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A New Harvest Operation Cost Model to Evaluate Forest Harvest Layout Alternatives

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Abstract: In this paper we develop a new model for harvest operation costs that can be used to evaluate stands for potential harvest. The model is based on felling, extraction, and access costs and is unique in its consideration of the interaction between harvest area shapes and access roads. We illustrate the model and evaluate the impact of stand size, volume, and road cost when determining harvest layouts. Since the approach lays the foundation for operational and tactical integration, future research will integrate the two levels for both the single and multi-period problem.

Key Words: Harvest scheduling problem, operations research modeling.

INTRODUCTION

In his widely accepted book, Cost *Control in the Logging Industry* (1942), D.M. Mathews introduced and articulated the reasons for proper spacing of roads and landings. In this paper we develop a new operational cost model based on determining the optimal number of landings and their locations. The approach is unique in its consideration of the interaction between harvest area shapes and the landing, skidding, and roading costs. The model specifies the optimal number of landings and their locations given the total size of the tract. The spacings between the landings and roads are solved implicitly so that the optimal number of landings and roads can be placed within the boundaries of the tract. The model also offers the flexibility of alternate road routing while maintaining a plan that minimizes total costs.

Forest planning decisions tend to be hierarchical with long-term strategic decisions setting the limits for shorter-term tactical decisions, which in turn are implemented with actual forest operations. Integrating rhe decision-making across all levels will lead to improved solutions, but it also increases the difficulty of the problem solving process. One of the difficulties of effectively integrating decision-making at the operational and tactical levels is simply due to spatial issues.

Main road projects must be carefully planned due to the increasing demand for multi-resource activities. Spatial constraints prohibit the progressive cut approach, therefore, access roads must be built in a very systematic manner to the stands selected for harvest. Also, from a silvicultural perspective, minimal roading impact is desired. Thus, it is extremely important to integrate the roading projects at the operational and the tactical levels to minimize impact. We will show how this can be accomplished in our approach.

There seem to be two areas of concentration in the literature regarding the number and the placement of landings. One area considers the uniform density case where the skidding regions have regular shapes. A number of contributions (Peters 1978, Suddarth and Herrick 1964, Sessions and Guangda 1987) have been made in this area since Mathews (1942). These approaches have concentrated on finding the optimal road and landing spacings for unbounded tracts.

The other area of concentration has been for irregular-shaped. nonuniform-density tracts. Peters and Burke

(1972) and others (Greulich 1991, Donnelly 1978) have located landings over entire, irregular-shaped tracts. Models for evaluating the optimal amount of roading for irregular-shaped tracts are difficult to develop so the emphasis has been landing locations and average skidding distances. We will consider the uniform density case, **but** for a bounded region or tract.

MOTIVATING EXAMPLE

The primary motivation of this paper is to develop an operational cost model that can be used to evaluate the harvesting costs of bounded tracts of timber with uniform densities and regular shaped skidding regions. Other approaches to this problem have concentrated on finding the most economical spacings of roads and landings, given the volume of timber over unbounded regions. Total costs are found using these spacings which may or may not be the final spacings, given the dimensions of the tract. Figure 1 illustrates the result of such a model.

Our approach considers the size of the bounded tract initially, and then determines the most economical landings, roading. and skidding. We implicitly calculate the spacings by determining the number and shapes of the grids in the tract, where a grid is defined as a rectangular area that is served by a single landing located in one comer of the grid.

In Figure 2 there are 8 grids, 2 landings and 0.75 $\sqrt{A}$ of roads where A defines the area of the entire tract. Since there are 4 rows and 2 columns of grids, the shape of the grids is rectangular where one side is twice as long as the adjacent side.

We will develop a model to optimally determine the number of landings and their placement considering landing, skidding, and road costs.

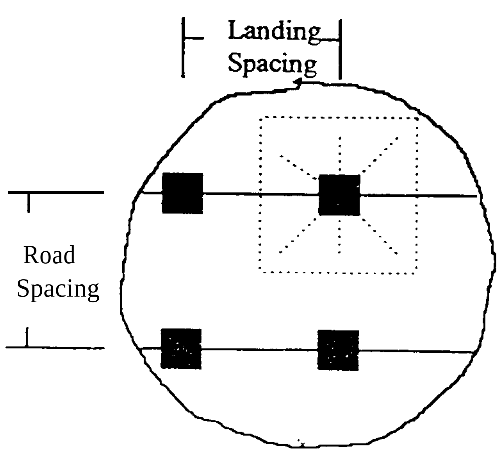


Figure 1: Optimal Spacing of Roads and Landings

EXTRACTION COST MODEL

The following parameten will be used. Note that some parameters could **vary** by species of trees on a particular tract. Also. some tracts will have more than one product class; therefore, the different volumes per tree should be accounted for in the model.

