Estimating and Validating Ground-Based Timber Harvesting Production Through Computer Simulation

Jingxin Wang and Chris B. LeDoux

ABSTRACT. Estimating ground-based timber harvesting systems production with an object-oriented methodology was investigated. The estimation model developed generates stands of trees, simulates chain saw, drive-to-tree feller-buncher, swing-to-tree single-grip harvester felling, and grapple skidder and forwarder extraction activities, and analyzes costs and productivity. It also measures the traffic intensity level of extraction machines across sites. The model components were validated using data from several independent field studies. The model was used to evaluate the interaction of stand variables, harvest treatments, machines, and extraction patterns. Using two main skid trails to harvest a block minimized traffic intensity. The model can be best used to evaluate alternative skidding configurations and their impact on cost, production, and traffic intensity. For. Sci. 49(1):64–76.

Key Words: Logging, timber harvesting, forest operations, cost, production, validation.

Computer simulation is one of the best methods for analyzing timber harvesting operations because of the complexity of various harvesting systems. Attempts to address the variability of timber harvesting have generated numerous computer programs ranging from regression models to stochastic process and simulation models (Baumgras et al. 1993), but the most feasible approach seemed to be the development of a logical model that would duplicate harvesting operations by simulation and be able to consider the many variables inherent in timber harvesting systems (Stuart 1981).

Computer simulation has been used to link the variable components in production and cost analysis (Goulet et al. 1979), evaluate a wide range of configurations, operating environments, and timber utilization options, and improve the profits of forest companies largely because of its ability to identify the weaknesses and/or oversights of different systems (Hassler et al. 1985).

Timber harvesting systems operating under similar stand and operating conditions have been compared (Lanford and Stokes 1995). However, field comparisons have been limited by the cost of replicating experiments for a variety of conditions, thus capturing at best only a sample of the production rates that are possible (Aedo-Ortiz et al. 1997). One way to analyze a wide range of conditions is to build a simulation model that can be run repeatedly with different equipment configurations and working conditions (LeDoux and Butler 1981, LeDoux et al. 1994).

Several interactive timber harvesting simulation models that relied on extensive human participation were introduced in the early 1980s. The use of graphical interactive simulation to study the design of swing-to-tree feller-bunchers in thinnings was reported by Fridley et al. (1985). A similar program was developed for drive-to-tree feller-bunchers by Greene and Lanford (1986), and Greene et al. (1987) examined the effects of stand and operating factors on the productivity of a small feller-buncher in second thinnings.

More recently, an interactive simulation program that includes a stand generator was used to evaluate the relationships among stands, equipment, and harvest prescriptions

Jingxin Wang, Assistant Professor, Division of Forestry, West Virginia University, Morgantown, WV 26506—Phone: (304) 293-2941, Ext. 2481; Fax: (304) 293-2441; E-mail: jxwang@wvu.edu. Chris B. LeDoux, Project Leader and Supervisory Industrial Engineer, USDA Forest Service, Northeastern Research Station, 180 Canfield Street, Morgantown, WV 26505—Phone: (304) 285-1572; E-mail: cledoux@fs.fed.us.

Acknowledgments: The authors thank W. Dale Greene, Charlie Blinn, B. Gopalakrishnan, and Mathew Smidt for their valuable comments on an earlier draft of this manuscript.

Manuscript received January 29, 2001, accepted October 31, 2001. Copyright © 2003 by the Society of American Foresters

that are typical of USDA Forest Service timber sales (Wang and Greene 1999). Earlier, Wang et al. (1998) used interactive simulation to examine the interactions of a variety of stand, harvest, and machine features. They found that this method was labor intensive, particularly for simulating skidding and forwarding. Simulating chain saw felling on a 0.16 ha plot took 10 to 35 minutes depending on stand density and harvest method, while simulated skidding on a 7.84 ha tract took 40–90 minutes depending on stand, harvest, and machine factors. It seems essential to model harvesting numerically, especially for skidding or forwarding with uniform patterns. In this article, we develop a numerical ground-based timber harvesting simulation model, validate the model using field study data, and perform an intensive experiment for evaluating the interaction of stand and machine types, harvest treatments, and extraction patterns on production, cost, and traffic intensity.

System Design and Structure

Object-oriented modeling techniques (OMT) were used in designing the system. A hierarchical structure among different modules is useful while modifying the program with OMT. A schematic hierarchy of the timber harvesting simulation was demonstrated with the following major layers/components:

1. **Graphical user interface (GUI) application layer.** This layer consists of multiple subapplication-type modules that deal with GUI support of functions such as browsing files, simulating harvesting, analyzing results, viewing, and reproducing outputs. This layer "talks" to underlying class layers that follow the system hierarchy.

2. **Module layer.** Objects, controls, and object-oriented data models are implemented here. The modules contain form, class, and standard modules.

3. **Data storage layer**. The module layer talks to this layer to obtain persistent data support.

Communicating among different modules in the system is achieved through Dynamic Data Exchange (DDE), Dynamic Link Libraries (DDL), and Windows API. The front end of the simulation system could be a Windows 95, 98, or NT platform. The Microsoft Visual Basic built-in jet database engine is used in the back end of the system.

The entire system is event driven as codes are executed in response to an event. Each object, e.g., form or control in the system, has a predefined set of events. When one of these events occurs, the system invokes the codes in the associated event procedure. Objects in the system using Visual Basic automatically recognize a predefined set of events whenever one is evoked. Usually, an event is invoked by a mouse click on a corresponding command button or item.

The system mainly contains a forest stand generator, a felling simulator, and a skidding/forwarder simulator. These components can be performed sequentially or independently. Natural or planted stands can be generated with random, clustered, or uniform spatial patterns, which are used in later felling simulations. The skidding/forwarding simulation is based on the results of felling simulations. In this numerical model, data structure, input, and output are similar to what Wang and Greene (1999) described in the interactive model.

Forest Stand Generation

Most stand generators adopt spatial distribution of trees either by using actual, observed locations taken from a representative portion of a stand (Dykstra and Riggs 1977) or by using simulations. Simulation techniques usually randomly distribute locations of trees with uniform or clustered patterns (Sessions 1979, LeDoux and Butler 1981). Newnham (1968) reviewed most of the basic spatial distribution methods and developed a simulator that incorporated many features of previous methodologies. In this model, a Weibull distribution was used as the form for dbh distributions of planted stands (Borders et al. 1990). The exponential function has been used to characterize the reverse J shape dbh distributions for natural stands (Moser 1976). Applicable volume equations were used to determine individual stem volume (Clark and Saucier 1990). Three spatial patterns (random, uniform, and clustered) were modeled for planted stands, and two spatial patterns (random and clustered) were modeled for natural stands.

Random Pattern

If a random spatial pattern is requested, a ratio of the stand density to the total number of possible tree locations based on minimum X and Y spacing is first calculated. Then a random number with a uniform distribution between 0.0 and 1.0 is generated for each possible tree location. If this number is less than or equal to the ratio described, the coordinate location is assigned a tree. If the random number is greater than the ratio, the coordinate location is considered to be unoccupied (Farrar 1981). The minimum X and Y spacing are considered in this procedure when we model natural stands. At each location, tree dbh is assigned randomly. The total height and volume of that tree are then calculated based on the assigned dbh (Borders et al. 1990).

Uniform Pattern

All possible grids for tree locations are identified based on stand density and X and Y spacing. If X and Y both meet the minimum spacing requirements, a tree location was assigned in the center of this X by Y rectangle. A random variation of a half X_{min} or Y_{min} was allowed in modeling both the X and Y coordinates for each tree's location.

Clustered Pattern

When the clustered pattern is used, the number of cluster centers specified by the user is located randomly within a plot. By generating the X and Y coordinates randomly using a pair of random numbers, each tree is provided an initial location. The distances from that tree location to each of the cluster centers are determined, and the nearest center is selected. The distance from this center to the tree is then multiplied by a random number between 0.0 and 1.0 to give a new location for that tree relative to the cluster center (Farrar 1981). New coordinates are then calculated for the tree and the distances between that location, and the neigh-

boring trees are checked to assure that minimum nearest distances are maintained. If a tree location has violated the distance parameter, the procedure is repeated; otherwise, the location is assigned as a tree location.

