Planning method for circular road networks considering geographical features

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Abstract:
In this study, we developed a program to plan circular road networks in mountainous regions. The program examined the main and branch strip roads using the Dijkstra method. Main strip roads that were orthogonal to the contour lines and used to reach the stand were planned to be on geographical features such as over ridges and through valleys. Branch strip roads were planned at regular intervals along the contour lines for operations; they formed a circular road network. The order of planning of main strip roads was changed at random for estimating the revenues and expenditures. Then, the road network with the largest benefit was planned. Moreover, the density of road networks was adjusted by decreasing the number of attainment points on the main strip roads. As a result, the program could plan a road network with higher benefits per unit cost of strip road construction.

Keywords: Dijkstra method, revenue and expenditure analysis, density of road network, traffic and operational efficiencies, ridge and valley

1 Introduction

For sustainable forest management and low-cost forestry operation, appropriate road networks must be developed. There are two kinds of road networks. One is the arborescent network and the other is the circular network. The arborescent network is cost-effective because in it the skidding/yarding distance is efficiently shortened. However, the migration pathways for traveling from site to site for forest management activities such as monitoring, and so on are limited and the migration distances are relatively large. On the other hand, the circular network provides alternatives for migration pathways that improve the traffic benefits by shortening the migration distances and providing a detour in the event of a disaster. However, the skidding/yarding distances are longer in a circular network. Therefore, it is important to balance the improvement of the skidding/yarding efficiency and 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 conducted. Also, research on the circular road network formation algorithm (Nitami, 1992; Sakai and Suzuki, 1993) and research on a prototype method for planning circular road networks (Kitagawa, 1993) have been carried out. However, little research has been performed on the balance between arborescent and circular road networks.

Our previous study (Ito et al., 2011) proposed a road network planning method for combining arborescent and circular road networks and developed a road network planning program. The program planned main strip roads for the arborescent road network and branch strip roads for the circular road network using the Dijkstra method to minimize earthwork volumes. However, this program did not consider terrain features like ridges and valleys, although forest roads were traditionally constructed along the valleys in Japan, whereas the forest roads nowadays tend to be constructed on ridge tops that do not collapse easily. Therefore, in this study, we have developed a planning method for circular road networks, considering the geographical features.

2 Study Site and Materials

The study site was the western part of a privately owned forest at latitude 36°34′ N and longitude 139°32′ E in Kanuma city, Tochigi prefecture, Japan (Fig. 1), and its elevation ranged from 500 m to 1,000 m. The forest area was about 230 ha. With regard to the operational site inclination, most of the forests were relatively steep, about 30° or more. The average density of the road network in the forest was about 100 m/ha. A remarkable road network was developed in this forest and a circular road network was formed.

The area of the study site was 97 ha (Fig. 2). The density of the forest road network was about 130 m/ha. The vegetation mainly consisted of Japanese cedar (*Cryptomeria japonica*) 50%, Japanese cypress (*Chamaecyparis obtusa*) 40%, and broad-leaved trees 10%. The forest roads in this site were constructed in 1961 and 1977. The strip road network was later rapidly developed to conduct thinning operations between 1995 and 2004. Thinning operations have been conducted in the forest along the extended strip roads. In this study site, roads orthogonal to the contour lines were constructed first, and roads along the contour lines were constructed later. The logging method used was chainsaw felling and processing, followed by grapple-loader with winch pre-yarding, and forwarder forwarding.

Forest-registration data (stand ages and tree species) and GIS data (sub-compartment layers) from the Tochigi Prefectural Government were used for the study as were 10-m-grid digital elevation models (DEM) generated from the 1/5,000 topographic map of 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.

