Optimization of Road Spacing for Log Length Shovel Logging on Gentle Terrain

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ABSTRACT

Shovel logging has become a popular logging system in the western United States due to its high productivity. Its low ground pressure and single pass, often on a matt of limbs result in little ground disturbance. Despite this increasing popularity, there have been few operational studies of shovel logging. This paper describes the optimal road spacing problem for shovel logging using a serpentine pattern on gentle terrain. A mathematical model for shovel logging is presented for two cases (1) to minimize the sum of shovel yarding costs plus road costs from the landowner's point of view and(2) to maximize profits from the point of view of a logging contractor. For the operating conditions assumed, the optimal shovel yarding distance is four swings when shovel yarding plus roads costs are minimized and three swings when logging contractor profit is maximized. For the example data, the model results demonstrate the flexibility of shovel logging in that there is little difference between total road construction plus skidding cost from the optimal number of swings to as many as six swings. Sensitivity analysis was performed on road cost and volume per ha and support the stability of the solution with the minimum logging cost occurring at four swings with just a small difference for as many as six swings over a range of road construction and volume removals.

Keywords: *Harvest planning, log transportation, harvesting costs.*

INTRODUCTION

As the story goes, shovel logging originated on a log landing in western Washington in the 1970's when a loader operator on a broken-down logging side decided to take the track-mounted hydraulic excavator loader off the landing and forward nearby logs to the landing by sequentially picking logs up with the grapple-equipped heelboom, rotating the boom 180 degrees and laying the logs down again (Figure 1). Although initially dubious to many, production was high, up to five truck loads per machine hour [4]. The method rapidly spread throughout the western US from California to Alaska and later to the US Southeast and Northeast. The popularity of the method is that one operator with one piece of equipment can do both the yarding and loading. Hydraulic loaders used for shovel logging usually are equipped with longer frames, wider tracks, higher clearance undercarriages, and heavier track drives. The wide tracks with low ground pressure and one pass of the shovel, often walking on debris, limits soil compaction. Floch (1988) reported that increases of soil bulk density of less than 8 percent in the shovel trails in a shovel logging study on the Olympic National Forest in western Washington (USA). Although shovel logging is usually done in clearcutting, it has been used in thinning and selective harvesting [3] and [4].

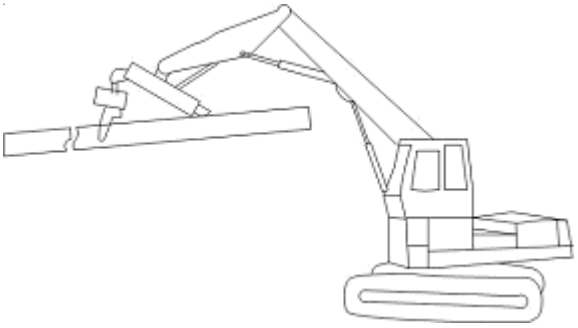

Figure 1. A sketch of a shovel logging machine. Shovel logging machines generally have longer, wider tracks, higher clearance, and heavier track drives than on-road log loaders.

Several production studies have documented shovel logging including those by [10], [4] and [1]. These studies described shovel yarding operations and provided production data but did not provide decision support models that could be used to either minimize the sum of road and logging costs or maximize the profits from shovel logging operations. This paper presents an analytical framework to evaluate the daily production and road spacing for shovel logging operations.

THE ROAD SPACING PROBLEM

The efficient combination of roads and landings is a classic forest engineering problem with a rich history. Matthews (1942) developed road spacing formulas for both continuous and discrete landings under the objective of

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minimizing the sum of road costs and skidding costs to the landowner. Sessions (1986) examined the ramifications of income tax rules on road spacing issues. Thompson (1988) considered road spacing from the perspective of a logging contractor wanting to maximize profits. Sessions and Yeap (1989) examined simultaneous allocation of equipment and road spacing from a contractor's point of view. Recently, Stewart (2003) revisited these ideas.

The classic road spacing problem of Matthews assumes that the marginal cost of skidding is constant with respect to distance and that road spacing is a continuous variable. Starnes (1985) used Matthews' least cost approach to estimate the optimal shovel logging road spacing using data from his production study at Yakutat, Alaska. Although it may be possible to approximate the shovel logging process using these assumptions, we believe more insight can be developed by a process-based approach that more closely reflects the elements of shovel logging.

