MODELING AND SIMULATING TWO CUT-TO-LENGTH HARVESTING SYSTEMS IN CENTRAL APPALACHIAN HARDWOODS

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ABSTRACT - The production rates and costs of two cut-to-length harvesting systems was simulated using a modular ground-based simulation model and stand yield data from fully stocked, second growth even aged central Appalachian hardwood forests. The two harvesters simulated were a modified John Deere 988 tracked excavator with a model RP 1600 single grip sawhead and an excavator based Timbco 425 with an ultimate 5600 single grip sawhead. The forwarder used in the simulations was a Valmet 524 with 8-foot log bunks. Production rates and costs were simulated for a range of stand conditions. The results should be valuable to managers, planners, and loggers considering the use of CTL and forwarding systems in the region.

INTRODUCTION

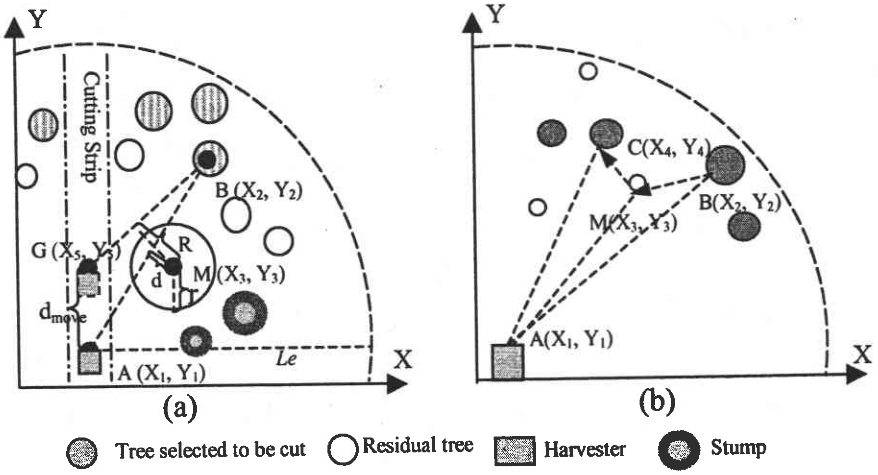
A fully mechanized cut-to-length (CTL) harvesting system consists of a harvester that performs cutting, delimbing, bucking, and piling and a forwarder that transports the logs to the landing. Compared to conventional harvesting systems, cut-to-length systems are more environmentally sound and less labor intensive. The CTL also significantly reduces the soil disturbance, compaction, and erosion by leaving the residues on the travel path. In addition, the number of trips of the forwarder also decreases because of the higher payload (Wang and Greene 1999, Wang and LeDoux 2003). The CTL system results in less stand damage by transporting the logs instead of the whole tree and is less sensitive to inclement weather (Lanford and Stokes 1995, LeDoux and Huyler 2001). Huyler and LeDoux (1996,1999) performed time studies on the performance of cut-to-length systems in eastern hardwoods. The objectives of this study were to (1) model two CTL systems with large and small harvesters, (2) generate two central hardwood stands with densities of 462 trees/acre and 194 trees/acre, respectively, (3) perform harvesting and forwarding simulations on these two stands.

SYSTEM MODELING

Six functions were modeled for the harvesters: move, boom extend/retreat, cut, swing boom, processing and dumping. More than one tree within the boom reach could be cut and processed at one machine stop. Felled trees were processed and piled on either side of the harvester trail for later forwarding. The harvester usually runs in straight trail and the trail width is set to 13 feet. All trees on the trail must be removed for the machine movement and trees on either side of the trail could be cut based on the harvesting processing option.

Each standing tree is also presumed as a potential obstacle to the tree to be cut and its position is checked (Figure 1 (a)). If the maximum boom reach is L_{boom}, and the boom reach ratio (the rate of the effective boom reach over the maximum boom reach) is r_{boom}, then the effective boom reach (L_e) could be expressed as $L_e = L_{boom} * r_{boom}$.

Let A (X_1, Y_1) be the current position of the machine, B (X_2, Y_2) be the coordinate of the nearest tree selected to be cut, and M (X_3, Y_3) be the coordinate of the tree being checked as an obstacle. The effective cutting area could be expressed as a circle centered at point A with radius equal to the effective boom reach L_e. If any portion of the tree being checked crosses line $\overline{AB}$ (line $\overline{AB}$ is tangent to or intersects the circlē) or the distance from the tree to the boom-moving route is less than 0.8 feet (minimum allowance), then this tree will be considered as an obstacle tree.