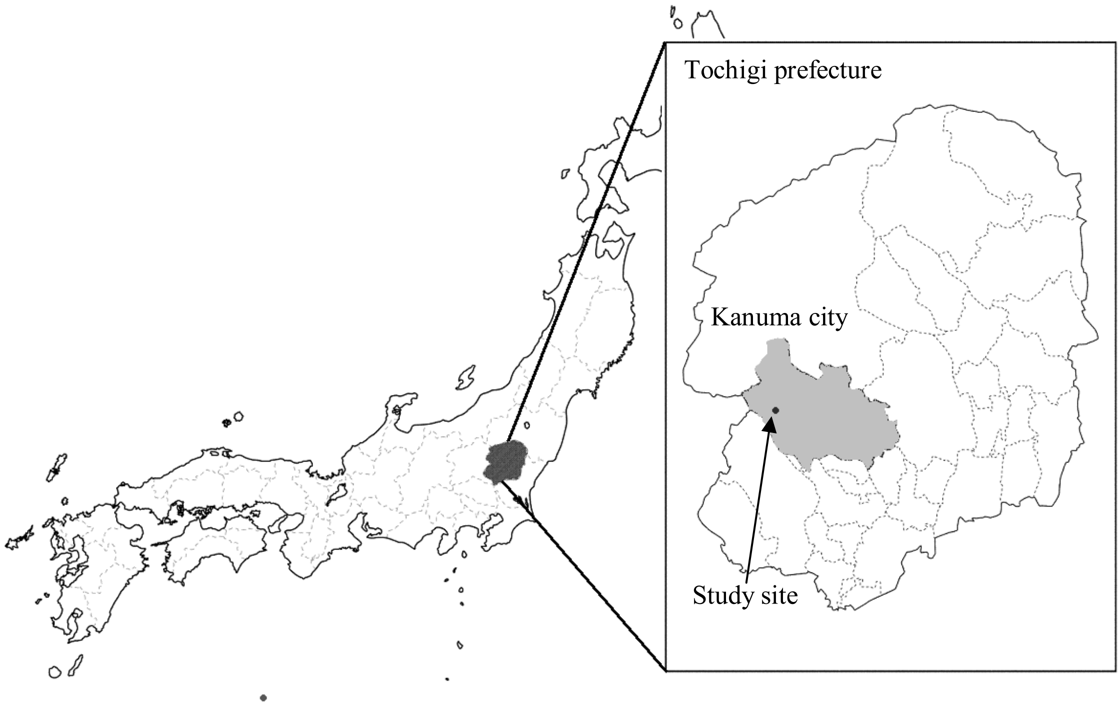

Figure 1: Location of study site

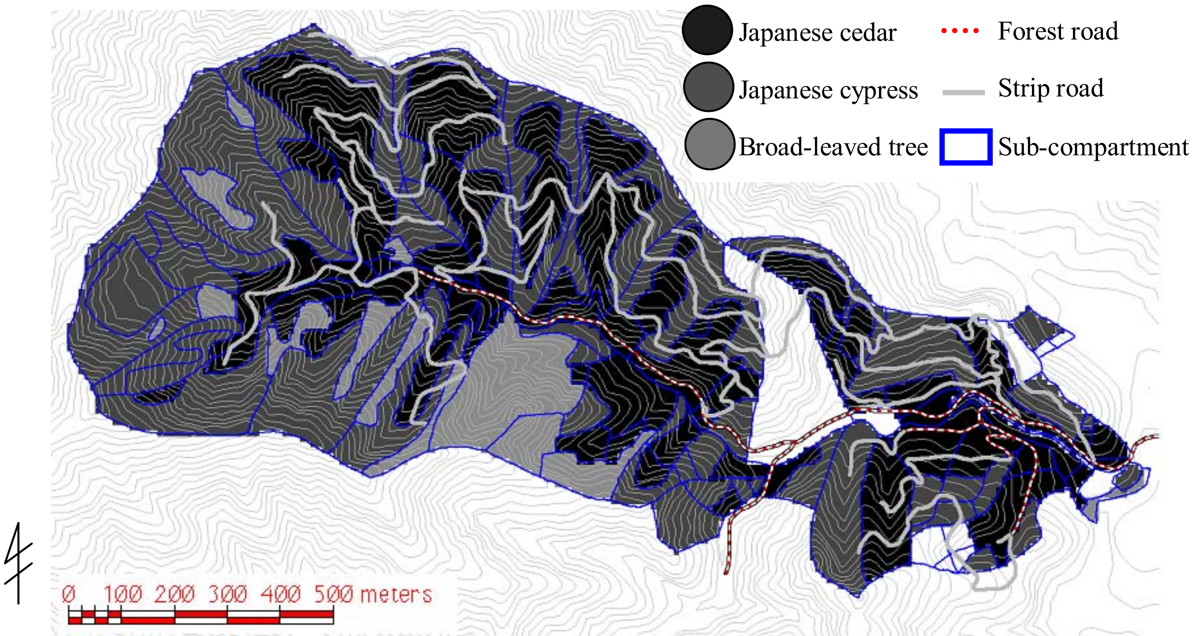

Figure 2: Study site

3 Methods

In this study, we have developed a program for planning a circular road network. Then, the road network planned by the program and the existing road network constructed by the forest owner were compared and examined using operational and traffic benefits as an index. A method for planning main and branch strip roads using the Dijkstra method was examined. Main strip roads orthogonal to the contour lines that reach the stand were planned along geographic features such as ridges and valleys. Branch strip roads along the contour lines for operations were planned from the attainment point of the main strip road or at regular intervals to form the circular road network. In addition, Chung et al. (2004 and 2008) optimized the forest road network considering yarding and skidding operations. This study also optimizes the road network considering the economic balances of operations.