A = total area of tract considered
a^f = volume per tree in a tract
a^d = density of trees per unit area
c = volume capacity of the skidder
f = total number of skidder loads
= $(A a^f a^d)/c$
s = variable skidding costs
x = fixed skidding cost per turn
r = road cost per unit distance
l = fixed cost per landing

Our cost model is based on the sum of felling (F) and extraction (E) costs; that is, the total cost, C, is found as follows:

$$C = F + E.$$

We assume that felling costs are a function of the area (A) and the density of timber on the harvest area. but. not its shape (P), since felling costs are related to the number and size of the trees harvested.

We assume that the extraction costs are a function of the area, density, and shape of the harvest area since extraction costs are based on the number of landings. the distance from the trees to the landings, and the technology used to extract the trees; that is,

$$E = g(A, a^d, P).$$

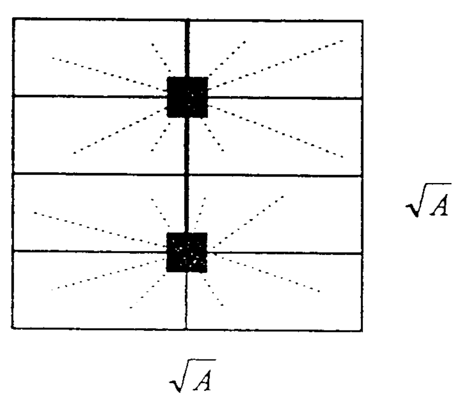


Figure 2: Bounded Tract with Equal-Sized Grids

We define total extraction costs to equal the sum of the landings costs, L, and the skidding costs, S, and the road costs, R; i.e.,

$$E = L + S + R.$$

As we noted earlier, E is a function of A, a^d, and P. In particular, P is a function of the following two decision variables: g (the number of grids) and n (the number of landings), where a grid defines an area that is harvested from one landing. Note that a tract is typically partitioned into multiple grids where up to four grids can be harvested from one landing.

Assumptions

In the following model we assume:
1. grids are rectangular;
2. skid distances are proportional to rectilinear distances (or can be adjusted with some proportionality constant, as suggested by Greulich (199 1)):
3. there will only be one means-of-egress to a stand;
4. all roads are orthogonal to the x and y axes:
5. the capacity of the skidder is fixed *a priori*.

Approximate Extraction Cost Model

After splitting the area into g grids, we then need to choose our n landing locations. Thus, we construct a model to determine both the optimal g and n for a given area. Note that since n is a function of g, we will use n(g) to denote this.

Mathews (1942) explained in detail the economic differences of placing a landing on the boundary of a tract versus building a road and placing the landing on the interior of a tract. So it is reasonable to say if g is less than or equal to 2 then there would be one landing located on the boundary of the tract that served each of the two grids. Alternatively, as long as g > 2, it seems reasonable to approximate n(g) as:

$$L = n(g) = g/4. \tag{1}$$

This indicates that the tract will be split into multiples of 4 with one landing serving 4 grids.

If we divide the tract area, A, into equal-area grids, we can determine the number of skidder loads per grid. Since the grids are not always square, we must modify the equation to allow for rectangular shaped grids. Thus,

$$S = sf\left(\frac{1}{a} + \frac{1}{b}\right) + fx \tag{2}$$

where a and b represent the number of grid rows and columns. Although a and b could be interchanged to represent the rows or the columns in this equation without changing the resulting value of S, we will show later that $a \geq b$ must always hold.

Generally, the amount of roading required is that which provides access to each of the landing locations. We can construct a table that shows the amount of roading required based on the size of the tract and the number of grids. For every harvest pattern we can calculate a constant value that can simply be multiplied by the length of one side of the square area to get the total amount of roading required. Table 1 shows the results of a number of different harvest patterns.