Felling Operations

The numerical simulation model for chain saw, feller-buncher, and harvester consists of two parts: (1) walk of the logger with a chain saw from tree to tree or machine movement from tree to tree; and (2) tree felling or processing (Figure 1).

Generally, the time elements or production of harvesting machines can be modeled based on either the machine's working parameters, e.g., cutting pace, delimbing speed (Eliasson 1999) or time and motion study data from published literature (Randhawa and Scott 1996). Since the distance traveled by the machine is recorded while performing a simulation, modeling the time that the machine traveled or logger walked was based on the distance and speed of the machine travel. Other time elements were modeled based on published time studies.

Chain Saw Felling

Walk to tree, acquiring, felling, limbing, and topping are modeled for the chain saw. The felling direction is first defined within a random variation range, and the sawyer is located at one end of a plot. Usually, the logger will move to the nearest tree to be cut and fell the selected tree in a narrow swath. When the logger reaches the other end of the plot, he or she will return to next nearest swath. Felling, limbing, and topping are expressed as the functions of dbh (Lortz et al. 1997).

Feller-Buncher Felling

Four functions were modeled for the drive-to-tree feller-buncher: move to tree, cut the tree, move to dump, and dump. The feller-buncher is first located at one end of the plot and then moves parallel to the rows of trees; the rows are 4.5 to 6 m wide. Marked trees on either side of the machine are removed. When the machine reaches the end of the row, it turns around and cuts another tree in the nearest swath, continuing until the plot is finished. The system searches for the "cut" tree and adds the tree to the felling head. A solid

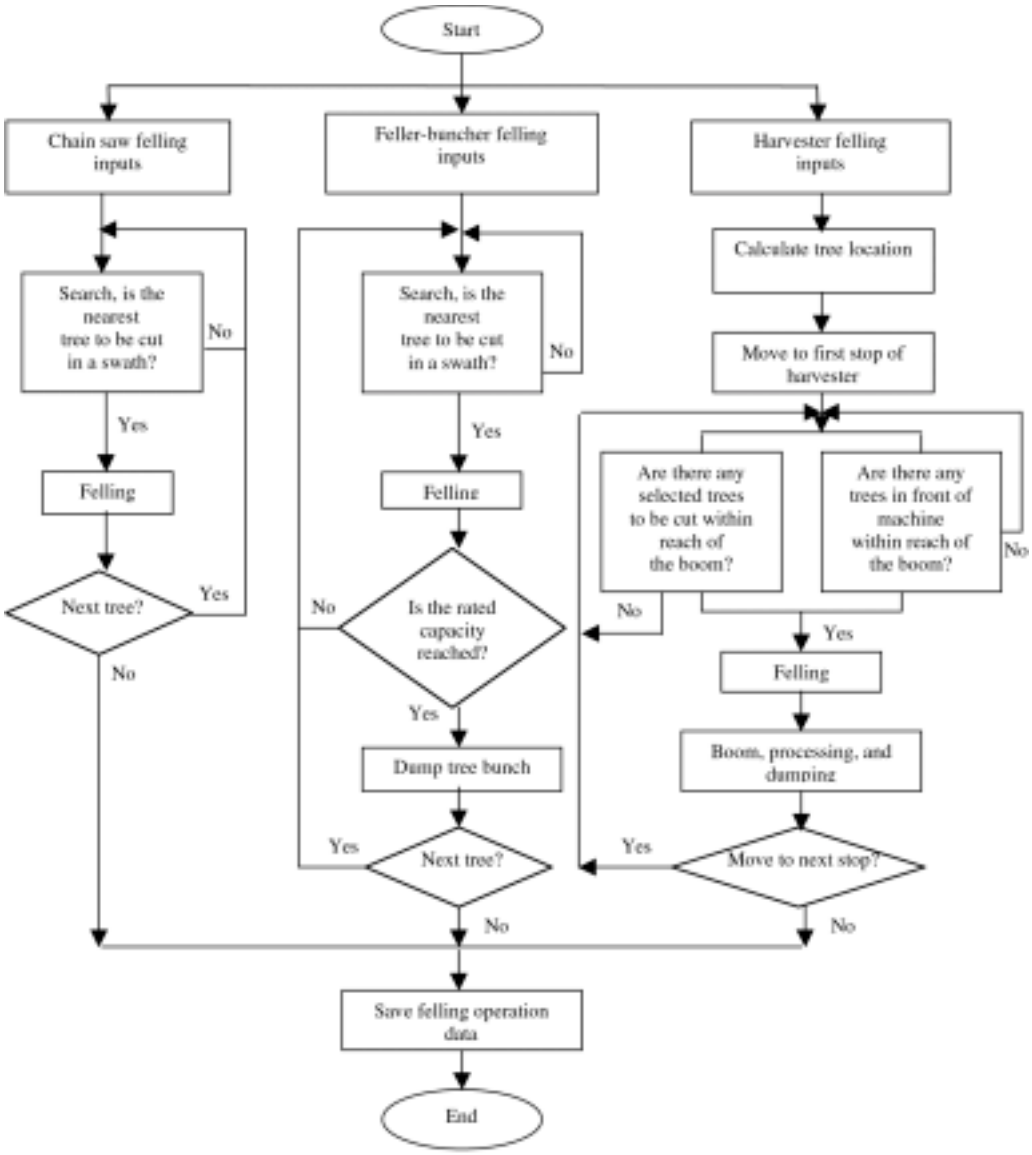

Figure 1. Flowchart of numerical felling operations.

black circle at the location of the cut tree will be drawn to signify the stump. This procedure is repeated until the head is full. The system then moves the machine image to the location of the bunch to be built and drops the trees. Felling and dumping elemental times were adopted from previous time study results (Greene and McNeel 1991).

Harvester Felling

Six functions were modeled for the cut-to-length harvester: move, boom extend/retreat, cut, swing boom, processing, and dumping. Unlike the feller-buncher, a harvester with a boom can reach several trees at a stop. Trees could be felled and processed with the same harvester (Figure 2). A circle around the harvester is drawn to indicate the reach range of the boom. This circle is moved as the harvester moves. The harvester usually runs in a straight trail and works in a 12 to 15 m wide strip depending on the boom reach. Trees on the trail must be removed for machine travel. Trees on either side of the machine within the boom reach can be removed based on the user's choice of harvest method. The processed trees are then dropped on either side of harvester trail for later forwarding.

Theoretically, the harvester operator can always use the maximum boom to reach the tree to be harvested. In practice, however, boom reach can be restricted, and the maximum boom reach is seldom used (Hassler et al. 1985, Mulari et al. 1996, Eliasson 1999). Let (x_i, y_i) be the center point of the front side of the harvester image. The equation of boom movements for a harvester at stops (x_i, y_i) and (x_{i-1}, y_{i-1}) are expressed as y' and y'' (Figure 2):

$$\begin{aligned} y' &= \sqrt{(R-d_i)^2-(x-x_i)^2}+y_i \\ y'' &= \sqrt{(R-d_i)^2-(x-x_i)^2}+y_i-TD_i \end{aligned} \tag{1}$$

where

R = maximum boom reach (m);

d_i = distance difference between theoretical maximum boom reach and actual maximum boom reach (m);

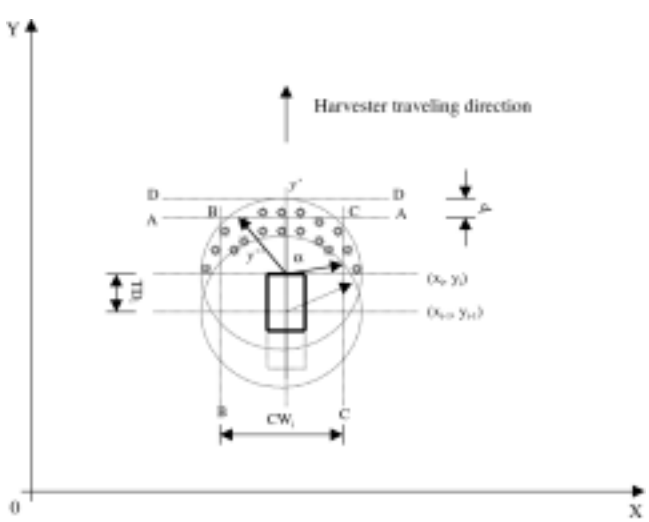

Figure 2. Diagram of harvester movement.

