# THINNING OPERATIONS IN JAPAN: DESCRIPTION AND MODELING

Edwin Miyata, Francis Greulich, Kazuhiro Aruga, Koki Inoue

Proceedings of: 13th PNW Skyline Logging Symposium, Corvallis, OR. April 1-6, 2007.

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**Abstract:** Thinning operations on planted forests are needed for the maintenance and improvement of their multifunctional role for society. The Japanese government has made a substantial commitment to thinning operations by subsidizing what is currently, in most circumstances, an uneconomic activity. There is great interest in improving the economic efficiency of the thinning process so that government subsidies can be reduced or eliminated. This paper examines the problem from a systems perspective and presents some initial thoughts on optimizing one possible thinning system design.

**Key words:** Non-linear optimization, thinning, hot deck swing, full tree processing, cost minimization, carbon sink.

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## Introduction

Japan comprises more than 3,000 small islands and the four main islands are Hokkaido, Honshu, Shikoku, and Kyushu. The total land area of Japan is approximately 38 million hectares (ha) and islands stretch nearly 3,000 kilometer (km) from north to south. About three quarters of the total land area is mountainous (Forest Agency 2001 and 2003). Most of the mountainous areas are steep, difficult to access sites. There are about 25 million ha of forestland in Japan and it covers about 67% of the total Japanese land area. Of the total forestland, plantations cover about 10 million hectares and natural forests and others make up 15 million hectares. Area of forests of 45 years or younger, which need thinning or other treatment, make up about 80% of the total planted forests. The growing stock of the forests is about 3.9 billion cubic meters ($m^3$) (Forest Agency 2002 and 2005).

The forests provide not only logs, lumber, pulp, and other wood products, but in addition, well managed forests also play important roles in various multiple eco-functions such as soil stabilization (prevention of landslides), in the conservation of soil resources and biodiversity, and expands opportunities for outdoor recreation and aesthetic enjoyment. Trees and vegetation on forestlands also remove carbon dioxide from the air (active carbon sink) and release oxygen (Fujimori 2001). Trees and vegetation also assist in protecting water quality and providing fish and wildlife habitat (Washington 1997 and Forestry Agency 2005). Forests have a significant role in maintenance and improvement of their multifunctional roles through its forestry operations (Forestry Agency 2004). In addition, it is stipulated in the Kyoto Protocol Target Achievement Plan (Cabinet Decision of April 2005) that 3.9 percent out of the 6 percent of Japan's emission reduction commitment should be achieved through forest carbon-sinks. Thinning with the proper timing and tree selection have impacts on present and future timber supply by providing wood volume at present and increasing value of the final crop. Also thinning operations revitalize the remaining trees which in turn increases the future absorption of carbon dioxide from the air and increases the release of oxygen. On the basis of this concept, in fiscal year 2005 the Forestry Agency began executing a 3-year program (300,000 ha per year) for the Promotion of Thinning Plan, which aims to promote regular thinning and the utilization of thinned wood products (Forestry Agency 2005). One of the reasons for sluggish forestry practices in Japan is the declining profitability of forestry. Cost reduction or improvement of profitability of forestry operations through promotion of intensive forestry management, better thinning machine systems and methods are essential (Forestry Agency 2001, 2004 and 2005). This paper examines the problem from a systems perspective and presents some initial thoughts on optimizing one possible thinning system design.

## General System Theory

The process begins with an awareness of a disequilibrium, difficulties, and necessities that must be integrated and considered to translate these issues into a rationale for allocating limited money and resources to improve the forestry operations. This rationale is stated as “issues statements” which lead directly to defining a problem. The purpose of this definition is to identify the underlying problem that the analysis will address. It combines the stated symptoms of disequilibrium into one precise definition of the problem (Iverson 1985).

Today's logging equipment ranges from chain saws to multifunctional high performance machine which can fell, delimb, buck, and haul products to the landing. Of these existing machines and operational systems we have to determine which are technically sound, economically efficient, and environmentally acceptable under the changing working and environmental conditions. The problem, therefore, is defined as how to evaluate alternatives and select the best machine and systems for the specific forestry activity. Although there may be different approaches, this paper presents one possible avenue to the evaluation of alternatives and the selection of the optimum number of processors' site to minimize the production cost of thinning operations.

