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OPTIMISING SPACING AND STANDARDS OF LOGGING ROADS ON UNIFORM TERRAIN

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YEAP, Y. H. & SESSIONS, J. 1988.Optimising spacing and standards of logging roads on uniform terrain. A technique is presented for determining the optimal spacing of local and collector roads on uniform terrain including the choice of collector road standard. An expression for total skidding , truck transport, and road construction costs is formulated. The Hooke and Jeeves Pattern Search algorithm is used to determine the local and collector road spacing and road standard along the collection road that minimises the average cost per unit volume removed.

Key words: Road spacing - road standards - numerical optimization - pattern search.

Introduction

An important problem in planning access to natural forests is to determine the spacing of road to efficiently achieve management objectives. Many authors have extended the basic ideas of Matthews (1942) for determining the spacing of roads to minimise the sum of harvesting plus road construction costs. Suddarth and Herrick (1964), Donnelly (1978), Perkins and Lynn (1979), and Gruelich (1987) have provided methods to more accurately estimate average skidding distance. Peter 1977 improved methodology to simultaneously determine road and landing spacing. Sessions and Li (1987) demonstrated numerical techniques to determine optimal road and landing spacing under with both linear and nonlinear skidding costs. Sessions (1986) demonstrated the effects of income taxes on road spacing decisions. Thompson (1988) considered road spacing decision from the perspective of a logging contractor optimising profit. Bowman and Hessler (1983) and Baldwin *et al.* (1987) considered simultaneous determination of local and collector road spacing. This paper presents a numerical technique for simultaneous determination of the local and collector road spacing including choice of road standard and relaxes the simplifying skidding pattern and road standard assumptions used by Bowman and Hessler (1983) and Baldwin *et al.* (1987). It can be extended to nonlinear skidding costs and multiple periods.

Problem formulation

Assume a stand of timber accessed by a mainline road. The objective is to design a collector and local road system (Figure 1) which will minimise the sum of skidding plus truck transport plus road construction costs. This is a necessary condition for a landowner trying to maximise returns from a forest tract. The variables to be determined are the spur road spacing, SE, the length of spur road, LE, the depth of radial skidding pattern setting, DE, and the standard of the collector road, low or high. Once determined, the collector roads will be spaced (2 LE + 2 DE) length units apart. The depth of the stand, D, is measured perpendicular to the mainline access road.