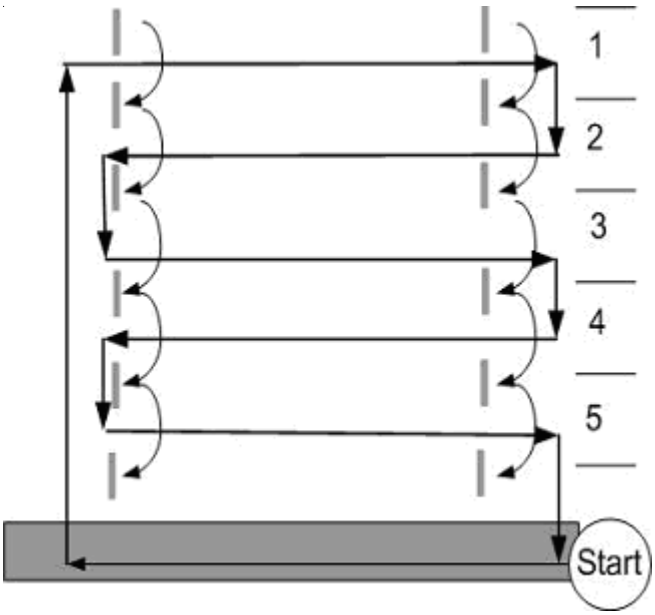

Figure 2. Serpentine shovel logging pattern for swinging long logs on gentle terrain. The operator often starts at the lower right straightening up the rack closest to the road, then proceeds to the back of the unit, and works toward the front on the unit in a serpentine pattern.

SHOVEL LOGGING PATTERN

Several shovel logging patterns are used, but all more closely resemble continuous landings as opposed to discrete landings. There are two common shovel logging patterns. The first is a serpentine pattern (Figure 2) where the shovel begins at the back of the unit and works its way forward accumulating the wood in rows, or racks, and moving the rows, or racks, forward. Sometimes an initial pass is made along the road to straighten the logs that will ultimately form the base of the log deck [6]. The serpentine pattern is most commonly used on flat terrain with long logs. An alternative pattern, more often used in sloping terrain (up to 40% slope) or with full trees is to travel on trails perpendicular to the road (Figure 3.) This paper analyzes the long-log, serpentine skidding pattern.

FORMULATION

We assume the objective for the planner is to either (1) minimize the sum of road plus shovel logging costs for the landowner or (2) maximize the profit for the shovel logger. We also assume the roads have not been constructed and once constructed will be used for this single entry. Additionally, it is assumed the terrain is gentle with shovel logging long logs to both sides of the road. From an operation's viewpoint, the assumptions are: one, that the shovel must complete its yarding pattern and return to the road periodically to load trucks after completing its serpentine pattern and two, it must deliver a minimum amount of wood to roadside each day. This will allow the shovel to serve both functions of yarding and loading trucks.

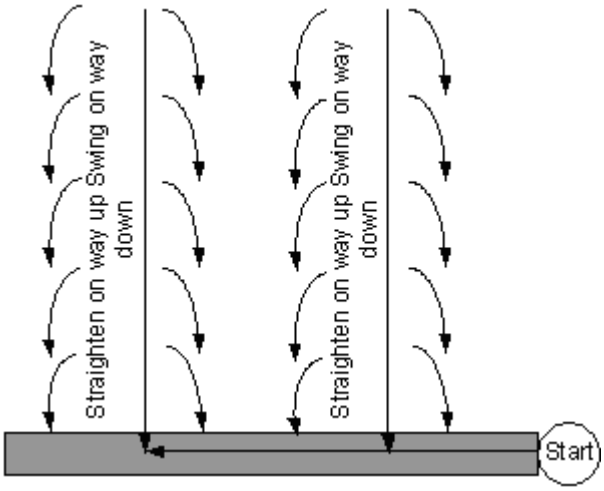

Figure 3. Vertical pattern for forwarding tree length or full trees to road side and for operations on steeper terrain. The shovel arranges trees or logs while preparing a trail perpendicular to the truck road and then returns along the trail forwarding the trees or logs to roadside.

The road spacing will be an integer of the swing distance of the shovel (Figure 4). Three shovel yarding activities are recognized. First, the shovel passes along the spur road creating a bed for the future logs by indexing the log butts in the first rack. Next, the shovel walks to the back-end of the unit to position itself at the last rack while moving any logs in its way to the side. Then, the shovel begins a serpentine walk back to the road. The problem assume three walking speeds, v_1, when moving along the road indexing the butts, v_2, while walking to the back of the unit, and v_3 while moving along the serpentine pattern. While straightening logs in the first (roadside) rack we assume a swing time per cycle, t_0, with each swing processing volume b_0.

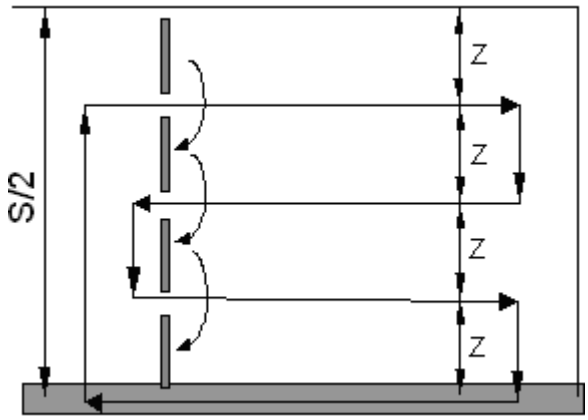

Figure 4. Forwarding pattern for two way shovel operation to the truck road. Straight lines indicate path of shovel and arcs indicated swings by shovel. Depending on the number of shovel passes (n, even or odd) and one-way versus two-way shovel logging to road side, the shovel may have to backtrack down the road to start the next harvest unit.

