Planning Circular Forest Road Networks Based on Water Catchment Areas

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Abstract: A planning program for circular forest road networks, including strip roads, was developed by considering water catchment areas. The forest road network planned by the program and the existing forest road network constructed by the forest owner were compared and examined using indices representing operational and traffic benefits. From the viewpoint of operational benefits, the average winching distance and ratio of average winching distance to the theoretical average winching distance for the road network based on water catchment areas were lower than those for road networks based on subcompartments. From the viewpoint of traffic benefits, the average distance between the attainment points of the road network based on water catchment areas was shorter. In addition, a connectivity reliability analysis was conducted to evaluate the alternative function, which is considered an index of traffic benefits, by using a shallow landslide risk map. Road failure was assumed to occur when a forest road passed over a shallow landslide risk area. The connectivity reliability of the road network based on water catchment areas was the highest because of its ladder-shaped structure. The economic benefit per unit road length of the road network based on water catchment areas was also larger. Therefore, the road network based on water catchment areas was the most suitable for the applied forest road network, assuming that the network was completely established.

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1. Introduction

For sustainable forest management and low-cost forestry operation, appropriate road networks, including forest roads for trucks and strip roads for forwarders, must be developed in Japan. There are two kinds of road networks, the arborescent network and the circular network. Arborescent networks are cost-effective because the forwarding distance is efficiently shortened. However, migration pathways for traveling from site to site for forest management activities such as monitoring are limited and thus, the migration distances are relatively long. On the other hand, circular networks provide alternative migration pathways that improve traffic benefits by shortening migration distances and providing detours in the event of a disaster. However, the forwarding distances are longer in circular networks. Therefore, it is important to balance improvements in forwarding efficiency with the advantages of the circular network.

In forest road network planning research, an examination of the theory of graphs (Kanzaki 1966) and research on automatic route design (Sakai, 1981; Kobayashi, 1984) have been carried out. In addition, studies of circular road network development algorithms (Nitami, 1992; Sakai and Suzuki, 1993) and of a prototype method for planning circular forest road network (Kitagawa, 1993) have previously been completed. Furthermore, Chung et al. (2004, 2008) optimized forest road networks considering yarding and skidding operations. However, little research has been conducted on balancing the advantages of arborescent and circular road networks.

Our previous study (Ito et al., 2011a) proposed a road network planning method that combined arborescent and circular road networks and developed a road network planning program based on subcompartments, which are traditional operational units in Japan. The program planned main strip roads as an arborescent road network and branch
strip roads as a circular road network in which main strip roads were connected with branch strip roads using the Dijkstra method (Dijkstra, 1959) to minimize earthwork volumes. However, this program did not consider terrain features like ridges and valleys; forest roads have traditionally been constructed along valleys in Japan, whereas forest roads currently tend to be constructed on ridge tops that do not collapse easily.

Therefore, our next study (Ito et al., 2011b) developed a planning method for circular road networks considering these geographic features. The program determined the route by assigning the value zero to earthwork volumes when the route of the main strip road passed over ridges or through valleys. Thus, the program selected the route of the main strip road preferentially based on these geographic features. Furthermore, the program optimized the road network with the largest benefit while changing the order of planning the main strip roads randomly. Moreover, the density of road networks was adjusted by decreasing the number of attainment points on the main strip roads. Using this approach, the program was able to develop the road network with the highest economic benefits per unit length of strip road construction. However, the subcompartments were not evenly distributed. Consequently, road networks were also unevenly distributed and some areas had higher densities of road networks than others. Forest road networks should be established over a large area.

In this study, we developed a program for planning circular road networks based on water catchment areas to help forest road planners design circular road networks over a large area. Then, the road networks planned by the program and the existing road network constructed by the forest owner were compared and examined using operational and traffic benefit indices.
2. Materials and Methods

2.1 Study Site

The study site was the western portion of a privately owned forest at latitude 36°34’ N and longitude 139°32’ E in Kanuma city, Tochigi prefecture, Japan (Figure 1). The overall forest area is about 230 ha with elevations ranging from 500 m to 1,000 m. With regard to the operational site incline, most of the forests are relatively steep, about 30° or more. A substantial circular road network had previously been developed in this forest with an average density of about 100 m/ha.