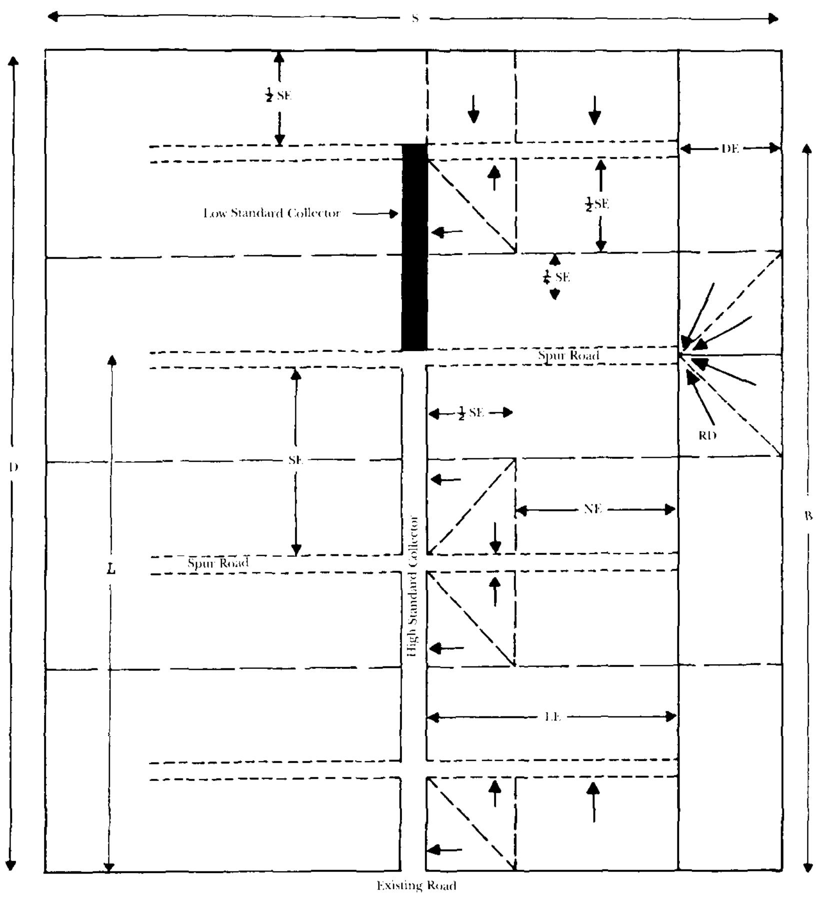

Figure 1. Basic geometry

The following assumptions are made:
1) The timber is evenly distributed over the area;
2) Uniform terrain which is regular enough to be fitted with a repeated pattern of logging settings;
3) Skidding cost is directly proportional to skidding distance; and
4) Continuous landings are permitted along collector and spur road.

The four variables (unknowns) are:

DE = The depth (*m*) (parallel to spurs) of radial skidding pattern setting (Figure 1);

NE = The length (*m*) of the right-angle skidding pattern setting along spur road;

J = The number of spur roads (must be at least one) on one side of the collector for the depth of the unit. This is also equal to the number of collector road segments; and

K = The number of road segments (can be zero and up to J) of low standard collector.

The values of J and K must be integers. The collector roads will be built perpendicular to the existing mainline. Perpendicular to each collector are evenly spaced spur roads on both sides of the collector. The spur road spacing, SE, is inversely proportional to the number of collector road segments. Therefore,

$$SE = D/J.$$

Along the collector, there are triangular skidding pattern settings with continuous landings on both sides. Surrounding each spur road are triangular, right-angle and radial skidding pattern settings. All the triangular skidding pattern settings are right-angle triangle in shape. Therefore, the altitude and the base each are equal to SE/2. The distance from the first spur road to the existing road and the last spur road to the boundary are also equal to SE/2. Therefore, the length of collector, B, is shorter than the depth of the unity by SE/2,

$$B = D - SE/2.$$

The length of high standard collector is

$$L = D - SE/2 - K \times SE.$$

At the end of each spur road, a landing is built for a radial skidding pattern setting. Given the base of the triangular skidding pattern, the length of spur road, LE, can be determined:

$$LE = SE/2 + NE.$$

Parallel to the spur roads, the distance between the collector land the boundary is LE + DE.

The collector spacing, S, is twice this distance,

$$S = 2(LE + DE).$$

The various skidding pattern settings are labelled as follows (Figure 1):

Setting 1 = Right-angle skidding pattern setting along spur road,
Setting 2 = Radial skidding pattern setting at end of spur road,
Setting 3S = Triangular skidding pattern setting along spur road,
Setting 3C = Triangular skidding pattern setting along collector, and
Setting 4 = Right-angle skidding pattern setting at end of collector.

The definitions of skidding, haul, and construction cost coefficients are given in Table 1.

Table 1. Nomenclature used in formulation

Variables			Units
V	=	Volume removed	$m^3 m^{-2}$
RH	=	High standard collector construction cost	$\$/m$
RL	=	Low standard collector construction cost	$\$/m$
RS	=	Spur road construction cost	$\$/m$
SC	=	Skid cost to collector	$\$.m^3/m$
SS	=	Skid cost to spur roads	$\$/m^3/m$
HH	=	Haul cost on high standard collector	$\$/m^3/m$
HL	=	Haul cost on low standard collector	$\$/m^3/m$
HS	=	Haul cost on spur roads	$\$/m^3/m$

We calculate the road construction, skidding costs, and truck haul in six parts where

TOTAL COST = S1 + S2 + S3 + S4 + S5 + S6 [1]

and

S1 = Total spur road construction cost, $
S2 = Total skidding cost to spur roads, $
S3 = Total truck haul costs on spur roads, $
S4 = Total collector road construction cost, $
S5 = Total skidding cost to the collector, $
S6 = Total truck haul cost on the collector, $.

