An Interactive Simulation System for Modeling Stands, Harvests, and Machines

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ABSTRACT

An interactive computer simulation program models stand, harvest, and machine factors and evaluates their interactions while performing felling, skidding, or forwarding activities. A stand generator allows the user to generate either natural or planted stands. Felling with chainsaw, drive-to-tree feller-bunchers, or harvesters and extraction with grapple skidders or forwarders are currently modeled in the system and others may be added. Simulations are performed by moving machine images within stand maps on the computer screen. The residual stand, machine running paths, and extraction travel intensity are recorded for later analysis. Examples of simulations with common logging machines are illustrated.

Keywords: *Interactive simulation, system modeling, stand generator, partial cutting, forest operations.*

INTRODUCTION

Computer simulation has been used extensively in the analysis of forest harvesting systems. Due to the wide variety of logging systems used and the variation among the types of forest stands harvested, simulation often offers the only way to examine certain logging situations. In general, simulation involves building a model of a system to assess how it reacts to changes in its operating environment. Model formation is recognized as the most difficult phase in building a simulation program.

Forest harvesting simulations have been addressed by many researchers during the last three decades. These simulation models were either tree-to-mill models or phase models. Tree-to-mill

models focused on the entire harvesting process. The phase models, on the other hand, modeled or evaluated only a certain phase or part of the harvesting process.

The earliest known published study in the United States was an attempt at simulating a pulpwood harvesting system using a strictly deterministic approach (21, 32). A more extensive simulation was then reported by Johnson *et al.* (22) and Johnson and Biller (23). This approach did allow for stochastic variations as experienced by a real system. Although this represented perhaps the first real attempt at duplicating a harvesting system's performance, the reported results indicated that additional explanations and improvements were needed.

Bare *et al.* (1) developed a computer simulation model for evaluating logging residue handling systems. Yarding, chipping, sorting, loading, transporting, and unloading were modeled in the program. Because it was a fixed-time simulator, the program did not account for interactions between dependent operations within a time period.

Goulet *et al.* (13, 14, 15) reviewed and summarized the models available through 1980. Eight models were described and their properties collated.

A numerical simulation system for modeling individual machine activities was developed by Stuart (30). The program (GENMAC) defined the working area of the machine as a swath of a certain width. The machine first moved to cut the tree in the swath with the smallest x-coordinate. The machine then moved to cut the tree with next smallest x-coordinate.

Winsauer and Bradley (33) modeled a rubber-tired feller-buncher to examine its productivity and operation. It was a discrete event simulation program. The model consisted of two GPSS (General-Purpose Simulation System) segments: timer segment and feller-buncher segment. The formatted output was provided by two FORTRAN subroutines. By using the same technique, Winsauer (34) also modeled a grapple skidder and whole-tree chipper to evaluate the productivity and efficiency of a given skidder-chipper combination. The trees to be skidded in the model were assumed to be bunches left by earlier felling.

Garbini *et al.* (12) used numerical simulation

with graphical animation to illustrate material movement and machine activities in continuous simulation of a log merchandiser. The program was developed to increase piece production rates of log merchandisers with smaller tree sizes being harvested. In another decision simulator application, graphical animation and numerical data were used to make log bucking decisions (25). This described an interactive program that allowed individual operators to compare their own attempts at log bucking with actual computed optimal solutions. This application saved millions of dollars for a major forest products company by improving the use of their raw material furnish.

Fridley *et al.* (8, 10) and Fridley and Jorgensen (9) reported the use of graphical interactive simulation for studying the design of swing-to-tree feller-bunchers used for thinning. The program used graphical animation as output for verification and evaluation purposes. The program was used to identify the effect of various design parameters on feller-buncher performance during thinning (11).

Greene and Lanford (16, 17) developed an interactive simulation program for modeling feller-bunchers. Working with this simulation, Greene *et al.* (18) examined the effects of stand and operating factors on the productivity of a small feller-buncher in second thinning operations and concluded that average tree diameter and the number of trees per accumulation were the most important factors observed and bunch size, the spacing between corridors, and the average distance between trees were less important but still significant. They also found that variability between simulation operators existed but did not appear to affect the usefulness of interactive simulation (19).

A tree harvesting simulator (TREESIM) was developed on the foundation of the Auburn Harvesting Analyzer (31) based on Lotus 1-2-3 spreadsheet to estimate costs of an entire forest harvesting system (7). The program, along with experience, common sense, and basic information on logging systems, was an addition to the logger's toolbox that could be used to improve the operations.

Reisinger *et al.* (28) described and evaluated three PC-based programs for analyzing harvesting systems including Auburn Harvesting Analyzer (31), Harvesting System Analyzer (20), and Harvesting System Simulator (30). They concluded that three microcomputer-based programs produced comparable results using realistic system data and the appropriateness of these models depended on the user's choices.

A three-dimensional, color, interactive, real-time, computer graphics simulation of a feller-buncher was developed by Block and Fridley (3). The simulation operator viewed on the computer screen what would be seen looking through the windshield of a feller-buncher in operation. The software allowed the programmer to vary physical parameters of the feller-buncher that would affect its performance in the forest.

A ground based harvesting system simulation model was also developed to estimate stump-to-truck production rates and multi-product yields for conventional ground-based timber harvesting systems in Appalachian hardwood stands (2). This program evaluated a model numerically over a time period of interest, and data were gathered to estimate the desired true characteristics of the model.