TD_i = distance traveled of harvester from one cutting stop to the next nearest one (m).

Therefore, the range of searching for a selected tree to be cut is:

$$\begin{aligned} & x_i-\frac{CW_i}{2}<x\le x_i+\frac{CW_i}{2} \\ & \sqrt{(R-d_i)^2-(x-x_i)^2} \\ & +y_i<y\le\sqrt{(R-d_i)^2-(x-x_i)^2}+y_i-TD_i \end{aligned} \tag{2}$$

where CW_i = cutting width of harvester (m).

The cutting area equals the cutting width of the harvester times the travel distance from one stop to the next. The actual cutting area of the harvester at a stop is expressed as:

$$CA_i = \int_{x_i-\frac{CW_i}{2}}^{x_i+\frac{CW_i}{2}} \left\{ \left[\sqrt{(R-d_i)^2-(x-x_i)^2}+y_i\right] - \left[\sqrt{(R-d_i)^2-(x-x_i)^2}+y_i-TD_i\right] \right\} dx = CW_i \times TD_i \tag{3}$$

The relationship of moving distance of the harvester between the two nearest stops and the cutting width is:

$$TD_i=\sqrt{(R-d_i)^2-\left(\frac{CW_i}{2}\right)^2}-\frac{CW_i}{2}Ctga \tag{4}$$

where α = the angle of the boom turned from the centerline of the harvester in degrees.

TD_i is used to compute the ground travel time of the harvester. Boom movement times are functions of linear distance of the boom extended and angular distance of the boom swing and their corresponding velocities, respectively. Felling and processing elemental times were denoted as functions of dbh and the number of logs being processed from the tree-length (Tufts and Brinker 1993).

Machine Image Movement

As the mouse cursor is moved from one point to another point, the machine image is moved correspondingly. The machine image can be rotated 360° by adopting the transformation of a coordinate system, which is in a rectangular form for felling machines. When the machine image is moved from position (X_{i-1}, Y_{i-1}) to position (X_i, Y_i), there are two transformations of its vertex coordinates: first machine image is translated from (X_{i-1}, Y_{i-1}) to (X_i, Y_i), and then the machine image is rotated certain degrees (β – α) around (X_i, Y_i) (Figure 3).

Let

$$
\begin{aligned}
d &= \sqrt{(Y_i - Y_{i-1})^2 + (X_i - X_{i-1})^2} \\
C_s &= \frac{X_i - X_{i-1}}{d} \\
S_N &= \frac{Y_i - Y_{i-1}}{d} \\
M_W &= machine \quad width(m) \\
M_L &= machine \quad length(m)
\end{aligned}
\tag{5}
$$

So the coordinates of vertexes of machine image (A, B, C, and D) at position (X_i, Y_i) are expressed as:

$$A \Rightarrow (X_i - \frac{M_W \times S_N}{2}, Y_i + \frac{M_W \times C_S}{2})$$

$$B \Rightarrow (X_i + \frac{M_W \times S_N}{2}, Y_i - \frac{M_W \times C_S}{2}) \tag{6}$$

$$C \Rightarrow (X_i + \frac{M_W \times S_N}{2} - M_L \times C_S, Y_i - \frac{M_W \times C_S}{2} - M_L \times S_N)$$

$$D \Rightarrow (X_i - \frac{M_W \times S_N}{2} - M_L \times C_S, Y_i + \frac{M_W \times C_S}{2} - M_L \times S_N)$$

Extraction Simulation

Functions modeled for the grapple skidder are move to load, grapple load, travel loaded, and unload. Move to load, load, travel loaded, and unload were modeled for the forwarder. Grappling and ungrappling elemental times were modeled based on results reported by Tufts et al. (1988). Loading and unloading times for a forwarder were formulated as functions of log size, product type, the number of logs being processed from a tree, and the number of grapple loads required to unload the forwarder (Tufts and Brinker 1993).

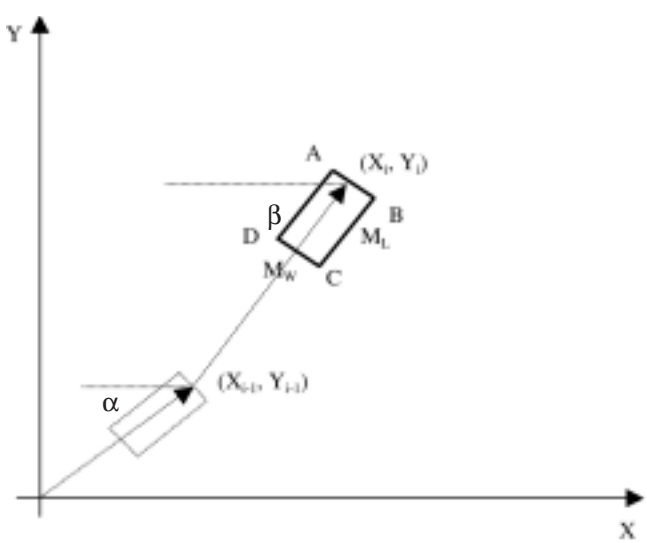

Figure 3. Diagram of machine image movement.

Since two separate modules were adopted, one module performed simulation and the other performed analysis. Elemental time equations for an individual machine can be modified based on specific simulation conditions such as terrain and tree size. Changes do not affect any of the simulations performed earlier in another module.

Extraction Patterns

In an interactive skidding simulation, a landing must be located first in the logging area that was created by felling a plot a fixed number of times. Tree or log pile data are provided by the felling simulation. The skidder machine will begin at the landing at the nearest tree pile and then move to the next closest pile until it is fully loaded. Then the loaded machine will travel back to the landing. While the forwarder is simulated in a similar manner, it follows the harvester's trail and loads logs with a self-mounted boom.

Although interactive simulation allows constant and direct human input to the simulation, it is time-consuming and often repetitive, especially with respect to uniform skidding or forwarding patterns. As a result, a numerical skidding or forwarding simulation was modeled in the system (Figure 4). To date, four skidding or forwarding patterns (SP1, SP2, SP3, and FP1) have been modeled (Figure 5):

SP1—freestyle skidding (no designated skid trail)

SP2—skid trail runs through the center of plot (one trail)

SP3—skid trails traveling from the landing to the corners of plot (two trails)

FP1—forwarding along the trails of the harvester (forwarding direct to road)

The program also allows the user to choose the landing location and the machine payload. The landing must be located before performing a simulation. The machine will begin at the landing and move to the nearest tree bunch or log pile, then move to the next nearest one until it is fully loaded. The machine then follows the specified extraction pattern throughout the entire simulation process.

Traffic Intensity

The traffic intensity within each smaller grid (e.g., 5 by 5 m) is recorded into a file while the numerical extraction simulation is being performed. Four travel intensity categories for a skidder or forwarder were defined in the system (Carruth and Brown 1996):

TI1—Trees on the plot have been felled.

TI2—Trees that stood on the plot have been removed and no other traffic has passed through the plot.