Total spur road construction cost

The road construction cost for a spur road is equal to RS x LE. For the whole unit, the total spur road construction cost would be

$$S1 = 2 \times J \times RS \times LE. \quad [2]$$

Total skid cost to spur roads

The skid cost for volume(s) from all settings on one side of the collector can be calculated by summing the skid costs for four setting patterns:

i) Setting Pattern 1 (both sides along spur roads)

$$= J \times SS \times \frac{SE}{4} \times \left(LE - \frac{SE}{2}\right) \times SE \times V, \qquad [3]$$

ii) Setting Pattern 2

$$= J \times SS \times RD \times DE \times SE \times V. \qquad [4]$$

Peters' (1978) average skidding distance formula is applied in these settings. In which,

$$RD = \frac{1}{6}\{(SE^2 + LK^2)^{\frac{1}{2}} + (LK^2/2SE)\ \ln\ [\left(SE + (SE^2 + LK^2)^{\frac{1}{2}}\right) / LK] \qquad [5]$$

$$+ (SE^2/2LK) \ln[\left(LK + (SE^2 + LK^2)^{\frac{1}{2}}\right) / SE]\}$$

where LK = 2DE

iii) Setting Pattern 3S (both sides along spur roads)

$$= (2J - 1) \times SS \times \frac{1}{3} \times \frac{SE}{2} \times \frac{1}{2}\left(\frac{SE}{2}\right)^2 \times V \qquad [6]$$

$$= \frac{(2J - 1) \times SS \times SE^3 \times V}{48} \qquad [7]$$

iv) Setting Pattern 4

$$= SS \times \frac{SE}{4} \times \left(\frac{SE}{2}\right)^2 \times V \qquad [8]$$

$$= \frac{SS \times SE^3 \times V}{16} \qquad [9]$$

Summing up all four skidding pattern costs and simplifying, the total skid cost to spur roads becomes

$$S2 = 2xSSxSExV\left\{J[\frac{SE}{4} \times \left(LE - \frac{SE}{2}\right) + RDxDE] + [\frac{(2J-1)}{48} + \frac{1}{16}] \times SE^2\right\} \quad [10]$$

Total truck haul cost on spur roads

The haul cost for volume(s) from all settings on one side of the collector can be calcilated by summing the truck haul cost for the individual setting patterns:

i) Setting Pattern 1 (both sides along spur roads)

$$= J \times HS \times [\frac{SE}{2} + \left(\frac{LE - \frac{SE}{2}}{2}\right)] \times \left(LE - \frac{SE}{2}\right) \times SE \times V \quad [11]$$

$$= \frac{1}{2} \times J \times HS \times SE \times [LE^2 - \frac{SE^2}{4}] \times V \quad [12]$$

ii) Setting Pattern 2

$$= J \times HS \times LE \times DE\ SE \times V \quad [13]$$

iii) Setting Pattern 3S (both sides along spur roads)

$$= (2J - 1) \times HS \times \frac{2}{3} \times \frac{SE}{2} \times \frac{1}{2} \times \left(\frac{SE}{2}\right)^2 \times V \quad [14]$$

$$= \frac{(2J - 1) \times HS \times SE^3 \times V}{24} \quad [15]$$

iv) Setting Pattern 4

$$= \frac{1}{2} \times HS \times \frac{SE}{2} \times \left(\frac{SE}{2}\right)^2 \times V \quad [16]$$

$$= \frac{HS \times SE^3 \times V}{16} \quad [17]$$

Summing all the haul costs and simplifying, the total haul cost on spur roads is

$$S3 = 2xHSxSE\ xV\left\{J[\frac{1}{2}\ LE^2 - \frac{SE^2}{4} + LE \times DE] + [\frac{(2J-1)}{24} + \frac{1}{16}]xSE^2\right\} \quad [18]$$

Total collector construction cost

The collector could be made up of both high and low standard sections, of only high standard or of only low standard sections.