3.1 Development of Road Network Planning Program

In this study, the road network planning program was developed based on sub-compartments, which are the traditional operational units in Japan. The study site had a hundred sub-compartments. First, the developed planning method selected the target sub-compartment that had the highest revenue among all sub-compartments in order to plan the main strip roads, as in our previous study (Ito et al., 2011). The revenues were estimated from the species (Fig. 2), forest age, yield tables, and log prices. Log prices for Japanese cedar and cypress were set as 13,500 yen/m^3 and 28,700 yen/m^3, respectively (Japan Forestry Association, 2009; 1 euro = 110 yen on 2/15/2011).

After selecting the target sub-compartment, the program determined an attainment point, which was the terminal point of the main strip road of the target sub-compartment. The target attainment point was the point to which the total distance from all grids in the target sub-compartment was minimized. The program also determined the main strip road route from the target attainment point to the existing roads or pre-planned roads after the second search using the Dijkstra method (Dijkstra, 1959). The Dijkstra method is a technique of route selection in which the evaluation function is minimized. In this program, the route with the minimum earthwork volumes, where the gradient of the main strip road was limited to below 50%, was determined by repeating eight-neighborhood searches from the target attainment point. The earthwork volumes were estimated from the slope angles of cross-sections and assumptions such as road width (2.5 m), right cut slope angles, and no fillings.

The program in the previous study (Ito et al., 2011) did not consider geographical features such as ridges and valleys while determining the route of the main strip road. In this study, the program determined the route by estimating earthwork volumes as zero 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 geographical features.

After the routes of the main strip roads from all attainment points in all sub-compartments with the most revenues had been determined sequentially, the program checked whether a branch strip road could be planned along the contour lines from the attainment point of the main strip road to the existing roads or pre-planned 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. This method had the merit of shortening the migration distances between sub-compartments. However, branch strip roads were actually constructed at a certain interval, for example, 60 m, which is double the maximum pre-yarding distance of the site considered in this study. Therefore, the program checked whether a branch strip road along contour lines could be planned at regular intervals as an alternative way. The starting point for each branch strip road was set at 100-m intervals along the main strip road due to the detour of the main strip road. The program repeated these processes until all the start points for the branch strip roads on the main strip roads were checked.

The program was executed in six cases: three methods to determine the routes of main strip roads, such as no consideration for geographical features, preferential consideration of ridges or valleys, and two methods to determine the start points of branch strip roads, such as attainment points of the main strip roads and points between 100-m intervals on main strip roads. Values of limitation for road gradients were set to be larger, such as 50% on the main strip roads and 30% on the branch strip roads, than those for existing roads because of the grid-based program.

3.2 Evaluation

The road network planned by the program and the existing road network were compared and examined using operational and traffic benefits as an index. First, the road density and average pre-yarding distance were estimated. Then, the theoretical pre-yarding distance was estimated using a rectangular model (theoretical average pre-yarding distance = 2,500/road density) and the ratio of the average pre-yarding distance to the theoretical average pre-yarding distance was estimated in order to compare the operational benefits. The average distance between the attainment points of the main strip roads in all sub-compartments was estimated in order to compare the traffic benefits. The existing road network did not reach a few attainment points. Therefore, the distances between such attainment points and the closest points of the existing road network were estimated by multiplying their straight line distances by the average detour ratio (0.5) of this site and adding to the average distance between attainment points.

In addition, the economic benefits of thinning operations on both 30-m sides along the existing or planned roads were estimated using a 20% thinning rate of stocks. The revenues were estimated using thinning volumes and log prices. The expenditure includes 3,000 yen/m^3 for felling and processing by chainsaw and pre-yarding, 0.32 yen/m^3/m for forwarding, and strip road construction costs. Forwarding distances were estimated as the distance between the thinning sites and landings (Fig. 3). Strip road construction cost C (yen/m) was estimated using the following equation:

$$C = \frac{\tan\theta \times W^2}{2} \times C_a + W \times C_b, \quad (1)$$

where, θ is the slope angle of cross-sections (°), W is the road width (2.5 m), C_a is the cutting and filling cost (437 yen/m^3), and C_b is the clearing and grubbing cost (203 yen/m^2).