We approximate the total cost of roading, R. with the following equation:

$$R = r\left(\frac{\sqrt{A}}{a}\left((a-2)\frac{b}{2}+1\right) + \frac{\sqrt{A}}{b}(b-2)\right) \tag{3}$$

where a and b represent the number of columns and rows of grids. Note that (3) requires that $a \geq b$ and $b \geq 2$. As we wil! show later, the harvest pattern could rotate, thus. a could represent the rows or the columns and likewise for b. So, a does not necessarily represent the columns or the rows but the greater of the two, unless the columns and rows are equal. It follows then that $g = ab$.

The cost of roading is approximated well by (3). In fact. (3) appears to provide the exact amount of roading costs as long as b is even and ≥ 2. Notice that in Table 1 all of the possible b's are even or one. This is due to there not being a feasible solution where b is both odd and greater than one when there are g 14 landings. Note from the Roading column in Table 1 that for

Table 1. Grid, road, and landing combinations.

Pattern	*Grids*	*Col.*	*Rows*	*Landings*	*Roading*
1	2	1	2	1	0
2	4	2	2	1	0.500
3	8	2	4	2	0.750
4	12	2	6	3	0.830
5	16	2	8	4	0.875
6	20	2	10	5	0.900
7	24	2	12	6	0.916
8	16	4	4	4	1.750
9	24	4	6	6	2.000
10	32	3	8	8	2.135
11	40	4	10	10	2.200

each of the harvest patterns in the table we have assumed that a tract has one means-ofcgress, but its location is not fixed. In reality, tracts that are located adjacent to existing roads may have multiple means-of-egress. However, in a large forest there will be very few tracts adjacent to existing roads. Of course, (3) could be modified to approximate the amount of roading with more than one means-of-egress, but for purposes of consistency here, we make this generalization.

We have approximated *L*, *S*, and *R*, and now we are ready to write our total cost model. Detailed derivations of these three models can be seen in Clark et *al.* (1997). We can approximate *E as* follows:

$$E = L + S + R \tag{4}$$

We know the following about the components of total extraction cost function, *E*. *The* landings cost, *L*, linearly increases with respect to *n*. The total skid cost, S, is convex in n. And although we cannot show that the roading cost function, *R*, is convex in *n* (since *R* is not convex in *a* orb), *R* is increasing in a and *b*, and is approximately linear in both *a* and *b*. Therefore. we will use convex analysis to determine the values of a^* and b^* (which imply g^*). The continuous values of a^*, b^*, and g^* are utilized to find optimal integer values forg and *n*.

Minimizing the total extraction cost, *E*, is found by taking the first derivative of our total extraction cost function, (4), with respect to a and *b*, setting them equal to zero, and solving the two equations simultaneously for a^* and b^*, and ultimately g.

$$\frac{\partial E}{\partial a} = \frac{lb}{4} - (sf\sqrt{A} - rb\sqrt{A} + r\sqrt{A})a^{-2} = 0 \tag{5}$$

$$\frac{\partial E}{\partial b} = \frac{la}{4} - \frac{sf\sqrt{A}}{b^2} + r\sqrt{A}\left(\frac{1}{2} - \frac{1}{a} + \frac{2}{b^2}\right) = 0 \tag{6}$$

Note that since *g* must be integer, adjustments to a*, b^*, and g^* must be made.

Let's look at some examples. For our base case, let's assume the following: *A* = 647,476 sq m (160 acres); *f* = 3322 loads (a^d x a^f = 256.5 cu m/ha and c = 5.0 cu m/skidder load); *s* = \$.0134/m (\$0.0041/ft.); *x* = \$2 per turn; *r* = \$6.56/m (\$2 per ft) and *l* = \$300. Solving (5) and (6) simultaneously for a and b gives a^*=10.83 and b^*=2.92. Therefore, g^*=31.62.

Before we consider how to adjust the continuous value of g^*, let us consider the following parametric change\ to this base case:

Change	g^*
double landing cost; I = \$600	22.26
cut *s* in half; *s*=\$0.0067	17.21
cut area in half; *A*=323,738	26.52
cut area and turns in half; *f* =1661	14.76
cut area by a factor of 4; *A* = 161,869	22.26
double *s*; *s* = \$0.0268	56.10

Thus, the model behaves as expected.

To find the final integer value of *g*, one would need to evaluate (4) with $\lceil g^* \rceil$ and $\lfloor g^* \rfloor$ from Table 1, and choose the harvest pattern that produces the smaller total extraction cost. The harvest operation cost model may be used to quickly determine the most efficient number of landings and grids in an area to be harvested.