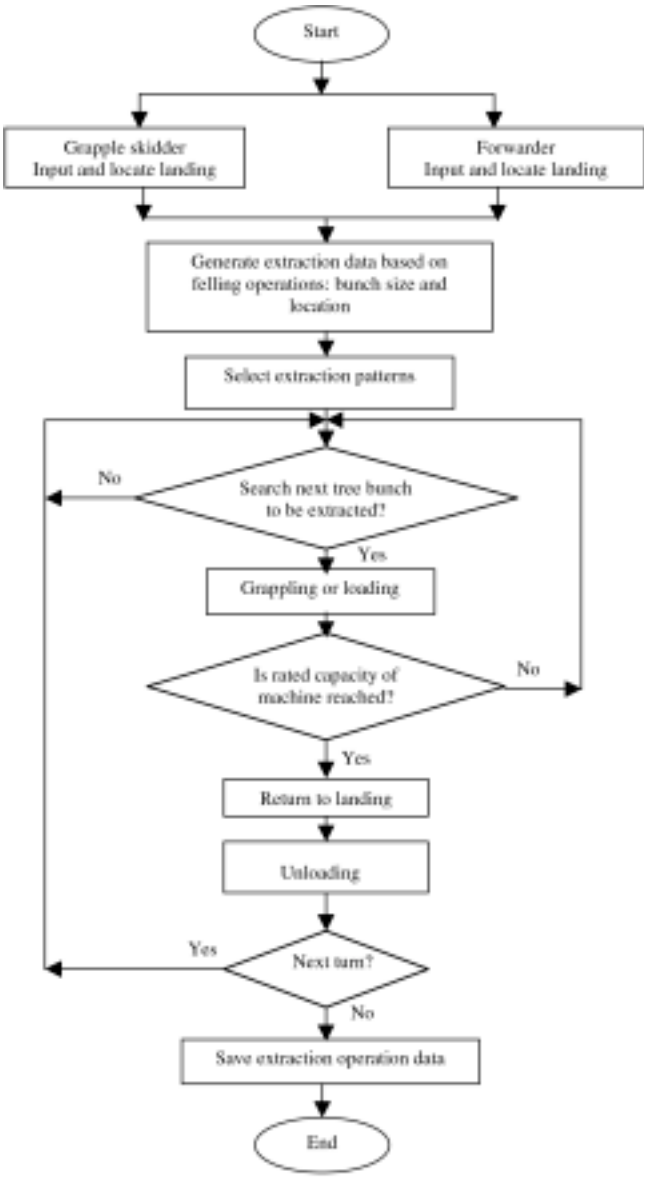

Figure 4. Flowchart of numerical extraction simulation.

TI3—Trees that stood on the plot have been removed and trees outside the plot have been skidded through the plot. There have been 3 to 10 passes with a loaded machine.

TI4—There have been more than 10 passes with a loaded machine through the plot.

After the machine is fully loaded, it will begin to return from its current position to the landing by the shortest and easiest route depending on the extraction pattern. The skidding area is divided into cells (5 by 5 m) for accurate recording of travel intensity. This grid width allows two machines to pass each other on a trail. There are eight possible direction options for a machine to move from its current position to the next position (Figure 6).

An array is used to hold the number of passes a machine traveled loaded through a plot. When the machine is moved from point (X_{i-1}, Y_{i-1}) to point (X_i, Y_i) (Figure 6), $X_i > X_{i-1}$ and $Y_i < Y_{i-1}$. A linear equation can be formulated for line segment (X_{i-1}, Y_{i-1}) to (X_i, Y_i). Let

$$\begin{aligned} Y &= \beta_0 + \beta_1 \times X \\ \beta_1 &= \frac{Y_i - Y_{i-1}}{X_i - X_{i-1}} \\ \beta_0 &= Y_{i-1} - \beta_1 \times X_{i-1} \end{aligned} \tag{7}$$

The coordinates of any point on this line can be tracked. It can be determined which grid the skidding machine passed through based on the coordinate as the machine moves from its start point to the end point. First, the locations of grids for the starting and ending points must be calculated, as represented by a two-dimension array *GridL(i, j).* Let the grid location of the start point (X_{i-1}, Y_{i-1}) be *GridL(i, j);* the grid location of the end point will be *GridL(i + p, j – n).* Here, p and n are the number of grids that the machine had passed through in both X and Y coordinate directions. Then, the next point is determined starting from (X_{i-1}, Y_{i-1}). The next point could be:

$$\begin{aligned} &\textit{If } x \textit{ is known first,} \\ &\begin{cases} x = (i+1) \times C_w \\ y = \beta_0 + \beta_1 (i+1) \times C_w \end{cases} \\ &\textit{If } y \textit{ is known first,} \\ &\begin{cases} y = j \times C_w \\ x = \dfrac{j \times C_w - \beta_0}{\beta_1} \end{cases} \end{aligned} \tag{8}$$

where

i = ith cell in X coordinate;

j = jth cell in Y coordinate;

C_w = cell width (5 m).

There would be three conditions to record the travel intensity in a grid after we obtain $x - y$ coordinates for a new point. Another two-dimensional array *TIP(i, j)* is used here to record the travel intensity levels in each grid.

$$\begin{aligned} &\textit{If } y > j \times C_w, \\ &TIP(i+1, j) = TIP(i+1, j) + 1 \\ &\textit{If } x < (i+1)C_w, \\ &TIP(i, j-1) = TIP(i, j-1) + 1 \\ &\textit{If } x = (i+1)C_w \textit{ and } y = jC_w, \\ &TIP(i+1, j-1) = TIP(i+1, j-1) + 1 \end{aligned} \tag{9}$$

This procedure was repeated until the end point (X_i, Y_i) was reached. The number of passes was recorded and

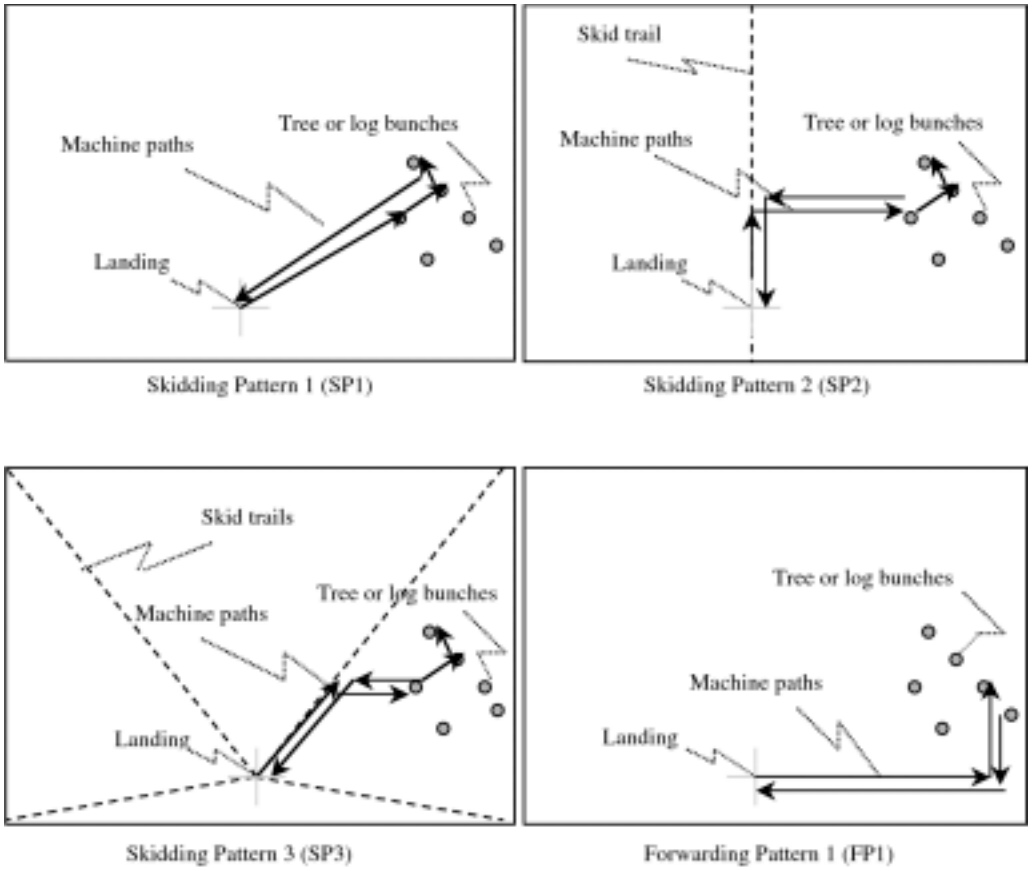

Figure 5. Diagram of extraction patterns.

accumulated for each grid that the loaded machine passed through as we traced from start point to end point. The travel intensity category in each grid is displayed in four ways depending on the intensity level (Figure 6). After the tracking is completed along the entire line segment, the number of passes for the loaded machine in each grid is stored in computer memory and saved to a file after the simulation is completed.

