 1 illustrates a simplified concept of connectivity process. Connectivity analysis begins with creating a proximity map to a starting location. There are two different approaches to create a proximity map. In the case of the simple distance map, each grid cell is simply assigned a value representing the actual Euclidean distance from the starting location (Figure 1a). Unlike the simple distance measurement, the weighted distance measurement requires a separate map of friction values to calculate a weighted proximity map. In the weighted distance map, the distance values were calculated based on the weighting factors of friction map (Figure 1b). The friction map, often called as cost surface, can be used to represent a barrier effect for each individual cell. For instance, a slope map can be easily used as a friction map to decide the suitability for road site by assigning high fiction values to the locations with steep slope. In this study, the friction map was used to designate the suitability for road site under the considerations of slope, soil erosion, and aesthetic value.

The optimal path between starting and target location can be identified by tracing the lowest value among the immediate neighboring cells over the proximity map. Searching process starts at the target location and moves toward the starting point. Because the proximity map was created from a starting point that should have zero value on it, the searching process will eventually stop at the starting point no matter where it is. Optimal path must be a straight line (shortest distance) on the simple proximity map, while optimal path on the weighted distance map appears to avoid the center portion where the friction values are high. Consequently, the fundamental approach used for this study is to generate a set of friction maps in which each friction map represents a combined restriction for a forest road projection.

Due to the rapid development of current computer technology, these types of computer-assisted map analysis functions are readily available from most raster-based GIS packages. Although several software packages running on a desktop microcomputer or workstation environment were employed, the primary software used for the map analysis was Professional Map Analysis Package (SIS, 1989) running on a microcomputer.

Three Alternatives of Forest Road Planning

For this study, three hypothetical criteria were given for forest road planning : 1) locating low slope area, 2) minimizing soil erosion, and 3) reducing aesthetic impacts. All three alternatives share common assumptions of which the new road should be built without crossing private lands and it starts from the ending point of current access road. The three route projections are separately illustrated as a form of cartographic model in Figure 2. Each rectangle indicates a map with name on it and arrows are directions of the map transformation through spatial analysis.

The first scheme (Figure 2a) to project a forest road simply substitutes a conventional manual approach by computer process, which finds the lowest slope locations from the starting point to target. Once the slope map was obtained from the DEM data, each value on the slope map was used as a friction value to indicate the relative suitability for a road site. To exclude private lands, the boundaries of land ownership were overlaid to extract the study area only.

Locations having higher friction values (steep slope) suffer longer distance values on the proximity map and, therefore, they are less likely to be candidates for the optimal connection path. Consequently, the connectivity analysis traces the grid cell having the lowest slope among the immediate neighboring cells, starting from the target location. The number of immediate neighboring cells is usually eight except for edge cells having either five or three neighboring cells. The target points were selected to be located approximately at the center location of each compartment so that they can be equally reached from all stands. Distance measurements and connectivity analysis were repeated on each pair of target points, such as from start to target1, target1 to target2, and target3 to start. Therefore, the resultant forest road appears to be a loop connecting all compartments from the starting location.

There has been increasing concern of environmental impacts caused by forest road construction. Unlike the first plan in which slope was the only factor considered, the second alternative (Figure 2b) was designed to locate forest road that can minimize soil erosion. Soil type and the distance from stream were the two factors to assess the susceptibility of soil erosion. If a forest road is built close to stream, it would probably cause high physical damage to both ground and water. Thus, higher friction values were given to the areas closer to stream. The soil type map was reclassified according to the soil characteristics (clay and silt contents and soil depth) so that each soil type can represent relative vulnerability for soil erosion. After the three friction maps (slope, stream, and soil) were obtained, they were averaged to create a final friction map. At this stage, the relative importance among the friction maps can be manipulated. If it is necessary to give more emphasis on one factor over the other two, one could simply use a weighted averaging method. The averaged friction map (FRICTION-2) was then used for distance measurement and connectivity analysis, as the same way for the FRICTION-1 at the first model.