## The Process of Evaluation

Proper planning of forest activities is essential to minimize negative environmental impacts. It is important to study the site-specific forest practice (activities) rules that are designed to protect ecosystems. The operational rules may vary with each prefecture in Japan. Precipitation in the form of rain or snow generally infiltrates into forest soils but much of it eventually drains or runs off following a course determined by the local topography. The runoff flows into creeks and streams which merge to form a river. The geographic area drained by a single river and its tributaries is called a watershed. When a logging site within a watershed area is harvested, the harvesting related activities such as road construction, logging, slash abatement, site preparation, planting and weed control impact not only the logging site but the entire watershed area. Watershed protection is the first line of defense in protecting water quality. Forestry related operational activities must be carefully planned to minimize potential impacts on water quality in the watershed. Thus, the spatial unit for forestry operational activities and planning should be at the watershed scale in most situations. Planning must include all activities which are necessary before, during, and after the harvest.

1) Develop background information: A detailed site description is a prerequisite to good planning. After a planning map is made, the site must be visited to assure accuracy of the data, including terrain condition, soil, and description of the site to identify what types of management and environmental protection requirements (watersheds analysis, riparian and wetland protection) that may be required for the specific site.

2) Measurement criteria: Based on the background information, measurement criteria must be developed to evaluate existing machine, systems, and methods available. Measurement criteria will revolve around cost, productivity, and environmental aspects. Costs include the production costs of each alternative. Productivity items include the productivity of each machine and a complete operational system requirements evaluation. Environmental criteria are evaluated, including soil erosion, soil compaction, and all environment protection requirements determined by the Japanese government.

   The next step in general systems theory requires that a set of alternatives (courses of action) be generated. The analysis phase begins with the initial evaluation of the alternatives. A review of related research will yield the necessary information to perform a cost benefit analysis. Information on existing yarding techniques is gathered through a literature search, and alternatives are compared to the operational characteristics of ideal yarding machine and systems.

3) Evaluate alternatives: Many government, university, and industry investigators have studied and reported the performance of various equipment and systems under different operational conditions in Japan (Sakaguchi 1996). Some machines work well on gentle slopes and firm ground. Some other machines operate on over 20% slope, but expose more soil to erosion. The cable systems being used for yarding large, high-value timber in the Pacific Northwest of the United States are too large and expensive to use in Japan. An excellent data source for evaluation is the manufacturers' web sites. Information on existing equipment and systems is gathered through a literature search. Forestry Agencies and the Forest Product Research Institute have information on Japan. In addition, the Prefecture Forest Experiment Stations have information on local areas. All available alternatives are compared against the measurement criteria. Candidate alternatives are selected, and then a computer simulation and operations research techniques can be used to evaluate these alternatives to match a given set of activity sites. Reliable and accurate data is needed for computer analysis. If available data is insufficient or incomplete to evaluate candidate alternatives, we must either a) secure additional assistance from people most familiar with the machine and systems, b) negotiate with manufacturers, local loggers, and timber owners to conduct work measurement studies, or c) determine acceptable

assumptions for analysis. Data collection is an ongoing process. A data bank of the performance information for different activity conditions should be continuously accumulated and kept current for forestry machine and systems.

4) Selection: This is the point of decision. Based on the evaluation of all alternatives, the best machine and systems for this specific activity site will be selected. New concepts need to be developed if existing equipment and systems are not suitable for use in the area.

5) Implementation: In this final step, the decision is implemented and the results are monitored. If current systems and equipment are not up to the job, then modifications, improvements, or new concepts must be investigated. A general systems approach and the order of priority are presented in Figure 1.