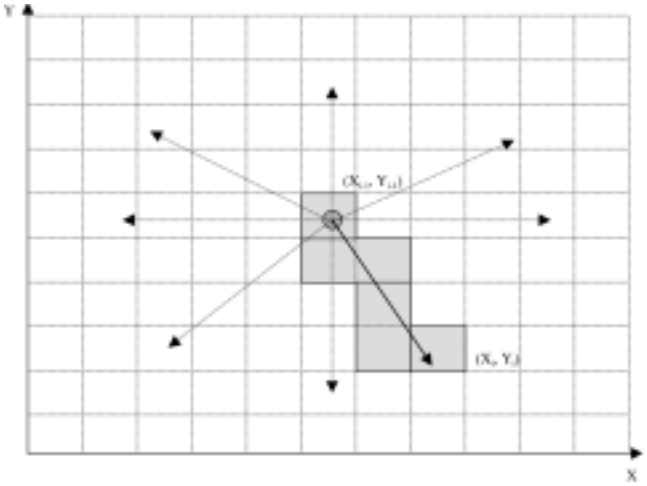

Figure 6. Diagram of skidder or forwarder's movement.

Model Validation

The felling and extraction components in this simulation model were validated by comparing the means of operational random variables achieved by the simulations with rates observed in field experiments (Table 1). In each test, those stand attributes necessary for input to the simulation approximated the conditions under which the field experiment was conducted. Operational random variables, such as average dbh removed and distance between harvested trees in felling, and turn size and average extraction distance in skidding/forwarding, were comparable.

The difference between simulated and observed production figures never exceeded 10% (Table 2). The differences in average extraction distance simulated for the harvester and average extraction distance observed in field studies were over 7% since these distances were affected not only by stand conditions but also by site slopes. Differences between simulated and field study results were also noted for the number of trees felled per accumulation for the feller-buncher or per stop for the harvester. If the average number of trees simulated and observed in field studies are rounded to the next larger integer, the difference will be negligible. The validation test comparisons showed small differences, suggesting that this model can be used to estimate production and cost for the ground-based systems modeled.

Table 1. Operational conditions of previous field studies used in validation tests.

Field study	Machine	Stand condition	Harvest
Lortz et al. 1997 Kluender et al. 1997	Chainsaw and grapple skidder	Southern pine plantation 375 trees/ha Dbh 15–50 cm	Selection cut (removed 49% of basal area)
Kluender and Stokes 1994*	Chainsaw and grapple skidder	Southern pine plantation 338 trees/ha Ave. Dbh 27 cm	Single-tree (cut 29% of trees)
Kluender and Stokes 1994†	Chainsaw and grapple skidder	Southern pine plantation 310 trees/ha Ave. Dbh 28 cm	Clearcut
Greene and McNeel 1987	Feller-buncher	Natural loblolly pine 250 trees/ha Dbh 15–60 cm	Clearcut
Greene and McNeel 1991	Feller-buncher	Southern pine 500 trees/ha Dbh 8–56 cm	Clearcut
Tufts and Brinker 1993	Harvester and forwarder	19-yr-old loblolly pine plantation 750 trees/ha Dbh 10–46 cm	Second thinning (cut 400 trees/ha)

* Harvest treatment was a single-tree selection.
† Harvest treatment was a clearcut.

Simulation Application

Simulation Factors

The simulations in this article evaluate the impacts of extraction machines and patterns on traffic intensities across the harvested sites using the numerical simulation model that was developed and validated. There are 18 independent combinations of stand, machine, and harvest factors (Table 3). Each combination was replicated three times for a total of 54 felling experiments. Another 54 extraction simulation runs were performed based on felling results. Each skidding or forwarding operation was examined with three skidding patterns or one forwarding pattern, respectively (Figure 5);

Table 2. Comparisons of means of operational variables between field tests and simulations.

Validation test	Variable	Field test	Simulation	Difference (%)
Chainsaw felling				
Lortz et al. 1997	Ave. Dbh removed (cm)	34.8	33.0	–5.5
	Distance* (m)	13.0	12.8	–1.6
Kluender and Stokes 1994†	Ave. Dbh removed (cm)	29.0	28.5	–1.8
	Distance* (m)	22.4	21.3	–5.2
Kluender and Stokes 1994[c]	Ave. Dbh removed (cm)	29.7	29.0	–2.4
	Distance* (m)	14.6	14.7	+0.7
Feller-buncher				
Greene and McNeel 1987	Ave. Dbh removed (cm)	33.8	33.8	0
	Trees[b†]	1.0	1.0	0
	Distance* (m)	10.5	10.0	–5.0
Greene and McNeel 1991	Ave. Dbh removed (cm)	24.4	25.7	+5.1
	Trees†	1.5	1.4	–7.1
	Distance* (m)	8.7	8.2	–6.1
Harvester				
Tufts and Brinker 1993	Ave. Dbh removed (cm)	19.6	19.3	–1.6
	Trees†	2.3	2.4	+4.2
	Distance* (m)	8.3	9.1	+8.8
Grapple skidder				
Kluender et al. 1997	Trees per turn	4.2	4.0	–5.0
	Volume per turn (m^3)	2.5	2.5	0
	Extraction distance (m)	404.7	376.2	–7.6
Kluender and Stokes 1994††	Trees per turn	4.1	4.5	+8.9
	Volume per turn (m^3)	2.3	2.3	0
	Extraction distance (m)	194.4	210.9	+7.8
Kluender and Stokes 1994§	Trees per turn	4.5	4.8	+6.3
	Volume per turn (m^3)	2.8	2.6	–7.7
	Extraction distance (m)	188.4	173.7	–8.5
Forwarder				
Tufts and Brinker 1993	Volume per turn (m^3)	7.8	7.6	–2.6
	Extraction distance (m)	228.0	249.0	+8.4

* Distance refers to the distance between harvested trees for chainsaw and feller-buncher felling, and between harvesting stops for harvester.
† Number of trees felled per accumulation for feller-buncher and per stop for harvester.
†† Harvest treatment was a single-tree selection.
§ Harvest treatment was a clearcut.

Table 3. Variables included in the simulation experiment.

Factor	Levels*	No. of experiments
Stands	Loblolly pine planted stand (P) of uniform generation with initial stand density 1010 trees/ha 20.8 cm average Dbh and 301.8 m^3/ha Natural stand (N) of random generation with initial stand density 674 trees/ha 18.0 cm average Dbh and 111.5 m^3/ha	2
Harvests	Clearcutting (CC) (base method for comparisons) Shelterwood (SW) (192 trees/ha residual) Single-tree selection (SS) (423 trees/ha residual)	3
Systems	Chain saw (CS) and grapple skidder (SD) Feller-buncher (FB) and grapple skidder (SD) Harvester (HV) and forwarder (FW)	3
Patterns	Skidding pattern 1 (SP1) Skidding pattern 2 (SP2) Skidding pattern 3 (SP3) Forwarding pattern 1 (FP1)	4
Operations	Felling Skidding/forwarding	2

* Abbreviations defined in parentheses are used in later tables and texts.

126 skidding and forwarding simulation experiments were conducted. The order in which extraction combinations were simulated was assigned randomly. Felling was performed on a 0.16 ha (40 by 40 m) square plot. Skidding and forwarding simulations were performed on a 7.84 ha area that was created by replicating the felling plot 49 times (7 by 7 grids). Extraction machine travel was monitored in a smaller grid (5 by 5 m) that is wide enough to allow a wide-tired machine to pass or two skidders with narrow tires to pass each other. The landing was located at the same point that was in the middle of the lower side of the extraction area for each simulation run. Stand, harvest, machine, extraction pattern, bunch size, cycle time, volume per turn, volume per productive machine hour (PMH), and traffic intensity of each grid were recorded for analysis once a simulation was completed.