Case 1

High and low standard sections (Figure 1). The collector construction cost is

$$S\,4 = \left(D - \frac{SE}{2} - K \times SE\right) \times RH + K \times SE \times RL \qquad [19]$$

Case 2

The whole collector is a high standard collector. The collector construction cost is

$$S\,4 = \left(D - \frac{SE}{2}\right) \times RH \qquad [20]$$

Case 3

Only low standard collector. The collector construction cost is

$$S\,4 = \left(D - \frac{SE}{2}\right) \times RL \qquad [21]$$

Total skid cost to collector

Timber from Setting Pattern 3C is skidded directly to the collector. Total skid cost to the collector is:

$$S5 = 2 \times (2J - 1) \times SC \times \frac{1}{3} \times \frac{SE}{2} \times \frac{1}{2} \times \left(\frac{SE}{2}\right)^2 \times V \qquad [22]$$

Simplifying,

$$S5 = \frac{(2J - 1) \times SC \times SE^3 \times V}{24} \qquad [23]$$

Haul cost on collector

Since the collector could consist of a combination of low and high standard road, the haul cost must consider the different possible combinations.

Case 1

The whole collector is a high standard collector. The haul cost on the collector is

$$S6 = HH \times LL \times S \times D \times V \qquad [24]$$

where

LL = Average haul distance on high standard collector only.

$$LL = \frac{L \times VS + \left\{ \frac{1}{2}\left(\frac{L}{SE} - \frac{1}{2}\right)^2 \times VL + \left[\left(\frac{L}{SE}\right)^2 - \frac{1}{12} \right] \times VC \right\} \times SE}{VS + \left(\frac{L}{SE} - \frac{1}{2}\right) \times VL + \frac{2L}{SE} \times VC} \qquad [25]$$

where

$$VS = (LE + DE) \times SE \times V - \frac{1}{2}\left(\frac{SE}{2}\right)^2 \times V \qquad [26]$$

VS = Volumes enter the last spur road except volume from Setting Pattern 3C. See Figure 1.

$$VL = (LE + DE) \times SE \times V - \left(\frac{SE}{2}\right)^2 \times V \ , \qquad [27]$$

VL = Volumes enter each spur road except volumes from Setting Pattern 3C.

$$VC = \frac{1}{2}\left(\frac{SE}{2}\right)^2 \times V \ ,$$

Case 2

The entire collector is a low standard collector. The haul cost on it is

$$S6 = HL \times BB \times S \times D \times V \qquad [29]$$

where

BB = Average truck haul distance on low standard collector only,

$$BB = \frac{(D - \frac{SE}{2}) \times VS + \left\{ \frac{1}{2}(\frac{B}{SE} - \frac{1}{2})^2 \times VL + [(\frac{B}{SE})^2 - \frac{1}{12}] \times VC \right\} \times SE}{VS + (\frac{B}{SE} - \frac{1}{2}) \times VL + \frac{2B}{SE} \times VC} \quad [30]$$