Additionally, the assumption is that the logs in other racks are also not perfectly aligned so that logs that originate in racks, other than the rack closest to the road, require a swing time per cycle, t_1, moving a volume b_1. For wood that has been moved more than once, the assumption is that each rehandling requires a swing time, t_2, moving a volume b_2. Each time the logs are handled with the exception of the rack closest to the road they are moved a distance, z, closer to the road and that each rack contains the volume from the unit that is z wide.

If n is defined to be the number of shovel passes parallel to the road and y is the length along road to be yarded in one yarding period, then the total shovel time can be divided into four components: (1) straightening logs in the roadside rack, (2) moving logs from their original rack to the next rack, (3) forwarding logs that have been handled once to the roadside rack, and (4) summing total walking time for the loader.

If the volume per unit area is w, the time to move the logs from rack i to the roadside rack equals moving logs from the original rack i to the rack (i-1) plus rehandling logs after they have been initially handled across the remaining (i-1) racks.

Summing up the time spent overall, the total shovel time, shovel yarding cost, shovel yarding production, area yarded per day, and volume yarded per day can be calculated as follows:

Straightening logs in the roadside rack as a result of the felling pattern:

$$T_1 = t_0 (yw\, z)/ b_0$$

Moving logs from their original rack to the next rack:

$$T_2 = n\, t_1 (yw\, z)/ b_1$$

Moving logs that have been handled once to the roadside rack:

$$T_3 = 0.5\ (n\text{-}1)\ n\ t_2 (yw\, z)/b_2$$

Summing walking time for the shovel:

$$T_4 = y\, v_1 + n\, z\, v_2 + n\, (y+z)\, v_3$$

The total shovel time for one side of the road is:

$$TT = T_1 + T_2 + T_3 + T_4$$

The total shovel cost for one side of the road is:

$$C = c_1 T_1 + c_2 T_2 + c_3 T_3 + c_4 T_4$$

where c_i is the cost per minute of element T_i. The total volume to be yarded to one side of the road is:

$$W = (n+1)\, z\, y\, w$$

since there is one more rack than shovel pass required. The production per minute is:

$$p = W/TT$$

The production per yarding period is $P = 480\ p$ assuming an 8-hr yarding period

If the shovel is to return to the road at the end of each yarding period, then the area to be yarded each period is:

$$A = P/w = (n+1)\, z\, y$$

Therefore, the length of the shovel logging rack, $y = P/(w\,(n+1)\,z)$. If the shovel is required to produce at least K tonnes per day, then a feasible solution must result in

P≥K. If the optimal road spacing results in P<K then the distance between roads must be reduced to the point the P≥K.

If the objective is to minimize the road plus logging cost for the landowner, the optimal road spacing is $2(n+1)\ z$. Therefore, the goal is to find the n that minimizes the total cost of roads plus shovel logging each day where the

Total Cost of Roads + Shovel Logging per unit volume = $(R\ y + 2\ C) / (2\ W)$

On the other hand if it were desirable to find the road plus logging cost for a logging contractor being paid m dollars per unit volume at roadside and who can purchase roads at a cost of R dollars per unit length, the goal is to find n that maximizes the daily profit where the daily profit is

Daily Profit = Daily Revenue – Daily Shovel Cost – Road Cost $= m\ P - C - R\ y/2$

Since n is an integer, and the optimal number of shovel passes is probably less than 10, summing the total costs or profits starting with $n = 1$ and increasing n until one reaches minimum cost or maximum profit is an easy way to find the road spacing that reaches the appropriate objective. If the goal was to have a minimum required production rate that constrains us from reaching the cost or profit goal, then iterations stop at that n.

Example

The example uses a machine with a swing length of 16.15 m on gentle terrain allowing for the serpentine pattern to be used with two-way forwarding to roadside. The volume to be removed is 375 tonnes/ha. The inputs (Table 1) describe the typical Pacific Northwest, USA conditions. The assumed objective is to determine the road spacing for the cases that minimize the cost to the landowner and maximize profit to the contractor.

Four scenarios were analyzed in a factorial design; two include the constraint that the shovel had to return to the landing once per day. The other scenarios required the shovel to return the road twice per day to load trucks. Two scenarios used a travel speed of 0.7 kph and, the other had a speed of 1.3 kph.

The minimum cost per tonne and cost per ha were found when there were four swings (Figures 5 and 8), but the maximum returns to the contractor occurred with 3 swings (Figures 9). For the range of operating conditions in this study the optimal solution is insensitive to the travel speed and the required number of times the shovel will return to the truck road to load trucks. Additionally, there is little difference in the cost per tonne, and cost per ha for the longer swings. Although the shovel costs have an initial high cost for arranging the piles with a linear cost with respect to yarding distance (Figure 6), the road cost per tonne decreases nearly at the same rate. The result is that the total logging cost per tonne remains relatively constant after two or more swings.