3.3 Optimization

Main strip roads were sequentially planned from the sub-compartments that had the highest revenues. However, the order of the planning of main strip roads may not be the best. Therefore, the order of planning of main strip roads was changed at random while revenues and expenditures were estimated. Then, the road network with the largest benefit was planned. Moreover, the attainment points in the sub-compartments were not evenly distributed. Consequently, the main strip roads were also unevenly distributed and some areas had high densities of main strip roads. Therefore, the density of the road network was adjusted by decreasing the number of attainment points of the main strip roads in order to eliminate overlap of the operational areas.

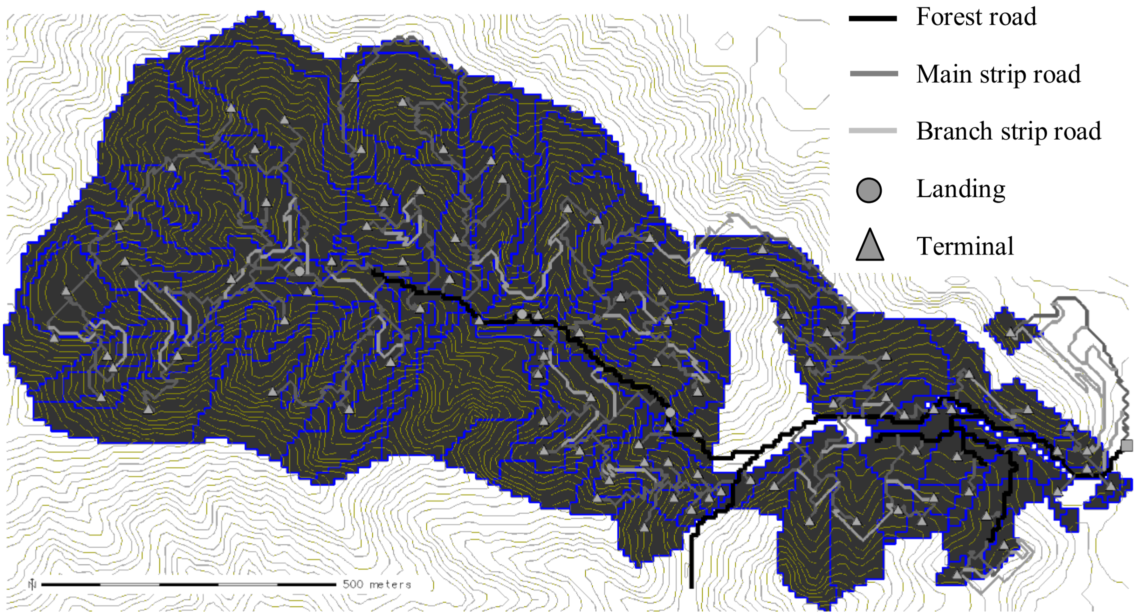

Figure 3: Road network with main strip roads on ridges and branch strip roads at 100-m intervals

4 Results

4.1 Road Network

Figure 3 shows the road network with the main strip roads on ridges and branch strip roads at 100-m intervals. This figure shows the main strip roads passing over ridges as intended, but branch strip roads were not planned as expected because steep terrains prevented the branch strip roads from being connected to the main strip roads. Therefore, this road network (Figure 3) contains many arborescent roads instead of circular roads compared to the existing road network (Figure 2). This tendency was similar to that of road networks with main strip roads planned without consideration of geographical features or those planned in valleys.

Table 1 shows the evaluation results for the road networks. The previous study (Ito et al., 2011) planned two road networks with different road densities, for example, 130 m/ha, which is the same as the existing road network, and 167 m/ha, which was the theoretical value estimated from a rectangular model (theoretical road density = 5,000/maximum pre-yarding distance) by assuming the maximum pre-yarding distance to be 30 m (as a result of using a winch with a grapple-loader). The densities of road networks planned in this study were higher than those of the existing road network and road networks planned in the previous study (Ito et al., 2011) because this study planned the branch strip roads after the routes of the main strip roads from all attainment points in all sub-compartments were determined in order to plan many branch strip roads. Unlike this study, the previous study (Ito et al., 2011) planned each branch strip road after each route of the corresponding main strip road was determined from each attainment point in each sub-compartment. Thus, the previous study (Ito et al., 2011) planned only a small number of possible branch strip roads (Table 1) because the program could not plan the branch strip roads until the program planned some portion of the main strip roads. Since this study planned a large region of branch strip roads, and more branch strip roads with gentle gradients could facilitate more efficient operations, the road networks planned by this study were more effective than those of the previous study (Ito et al., 2011).