Case 3

The collector is made up of both high and low standard collector. The total haul cost is:

$$S6 = [S \times SE \times K + \left(\frac{SE}{2}\right)^2] \times [(HL \times BL) + (HH \times L) \times V \quad [31]$$

$$+ \left\{ S \times D - [S \times SE \times K + \left(\frac{SE}{2}\right)^2] \right\} \times HH \times LB \times V$$

where

BL = Average haul distance on low standard collector,

$$BL = \frac{K\{VS + (\frac{K-1}{2}) \times VL + K \times VC\} \times SE}{VS + (K-1) \times VL + 2K \times VC}, \quad [32]$$

and

LB = Average haul distance on high standard collector

$$LB = \frac{\left\{ \frac{\left(\frac{L}{SE} + \frac{1}{2}\right)^2}{2} \times VL + [(\frac{L}{SE})^2 - \frac{1}{12}] \times VC \right\} \times SE}{(\frac{L}{SE} + \frac{1}{2}) \times VL + \frac{2L}{SE} \times VC} \quad [33]$$

Haul cost on low standard collector for volumes to low standard collector

$$= [S \times SE \times K + \left(\frac{SE}{2}\right)^2] \times HL \times BL \times V \quad [34]$$

Haul cost on high standard collector for volumes to low standard collector

$$= [\ S \times SE \times K + \left(\frac{SE}{2}\right)^2] \times HH \times L \times V \qquad [\ 35\ ]$$

Haul cost on high standard collector for volumes to high standard collector

$$= [\ S \times D - \left\{ S \times SE \times K + \left(\frac{SE}{2}\right)^2 \right\}] \times HH \times LB \times V \qquad [\ 36\ ]$$

Average cost

To find the average cost per unit area, AC, of road construction plus skidding plus truck transport we divide the total cost by the total area

where,

$$\text{TOTAL COST} = S1 + S2 + S3 + S4 + S5 + S6,$$

$$\text{TOTAL AREA} = S \times D\,,$$

And average cost per unit area, AC, is

$$AC = \frac{\text{TOTAL AREA}}{\text{TOTAL COST}} \qquad [37\ ]$$

Solution procedure

We seek to identify values of the spatial variables which minimize the average cost, AC, of road construction, skidding, and truck transport. This is a complex non-linear multivariable equation. All the values for the variables are assumed known except J, K, NE snd DE. For the formulation derived, the value for J must be at least one. K can be any value from zero and up to J. The variables J and K must be integers. The lower bound value for both NE and DE is zero. When NE and DE equal to zero, only triangualr skidding pattern settings can exist.

The Hooke and Jeeves pattern search method (Shoup & Mistree 1987) can be used to find the values which minimize AC. The advantage of the Hooke and Jeeves pattern search for this problem is that it avoids the need to take the derivative of the average cost equation; a requirement of many other gradient search techniques. Essentially, the pattern search algorithm evaluates the objective function for an incremental move (step)in all diretions from the current point and then moves in the direction of the most promising direction by an amount determined by some multiple of the current step size. If the move is unsuccessful, the step size is reduced and the process repeated until the step size is reduced below the minimum allowed step size and the process is terminated. Constraints can be handled through definition of a penalty surface which returns a penalty value for the objective function when the search procedure examines a point which is not feasible. The pattern search requires a choice of step size factors including the initial step size, final step size, an acceleration factor for projecting the move from the old point in the direction of the most promising direction and a feasible solution.

Because the variables J and K must be integers, certain rules need to be followed in the choice of the initial step size, final exploration step size,and the acceleration factor. One set of rules that can be used to provide integer values for J and K are (1) to start the initial step size as an even number, (2) to have a final exploration step size as 1.0, and (3) to choose an acceleration factor that is an integer.The rationale for these rules is that the pattern search algorithm divide the step size by two in stepping down to the final exploration step size. The algorithm terminates when all variables have been reduced to a step sizeless than the final exploration step size. This implies that if the final step size for all variables will be one, that the starting point must be a multiple of two and the choice of acceleration factor must keep the step size as an even number until the final exploration step size of 1.0 is reached. For the road spacing problem investigated here, an acceleration factor of 1.0 or 2.0 seems reasonable.