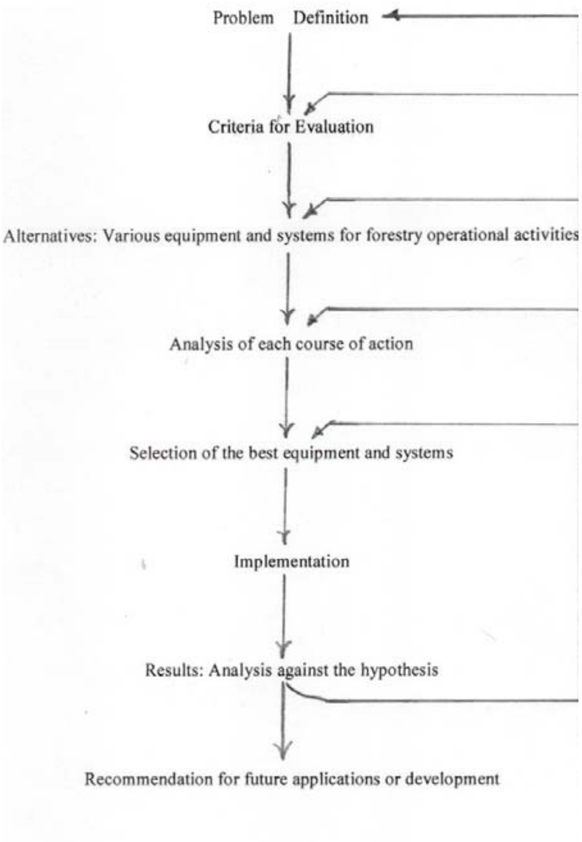

**Figure 1: The Decision-Making Process**

## Literature Research

A search of the literature on the forestry operations that satisfies the measurement criteria can be conducted. Many pertinent publications have been studied within and outside Japan. In harvesting operations, trees are felled by a chain-saw, feller-buncher, or harvester. Narita (2003) and Hashira (2001) studied a chain-saw and high performance processor. Mitsudome (2005) reported the productivity of the skidder and the backhoe with a winch for yarding operations, and Goto (2002) used a swing yarder and a high performance processor. Yoshida et al. (2006) studied the productivity of yarding system for forest biomass with a tower yarder. Sawaguchi (1996) studied the characteristics of parameters for forest-road evaluation and reported valuable information on thinning operations of planted forests in Japan. Garner (1978) reported a contractor hauling system and Aruga et al. ( 2006) studied the reduction of skidding or yarding distance. Zabinsky et al. (1992) examined nonlinear programming optimization methods to reduce yarding costs. Peters (1978) and Greulich (2000) applied operations research techniques to reduce harvesting costs.

## Model Development

Given the current heavy emphasis on thinning operations in Japanese forests it was decided to construct a model that might potentially serve as a guide to operations planning. Here we present some initial thoughts and results on that modeling effort. We acknowledge that these results are of a preliminary nature and would require additional work to be of any substantial assistance to managers of Japanese thinning operations.

We assume that a cable thinning operation is to be conducted on steep ground. Full tree yarding up-hill to a low-standard, single-lane, contour road is to be done. A hot-swing along the road to a processor where the full-tree will be delimbed, topped, and bucked, is planned. In this first pass at a model we assume that harvestable trees are uniformly distributed over the area to be thinned. Full trees are cable yarded up a series of parallel cable roads that are perpendicular to the truck road from which the yarder operates. The turns are continuously decked along the road centerline on that side of the yarder currently accessible to the swing machine. We also assume that logging trucks can access the processor site from either direction along the contour road and that they have equal hauling costs in both directions. The trucks will arrive at the processor from the side opposite the ongoing yarding operation, but we assume that there is sufficient space for the yarder to bypass the processor when necessary as it works up the road.

The objective is to yard, swing, process, and haul the total volume from the site at minimum cost. The decision variables are the number of processor sites to establish along the road as well as the location of these sites. We assume that the relevant costs for this initial model are: the cost of moving and setting up a processor site and the cost of swinging trees from the yarder location to the processor. The processor cost is a lump sum amount per move and the swing cost is a linear function of the distance from the yarder to the processor. All other costs are assumed to be insignificant or irrelevant to this initial problem statement. We also assume for this development that the road is a long tangent section with little or no grade.

Given a decision to have "n" processor sites along the road our immediate objective is to locate those sites so as to minimize the expected total cost of swinging the material to the processor. Since the swing cost is a linear function of the distance travelled we may write the objective function quite simply as the minimization of the expected one-way distance of the swing:

$$\underset{L_i,\ i=1,n}{\text{Min:}} \quad E\{s\}=\frac{1}{A}\sum_{i=1}^{n}\left[\int_{M_{i-1}}^{L_i}\left(L_i-x\right)h\left(x\right)dx+\int_{L_i}^{M_i}\left(x-L_i\right)h\left(x\right)dx\right] \tag{1}$$

where

$$A=\int_a^b h\left(x\right)dx \tag{2}$$

is the horizontal area between the road tangent, which is the near boundary of the thinned area, and the outer thinning boundary. The horizontal distance measured perpendicularly from the road centerline to the outer thinning boundary is denoted h(x). The thinned area starts at point a and ends at point b along the road. With the exception of the thinning unit start and end points along the road, $M_i$ denotes the midpoint between processor location $L_i$ and processor location $L_{i+1}$; viz., $M_i=(L_i+L_{i+1})/2$, with $M_0 \equiv a$, and $M_n \equiv b$.