Table 1: Road network results

Method	Density [m/ha]	Ratio of branch strip road [%]*	Average pre-yarding distance [m]	Ratio of pre-yarding distance [%]**
Existing road	130	-	56.9	2.96
Previous study (130 m/ha)	130	12.4	37.8	1.97
Previous study (167 m/ha)	167	16.2	34.7	2.31
Main 1 Branch 1	211	32.6	32.8	2.78
Main 1 Branch 2	200	28.7	33.3	2.66
Main 2 Branch 1	202	25.9	32.5	2.62
Main 2 Branch 2	200	25.2	32.8	2.62
Main 3 Branch 1	210	28.5	32.4	2.72
Main 3 Branch 2	209	28.4	32.2	2.69

Method	Average distance between attainment points [m]	Average forwarding distance [m]	Benefit [yen]	Benefit per road length [yen/m]
Existing road	1,097	504	34,559,280	2,747
Previous study (130 m/ha)	1,023	449	38,618,582	3,055
Previous study (167 m/ha)	1,010	452	41,149,693	2,534
Main 1 Branch 1	932	458	42,300,118	2,057
Main 1 Branch 2	974	477	41,350,792	2,129
Main 2 Branch 1	1,023	517	40,668,088	2,072
Main 2 Branch 2	1,001	476	42,901,916	2,207
Main 3 Branch 1	941	454	43,276,206	2,121
Main 3 Branch 2	985	467	43,358,136	2,129

*Ratio of branch strip road length to total road length. **Ratio of average pre-yarding distance to theoretical average pre-yarding distance. Main 1: main strip roads planned without consideration of geographical features. Main 2: main strip roads planned over ridges. Main 3: main strip roads planned in valleys. Branch 1: branch strip roads planned from the attainment points of main strip roads. Branch 2: branch strip roads planned at 100-m intervals.

The average pre-yarding distances of the road networks planned by the program were shorter than those of the existing road network because the densities of road networks planned by the program were higher than those of the existing road network, and higher densities tend to lead to shorter pre-yarding distances. The ratio of the average pre-yarding distance to the theoretical average pre-yarding distance of the road network planned in the previous study with the same density as the existing road network (130 m/ha) was the highest. The road network planned by the previous study contained a large region of arborescent roads, but a small region of circular roads. Thus, pre-yarding distances were efficiently shortened. On the other hand, the ratios of road networks planned by this study were lower because these road networks contained a large region of branch strip roads that formed circular road networks.

Average distances between the attainment points of the main strip roads in the road networks planned by this study were shorter than those of the existing road network. Road networks planned by this study contained a large region of branch strip roads, which formed circular road networks. Thus, the road networks shortened the average distances between attainment points. Main strip roads shortened pre-yarding distances, whereas branch strip roads shortened the migration pathways from site to site. Therefore, circular road networks with main and branch strip roads improved both operational efficiencies and traffic benefits.

Average forwarding distances on road networks planned by the program, excluding the road network Main 2 and Branch 1 in Table 1, were shorter than those of the existing road network. However, average forwarding distances on the road networks planned by this study were longer than those on the road networks planned by the previous study because higher densities of road networks made the sites far from the landings and increased forwarding distances.

The economic benefits of the road networks planned by the program were higher than those of the existing road network and higher densities of road networks led to higher economic benefits. However, the economic benefits per road length for the road networks planned in this study were lower than those of the existing road networks and road networks planned by the previous study because the road networks planned by this study contained a large region of branch strip roads, which had less effect on shortening the pre-yarding distances and, therefore, were less effective in extending operational sites.