Once the number of grids are known we can determine the harvest pattern; i.e., the number of landings and their placement. and the amount of roading. By referring to Table 1. we can see how we've reduced an infinite field of solutions to a finite number of alternatives. These, of course, vary by the number of grids. the grid shapes, the number of landings, and the amount of roading. Since there could be more than one harvest pattern for a specific number of grids, the total extraction cost must be evaluated to determine the least cost alternative.

EXAMPLE PROBLEMS

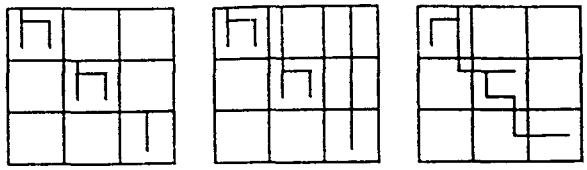
In this section, we will illustrate the operational cost model by solving a number of example problems. We will consider examples where we will employ (4) to model the total extraction costs. The problems have been chosen to show the impact of different parameter values.

First, we solve three problems all with the same cost parameters, but with different volumes. The cost parameters are equivalent to the ones used in the example problem earlier, including a road cost of \$6.56 per meter. We consider three volumes: 139.9, 209.8. and 279.8 m^3/ha (24, 36, and 48 Mbf per acre). In the 139.9 m^3/ha case, we solve (5) and (6) simultaneously for a and *b we* get a^*=8.51, b^*=2.32 and g^*=19.74. By referring to Table 1, we can round g^* to the nearest *g* in the table and select the corresponding harvest pattern. From there we determine *g, a, b, n* and then evaluate (4) to find *E*, the total extraction cost. The results for this case and the other two volumes are shown in Table 2. In the second set of example5 we increased the variable skidding cost by 25% to \$0.0 1675 per meter. The results are shown in Table 3. Note that with the increased skid cost the shapes of the grids change to compensate for the increased cost.

INTEGRATION OF OPERATIONAL AND TACTICAL PLANS

The operational plan, as we've defined it, considers only the cost for harvesting a specific stand. The tactical plan specifies where and when to harvest specific tracts. The two must be integrated at some point in order to develop the overall harvesting plan. Since roading is a major decision variable at both levels, it could be a means by which the two levels are integrated. This integration could lead to multiple stands sharing the same roads. After the most economical landing and road placements are known at the operational level this integration could be enhanced.

Another reason for multiple roading alternatives is to provide a basis for the integration of these operational plans with the tactical plan. For example, consider a forest with nine stands with an access road running along the northern boundary and we select three of those stands for harvest in the first period. Furthermore, assume that the harvest patterns are similar to those in Figure 4(a), then we have the flexibility to manipulate the harvest patterns while maintaining minimum harvesting costs. Also, we might be able to share hauling roads in an effort to minimize the total amount of roading. If we can't share the roading, the result to the tactical plan might resemble Figure 4(b). But with shared roading, the result might resemble Figure 4(c). It is clear that some additional costs must be incurred to upgrade the roads for additional capacity, but this cost might be incurred in any plan.



(a) (b) (c)

Figure 4. Integration of roading

CONCLUSIONS AND FUTURE RESEARCH

In this paper we have developed a model of timber harvest costs that enables us to find the minimum operational costs. The model was developed such that the size of the tract is considered so that the harvest pattern could be found to minimize the cost of the harvesting operations. We showed how these operational harvest patterns can be used as a foundation for the integration of the operational and tactical plans.

Future research will cover two related areas. First. we will look at tracts that are not square. Obviously, with the increasing use of GIS. more and more information may be used to define tract boundaries in an effort to make better harvesting decisions. Topography, soil conditions, existing roads, stream locations. etc., will all have an impact on the tract shape.

The second area of future research is to develop an algorithm for efficiently solving the tactical level problem while considering the integration of the operational plan. The results in Nelson and Brodie (1990) and O'Hara *et* al. (1989) indicate that in order to solve larger problems the use of a heuristic-search algorithm will be required.