It would appear that analytic solutions can be found for only relatively simple cases. For example, if h(x) is a constant distance from the road (a rectangular thinning unit) then the optimal spacing is quite intuitive and easily confirmed by the calculus. For a triangular thinning unit where, for example h(a)=0 and h(b) is some positive distance, the optimal spacing is not intuitively obvious but analytic solutions can also be obtained fairly readily. (These cases for low values of n (e.g., 1 or 2) and some variations from the current assumptions are good student exercises in the application of the calculus.)

Figure 2 illustrates an example where the external yarding boundary of the thinning unit has been freehand plotted as a smooth curve on a logging plan. We approximate this curve with a series of straight line segments as illustrated in Figure 3. The coordinates (in meters) of this approximating string of line segments, starting at point a and ending at point b, are given in Table 1.

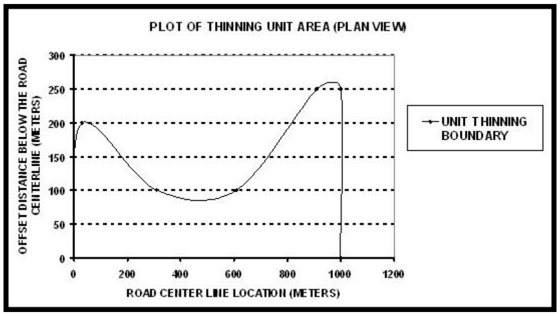

**Figure 2. A hypothetical thinning unit shown in plan view as recorded and plotted on the harvesting plan. The horizontal axis represents the centerline of a 1 kilometer tangent section of road forming one boundary of the unit.**

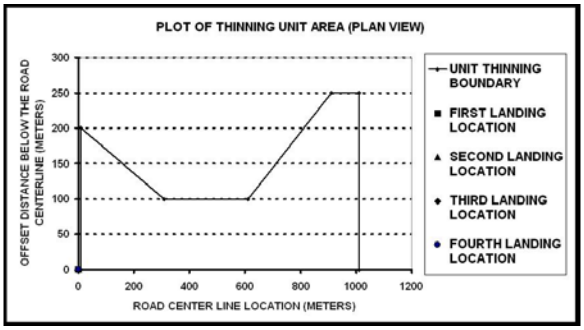

**Figure 3. The same thinning unit as shown in Fig. 2 as approximated by a series of linked straight line segments in preparation for mathematical modeling.**

**Table 1. Coordinates for line segment approximation to the thinning unit boundary.**

| j | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| $x_j$ | a = 10.0 | 10.1 | 310.0 | 610.0 | 910.0 | 1010.0 | b = 1010.1 |
| $h(x_j)$ | 0.0 | 200.0 | 100.0 | 100.0 | 250.0 | 250.0 | 0.0 |

Perhaps the easiest solution is achieved by numerical optimization using the Solver add-in for the MS Excel spreadsheet program. A spreadsheet based optimization program is easily written. When run for this problem results for up to 4 processor sites are found; optimal site coordinates are given in Table 2.

**Table 2. Optimal processor site coordinate along the road tangent and the associated mean swing distance for 1 to 4 sites.**

| n | $L_1^*$ | $L_2^*$ | $L_3^*$ | $L_4^*$ | E{s} |
|---|---|---|---|---|---|
| 1 | 622 | | | | 283.6 |
| 2 | 207 | 830 | | | 118.8 |
| 3 | 146 | 535 | 879 | | 80.7 |
| 4 | 123 | 417 | 718 | 919 | 60.2 |

These optimal processor locations, $L_i$*, are given in meters measured from the origin of the coordinate system, 10 meters to the left of point a. Figure 4 shows the optimal processor sites if it is decided to have a total of 4 sites along the road. Some caution is needed in running this problem. The problem, as stated, has a non-convex objective function and suboptimal solutions may be encountered. A good choice for the starting points of the optimization algorithm (the initial $L_i$ values) should result in at least a near-optimal, if not the optimal, solution in most cases. Restarting the algorithm with a variety of initial point combinations is also advisable. It is also to be noted that the objective function is quite flat near the optimal point and the algorithm is providing solutions, $L_i$*,within about ±3 meters. This variation is a function of not only the algorithmic procedure itself but also the numerical estimates provided by the spreadsheet formulation of the problem; e.g., the size of $\Delta x$ used to approximate the differential dx. A flat objective function near the optimal is encouraging when encountered since it provides flexibility in the actual siting decision with little subsequent departure from the optimal cost minimum.