4.2 Optimization

In this section, the road networks with main strip roads on ridges and branch strip roads at 100-m intervals were optimized (Figure 4 and Table 2). The optimized road networks (Figure 4) contained main strip roads along ridges on borders of the study site, which were relatively gentle slopes; consequently, construction costs were lower and benefits were higher than those of the road networks before optimization with main strip roads along the ridges on hillsides (Figure 3). Optimized road networks extended operational sites (Table 2). However, the attainment points were not evenly distributed in the sub-compartments. Consequently, the main strip roads were also unevenly distributed and some areas had high densities of main strip roads.

Therefore, the density of the road network was adjusted by decreasing the number of attainment points on the main strip roads in order to eliminate any overlap of the operational areas. Figure 5 shows the 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 2), and the main strip roads of this road network were more evenly distributed (Figure 5). In the areas where the main strip roads were canceled, 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 2).

The average pre-yarding distances of the road networks after decreasing the number of attainment points were longer, but this occurred by decreasing the densities of the road networks. Therefore, the ratios of average pre-yarding distances to theoretical average pre-yarding distances were similar to those of the road network before decreasing the number of attainment points. The average distances between the attainment points and average forwarding distances of the road networks after decreasing the number of attainment points were also similar to those of the road network before decreasing the number of attainment points.

The benefit of the road network before decreasing the number of attainment points was largest because the density and the ratio of the pre-yarding capable areas on this road network were the highest. However, the benefits per road length of the road networks after decreasing the number of attainment points were larger than that of the road network before decreasing the number of attainment points and the benefit per road length of the road network with 70 attainment points was the largest among those of the road networks after decreasing the number of attainment points.

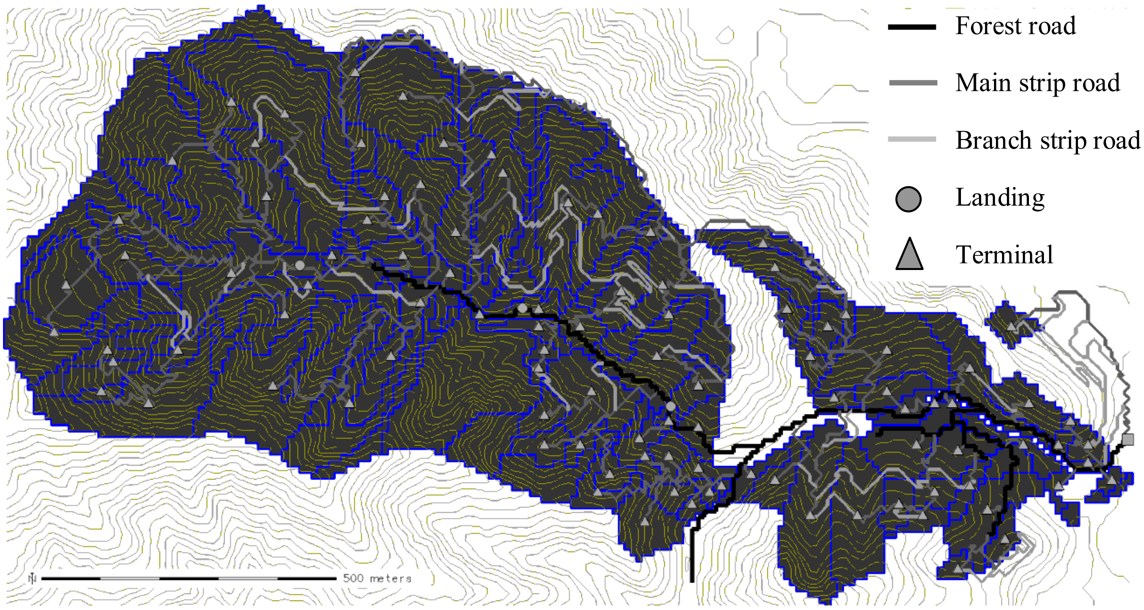

Figure 4: Optimized road network with main strip roads on ridges and branch strip roads at 100-m intervals

