The formulation of a technique for finding an optimal skidding road layout

by Michael Richard Carter

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Industrial and Management Engineering
Montana State University

Abstract:
The objective of this thesis is the formulation of a technique for the determination of the minimum cost layout of logging work (skid) roads, A study of the factors affecting layout costs showed that the most important factor in layout is spacing. The spacing factor was also found to be most important in the layout for landings.

A total cost equation is set up which contains all the factors found to affect cost. The relationships among these factors are derived to permit their combination. The form of the total cost equation indicates that, by using the methods of calculus, an optimal spacing can be determined.

The calculus approach to optimization proved a successful technique for determining the optimal layout and therefore the minimum cost of log removal. The results, however, are dependent on the accuracy of the input data and the exactness of simplifing assumptions made in the derivations. Any application of this technique would require knowledge of these factors.

The conclusion is that this technique of determining optimal layout is a feasible approach to the problem of road and landing spacing. In addition, it is felt that it can be used to give a deeper understanding of the various factors affecting log removal costs.

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ABSTRACT

The objective of this thesis is the formulation of a technique for the determination of the minimum cost layout of logging work (skid) roads. A study of the factors affecting layout costs showed that the most important factor in layout is spacing. The spacing factor was also found to be most important in the layout for landings.

A total cost equation is set up which contains all the factors found to affect cost. The relationships among these factors are derived to permit their combination. The form of the total cost equation indicates that, by using the methods of calculus, an optimal spacing can be determined.

The calculus approach to optimization proved a successful technique for determining the optimal layout and therefore the minimum cost of log removal. The results, however, are dependent on the accuracy of the input data and the exactness of simplifing assumptions made in the derivations. Any application of this technique would require knowledge of these factors.

The conclusion is that this technique of determining optimal layout is a feasible approach to the problem of road and landing spacing. In addition, it is felt that it can be used to give a deeper understanding of the various factors affecting log removal costs.

CHAPTER I

INTRODUCTION

HISTORICAL BACKGROUND OF THE PROBLEM

The forest industry has always been an important segment of our national economy. A study[8/] by the U. S. Forest Service shows that nearly five percent of our national income is obtained from wood related industries. The continuous use of this limited resource requires that our forest reserves be used in a prudent and economical manner.

The managers of our forests have maintained a high and steady level of production by using scientific forestry methods. This type of management dictates the amount of wood which can be removed annually. The logging operators, who actually remove the wood, are therefore limited in the amount they can remove. Their problem is to move this amount of wood from the forest to the mill at minimum cost.

The process of moving wood from the forest to the mill can be broken down into several steps. The first is the conversion of standing trees into logs. This basically involves falling the tree and cutting it into measured log lengths. The second step is the moving of the logs from the forest to the road where they can be loaded for movement to the mill. This step has two major parts; the construction of a system of work (skid) roads and landings to receive the logs and the actual skidding of the logs to the road system. The final step in getting the wood to the mill is the loading of the logs on the truck or other means of transportation and then hauling them to the mill where they are unloaded.

For most practical purposes, the degree of independence amoung the above steps makes it possible to minimize the total cost of wood removal by minimizing the cost of each step. Work has been done on each of the steps with the hope of finding the most economical way to perform that function. There has not, however, been much innovation in either the methods or machinery used in performing the steps. Probably the greatest amount of study has been concentrated on skidding logs to the road. This concentration of effort is due primarily to the fact that skidding costs vary widely because of variations in terrain and stand characteristics. The cost of falling depends primarily on the number of trees, the cost of loading depends basically on the number of logs, and the cost of hauling depends mainly on the distances hauled. Due to these stable factors, these costs are not as variable as the cost of skidding.

Research on skidding costs has been done by different groups, but this author found that the most extensive work has been done by the U. S. Forest Service, Intermountain Forest and Range Experiment Station at Bozeman, Montana, in cooperation with the Industrial and Management Engineering Department of Montana State University. This work, consisting of several master's theses and supplementary research work, has progressed to the stage where D. B. Brown[1/] has developed reliable techniques for determining the effect of terrain and stand variables on the cost of skidding. At this point in the research there is a need for a method of determining how these terrain and stand variables affect the cost of the road system used in skidding. With knowledge of how skidding costs and road costs are affected by the terrain and stand variables, it will be possible to determine which skidding method and corresponding road network would provide removal of the logs at a minimum cost. This component of cost, for one of the three steps involved in moving the wood from where it stands in the forest to the mill, is the primary concern of this paper.