An example

The data from Bowman and Hessler (1983) are used to demonstrate the method and to compare the results to a more restrictive formulation. Bowman and Hessler assumed that all skidding must be in right angle to the spur roads, that the collector must be high standard, that LE must be equal to (S-SE)/2 and that no skidding was permitted to the collector road. The costs used by Bowman and Hessler converted into metric units are in Table 2.

Table 2. Inputs for example problem (Bowman & Hessler 1983)

V = 6.99778/1000	Volume removed, m^3/m^2
D = 2438.4	Depth of the units (Figure 1), m
RH = 11000/1609.3	High standard collector cost, $\$/m$
RL = 5700/1609.3	Low standard cvollector cost, $\$/m$
RS = 5700/1609.3	Spur road cost, $\$/m$
SC = 20.158/1000	Skid cost to collector,$\$/m^3/m$
SS = 20.158/1000	Skid cost to spur roads,$\$/m^3/m$
HH = $4.39/10^4$	Haul cost on high standard collector, $\$/m^3/m$
HL = $1.13/10^3$	Haul cost on low standard collector, $\$/m^3/m$
HS = $1.13/10^3$	Haul cost on spur roads, $\$/m^3/m$

In our formulation, we permitted the opton of skidding to the collector road, of constructing the collector to some combination of low standard collector (spur road) and high standard collector road.

Bowman and Hessler's (1983) results for single entry with only right-angle skidding pattern settings along spur roads are shown in Table 3.

Table 3. Results from Bowman and Hessler (1983)

Volume (m^3 ha^{-1})	35	70	105
Collector spacing (*m*)	2612	1847	1509
Spur road spacing (*m*)	445	314	257

We simulate Bowman and Hessler's results (Table 4) by setting LE equal to NE and DE equal to zero and limiting the collector standard to high standard collector only.

Table 4. Road spacing and average costs for single entry with linear skidding costs and right-angle skidding pattern settings

Volume (m^3 ha^{-1})	35	70	105
Collector spacing (*m*)	2494	1800	1474
Spur road spacing (*m*)	488	305	271
Average cost ($/*ha*)	226.65	332.32	417.72

Table 4 results compare very closely with the values calculated by Bowman and Hessler. Table 5 shows the results for linear skidding costs and a single entry. These values are derived by considering various skidding pattern settings and multiple collector standards.

Table 5. Road spacing, road segments and average costs for single entry with linear skidding costs

Volume (m^3 ha^{-1})	35	70	105
Collector Spacing (*m*)	1444	1213	1007
Spur Road Spacing (*m*)	406	305	271
Collector Segments, J	6	8	9
Low Standard Collector Segments, K	1	0	0
Average Cost ($/*ha*)	211.53	312.53	393.58

Comparing the average costs in Table 4 and 5, the difference of the corresponding values shows the saving from harvesting with various skidding patterns, settings, layout and multiple road standards for the collector. Here, the low standard collector road is permitted to extend along the collector. The road standard for the low standard collector is the same as for spur road. In other words, they have the same construction and haul cost. In Table 5, the J and K values indicate the number of collector segments and the number of low standard collector segments respectively. When K is equal to or greater than one there is a change in collector road standard.

The differencesw in cost for the 35, 70 105 m^3 ha^{-1} volume removals are approximately 7.1, 6.3, and 6.1 % lower than the skidding patterns and road standards permitted by owman and Hessler.

Conclusion

The procedure demonstrated here is applicable for microcomputers. Solution time for the example problems was approximately 6 *s* each for a program written in BASIC Turbo Compiler operating on a 4.7 MHz IBM Personal Computer with a mathematics coprocessor. This method can be extended to multiple periods and nonlinear costs (Yeap1988). Alternatively, using the same expressions for costs, the road spacing problem can be reformulated from the point of a logging contractor trying to maximise profit given a mix of skidding and road construction equipment. A similar procedure is then used to solve for the optimal road spacing.

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