In addition to the limits of slope and soil erosion, the third alternative (Figure 2c) considers the aesthetic value of forest landscape. Forest road construction in a mountainous area can produce severe visual impacts. There has been a growing concern of reducing aesthetic damages by road construction in mountainous forests. This can be a particularly sensitive issue for the areas where public has fre-

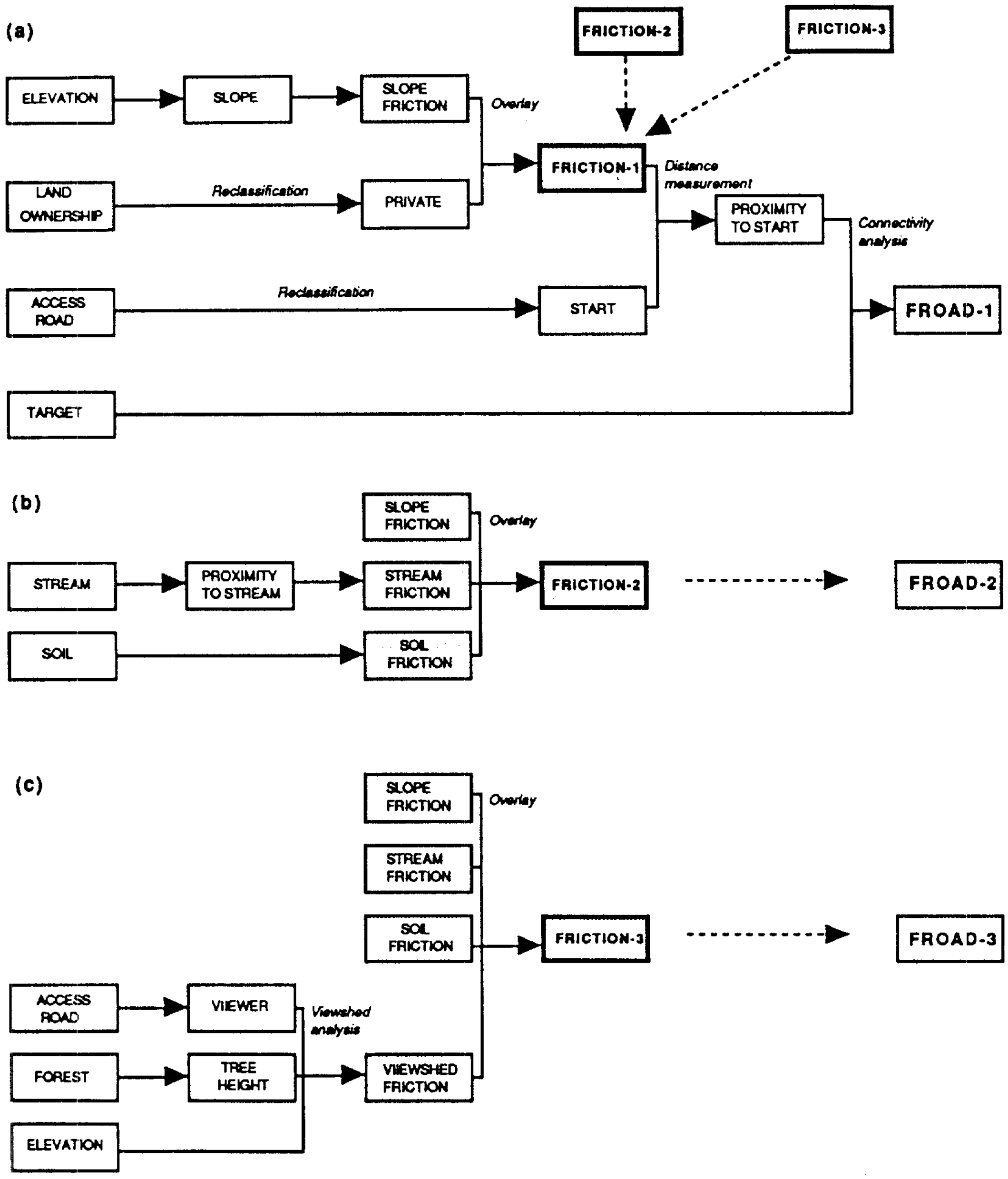


Figure 2. Three cartographic models to project forest road under the considerations of (a) slope, (b) slope and soil erosion, (c) slope, soil erosion, and aesthetic value.