The research presented here was undertaken for the purpose of formulating a model which would relate terrain and stand variables to the total removal cost. By applying optimization techniques to this model, the road layout required for minimum removal cost could then be found.

STATEMENT OF THE PROBLEM

To achieve the minimum cost of moving logs from stump to road, one must determine the best combination of skidding method and road layout which results in the lowest cost. The total cost involved can be broken into the cost of skidding and the cost of the road system. The cost of skidding can generally be reduced by shortening the distance the logs must be moved. This would imply that the roads should be very close together in order for a minimum cost to be achieved. The road cost, however, increases as the length of road increases. This implies that the roads should be built farther apart, which would reduce the length required and therefore the cost. It is easy to see that these are two opposing costs and cannot therefore be minimized at the same time.

Since the two costs oppose each other, the nature of their relationship to some common variable must be found if the total cost is to be minimized. Once these relationships are determined, a mathematical optimization technique can possibly be used to find the combination of the two costs which produces a minimum total cost. The problem is then to determine the total cost equation as a function of skidding and road costs and to optimize it with respect to the common variable. This would then allow one to determine the best combination of skidding method and road layout for a given logging area.

SUMMARY OF PAST WORK

Past research on this subject has been scattered and mostly unrelated to the actual problem set forth here. A group of Japanese researchers in the fields of logging, forest engineering, and forest management have published several studies on forest road systems. A number of these studies describe work performed by a group headed by Dr. Seihei Kato[3/ 4/]. This group was concerned with the density of roads within an entire forest area. The roads they studied were permanent access or primary roads, which makes them different from skidding roads, since the latter are built in a logging area for temporary use in the removal of logs from the forest. In addition, Kato's macro approach dictated that he consider only certain classes of forests and the general type of equipment best suited for each class. This approach does not lend itself to the problem of determining the combination of skidding method and road layout that yields the minimum cost for a single logging area.

A Canadian forest management researcher, L. J. Lussier, has developed several simplied models[5/ 6/] for dealing with the problem of finding the road and landing spacing which give the minimum log removal costs. His method of optimization is similar to the method used by the Japanese in their macro outlook. As it turns out, the same method is used by this author in this work, which could be termed a micro look at log removal costs. The biggest drawback with Lussier's work is that it does not consider enough of the variables affecting cost. His work is more of a general example showing how to minimize a total cost equation when one already knows the variables and their relationships.

The work of D. B. Brown 1/ was not directly related to the study of optimal road layout. It concerned the determination of the effect of various variables on the cost of skidding. This, however, has set the stage for the development of a total cost equation which can be optimized to obtain the minimum total removal cost and the optimal road layout.

CHAPTER II

DEVELOPMENT OF A TOTAL COST EQUATION

INTRODUCTION

The development of a total cost equation requires the identification of all the costs involved and the variables that affect these costs. After the various costs and variables are determined, they must be combined in such a way that the resulting equation represents the total cost of the phenomenon under study. Once the equation is established, it can then be optimized with respect to the variable(s) of interest. In this study the desired result is to obtain the minimum total cost of log removal as a function of controllable system variables.

IDENTIFICATION OF COSTS AND COST FACTORS

Each of the phases of log removal consists of several costs. To build the system of roads and landings one must

1. Move in construction equipment
2. Plan and lay out the road and landing system
3. Construct roads
4. Construct switchbacks
5. Construct landings.

Each of these activities incurs a cost, and while they may not all be required on a particular logging site, in general all five of these functions must be accomplished. The costs of the last three activities are similar since roads, switchbacks, and landings are normally constructed with the same machinery. But, as will be shown later, it is better to treat these three costs separately, in order to more accurately describe the system.

For the process of skidding the logs to the road or landing, the following functions are required:

1. Move in skidding equipment
2. Set up equipment for each section
3. Skid logs.

The set-up operation is different from the move-in operation, in that it may have to be repeated periodically while skidding the total area. The set-up operation is required for high-lead and jammer skidding, two of the most popular methods of line skidding.

All costs associated with the various activies in road building and skidding are functions of several variables. Each cost and the associated variables are listed below. Values shown in parentheses are used throughout this paper to refer to the corresponding costs.

I. Cost to move in construction

equipment (C_1) = function of

1. distance moved
2. type of equipment moved
3. moving method used.

II. Cost to plan and layout roads (C_2) = function of

1. planning and layout method
2. cost of men and materials
3. productivity of the men
4. length of road required
   = function of
   a. road spacing
   b. total area.