![Figure 1. Location of the study site.](image)

The area of the study site within the forest was 97 ha (Figure 2). The density of the forest road network in the study area was about 130 m/ha. The vegetation mainly consisted of Japanese cedar (Cryptomeria japonica) at about 50%, Japanese cypress (Chamaecyparis obtusa)
at 40%, and broad-leaved trees at 10%. The 3.5-m-wide forest roads within this site were originally constructed in 1961 and 1977. The 2.5-m-wide strip road network was later rapidly developed to support thinning operations between 1995 and 2004. Within the study site, strip roads orthogonal to the contour lines were constructed first, followed by strip roads along the contour lines. The logging method used was chainsaw felling and processing, followed by grapple-loader winching and forwarder forwarding.

Forest registration data (stand ages and tree species) and GIS data (subcompartment layers) from the Tochigi Prefectural Government were used in the study as were 10-m-grid digital elevation models (DEM) generated from the 1/5,000 topographic map prepared by the Geographical Survey Institute, Japan. Contour lines were also generated from the 1/5,000 topographic map. The road network was measured using GPS. The data were converted into 10-m-grid raster data for consistency with the DEM data.
2.2 Planning Method Based on Subcompartments

Road network planning was initially conducted based on the subcompartment method (Ito et al., 2011a, 2011b). The study site had 100 subcompartments. First, the planning algorithm selected the target subcompartment with the highest revenue among all subcompartments to plan the main strip roads. Revenues were estimated based on the species (Figure 2), forest age, yield tables, and log prices. Log prices for Japanese cedar and cypress were set at 13,500 yen/m$^3$ and 28,700 yen/m$^3$, respectively (Japan Forestry Association, 2009).

After selecting the target subcompartment, the program determined an attainment point, which was the terminal point of the main strip road for the target subcompartment (Figure 3). The attainment point was the point to which the total distance from all grids in the target subcompartment was minimized. The program also determined the main strip road route from the attainment point to existing roads or preplanned roads after a second search using the Dijkstra method (Dijkstra, 1959). Using this program, the route with the minimum earthwork volume, with the gradient of the main strip road limited to below 50%, was determined by repeating eight-neighborhood searches from the attainment point. Earthwork volumes were estimated based on the slope angles of the cross-sections and assumptions such as road width (2.5 m), right cut slope angles, and no fills. The program determined the route by setting earthwork volumes to zero when the route of the main strip road passed over ridges or through valleys.

After the routes of the main strip roads from all attainment points in all subcompartments had been determined sequentially based on revenues, the program determined whether a branch strip road could be planned along contour lines from a starting point along the main strip road and terminating at existing roads or preplanned roads, using the Dijkstra method to minimize distances. The gradient of the branch
strip road was limited to below 30%. If it was possible to connect the branch strip road, the branch strip road was added to the plan. Potential starting points for branch strip roads were established at 100-m intervals along the main strip road starting at 60 m, double the maximum winching distance of the site considered in this study and the detour distance for the main strip road. The program repeated these processes until all potential starting points for the branch strip roads on the main strip roads were checked.

Road gradients were limited to 50% on the main strip roads and 30% on the branch strip roads, larger than those for existing roads, around 30% because of the 10-m grid-based program. In the forest, the route could be selected more precisely than by the 10-m grid-based program. The actual road length tended to be 1.5 to 2 times the straight distance of the road plan on the steep terrain in Japan. Therefore, planned
road gradients of 50% and 30% corresponded to actual road gradients of around 30% and 18%, respectively, with the detour.

Main strip roads were sequentially planned starting with the sub-compartments with the highest revenues. However, this approach may not lead to the best planning order for the main strip roads. Therefore, the order of planning the main strip roads was randomized and associated revenues and expenditures were estimated. The road network with the largest economic benefit was selected and planned. Moreover, the attainment points in the subcompartments were not evenly distributed. Consequently, the main strip roads were also unevenly distributed and some areas had higher densities of main strip roads than others. Therefore, the density of the road network was adjusted by decreasing the number of attainment points for the main strip roads to eliminate overlap of the operational areas.