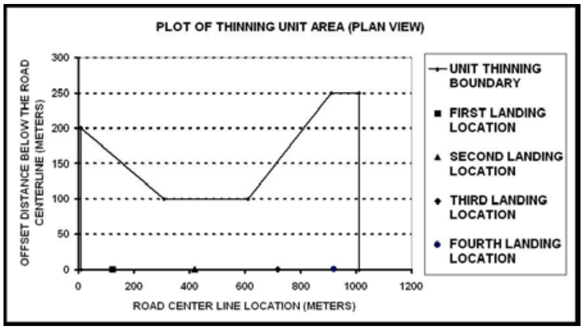

**Figure 4. The optimal processor siting locations as determined by the numerical optimization model when it has been decided that exactly 4 processor sites will be employed for the unit.**

With these results now in hand it is possible to examine the total cost relationship as the number of processor sites is varied between 1 and n (Figure 5). In this illustrative example n has been set equal to 4 and the optimal number of processor moves is 2. The optimal number of processor moves will depend on the size and configuration of the thinning unit as well as the relative costs of the two activities. At a minimum, one processor siting location is obviously required, but the optimal number may be quite large in some cases. In this latter situation the computational effort to determine optimal processor siting may be found excessive.

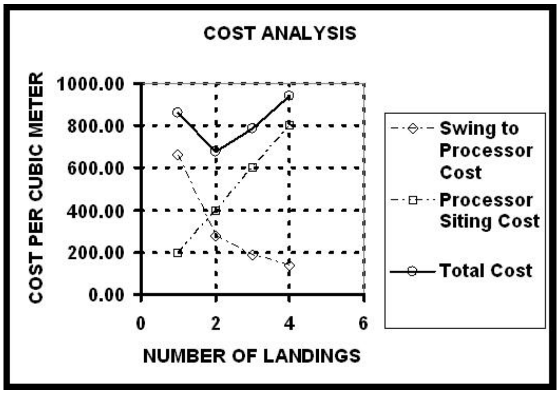

**Figure 5. The individual and total aggregated costs for swinging and processing trees for the specified thinning unit. In the absence of actual harvesting cost data arbitrary costs have been assigned to the swing and processing operations.**

Some interesting variations of the problem are possible, for example: 1. conditioning the hauling cost on which side is accessed by the truck, 2. restricting logging truck access to only one side, 3. placing the road on a grade and conditioning the swing cost on the adverse or favorable grade, 4. making the swing cost a quadratic function of distance, and, 5. generalizing the turn distribution along the road centerline. This latter change is easily done. The use of a road tangent, the spatial description of the thinning unit, and the specification of a uniform distribution of thinned trees, were only done for clarity of presentation in this paper. It is the distribution of turns along the road centerline that is needed for the optimization process; how that distribution along the centerline is determined is a separate, and rather pedestrian, issue.

## Concluding Statement

In order to meet their commitment to Kyoto Protocol targets, the Japanese government is emphasizing carbon sequestration through management activities on Japanese forests. Due to unfavorable economic conditions the active management of their forests has been at a very low level for many years. Many of the forested areas of Japan are in need of thinning operations. In order to encourage thinning the government is now subsidizing these operations.

Most of these forests are on steep ground of difficult access, and substantial costs are incurred during thinning. A systems approach to this issue suggests, among other things, that an effort should be made to identify the most efficient procedures in the use of equipment under different operational conditions. This paper presents some initial thoughts on improving the operational efficiency of cable thinning on steep terrain using pre-existing low-standard access roads with minimal environmental disturbance.

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## Author Contact Information

Edwin Miyata
Institute for International Development
Takushoku University, Hachioji-Si
Tokyo, Japan
TEL 042-665-1448
smiyata@ner.takushoku-u.ac.jp
(Affiliate Faculty
College of Forest Resources
University of Washington)
TEL 206.616.0770
esm@u.washington.edu

Francis Greulich
College of Forest Resources
University of Washington
Seattle, WA 98195-2100
TEL 206.543.1464
greulich@u.washington.edu

Kazuhiro Aruga
College of Agriculture
Utsunomiya University
Utsunomiya-Shi, Tochigi, Japan
TEL 028 649 5537
aruga@cc.utsunomiya-u.ac.jp

Koki Inoue
College of Bioresource Sciences
Nihon University
Kanagawa-Ken 252-8510  Japan
TEL 046068403669
koki@brs.nihon-u.ac.jp