quent access, such as national parks or recreational areas. One alternative to reduce the visual impact is to build forest roads outside from public viewshed. To find out the areas that are highly visible from public eyes, viewshed analysis can be effectively used. Viewshed analysis requires two maps of a terrain surface and the location of viewer. Viewer can be a single point, a line of road, or an area.

In this study, the current access road was treated as viewer. The terrain data were slightly modified by adding tree height above the digital elevation data, which has certain influence in sight visibility. The viewshed analysis produced a map in which each cell value represents relative visibility (the number of times seen by viewers). The viewshed friction map was then generated by simply reclassifying the visibility map. The highly visible locations are assigned by high friction value and, therefore, they are less likely to be sites for the forest road. The viewshed friction map was combined with three previous friction maps in the second model to create a final friction map (FRICTION-3) for the third model.

Comparisons of the Alternatives

Each of the three analyses produced a forest road connected from the current access road at the bottom of the watershed. To visualize the exact location of projected routes, the three forest roads were overlaid to the three-dimensional display of the digital elevation data (Figure 3). The first design linking the lowest slope locations exhibits a route that passes through mainly valley areas (Figure 3a). Although the figure does not show the stream lines, the first route crosses the stream several times. It may be necessary to build several bridges to prevent excessive soil loss and to preserve water quality. The second alternative route turns out to be a complete circle connecting the target points (Figure 3b). Due to the constraints to reduce soil erosion, the projected route tends to be away from the stream and placed over rather high elevation areas where soils are generally less erodible. The third route appears to be very similar to the first one (Figure 3 c). However, the projected route seems to avoid the aspects that are facing to the viewer's locations of the current access road at the lowest elevation zone.

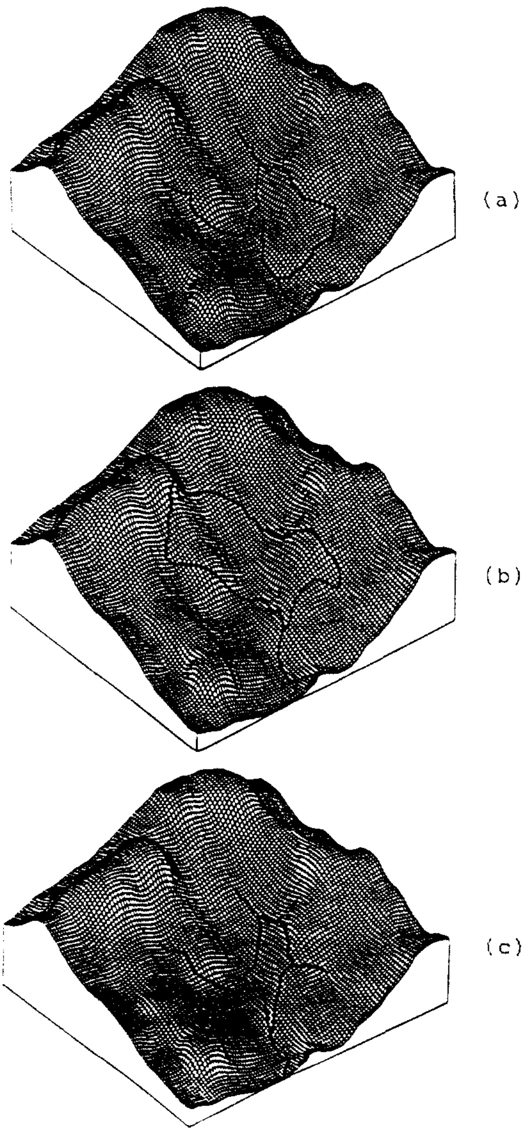


Figure 3. Forest roads derived from the three alternatives of (a) slope, (b) slope and soil erosion, (c) slope, soil erosion, and aesthetic value.