2.3 Planning Method Based on Water Catchment Areas

The study site was next divided into water catchment areas. The main strip roads were then planned starting at the highest points of the water catchment areas, which were identified as attainment points on the main strip roads under this method (Figure 4). Like the planning method based on subcompartments, the program determined the main strip road route from the attainment point to forest roads using the Dijkstra method.

After the routes of the main strip roads from all attainment points in all water catchment areas had been determined, the program evaluated whether a branch strip road could be planned along contour lines from a starting point along the main strip road to the existing roads or preplanned roads using the Dijkstra method (hereafter, road network 1), similar to the planning method based on subcompartments.

As a refinement to the above method, another approach was devel-
Figure 4. Planning method based on water catchment areas.

Developed to plan branch strip roads more consistently along contour lines (Kitagawa, 1993). Under this method, the program identified points making up a route with the smallest difference in elevation from the starting point by repeating eight-neighborhood searches until existing roads or preplanned roads were reached (hereafter, road network 2).

Two searches for a branch strip road from each starting point were conducted to increase the number of branch strip roads, which was small if only one search was conducted because the number of main strip roads was smaller than that in the method based on subcompartments (Figures 3 and 5). To avoid overlap of operational areas, two searches for a branch strip road were conducted on both sides of each starting point. The program repeated these processes until all the starting points on the main strip roads had been checked.
2.4 Evaluation

The road networks planned by the program and the existing road network were compared and examined using operational and traffic benefits as indices. First, the road density and average winching distance were estimated. The theoretical winching distance was then estimated using a rectangular model (theoretical average winching distance = 2,500/road density) and the ratio of the average winching distance to the theoretical average winching distance was estimated to compare operational benefits. The average distance between the attainment points of the main strip roads in all subcompartments was estimated to compare traffic benefits. The existing road network did not reach a few of the established attainment points. Therefore, the distances between such attainment points and the closest points on the existing road net-
work were estimated by multiplying the straight-line distances by the average detour ratio (0.5) of this site and adding this amount to the average distance between attainment points.

In addition, the economic benefits of thinning operations on both 30-m sides of the existing or planned roads were estimated using a 20% thinning rate for the stocks. Revenues were estimated using thinning volumes and log prices. Expenditures included 3,000 yen/m$^3$ for felling and processing by chainsaw and winching, 0.32 yen/m$^3$·m for forwarding, and strip road construction costs. The forwarding distance was estimated as the distance between the thinning site and the landing (Figure 3). The strip road construction cost $C$ (yen/m) was estimated as follows:

$$C = \frac{\tan \theta \times W^2}{2} \times C_a + W \times C_b$$

where $\theta$ is the slope angle of the cross-section ($^\circ$); $W$, the road width (2.5 m); $C_a$, the cutting and filling cost (437 yen/m$^3$); and $C_b$, the clearing and grubbing cost (203 yen/m$^2$).

2.5 Connectivity Reliability Analysis

In addition to the above operational and traffic benefits used in our previous studies (Ito et al., 2011a, 2011b), the planning methods were evaluated using a connectivity reliability analysis as an index of traffic benefits (Iida, 1999; Suzuki et al., 2010). Connectivity reliability is defined as the probability that there exists at least one path without disruption to a given destination. For example, if certain road links were degraded because of a disaster, any pair of nodes in the road network should be connected by at least one path. If the connectivity reliability between an origin-destination pair is 0.6, then a trip from the origin can reach its destination 6 times out of 10.

To analyze the connectivity reliability of a road network, the relia-
bility of the links within the network must be first determined. The reliability of the links was estimated by the potential for road slope failure. A road failure was assumed to occur when a forest road passed over a shallow landslide risk area. An infinite slope stability analysis was conducted to identify areas with a shallow landslide risk at 10-year probable rainfall intensity. Shallow landslide risk areas with 10-year probable rainfall intensity have the potential to cause shallow landslides from rainfall every 10 years. In any given year, the probability of shallow landslide risk is 0.1. Thus, the probability of road failure for strip roads was assumed to be 0.1. It was also assumed that the probability of road failure for forest roads was 10 times less than that for strip roads because of its rigid structure. Thus, the probability of road failure for forest roads was set at 0.01. Connectivity reliability analysis was then conducted from the origin of the road network to the destination, which was the point farthest from the origin along the roads in this study area (Figures 2, 3, and 5).