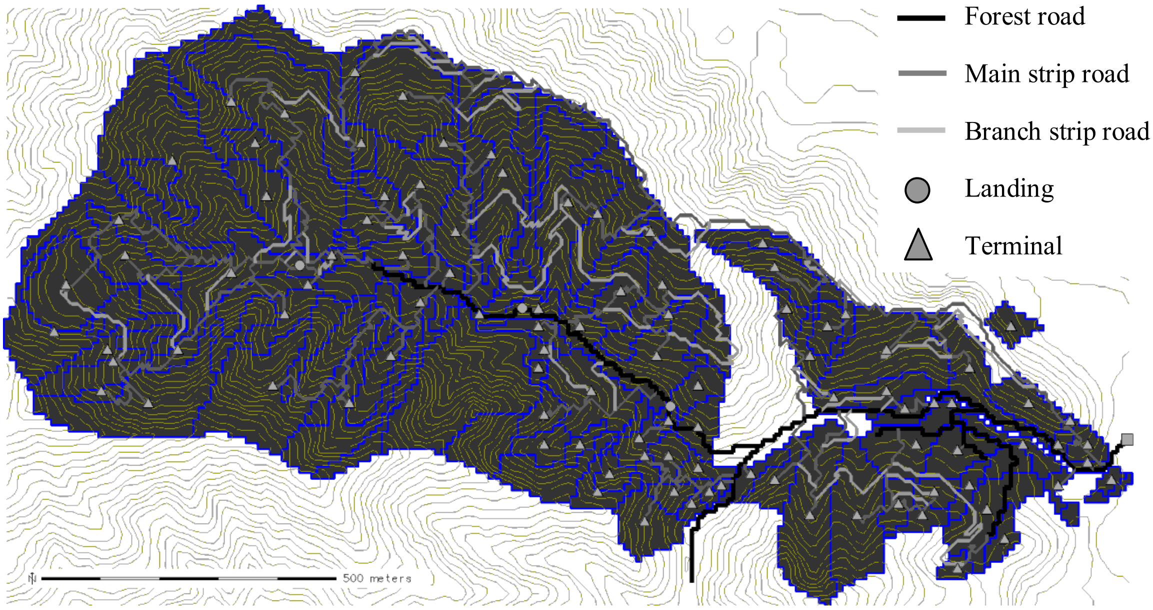

Figure 5: Optimized road network with 70 attainment points on main strip roads on ridges and branch strip roads at 100-m intervals

Table 2: Results of optimized road network with main strip roads on ridges and branch strip roads at 100-m intervals

Method	Density [m/ha]	Ratio of branch strip road [%]*	Average pre-yarding distance [m]	Ratio of pre-yarding distance [%]**
Existing road	130	-	56.9	2.96
Before optimizing	200	25.2	32.8	2.62
After optimizing	211	26.9	30.3	2.56
90 attainment points	218	30.7	31.2	2.72
80 attainment points	197	30.2	32.5	2.55
70 attainment points	188	29.8	34.1	2.56
60 attainment points	192	34.0	35.4	2.72

Method	Average distance between attainment points [m]	Average forwarding distance [m]	Benefit [yen]	Benefit per road length [yen/m]	Ratio of pre-yarding capable area [%]
Existing road	1,097	504	34,559,280	2,747	58.9
Before optimizing	1,001	476	42,901,916	2,207	68.3
After optimizing	993	507	45,750,339	2,228	72.2
90 attainment points	1,043	504	45,415,326	2,140	71.2
80 attainment points	1,061	513	44,585,366	2,332	69.9
70 attainment points	1,026	499	44,172,609	2,420	68.1
60 attainment points	1,079	539	42,931,015	2,297	65.5

*Ratio of branch strip road length to total road length. **Ratio of average pre-yarding distance to theoretical average pre-yarding distance.

5 Discussion

This study developed a program for planning circular road networks with traffic and operational benefits for sustainable forest management and low-cost forestry operation. The program planned circular road networks with main strip roads on geographical features and branch strip roads along contour lines at certain intervals along the main strip roads. The main strip roads extended the operational areas, whereas the branch strip roads improved traffic benefits and operational efficiency with their gentle gradients. Furthermore, the program optimized the road networks by changing the order of planning of the main strip roads and decreasing the number of attainment points. As a result, the average pre-yarding distance and the average distance between terminals on the road network after optimization were the shortest and the economic and operational benefits of this road network were the largest. The benefit per road length for the road network with 70 attainment points was the largest among all road networks except the existing road network and the road networks planned in the previous study (Ito et al., 2011). However, this road network was more effective because more branch strip roads with gentle gradients enabled more efficient operation.

The average forwarding distances on the road networks planned by this study were longer than those on the road networks planned by the previous study because the higher density of road networks made the sites far from the landings and extended forwarding distances. Future studies should optimize the landing locations in order to improve forwarding operational efficiency. Furthermore, slope failure, which is an important factor in forest road design and establishment in the mountainous regions of Japan, was not considered in the study. Therefore, future studies should plan road networks by considering slope failure.

6 Acknowledgement

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