Visual assessments on the 3-d display can be very effective to compare different alternative routes. In addition to such visual assessment, it is also possible to obtain quantitative information by overlaying the outcome road map to the topographic maps and extracting topographic data along the route. Quantitative data that can be easily derived include the total length of road, the cross-sectional profile, and the amount of cut-and-fill. Figure 4 shows the cross-sectional profiles of the three alternative routes, which can be useful to determine the overall slope of the projected road and the total length. From the figure, it appears that the second alternative has length of about 3,300 meters compared to 3,150 meters for the first route and 3,050 meters for the third route.

As briefly mentioned earlier, the projected route may not possess enough accuracy to be used in actual construction. To achieve a final forest road, it is necessary to conduct a detailed field survey for construction purposes. The main function of computer-assisted map analysis is to provide a preliminary designing tool to compare several alternatives in forest road planning. Although manual methods can still be applied, it will be very time consuming and, occasionally, impossible for situations where several complex factors should be regarded.

Limitations

Among the three alternatives, it may be inappropriate to claim that a single alternative route is superior than the others, since the selection of the final forest road network largely depends on specific management goals for a project area. Furthermore, this study does not include harvesting plan, which is a key factor to control the design of forest roads. Once a certain harvesting scheme is adopted, the cartographic models should be modified to adjust several engineering specifications.

However, although all the required specifications are provided to assemble a cartographic model for designing forest road network, it would still be precarious to totally rely on the outcome of the computer-assisted map analysis. In a numerical analysis, such as a statistical model, we are able to obtain the level of error for the estimation made by the model. Unfortunately, there is no standard methodology currently available for assessing the confidence for the outcome of computer-assisted map analysis. Therefore, computer-assisted map analysis should be used as a tool for decision making process rather than an explicit solution for a problem.

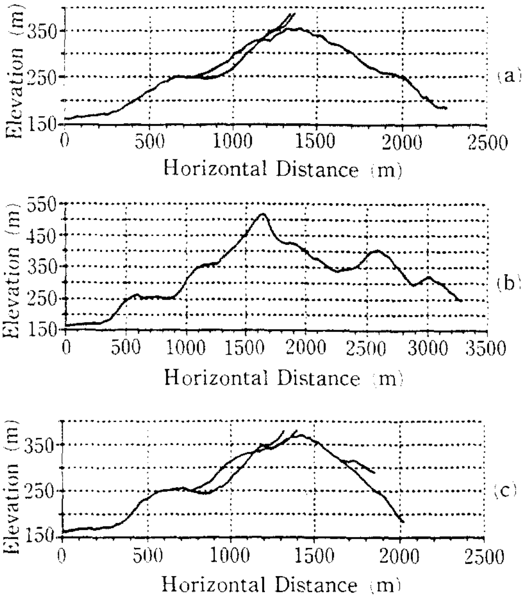


Figure 4. Cross sectional profile of the three projected forest roads.

CONCLUSIONS

Computer-assisted map analysis techniques were introduced to test the effectiveness of deriving several alternatives of forest road planning. Forest road planning was based on three separate alternatives considering slope, soil erosion, and aesthetic value. Three cartographic models produced potential routes of forest road. Visual assessment of three-dimensional display and quantitative comparison of projected road specifications were very effective to derive a preliminary road network.

Rapid developments of GIS technology show a great potential to help designing process of forest road network, particularly for the area where road construction will cause conflicts between management options and environmental concerns. Even though computer-assisted map analysis can be effective for comparing several alternatives, the analysis results should be recognized as a preliminary outcome and needed further refinements. To achieve a practical use of computer-assisted map analysis, there are several factors that need to be improved. In particular, data quality and error propagation are two major topics that need further studies. Although GIS technology has been developed based on the needs from many different disciplines, it is still ongoing process to apply this technology for many real life problems.

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