Table 1. Inputs for shovel logging – road spacing model example.

Item	Value
Shovel swing length (meters)	16.15
Volume (tonnes per ha)	375
Effective hour (minutes)	50
Seconds per swing- 1st handling	30
Seconds per swing – 2nd handling	30
Tonnes moved per swing – 1st handling	1
Tonnes moved per swing – 2nd handling	2
Shovel cost per hour walking or swinging	$125
Seconds per swing except at roadside	30
Seconds per swing at roadside	20
Price per tonnes for wood delivered roadside	$4.00
Road cost per kilometer	$6,211

Sensitivity analysis was performed on road construction costs and volume per hectare to determine the impact of these parameters on the solution. In both cases, the optimal solution remains the same with regard to the cost per tonne being minimized at four swings. This demonstrates the stability of the optimal policy to minimize the operating costs at four swings (Figures 10, 11 and 12) for the range of conditions and assumptions described in this study.

DISCUSSION AND CONCLUDING REMARKS

We have assumed walking time is independent of the number of shovel passes, n. In reality, the total walking distance varies by a factor of $y/2$ depending if n is even or odd. This is because the loader ends up at different ends of the strip depending on whether n is even or odd and has to walk back to begin the next strip.

For our example, the lack of sensitivity to the number of times that the shovel needs to return to the road in order to be responsive to trucking needs may allow this logging system to avoid a dedicated loader at the landing.

In our example, it was assumed the objective of the

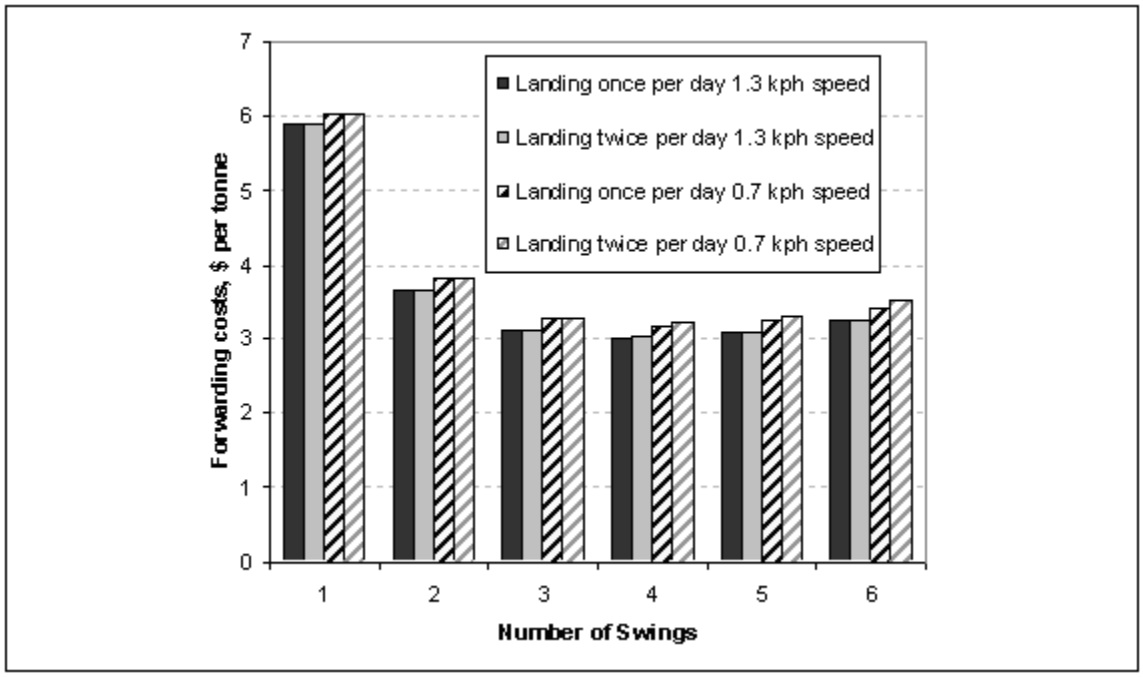

Figure 5. Cost per tonne for shovel logging with 1 to 6 swings including truck road costs and shovel logging costs. Costs do not include felling.