Table 2. Results of three example problems

Volume (m³/ha.)	a^*	b^*	g^*	Grids(g)	Columns	Rows	Landings	E(\$)
139.9	8.51	2.32	19.74	20	2	10	5	18,031
209.8	9.52	2.95	27.43	24	2	12	6	23,819
279.8	10.11	3.43	34.67	32	4	8	8	28,343

Table 3. Results of three example problems with increased skid cost

Volume	(m³/ha.) a^*	b^*	g^*	Grids (g)	Columns	Rows	Landings	$E(X)$
139.9	8.86	2.65	23.47	24	2	12	6	20,884
209.8	9.90	3.31	32.81	32	4	8	8	27,354
279 8	10.85	3.82	41.45	40	4	10	10	31,707

PROCEEDINGS

Forest Operations for Sustainable Forests and Healthy Economies

Council On Forest Engineering (COFE)

20th Annual Meeting
July 28 - July 31, 1997
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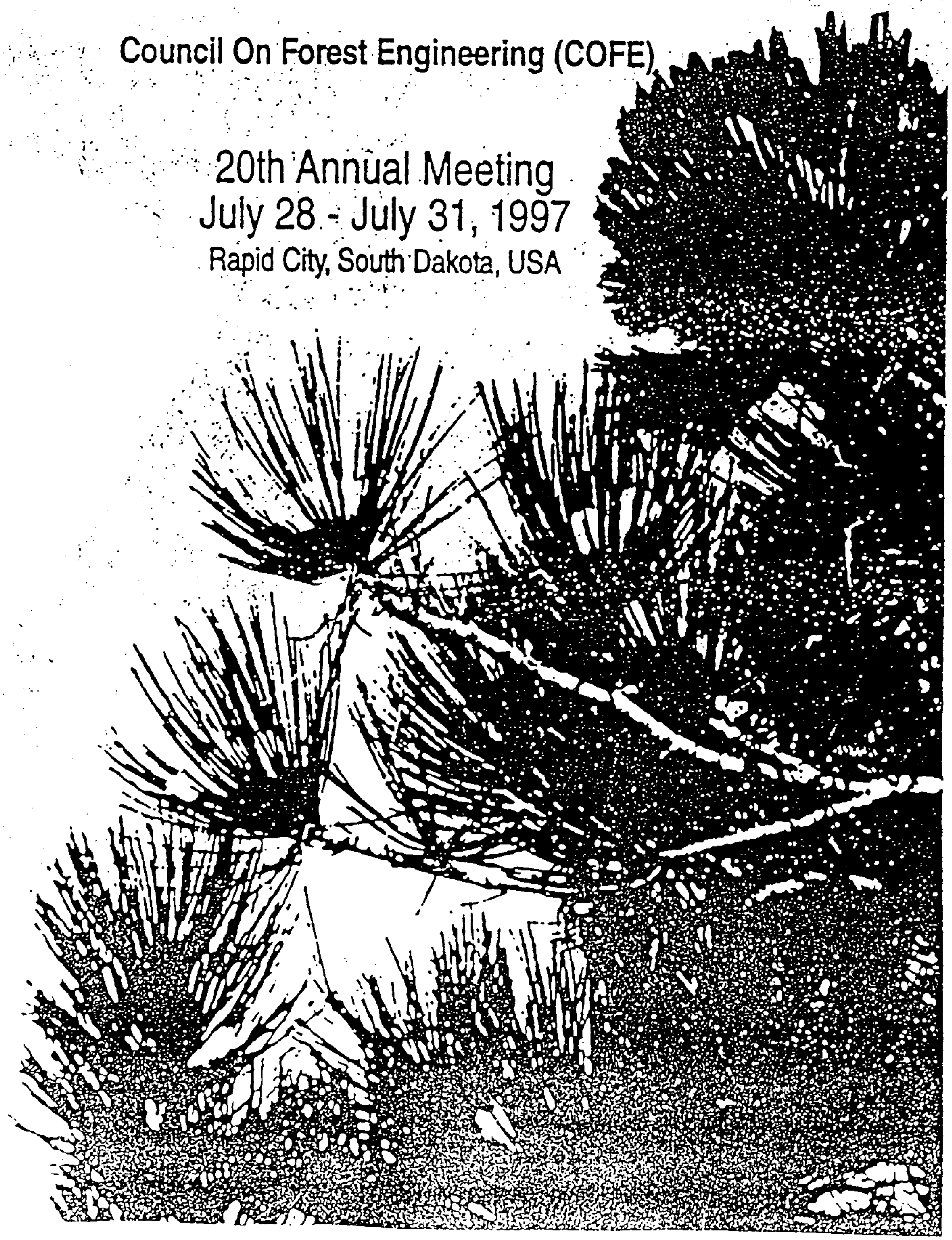

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