Analysis

An analysis of variance (ANOVA) model was used to determine any differences in cycle time, average extraction distance, cycle volume per PMH, and travel intensity category by stand, harvest, machine, and extraction pattern. The ANOVA model can be stated as:

$$\begin{aligned} Y_{ijkl} &= \mu + S_i + H_j + M_k + SP_l + \varepsilon_{ijkl} \\ i &= \text{set of stands } \{1,\ 2\} \\ j &= \text{set of harvest factors } \{1,\ 2,\ 3\} \\ k &= \text{set of machine factors } \{1,\ 2,\ 3\} \\ l &= \text{set of extraction patterns } \{1,\ 2,\ 3,\ 4\} \end{aligned} \tag{10}$$

where Y_{ijkl} represents the cycle volume, average extraction distance, cycle time, volume per PMH, and travel intensity category 1 to 4, respectively; μ is the grand mean of each response variable; S_i is the effect of stand factors; H_j is the effect of harvest factors; M_k is the effect of machine factors; SP_l is the effect of extraction patterns (Table 1); and ε_{ijkl} is an error component that represents all uncontrolled variability.

Means of cycle time, average extraction distance, cycle volume per PMH, and travel intensity category also were used to examine the differences of these operational variables by harvest, machine, and extraction pattern.

Results

Cycle volume differed among stands (F = 58.81; df = 1,118; P = 0.0001) and harvests (F = 11.68; df = 2,118; P = 0.0001), but was not significantly different between chain saw and feller-buncher felling (F = 0.01; df = 2,118; P = 0.99159) and among skidding patterns (F = 0.00; df = 2,118; P = 0.9998) (Table 4). However, the cycle volume of the forwarder was 10.5 m^3, which was much higher than the grapple skidder's 2.2 m^3.

Average extraction distance (ASD) did not differ significantly between the chain saw and feller-buncher (F = 0.13; df = 1,118; P = 0.7236) or between stands (F = 0.16; df = 1,118; P = 0.6865) (Table 4). However, the average forwarding distance of 223.5 m in harvester felling sites differed significantly from average skidding distances of 212.4 and 212.9 m in chain saw and feller-buncher sites, respectively. Average skidding distance was significantly different among harvest methods (F = 450.49; df = 2,118; P = 0.0001) and skidding patterns (F = 315.93; df = 2,118; P = 0.0001).

Cycle time was significantly different between stands (F = 107.74; df = 1,118; P = 0.001), among machines (F = 13.44; df = 1,118; P = 0.0004), and among harvests (F = 20.56; df = 2,118; P = 0.0001) (Table 4). It did not differ among skidding patterns (F = 3.435; df = 2,118; P = 0.4106) while the cycle time of 34.5 minutes with the forwarding pattern was significantly greater than the cycle times of 8.7 minutes with skidding patterns.

The stand (F = 162.29; df = 1,118; P = 0.0001), harvest (F = 157.90; df = 2,118; P = 0.0001), machine (F = 198.54; df = 1,118; P = 0.0001), and extraction pattern (F = 13.84; df = 2,118; P = 0.0001) all affected cubic meters per PMH

Table 4. Means and significance levels of extraction simulation variables.*

Item	Stand		Harvest			Felling machine			Extraction pattern†			
	Planted	Natural	Clearcut	Shelter-wood	Single tree	Chainsaw	Feller-buncher	Harvester	SP1	SP2	SP3	FP1
Cycle vol. (m^3)	3.5a	3.2b	3.5c	3.2d	3.5c	2.2f	2.2f	10.5g	2.2i	2.2i	2.2i	10.5j
Mean extraction distance (m)	214.5a	213.9a	189.6c	208.9d	244.1e	212.4f	212.9f	223.5g	184.0i	230.0j	223.9k	223.5k
Cycle time (min)	10.5a	14.1b	11.3c	13.8d	11.7c	9.3f	7.9g	34.5h	8.2i	8.7i	8.7i	34.5j
Vol./PMH (m^3)	20.8a	13.8b	18.6c	15.1d	17.8e	14.3f	17.0g	26.5h	16.5i	15.1j	15.4j	26.5k
Travel intensity												
TI1 (%)	23.3a	46.5b	25.6c	37.6d	41.6e	30.6f	28.1f	68.3g	20.7i	31.7j	35.6k	68.3m
TI2 (%)	27.2a	32.6b	29.3c	31.2c	29.2c	31.1f	32.9f	17.2g	28.5i	31.5i	36.1j	17.2k
TI3 (%)	37.6a	16.8b	33.9c	24.4d	23.4d	29.3f	29.9f	12.7g	33.7i	32.9i	22.4j	12.7k
TI4 (%)	11.8a	4.05b	11.2c	6.9d	5.8d	8.9f	9.0f	1.8g	17.1i	3.9jk	5.9j	1.8k

* Means with the same letter in a row are not significantly different at $\alpha = 0.05$ (ANOVA).
† Skidding patterns 1, 2, 3, and forwarding pattern 1.

of extraction significantly. However, hourly skidding production with SP2 and SP3 differed little in m^3/PMH.

The proportion of travel intensity category was defined as the number of 5 by 5 m grids in this category over the total number of such grids in a logging area of 7.84 ha. It was used to evaluate how machine, harvest, and extraction pattern affected travel intensity across the harvested site. Travel intensity category 4 (TI4) did not differ significantly among felling machines (F = 0.01; df = 1,118; P = 0.9237) but differed significantly between stands (F = 80.48; df = 1,118; P = 0.001), among harvests (F = 14.33; df = 2,118; P = 0.001), and among skidding patterns (F = 76.63; df = 2,118; P = 0.001) (Table 4). Travel intensity categories 1, 2, and 3 also differed significantly among stand, harvest, and skidding patterns.

The ASD increased sharply when moving to the partial cuts from the clearcuts (Table 5). The shortest ASD, 160.6 m, was associated with skidding pattern 1 in clearcuts and increased to 264.3 m with skidding pattern 2 in single-tree selection cuts. The ASD's were similar for skidding pattern 3 and forwarding pattern 1. Hourly production was consistently highest in clearcuts and lower in partial cuts. Shelterwood harvests resulted in lower hourly production than single-tree selection cuts due to the smaller size of trees removed. Hourly extraction production also varied with skidding or forwarding patterns. Forwarding had higher hourly production than skidding. Skidding with pattern 1 always resulted in higher hourly production than with patterns 2 and 3.

TI4 was the level of greatest concern since it causes the most damage to the soil. About 25 and 7% of the logging area (7.84 ha) was in TI4 with SP1, SP2, and SP3 after skidding, but only 3% of the same area was in TI4 after forwarding in clearcuts (Table 6). Skidding with SP1 always resulted in a higher proportion of TI4 than with SP2 and SP3 that used the designated skid trails. The proportions of TI4 with SP2 and SP3 also were similar. Harvest methods also affected travel intensity. Since

Table 5. Operating variables affected by machine, harvest, and extraction patterns during extraction.*

Harvest	Machine and extraction patterns†						
	Chain saw and grapple skidder			Feller-buncher and grapple skidder			Harvester and forwarder
	SP1	SP2	SP3	SP1	SP2	SP3	FP1
	Vol. per turn (m^3)						
Clearcut		2.13			2.16		10.75
Shelterwood		2.03			1.97		10.23
Single tree		2.19			2.24		10.48
	Ave. extraction distance (m)						
Clearcut	160.6	204.8	199.6	161.2	203.0	198.4	199.6
Shelterwood	178.6	224.3	217.6	182.6	223.7	217.3	218.2
Single tree	212.1	260.0	253.9	208.8	264.3	256.6	253.0
	Cycle time (min.)						
Clearcut	8.2	8.8	8.7	6.8	7.3	7.2	32.1
Shelterwood	10.6	11.1	11.1	8.5	8.9	9.0	37.8
Single tree	7.9	8.5	8.4	7.3	7.9	8.1	33.7
	Vol. per PMH (m^3)						
Clearcut	16.2	15.1	15.4	19.7	18.1	18.4	28.4
Shelterwood	12.7	11.9	12.2	15.4	14.3	14.6	24.0
Single tree	15.7	14.6	14.9	18.4	16.7	17.0	27.3

* Six simulations per cell.
† Skidding patterns 1, 2, 3, and forwarding pattern 1.