Areas where the safety rate \( F \) determined by the following equation was \( \leq 1 \) were identified as shallow landslide risk areas:

\[
F = \frac{c + (\gamma_s \cdot h - \gamma_w \cdot h_w) \cdot \cos^2 \theta \tan \phi}{\gamma_s \cdot h \cdot \cos \theta \sin \theta}
\]

where \( c \) is the soil cohesion (N/m²); \( h \), the soil depth (m); \( \theta \), the slope angle (°); \( \phi \), the soil internal frictional angle (°); \( h_w \), the groundwater level (m); \( \gamma_s \), the soil density (kg/m³); and \( \gamma_w \), the water density (kg/m³).

Input values were determined as follows: \( c \), \( \phi \), and \( \gamma_s \) were assumed to be 1,730 N/m², 30°, and 2,000 kg/m³, respectively, based on classification of the surface soil as sandy soil (Goshima et al., 2008). \( \gamma_w \) is 1,000 kg/m³. \( \theta \) was calculated from the 10-m-grid DTM. \( h_w \) was calculated using the 10-year probable rainfall intensity for 1 h, which is 50.6 mm/h calculated using the fair formula from the Automated Meteoro-
logical Data Acquisition System’s probable rainfall intensity calculation program for each return period (Public Work Research Institute, 2010).

$h$ was estimated based on field observations during the investigation using simple penetration tests at 101 points (Goshima et al., 2008). This test methodology identifies a vertical change in the resistance of the soil layer based on the number of times a 5-kg hammer has to fall from a 50-cm height ($N_c$ value) to push a cone 10 cm into the soil. The soil layer depth was determined based on an $N_c$ value of $\leq 20$, because the basement geology belongs to the Neogene Tertiary Formation and the Kanto loam soil layer (Ohsaka and Tsukamoto, 1987). The spatial distribution for soil depth was estimated using the method of Iida and Tanaka (1997), which takes into account the inclination and average depth of the water catchment area, and estimates soil depths as logarithmic normal distributions with five classes of slope angles and four classes of average depths for a water catchment area.

Finally, the $\alpha$ index was estimated and compared with connectivity reliability. The $\alpha$ index is used for analysis of circular roads (Sakai and Naya, 1992) and is the ratio of the number of existing circular roads to the number of circular roads when the nodes of the networks are completely connected. The $\alpha$ index was estimated as follows:

$$[3] \quad \alpha = \frac{m - n + p}{2n - 5}$$

where $m$ is the number of links; $n$, the number of nodes; and $p$, the number of networks.
3. Results and Discussion

3.1 Road Networks Based on Subcompartments

Road networks were optimized with the main strip roads on ridges and the branch strip roads at 100-m intervals along the main strip roads. The optimized road networks included main strip roads along the ridges on the borders of the study site that had relatively gentle slopes; consequently, construction costs were lower and benefits were higher than those of the road networks before optimization, which had the main strip roads along the ridges on the hillsides (Ito et al., 2011b; Table 1). The optimized road networks extended the operational sites. However, the attainment points were not evenly distributed within the subcompartments. Consequently, the main strip roads were also unevenly distributed and some areas had higher densities of main strip roads than others.

Therefore, the density of the road network was adjusted by decreasing the number of attainment points on the main strip roads to eliminate any overlap of operational areas. Figure 3 shows the resulting optimized road network with 70 attainment points on the main strip roads. The density of this road network was lower than that of the road network before decreasing the number of attainment points (Table 1), and the main strip roads in this road network were more evenly distributed. In the areas where main strip roads were eliminated, branch strip roads were planned. Thus, the ratio of branch strip road length to total road length for this road network was higher than that for the road network before decreasing the number of attainment points (Table 1).