III. Cost of road construction (C_3) = function of

1. cost of equipment (owning and operating, including men)
2. production rate of equipment
   = function of
   a. slope of sidehill
   b. percent rock in excavation
3. amount of road required
   = function of
   a. road spacing
   b. road width

IV. Cost of switchback construction (C_4) = function of

1. cost of equipment (owning and operating, including men)
2. production rate of equipment
   = function of

a. slope of sidehill

b. percent rock in excavation

3. swichback size = function of

a. radius of switchback

b. road width

c. backslope of cut

4. number of switchbacks

= function of

a. road spacing

b. distance between switchbacks

V. Cost of landing construction (C_5) = function of

1. cost of equipment (owning and operating, including men)

2. production rate of equipment

= function of

a. slope of sidehill

b. percent rock in excavation

3. landing size = function of

a. timber volume / unit area

b. landing spacing

c. road spacing

4. number of landings

= function of

a. landing size

b. volume of timber per unit area.

VI. Cost to move in skidding equipment (C_6) = function of

1. distance moved
2. type of equipment moved
3. moving method used.

VII. Cost to set up skidding equipment (C_7) = function of

1. skidding method
2. set-up time
3. number of set-ups = function of
   a. road spacing
   b. distance between set-ups.

VIII. Cost of skidding (C_8) = function of

1. cost of skidding equipment (owning and operating)
2. volume of timber / unit area
3. productivity of equipment = function of
   a. slope of sidehill
   b. number of logs per cycle
   c. size of the logs.

d. distance hauled to road.

The variables listed above are summarized in Table I on page 13. This table shows the functional relationship between each variable and the various costs. It assigns to each variable a symbol which will be used to identify it throughout the remainder of this paper. Also, the units used for each variable are listed.

DEVELOPMENT OF A TOTAL COST EQUATION

The total cost of moving the logs from the forest to the road is equal to the summation of the component costs (I to VIII) listed in the last section. To make the costs comparable and the summation possible, all costs are converted to the common units of dollars per one thousand board feet of wood removed. The symbol, $/MBF, will be used to denote these units.

The following discussion sets forth the logic used in setting up the equations for component costs. All equations are represented by symbols beginning with capital letters. Other factors are represented by lower-case letters and are defined as they are introduced.

In the development of the following cost equations, the measure of timber volume per unit area is given the units of thousand board feet per horizontal acre of land or MBF/ acre where acre is defined to be a measure of horizontal

Table I: Relationship of System Variables to Costs

Symbol	Variable Description	Units	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A	total logging area	acres	x	x				x		
B	backslope of road cut	decimal %			x	x	x			
Dc	construction method cost	$/hr			x	x	x			
Dm	layout method cost	$/hr		x						
Ds	skidding method cost	$/hr							x	x
F	productivity(construction)	cu yd/hr			x	x	x			
Fm	productivity(layout)	ft / hr		x						
Hl	excavation / landing	yd/landing					x			
Hr	excavation / ft of road	yd/ft-rd			x					
Hs	excavation / switchback	yd/sw bk				x				
Le	landing length	feet					x			
Lv	#logs / volume of timber	logs/MBF								x
Mx	maximum road grade	decimal %			x					x
Nc	move-in cost(construction)	$/move	x							
Ns	move-in cost (skidding)	$/move						x		
Pc	productivity coef (const)	none			x	x	x			
Pm	productivity coef (Layout)	none		x						
Ps	productivity coef (skid)	none								x
Ra	int switchback radius	feet				x				
Ro	percent rock in excavation	decimal %			x	x	x			
S	slope of sidehill	decimal %			x	x	x			x
Sp	time / set-up (skidding)	hr/set-up							x	
V	timber volume/ horiz area	MBF/acre	x	x	x	x	x	x	x	x
Vc	volume/skidding cycle	MBF/cycle								x
W	road width	feet			x	x				
Wl	landing width	feet					x			
X	road spacing	feet		x	x	x	x		x	x
Y	landing spacing	feet					x			x
Zb	level road / switchback	feet				x				
Zs	distance between set-ups	feet							x	

area. This method of density measurement is used because in practice the total volume of timber for an area is divided by the horizontal area covered by the timber. Horizontal area is used because it is easily obtained from maps. Actual area of the rolling terrain would be very difficult to measure. This density is higher than would be the density measured with respect to the actural surface area covered by the trees.

The timber density over horizontal area is used to establish the unit of \$/MBF for the component costs. The areas used in the development of these cost equations must therefore be horizontal. Horizontal areas are therefore used to develop the cost equations. In this paper all measurements of road spacing and skidding distance are horizontal distances.