Table 6. Proportion of felling grids in each travel intensity category by machine, harvest, and extraction patterns after felling and extraction.*

	Travel intensity	Machine and extraction patterns†						
		Chain saw and grapple skidder			Feller-buncher and grapple skidder			Harvester and forwarder
		SP1	SP2	SP3	SP1	SP2	SP3	FP1
		(%)						
	TI1	15	21	25	14	16	22	66
	TI2	24	30	37	24	33	42	15
	TI3	36	42	31	37	46	30	16
Clearcuts	TI4	25	7	7	25	5	6	3
	TI1	22	35	36	23	35	41	69
	TI2	32	36	38	30	31	34	18
	TI3	32	26	20	32	30	19	11
Shelterwood	TI4	14	3	6	15	4	6	2
	TI1	25	46	49	24	37	41	70
	TI2	30	24	29	32	34	37	18
	TI3	33	28	17	32	26	17	11
Single tree	TI4	12	2	5	12	3	5	1

* Six simulations per cell and using the system described by Carruth and Brown (1996).
† Skidding patterns 1, 2, 3, and forwarding pattern 1.

clearcut produced more bunches with higher volume per hectare, the proportion of TI4 in the clearcutting area was higher than in shelterwood and single-tree selection areas.

Since most soil compaction occurs during the first three to six passes (Froelich et al. 1981), TI3 and TI4 can be added to illustrate the total area that was impacted with three or more passes by a loaded machine. TI3 and TI4 ranged from 60% for SP1 to 49% for SP2 to 38% for SP3 in clearcuts with the chain saw and grapple skidder system (Table 6). Results were similar for the feller-buncher and grapple skidder system. For the harvester and forwarder, 19% of the area was in TI3 and TI4 for clearcuts. TI3 and TI4 also varied with harvest methods and decreased from clearcuts to shelterwood to single-tree selection method.

The three harvesting systems also were examined based on their production per week and cost per unit on-board truck. A hydraulic loader was used to load trucks in the skidder systems. Other handling costs were assumed to be equal for the three systems. Their production rates were determined by the machine productivity in the system. Two chain saws and one skidder were used in the balanced chain saw/skidder system, one feller-buncher and two skidders in the feller-buncher/skidder system, and one harvester and one forwarder in the harvester/forwarder system. Felling was the limiting function in harvester/forwarder systems. However, skidding was the limiting function in feller-buncher/skidder and chain saw/skidder systems. Production decreased from clearcuts to single-tree selection to shelterwood and also varied decreasingly from SP1 to SP3 to SP2 (Table 8). The feller-buncher and grapple skidder system was the most productive system, ranging from 685.8 to 945.0 m^3 per week. The harvester and forwarder system ranked second with 504.9 to 658.8 m^3 per week. The chain saw and grapple skidder system was the least productive (286.2 to 388.8 m^3 per week).

System costs per unit were calculated on-board truck prior to hauling using assumptions of machine rates (Miyata 1980). Labor was $10/hr plus additional labor-related costs totaling 40% of wages. Salvage value of the machine was 20% of its purchase price. Interest, insurance, and tax were assumed as 15%. Fuel and lubricants were $0.46 and $1.23/liter, respectively. The total cost of a representative chain saw was $17.55/PMH (Lortz et al. 1997). Mechanical availability of the chain saw was assumed as 50%. Building cost of skid trails was assumed $6/30 m (Erickson and Hassler 1991). Other assumptions varied by machine (Table 7).

The feller-buncher/grapple skidder system in clearcuts and SP1 was the least expensive at $8.08/$m^3$ followed by the harvester/forwarder system (Table 8). The chain saw/grapple skidder system in shelterwood and SP2 was the most expensive at $13.72/$m^3$. System costs also varied increasingly from clearcuts to single-tree selection to shelterwood method and from SP1 to SP3 to SP2. In the feller-buncher/skidder system, the cost in shelterwood and SP2 was $11.04/$m^3$ or 26.7% more than $8.7/$m^3$ in clearcuts. However, the cost in single-tree selection and SP3 was $9.41/$m^3$ or 8.0% more than that in clearcuts and SP3 ($8.67/$m^3$). Similarly, with the feller-buncher/skidder, the cost in single-tree selection in SP2 was $9.42/$m^3$ or 8.6% more; and in SP3 was $9.41/$m^3$ or 8.5% more than in SP1 ($8.67/$m^3$). The cost difference between SP2 and SP3 were offset by the cost of skid trails. If the average size of trees to be harvested was larger in single-tree

Table 7. Cost assumptions for the harvesting systems.

Machine	Purchase price ($)	Economic life (yr)	Scheduled hr/yr	Fuel liter/PMH	Lube liter/PMH	M/R % of D*	MA† (%)
Feller-buncher	152,000	4	2,000	15.2	5.7	100	65
Grapple skidder	90,000	4	2,000	13.3	3.8	90	60
Hydraulic loader	70,000	4	2,000	7.6	2.9	90	75
Harvester	300,000	5	2,000	9.5	3.8	100	60
Forwarder	190,000	5	2,000	7.6	2.9	100	70

* Maintenance and repairs as a percent of depreciation.
† Mechanical availability of machine.

Table 8. System productivity and on-board truck cost comparisons.

Item	Chain saw and grapple skidder			Feller buncher and grapple skidder			Harvester and forwarder
	SP1	SP2	SP3	SP1	SP2	SP3	FP1
	(m^3/wk)						
Clearcut	388.8	361.8	369.9	945.0	869.4	880.2	658.8
Shelterwood	305.1	286.2	291.6	739.8	685.8	699.3	504.9
Single tree	375.3	348.3	356.4	880.2	804.6	815.4	634.5
	($/$m^3$)						
Clearcut	10.26	10.76	10.71	8.08	8.70	8.67	9.39
Shelterwood	13.10	13.72	13.66	10.35	11.04	11.01	12.22
Single tree	10.61	11.16	11.16	8.67	9.42	9.41	9.74

* Skidding patterns 1, 2, 3, and forwarding pattern 1.

selection cuts, the cost of the harvester/forwarder system at \$9.74/m^3 would be competitive with the feller-buncher/grapple skidder system in SP2. The cost difference would be only \$0.32/m^3.

Discussion

Object-oriented modeling techniques (OMT) are viable methods for modeling timber harvesting systems and examining the effects of stand, harvest, machine, and extraction pattern factors on harvesting operations and forest sites. These methods can be used on inexpensive computer equipment with simple graphics capability without sacrificing details. The timber harvesting simulator developed with OMT is a Windows® standard system. The graphical user interface allows the user easy access to any part of the system.

Numerical simulation with predefined extraction patterns reduced simulation time and allowed exploration of alternatives. Currently, the numerical extraction simulation took several seconds versus 50 to 190 minutes with interactive simulation (Wang and Greene 1999). Machine travel was monitored in each felling plot of 40 by 40 m with interactive simulation. This is clearly too coarse a measure. After a smaller grid of 5 by 5 m was adopted in numerical simulation, travel intensities were much more accurate as they were recorded in 3,136 small cells on the same area of forty-nine 0.16-ha felling plots. Only about 25, 5, 6, and 2% respectively, of the logging area reached TI4 after skidding with SP1, SP2, and SP3 and after forwarding with FP1, compared with about 50 and 30% of TI4 after skidding and forwarding in the same area using the 40 × 40 m grid (Wang et al. 1998).

The simulation study also found that travel intensity, ASD, and hourly extraction production were significantly affected by extraction patterns, while cycle time and volume were sensitive to stand and harvest method. Skidding with SP1 gave the shortest extraction distance, lowest cycle time, and highest hourly production because it was defined as a freestyle skidding and no designated trails were used. Hourly skidding production with SP3 was slightly higher than that with SP2. Since designated skid trails were used in SP2 and SP3, skidding with SP1 showed a high level of TI4 compared with the level of TI4 with SP2 and SP3 after skidding. The forwarder always showed a lower proportion of TI4 and higher hourly production than the skidder because the forwarder's higher holding capacity resulted in fewer passes to extract logs. The ASDs with SP3 and FP1 were about the same due to their similarity.