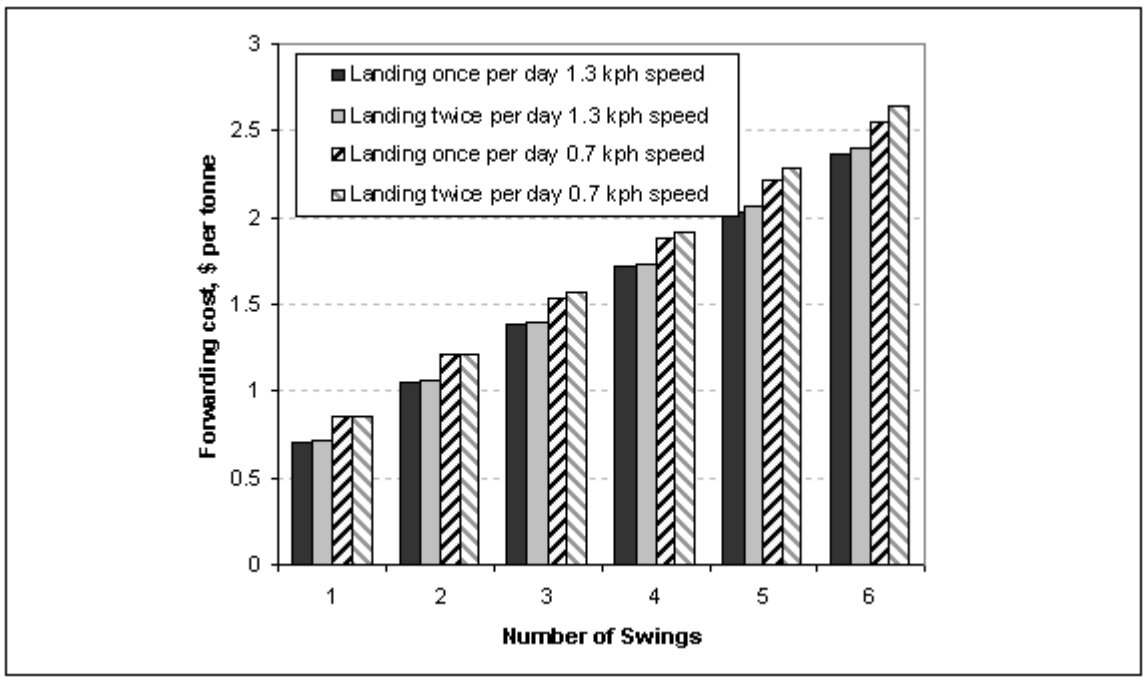

Figure 6. Yarding cost per tonne for shovel logging with one to six swings.

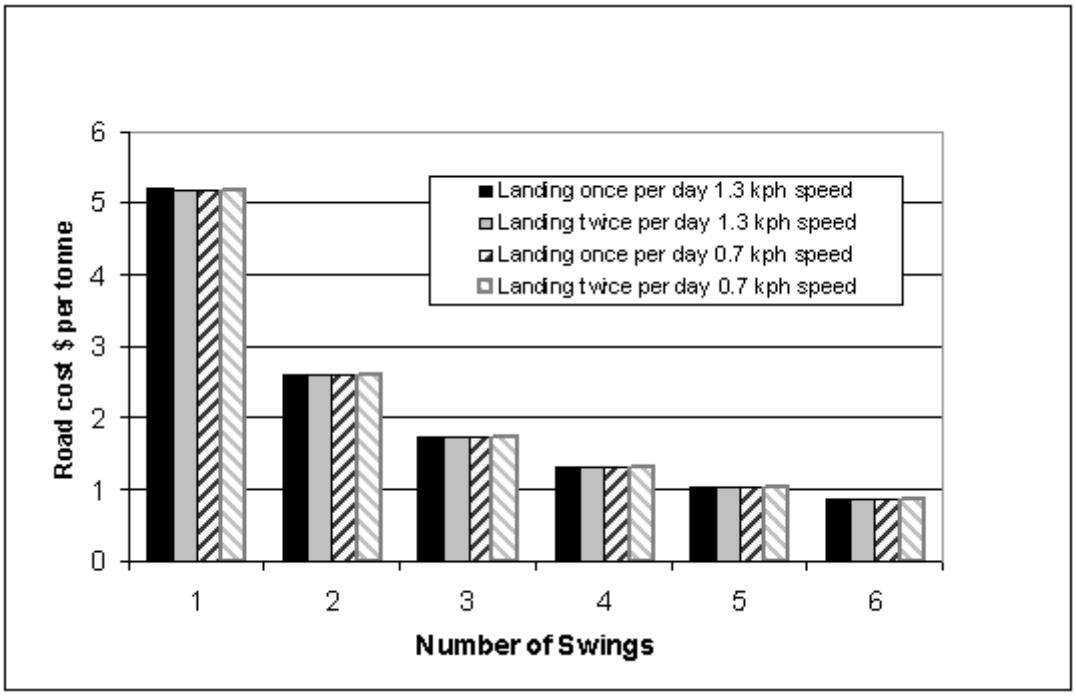

Figure 7. Road cost per tonne for shovel logging with road spacing varying from 1 to 6 shovel swings for two-way shovel logging to the truck road.