The first cost involved is for the move in of construction equipment. This cost, in terms of \$/MBF, would be equal to the total move-in cost divided by the product of the total logging area in acres and the volume of timber per acre. It should be noted that the total move-in cost is independent of variables at the logging site and is therefore a constant for a given site. The expression for cost to more in constuction equipment is therefore

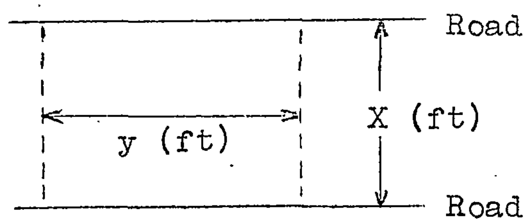
$C_1 = Nc/AV$ (\$/MBF) where

Nc = total cost to move in construction equipment ($)

A = total area to be logged (horizontal acres)

V = volume of timber per horizontal acre (MBF/acre)

The cost to plan and lay out a road system depends on the cost and productivity of the method used as well as the length of road. The length of road required to remove one MBF is developed as follows. Given an area y (ft) by X (ft) where y is the length of road along one side of the area, as shown in the sketch,



the amount of road per unit area would be

$$\frac{y}{yX}\ \frac{(\text{ft of road})}{(\text{sq ft})} = \frac{1}{X}\ \frac{(\text{ft of road})}{(\text{sq ft})} .$$

Converted to length of road per acre this would be

$$\frac{1}{X}\ \frac{(\text{ft of road})}{(\text{sq ft})} \times \frac{43560}{1}\ \frac{(\text{sq ft})}{(\text{acre})} = \frac{43560}{X}\ \frac{(\text{ft of road})}{(\text{acre})} .$$

Now the volume of timber removed per foot of road is obtained.

$$\frac{43560}{X}\ \frac{(\text{ft of road})}{(\text{acre})} \times \frac{1}{V}\ \frac{(\text{acre})}{(\text{MBF})} = \frac{43560}{X\ V}\ \frac{(\text{ft of road})}{(\text{MBF})}$$

The expression for the cost to plan and lay out the roads would then be

$$C_2 = \frac{Dm}{PmFm}\,\frac{(\$/hr)}{(ft/hr)} \times \frac{43560}{XV}\,\frac{(ft\ of\ road)}{(MBF)} = \frac{43560Dm}{PmFmVX}\,\frac{(\$)}{(MBF)} \qquad (2)$$

where Dm = cost per hour of layout method (\$/ hr)

Pm = productivity coefficient for layout (no units)

Fm = productivity of layout method (ft/hr).

The cost of building the road, like laying it out, depends on the cost and productivity of the method used and the amount of road required. The value, $\frac{43560}{VX}\,\frac{(ft\ of\ road)}{(MBF)}$, was obtained earlier for the latter. The cost and productivity of a particular construction method present somewhat of a problem, since the productivity of road building equipment depends on a number of factors. The most important factors are the slope of the sidehill, the percentage of rock in the excavation, and the width of the road. These are the factors that have been found by a past study[7/] to cause significant variation in the productivity of road building equipment. However, no one has developed relationships among these factors. Appendix I presents the development of a relationship among the above factors. This development uses graphical methods. Other methods, such as regression analysis, could be used in developing these relationships, but sufficient data for this approach was not available to the author and its collection was not a part of the plan for this work.

At this point we denote equipment productivity by the symbol, F, with units of (cu yd/hr) where F is a function of the slope and percent rock. Also, the variable, Hr (cu yd/ft of road), is introduced and will be a function of the road width and slope. The resulting expression for road cost is then

$$C_3 = \frac{Dc}{PcF} \frac{(\$)}{(\text{cu yd})} x \frac{Hr}{1} \frac{(\text{cu yd})}{(\text{ft of rd})} x \frac{43560}{X\ V} \frac{(\text{ft of road})}{(\text{MBF})} =$$

$$= \frac{Dc\ Hr\ 43560}{Pc\ F\ X\ V} \frac{(\$)}{(\text{MBF})} \qquad (3)$$

where Dc = hourly cost of construction method in dollars

Pc = productivity coefficient of construction equipment in dimensionless units

F = productivity of construction equipment in cu yd per hr .

The cost of constructing switchbacks is found in much the same manner as for roads. The productivity of the construction equipment will again be denoted by F. Hs (cu yd / switchback), which denotes the excavation required for each switchback, will be written as a function of the