The average winching distance of the road network after decreasing the number of attainment points was longer because the density of the road network decreased. However, the ratio of the average winching distance to the theoretical average winching distance was similar to that
Table 1. Evaluation of road networks.

<table>
<thead>
<tr>
<th>Method</th>
<th>Density (m/ha)</th>
<th>Density (%)</th>
<th>Winching distance (%)</th>
<th>Branch strip roads (%)</th>
<th>Average distance between attainment points (m)</th>
<th>Average winching distance (m)</th>
<th>Economic benefit (yen)</th>
<th>Economic benefit per road length (yen/m)</th>
<th>Winching capable area (%)</th>
<th>Connectivity reliability (n)</th>
<th>Connectivity α index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing road</td>
<td>130</td>
<td>---</td>
<td>56.9</td>
<td>2.96</td>
<td>1,097</td>
<td>34,559,280</td>
<td>2,747</td>
<td>58.9</td>
<td>0.23</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Before optimizing</td>
<td>200</td>
<td>25.2</td>
<td>32.8</td>
<td>2.62</td>
<td>1,001</td>
<td>42,901,916</td>
<td>2,207</td>
<td>68.3</td>
<td>0.70</td>
<td>42</td>
<td>9</td>
</tr>
<tr>
<td>After optimizing</td>
<td>211</td>
<td>26.9</td>
<td>30.3</td>
<td>2.56</td>
<td>993</td>
<td>45,750,339</td>
<td>2,228</td>
<td>72.2</td>
<td>0.76</td>
<td>39</td>
<td>9</td>
</tr>
<tr>
<td>70 attainment points</td>
<td>188</td>
<td>29.8</td>
<td>34.1</td>
<td>2.56</td>
<td>1,026</td>
<td>44,172,609</td>
<td>2,420</td>
<td>68.1</td>
<td>0.62</td>
<td>28</td>
<td>7</td>
</tr>
<tr>
<td>Road network 1</td>
<td>152</td>
<td>42.6</td>
<td>41.4</td>
<td>2.52</td>
<td>1,019</td>
<td>38,904,373</td>
<td>2,629</td>
<td>58.1</td>
<td>0.83</td>
<td>23</td>
<td>18</td>
</tr>
<tr>
<td>Road network 2</td>
<td>217</td>
<td>59.8</td>
<td>28.4</td>
<td>2.47</td>
<td>1,059</td>
<td>52,159,141</td>
<td>2,469</td>
<td>80.5</td>
<td>0.99</td>
<td>38</td>
<td>21</td>
</tr>
</tbody>
</table>

a Ratio of branch strip road length to total road length.

b Ratio of average winching distance to theoretical average winching distance.

c The program identified branch strip roads using the Dijkstra method, similar to the planning method based on subcompartments.

d The program identified branch strip roads by searching for points with the smallest difference in elevation from the starting point.
of the road network before decreasing the number of attainment points. The average distance between the attainment points of the road network after decreasing the number of attainment points was slightly longer than that of the road network before decreasing the number of attainment points, but a little shorter than that of the existing road.

The economic benefits of the road network before decreasing the number of attainment points were greatest because the density and the ratio of the winching capable areas for this road network were the highest (Table 1). However, the economic benefits per road length of the road network after decreasing the number of attainment points were larger than those of the road network before decreasing the number of attainment points, although they were lower than that of the existing road.

3.2 Road Networks Based on Water Catchment Areas

Road network 2 with the main strip roads on ridges and the branch strip roads along contour lines is shown in Figure 5. The main strip roads were planned along the borders of the water catchment areas because the program planned the main strip roads along ridges and the borders of the water catchment areas were formed by ridges. In addition, the main strip roads were relatively evenly distributed. However, the program was not able to connect many branch strip roads in road network 1 owing to the gradient limitation of 30%. Therefore, the density of road network 1 was only 152 m/ha (Table 1).

On the other hand, the program was able to connect many branch strip roads in road network 2 and the branch strip roads were evenly distributed in a ladder shape. However, the method did not include gradient limitations. Therefore, some branch strip roads might not be connected in an actual situation. Furthermore, no branch strip roads were planned in the south area of the study site, because the south
area consisted of larger water catchment areas in which the distances between the forest roads or main strip roads were too long for the program to connect branch strip roads.