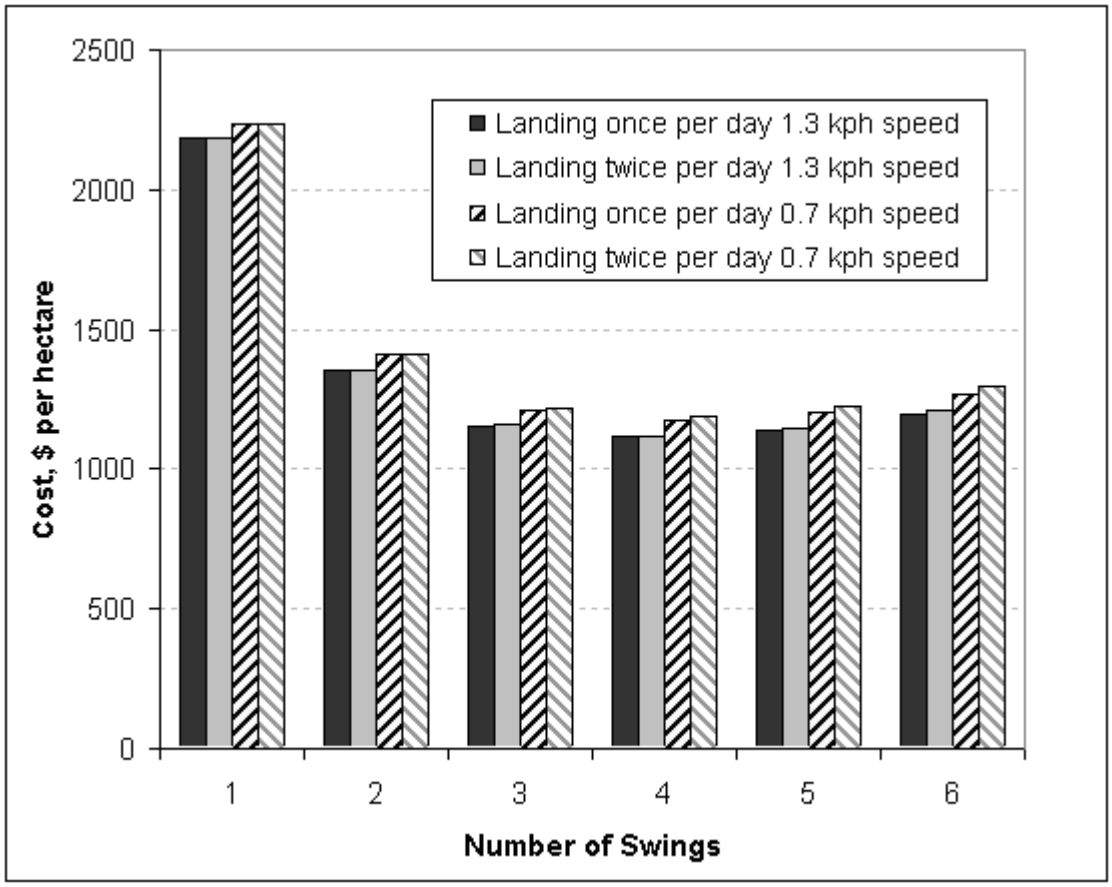

Figure 8. Cost per hectare for shovel logging with 1 to 6 swings for shovel logging cost plus truck road construction cost.

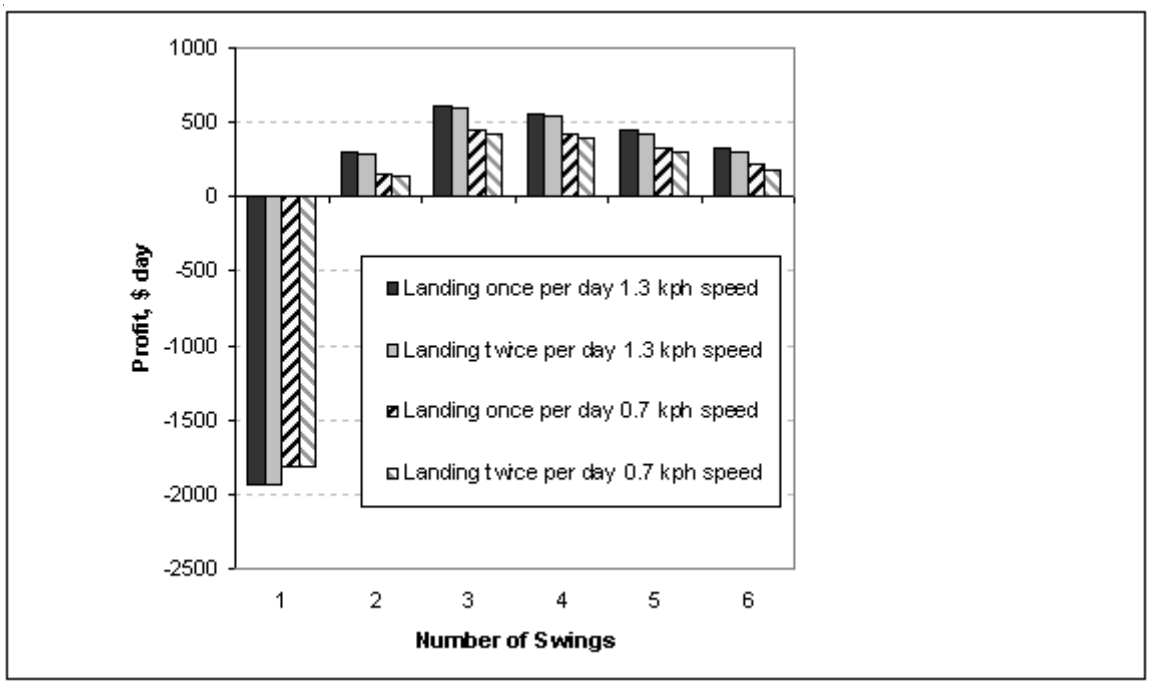

Figure 9. Contractor profits per day for shovel logging with one to six swings after payment for shovel logging and road costs. Costs do not include felling.