(a)

(b)

Figure 1. Algorithm for checking obstacle trees.

Where, d = the perpendicular distance from point M to line $\overline{AB}$;
r = half the DBH of the tree examined;
R = the perpendicular distance from the center of the tree to boom;

The line segment $\overline{AB}$ can be expressed as:

$$y = \frac{Y_1 - Y_2}{X_1 - X_2} + \left(Y_1 - X_1 \frac{Y_1 - Y_2}{X_1 - X_2} \right) x \tag{1}$$

The distance (d) from the center of the tree in between (X_3, Y_3) to line $\overline{AB}$ can be expressed as

$$d = \frac{\left| (Y_1 - Y_3)(X_2 - X_1) + (Y_2 - Y_1)(X_1 - X_3) \right|}{\sqrt{(Y_2 - Y_1)^2 + (X_2 - X_1)^2}} \tag{2}$$

If d< = r + 0.8, then there is some portion of a tree across line $\overline{AB}$ or the tree is within the protection distance, this tree is an obstacle. Therefore, the machine has to move to point G (X_5,Y_5) to cut the tree checked as an obstacle. To avoid tree damage, the following condition has to be met: $R \geq 0.8 + r$. Because the machine always move on the straight line, this equation will be true: $X_5 = X_1$. The next machine position G (X_5, Y_5) can be derived. Line $\overline{BG}$ can be express as

$$y = \frac{Y_5 - Y_2}{X_5 - X_2} + \left(Y_2 - X_2 \frac{Y_5 - Y_2}{X_5 - X_2} \right) x \qquad (3)$$

Let

$$a = \frac{Y_5 - Y_2}{X_1 - X_2}$$
$$b = Y_2 - X_2 \frac{Y_5 - Y_2}{X_1 - X_2} \qquad (4)$$

Then $R = \frac{|a * X_3 - Y_3 + b|}{\sqrt{a^2 + 1}}$ (5)

From equation (4), we can have $b = Y_2 - a * X_2$ (6)

Substitute b in equation (5) with equation (6), the following equation could be derived.

$R^2(a^2 + 1) = [a(X_3 - X_2) + (Y_2 - Y_3)]^2$ and Let $k_1 = \frac{X_3 - X_2}{R}, k_2 = \frac{Y_2 - Y_3}{R}$, then (7)

Equation (7) could be rewritten as

$$a^2 + 1 = (ak_1 + k_2)^2 \quad and \quad (k_1^2 - 1)a^2 + 2k_1k_2a + k_2^2 - 1 = 0 \qquad (8)$$

Then solving this quadratic equation for a, equation (10) could be obtained.

$$a = \frac{-k_1k_2 \pm \sqrt{k_1^2 + k_2^2 - 1}}{k_1^2 - 1} \qquad (9)$$

When a>0 the machine cuts the right side of the trail and when a<0 the machine cuts the left side of the trail. Based on the above calculation, the next machine position could be expressed as

$$\begin{cases} X_5 = X_1 \\ Y_5 = aX_1 + (Y_2 - aX_2) = a(X_1 - X_2) + Y_2 \end{cases} \qquad (10)$$

Then to avoid residual tree damage, the machine move distance should be $d_i = |AG| = |Y_5 - Y_1|$. If there are no trees having obstacles to cut at the current machine location, then the machine should move to next stop - $d_{move} = \min\{d_i\}$.

If the boom is already extended (Figure 1 (b)), the machine is at point A (X_1, Y_1), boom is at point B (X_2, Y_2), and the next tree selected to be cut is at point C (X_3,Y_3). Before swinging the boom directly from B to A, we have to check if there is a tree (X_3,Y_3) between line $\overline{AB}$ and line $\overline{AC}$ (Eliasson 1998). Mathematically, the following conditions have to be met to avoid residual tree damage.

(1) $Min\left\{|S_{\overline{AB}}|, |S_{\overline{AC}}|\right\} \le |S_{\overline{AM}}| \le Max\left\{|S_{\overline{AB}}|, |S_{\overline{AC}}|\right\}$

(2) $d_{\overline{Am}} \le d_{\overline{AB}}$

Where, $S_{\overline{AB}}$, $S_{\overline{AC}}$, $S_{\overline{AM}}$ is the slope for line $\overline{AB}$, $\overline{AC}$, and $\overline{AM}$, respectively.