The feller-buncher/skidder generally was more productive than the harvester/forwarder and chain saw/skidder. Production varied decreasingly from SP1 to SP3 to SP2. Similarly, system cost varied increasingly from SP1 to SP3 to SP2, but system costs in SP2 and SP3 were close. Extraction with SP3 always resulted in lower TI3 and TI4 than with skidding with SP1 and SP2. Skidding with designated skid trails is recommended to reduce the high-level travel intensity on logging sites. Results suggest that higher traffic intensity TI3 and TI4 could be reduced by about 22% using SP3 instead of SP1, but about \$0.6/m^3 is required for such trade-offs.

Terrain conditions of the forest site were not considered in the model. Also, the system does not simulate residual stand damage in partial cuts. The system should be modified to allow the use of irregular polygons whose boundary data can be obtained using a GPS unit or from digitized maps or photos. A model generation routine, search engine, and production equation database will be added into the system to allow the user to use other proposed machine types. In the future, it could be used as a harvest planning tool to lay out a planned timber sale and examine production, cost, and other factors. Further simulation will be conducted to vary the landing locations and payload size of the extraction machines. This work also will focus on modeling the environmental impacts of timber harvesting on soil disturbance and water quality.

Literature Cited

Aedo-Ortiz, D.M., E.D. Olsen, and L.D. Kellogg. 1997. Simulating a harvester-forwarder softwood thinning: A software evaluation. For. Prod. J. 47(5):36–41.

Baumgras, J.E., C.C. Hassler, and C.B. LeDoux. 1993. Estimating and validating harvesting system production through computer simulation. For. Prod. J. 43(11/12):65–71.

Borders, B.E., W.M. Harrison, D.E. Adams, R.L. Bailey, and L.V. Pienaar. 1990. Yield prediction and growth projection for site-prepared loblolly pine plantations in the Carolinas, Georgia, Florida, and Alabama. Univ. of Georgia PMRC Tech. Rep. 1990-2.

Carruth, J.S., and J.C. Brown. 1996. Predicting the operability of South Carolina coastal plain soils for alternative harvesting systems. USDA For. Serv. Gen. Tech. Rep. NC-186. 8 p.

Clark III, A. and J.R. Saucier. 1990. Tables for estimating total-tree weights, stem weights, and volumes of planted and natural southern pine in the southeast. Georgia For. Comm. Res. Pap. 79.

DYKSTRA, D.P., AND J.L. RIGGS. 1977. An application of facilities location theory to the design of forest harvesting areas. Trans AIIE 9(3):270-277.

ELIASSON, L. 1999. Simulation of thinning with a single-grip harvester. For. Sci. 45(1):26–34.

ERICKSON, M.D., AND C.C. HASSLER. 1991. Productivity and cost estimates for conventional ground based skidding on steep terrain using preplanned skid roads. USDA For. Serv., Morgantown, WV.

FARRAR, K.D. 1981. In situ stand generator for use in harvesting machine simulations. M.Sc. thesis, Virginia Polytech. and State Univ., Blacksburg. 211 p.

FRIDLEY, J.L., J.L. GARBINI, J.E. JORGENSEN, AND P.A. PETERS. 1985. An interactive simulation for studying the design of feller-bunchers for forest thinning. Trans. of ASAE. 28(3):680–686.

FROELICH, H.A., D.E. AULERICH, AND R. CURTIS. 1981. Designing skid trail systems to reduce soil impacts from tractive logging machines. Oregon State Univ. Res. Pap. 44.

GOULET, D.V., R.H. IFF, AND D.L. SIROIS. 1979. Tree-to-mill forest harvesting simulation models: Where are we? For. Prod. J. 29(10):50–55.

GREENE, W.D., AND B.L. LANFORD. 1984. Geometric simulation of feller-bunchers in southern pine plantation thinning. Am. Soc. Agric. Eng. Pap. No. 84-1612.

GREENE, W.D., AND B.L. LANFORD. 1986. An interactive simulation program to model feller-bunchers. Alabama Agric. Exp. Sta. Bull. No. 576.

GREENE, W.D., B.L. LANFORD, AND E.F. MYKYTKA. 1987. Stand and operating effects on feller-buncher productivity in second thinnings of southern pine. For. Prod. J. 37(3):27–34.

GREENE, W.D., AND J.F. MCNEEL. 1987. Productivity, costs, and levels of butt damage with a Bell Model T feller-buncher. For. Prod. J. 37(11/12):70–74.

GREENE, W.D., AND J.F. MCNEEL. 1991. Productivity and cost of sawhead feller-bunchers in the South. For. Prod. J. 41(3):21–26.

HASSLER, C.C., J.F. MCNEEL, AND D.P. BRADLEY. 1985. A comparison of cutting patterns for a track-type feller-buncher. For. Prod. J. 35(3):31–38.

KLUENDER, R., D. LORTZ, W. MCCOY, B. STOKES, AND J. KLEPAC. 1997. Productivity of rubber-tired skidders in southern pine forests. For. Prod. J. 47(11/12):53–58.

KLUENDER, R., AND B. STOKES. 1994. Productivity and costs of three harvesting methods. South. J. Appl. For. 18(4):168–174.

LANFORD, B.L., AND B.J. STOKES. 1995. Comparison of two thinning systems. Part 1. Stand and site impacts. For. Prod. J. 45(5):74–79.

LEDOUX, C.B., AND D.A. BUTLER. 1981. Simulating cable thinning in young-growth stands. For. Sci. 27(4):745–757.

LEDOUX, C.B., J.E. BAUMGRAS, AND J. SHERAR. 1994. Comparison of contemporary cable harvesting practices for eastern hardwoods on steep slopes. P. 155–166 in Proc. of meeting on Advanced technology in forest operations: Applied ecology in action, Oregon State Univ., For. Eng. Dep., Corvallis.

LORTZ, D., R. KLUENDER, W. MCCOY, B. STOKES, AND J. KLEPAC. 1997. Manual felling time and productivity in southern pine forests. For. Prod. J. 47(10):59–63.

MIYATA, E.S. 1980. Determining fixed and operating costs of logging equipment. USDA For. Serv. Gen. Tech. Rep. NC-55.

MOSER, J.W., JR. 1976. Specification of density for the inverse J-shaped diameter distribution. For. Sci. 22(2):177–184.

MULARI, J., R. HAARLAA, X. SUN, AND J. WANG. 1996. Mobility and feasibility of tracked excavators in forestry operations. Univ. of Helsinki, Dep. For. Resour. Manage. Publ. 11.

NEWNHAM, R.M. 1968. Generation of artificial population of points (spatial patterns) on a plane. For. Manage. Res. and Serv. Inst., Ottawa, Canada. Inf Rep FMR-X0101. 28 p.

RANDHAWA, S., AND T. SCOTT. 1996. Model generation for simulation process: An application to timber harvesting. Comp. Ind. Eng. 30(1):51–60.

SESSIONS, J. 1979. Effects of harvesting technology upon optimal stocking regimes of forest stands in mountainous terrain. Ph.D. Diss., Dep. of For. Manage., Oregon State Univ., Corvallis, OR. 259 p.

STUART, W.B. 1981. Harvesting analysis technique: A computer simulation system for timber harvesting. For. Prod. J. 31(11):45–53.

TUFTS, R.A., B.J. STOKES, AND B.L. LANFORD. 1988. Productivity of grapple skidders in southern pine. For. Prod. J. 38(10):24–30.

TUFTS, R.A., AND R.W. BRINKER. 1993. Productivity of a Scandinavian cut-to-length system while second thinning pine plantations. For. Prod. J. 43(11/12):24–32.

WANG, J., W.D. GREENE, AND B. STOKES. 1998. Stand, harvest, and equipment interactions in simulated harvesting prescriptions. For. Prod. J. 48(9):81–86.

WANG, J., AND W.D. GREENE. 1999. An interactive simulation system for modeling stands, harvests, and machines. J. For. Eng. 10(1):81–99.