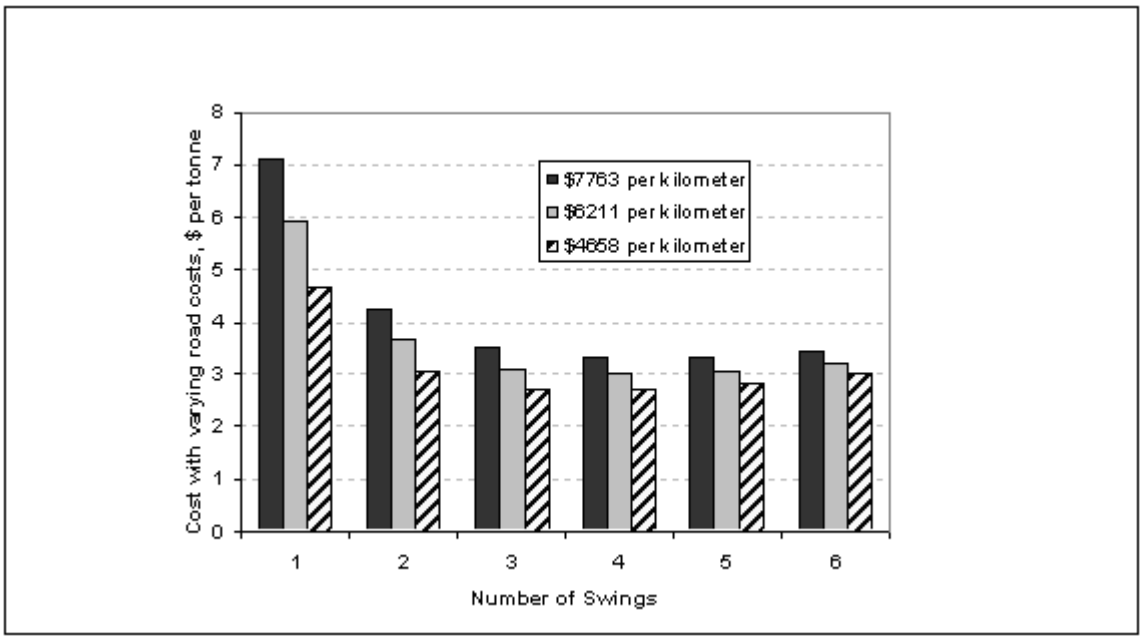

Figure 10. Cost per tonne for shovel logging with one to six swings including truck road costs and shovel logging costs. Costs do not include felling.

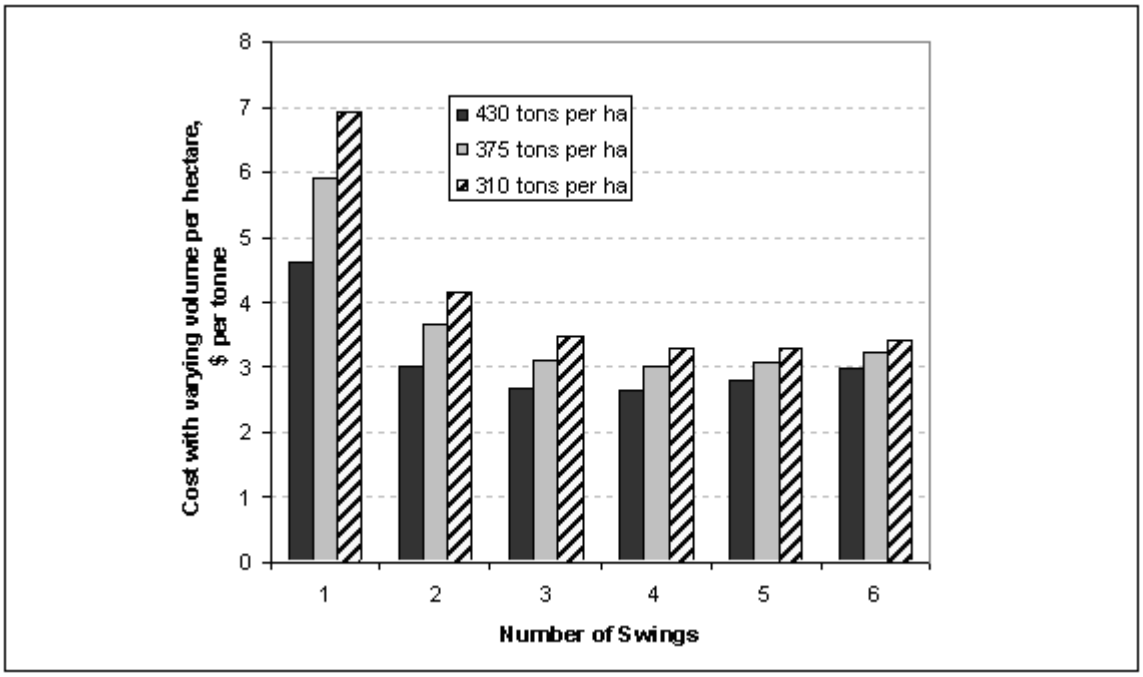

Figure 11. Cost per tonne for shovel logging with one to six swings including truck road costs and shovel logging costs. Costs do not include felling.