And $d_{\overline{Am}}, d_{\overline{AB}}$ is the distance from point A to point M and point B, respectively.

$$S_{\overline{AB}} = \frac{Y_2 - Y_1}{X_2 - X_1} \; ; \; S_{\overline{AC}} = \frac{Y_4 - Y_1}{X_4 - X_1} \; ; \; S_{\overline{AM}} = \frac{Y_3 - Y_1}{X_3 - X_1}$$

$$d_{\overline{AM}} = \sqrt{(Y_1 - Y_3)^2 + (X_1 - X_3)^2} \; ; d_{\overline{AB}} = \sqrt{(Y_1 - Y_2)^2 + (X_1 - X_2)^2}$$

If the above two conditions are met, the tree being checked is an obstacle. To cut the tree at C from B, the boom has to retrieve from B to M first, and then extend from M to C if no other trees between line $\overline{AM}$ and line $\overline{AC}$. Otherwise, the boom will swing from B to C directly.

The forwarder moves along the harvester trail, grips the logs from each pile and places them in the bunk at the back of the machine. When the payload is reached, the forwarder will go back to the landing and unload the logs. Four functions are simulated for the forwarder: travel loaded, travel empty, choking, and unchoking.

SIMULATION RESULTS

Felling and forwarding was simulated on two central Appalachian hardwood stands that were computer generated. The plot size was 1.0 acre, which was replicated 36 times for performing felling and forwarding simulations. The hourly machine rates used for this simulation were \$146.72 for harvester in CTL system 1 and \$115.00 for harvester in CTL system 2 (LeDoux and Huyler 2001) and the hourly machine rate for forwarder is set at \$110.00.

The combined simulated hourly productivity for the harvester and forwarder ranged from 747.26 ft^3 (shelterwood, stand 1) to 1339.50 ft^3 (clearcut, stand 2) for CTL system 1 and from 736.17 ft^3 (shelterwood, stand 1) to 1315.04 ft^3 (clearcut, stand 2) for CTL system 2 (Table 1). The CTL system 2 in a clearcut (stand 2) had the lowest cost \$0.35/ft^3 while the CTL system 2 conducting shelterwood cut in stand 1 had the highest cost \$0.73/ft^3 (Table 1). Although the combined system productivity is higher for the CTL system 1, the cost per unit for the small CTL system 2 is less for similar conditions. Operators can realize some savings efficiency by matching the size of machines to the size of wood harvested. Stands that have trees with DBH's larger than 14 inches should be harvested with the large CTL harvester.

We have successfully modeled and simulated the cost and productivity of two CTL systems operating in two central Appalachian hardwood stands. It is beyond the scope of this paper to deal with all of the modeling and production/cost results. Future research will investigate and document additional CTL systems, stand conditions, tract layout, traffic intensity, and production/cost results.

Table 1. CTL system production and cost comparisons.

System	Stand	Treatment	BA Removed (%)	Avg. DBH Removed (inch)	Harvester			Forwarder	
					Trees/min	FT^3/PMH	$\$/\text{FT}^3$	FT^3/PMH	$\$/\text{FT}^3$
CTL System 1	Stand 1	Clearcut	100	5.32	1.51	328.46	0.44	538.87	0.20
		Shelterwood	72.24	4.82	1.27	304.85	0.48	442.41	0.25
		Diameter Limit	35.56	13.79	1.08	313.32	0.47	678.08	0.16
	Stand 2	Clearcut	100	14.43	1.31	567.87	0.26	771.63	0.14
		Shelterwood	59.40	13.00	0.88	518.23	0.28	580.49	0.19
CTL System 2	Stand 1	Clearcut	100	5.32	1.46	317.43	0.36	513.36	0.21
		Shelterwood	72.24	4.82	1.20	295.19	0.39	440.98	0.25
		Diameter Limit	35.56	13.79	1.06	300.95	0.38	602.52	0.18
	Stand 2	Clearcut	100	14.43	1.29	564.37	0.20	750.67	0.15
		Shelterwood	59.40	13.00	0.79	510.13	0.23	552.92	0.20

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