The density and ratio of the branch strip road length to the total road length for road network 2 were the highest and the average winching distance and ratio of the average winching distance to the theoretical average winching distance were the lowest among the road networks planned by the program (Table 1). The average distance between the attainment points of road network 2 were slightly longer than for the other road networks planned by the program, but was slightly shorter than that of the existing road.

The economic benefits and the proportion of the winching capable areas for road network 2 were the highest among the road networks planned by the program. The economic benefits per road length of road network 2 were the greatest among the road networks planned by the program, excluding road network 1, although they were lower than that of the existing road.

3.3 Connectivity Reliability Analysis

Figure 6 shows an example comparison of the measured values for soil depth and a theoretical lognormal distribution for an incline of 35–45° and an average depth for the water catchment area of 0–20 m. The soil depth comparisons were relatively consistent; thus, this method could be used to approximate the soil depth with a lognormal distribution. Then, a soil depth map was prepared using the modes of the lognormal distributions as the estimated values for soil depth (Figure 7). Finally, shallow landslide risk areas were predicted using the 10-year probable rainfall intensity and the estimated soil depths. The shallow landslide risk areas were located in valleys in which forest roads were also located (Figure 5).
The connectivity reliability of road network 2 was highest because it had many alternative routes; it had a large number of branch strip roads. However, the number of circular roads in road network 2 was lower than in the road network before optimizing, while its connectivity
reliability was higher. Furthermore, the number of circular roads in road network 1 was lower than in the road network with 70 attainment points, although its connectivity reliability was higher. Thus, circular roads in the road networks based on subcompartments were not well located for connectivity reliability even though the number of circular roads was larger than that in road networks based on water catchment areas. Therefore, connectivity reliability analysis was able to more accurately analyze the effectiveness of the circular roads in the network.

The $\alpha$ index for road networks based on subcompartments was lower than that of road networks based on water catchment areas, even though the number of circular roads in road networks based on subcompartments was higher. Thus, road networks with a higher $\alpha$ index also had higher connectivity reliability. The connectivity reliability of the road network based on water catchment areas was highest, which may be attributed to its ladder-shaped structure, assuming the network was completely established although some branch strip roads might not be connected in an actual situation because the method did not consider gradient limitations.

4. Conclusions

In this study, planning program for developing circular forest road networks was constructed considering water catchment areas. The forest road network planned by the program and was compared with the existing forest road network constructed by the forest owner using indices of operational and traffic benefits. From the perspective of operational benefits, the average winching distance and the ratio of the average winching distance to the theoretical average winching distance for the road network based on water catchment areas were lower than those for road networks based on subcompartments. From the perspective of traffic benefits, the average distance between attainment points
was shorter and connectivity reliability was higher. The economic benefit per road length of the road network based on water catchment areas was also larger. Thus, the road network based on water catchment areas was better than that based on subcompartments, though the economic benefit per unit road length of the former was lower than that of the latter in the study area. Therefore, the program developed in this study could help forest road planners design “preliminary” road networks before forest road constructors designed and constructed road networks in the forest.

The program used 10-m grid DEM which had a lack of accuracy for geographical features. Therefore, the program could not generate detailed road design, and road gradients were limited to 50% on the main strip roads and 30% on the branch strip roads—these values are larger than those for existing roads. In order to improve the geographical features, Saito et al. (in press) developed a forest road design model using light detection and ranging (LiDAR) data; they demonstrated a significant improvement in representing relatively accurate geographical features. By combining the program developed in this study with the program of forest road design model using LiDAR, the program could generate more realistic road networks.

A connectivity reliability analysis was conducted using a shallow landslide risk map. Forest road failure was assumed to occur when the forest road passed over shallow landslide risk areas. The connectivity reliability analysis was able to accurately analyze the effectiveness of circular roads in this study. Connectivity reliability can be applied to various sites and road networks for any type of disruption related to disasters. However, estimating the probability of disruptions was difficult and may be a weakness of the connectivity reliability analysis method.
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