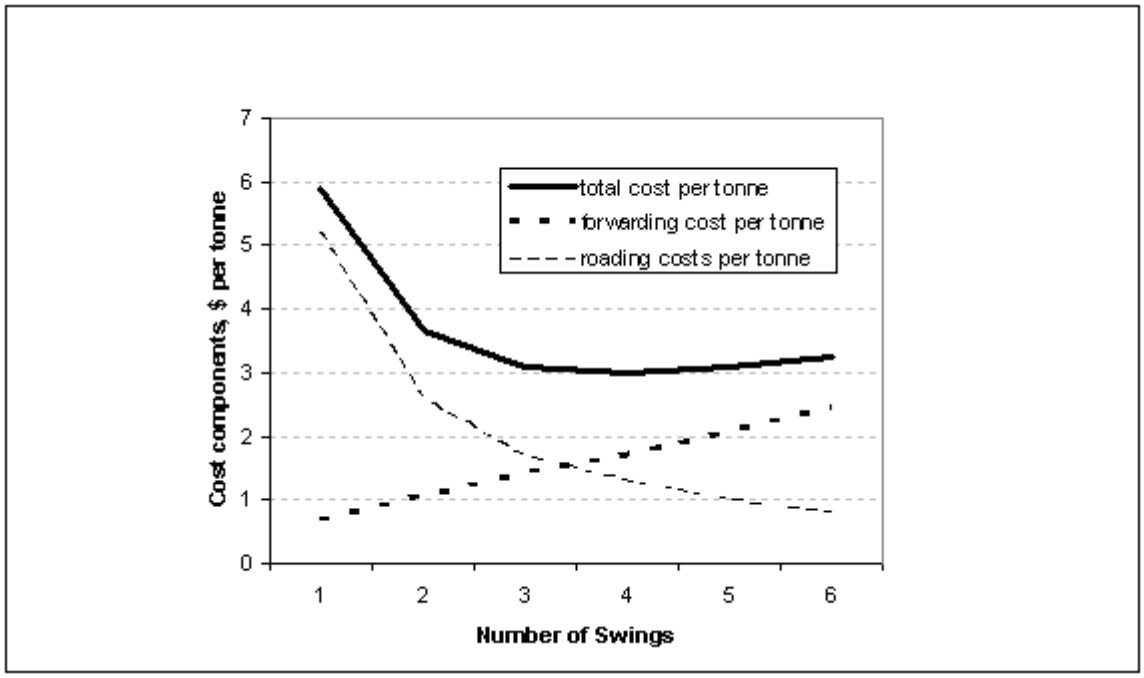

Figure 12. Total cost, forwarding cost and roading costs per tonne for shovel logging for the case where there is 375 tonnes per hectare, travel speed of 1.3 kph and one return trip to the landing per day.

layout was to determine the road spacing and shovel logging pattern that minimized cost to the landowner where the landowner costs were road construction and shovel logging cost. This road spacing also maximized landowner profits if the landowner faces a fixed price for his timber and maximizes profit by minimizing cost.

The same model was used to solve for the road spacing and shovel logging pattern for a contract logger who is paid on a $/tonne basis, purchases road construction, and wants to maximize contractor profits. If the logger is paid a fixed-price per tonne that corresponds to the cost per tonne at the road spacing that minimizes the sum of road construction and logging cost, the logger profit maximizing strategy yields the same road spacing as the cost minimizing strategy for the landowner and there is zero "excess profit". However, if the logger is paid a higher cost per tonne than the cost per tonne that minimizes the sum of road plus logging cost, the logger will try to reduce the road spacing and pay the additional road cost to get his profit as quickly as possible before moving on. This strategy has two important assumptions (1) the logger has a next job to move to upon immediate completion of this job under similar contract conditions or (2) his costs significantly decrease between jobs (Sessions and Yeap 1989).

There are still a number of research questions to be answered with regards to shovel logging. Several involve its interaction with felling methods. Under what conditions is log-length shovel logging superior to full-tree shovel logging? For whole tree yarding, what is the impact of felling and organizing the trees with feller-bunchers as opposed to motor-manual felling methods where stems are delimbed and topped in the woods? What is the cost effectiveness of shovel logging as compared to cut-to-length systems for clearcut harvests? Under what conditions could shovel logging transport shorter logs to forwarder trails be more effective than a dense system of forwarder trails?

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