A method of estimating tree damage was developed in conjunction with an interactive machine simulation program that could model harvesting performance in a variety of silvicultural operations (4). The damage estimation worked well in an empirical comparison, but further testing with data from other harvesting systems and stands might improve the model's usefulness.

One logging situation which has been difficult to accurately simulate with numerical simulation is the movement of a felling machine performing partial cuts or a skidding machine during extraction. The machines must avoid the remaining trees in the stand while effectively moving between the trees to be cut or the wood to be extracted. Many logging simulators do not model or adequately model these machine movements. Studies using interactive simulation to study felling or skidding machines have found it to be a useful method of studying mechanical harvesting in partial cuts.

The utility of interactive computer simulation has been demonstrated by these researchers. However, many of these reports are based on data from systems and conditions that are different from those encountered today. Furthermore, today's computer simulation environment and techniques can vastly improve and expand the forest

harvesting simulation approaches used previously.

OBJECTIVES

This paper reports on: (1) developing a stand generator to allow a user to create stand conditions to perform harvesting simulations conveniently and cost-effectively; (2) adapting reported techniques for interactive graphical simulation of forest harvesting operations to handle a variety of partial cuts and skidding or forwarding activities in mature stands; and (3) modeling chainsaw felling, drive-to-tree feller-bunchers, and cut-to-length harvesters performing felling duties, and grapple skidders and forwarders in extraction activities in the partial cuts considered.

METHODS

Computer simulation is a technique for modeling the behavior of both natural and man-made systems. Generally speaking, there are two basic types of simulation - physical and numerical (5). Interactive simulation is a hybrid of the above two types of simulations, which utilizes a high level of human participation. One of the most important decisions one must make in performing a simulation program is the choice of the simulation languages (24). In general, there are two types of simulation languages - specified-use simulation languages such as SLAM and GPSS or general-purpose languages such as FORTRAN, BASIC, C/C++, and Visual BASIC. Compared to the specified-use simulation languages, general-purpose languages provide the following advantages: (1) efficient execution time, (2) greater programming flexibility, and (3) lower software cost. However, they can not provide the natural ready-made framework for simulation modeling.

The approach used in this system relies on interactive graphical simulation techniques written with Visual Basic Version 4.0 (26), an event-driven programming language. The system requires: (1) any IBM-compatible machine with an 80386 or higher processor, (2) a hard disk with a minimum available space of 50 MB, (3) 8 MB of memory, and (4) Windows 95 or later. Visual Basic was selected because it allows the programmer to create robust and useful applications that make full use of the graphical user interface (GUI). In addition, the programmer can also create pow-erful and full-featured applications such as data access, Object Linking and Embedding (OLE), and dynamic-link library (DLL) with Visual Basic.

Object-oriented programming techniques were adopted in the system (29). They allowed the program to be organized as a collection of discrete objects that incorporated both data structure and behavior.

SYSTEM MODELING AND MODULARITY

System Modeling

Three felling machines - chainsaw, feller-buncher, and harvester - and two extracting machines - grapple skidder and forwarder - are now modeled and implemented in this simulation program. Other logging machines such as swing-to-tree feller-bunchers, clam-bunk skidders, shovels, or other machines can be easily modeled by slightly modifying the simulation program. Abstraction is one of the important aspects of building harvesting machine models since it can capture the crucial aspects of the problem and omit the others. The configurations of these five harvesting machines were defined as follows. The functions of the machine are later defined as the corresponding command buttons in the simulation system.

Chainsaw:	Walk to tree, acquiring, felling, delimbing and topping;
Feller-buncher:	Move to tree, cut, move to dump, dump;
Harvester:	Move to tree, boom extend/retreat, cut, swing boom, processing and dumping;
Grapple skidder:	Move to load, grapple load, travel loaded, delimbing using a gate, ungrapple.
Forwarder:	Move to load, load, move during loading, travel loaded, and unload.

Operating variables such as production rates for these machines are evaluated by simulating felling or skidding activities and comparing these figures to current production records or data from time studies. Distance traveled and the number of machine passes within the plot are recorded to indicate the potential damage to site or soil from equipment travel. Plot size used for felling simulation depends on the user's choice. Plot sizes of

larger than 400 m² (0.1-acre) but less than 4,000 m² (1.0-acre) work best. Stand map data involve locating each tree within a plot using a coordinate system and recording its species, DBH, total height, volume, whether or not it is to be harvested, and other information. This map information forms the basis for the simulation effort. The logging site for extraction simulation is an enlarged area created by replicating felling plots.

System Modularity

The program is written based on the principles of software engineering. An object-oriented structure model is employed with a three-level hierarchy (project, modules, and procedures) with built-in methods and custom controls. Correspondingly, there are three-level declarations of variables. The hierarchy of this simulation program (project) consists of 28 form class modules and a standard module. Project is a systematic structure of all modules and objects in the system. Each form class module contains one or more procedures. Each procedure includes one or more methods and custom controls. About 80 event and general procedures with 1800 methods and controls are included in the program, some of which are represented as the objects in the process of object-oriented programming.

SYSTEM STRUCTURE AND REQUIREMENTS

The modularity or internal organization of this simulation program served as a functional tool for project management. To help users perform the simulation program conveniently and easily, the system adopted the event-driven techniques using GUI. Usually, an event is executed by clicking a corresponding command button or an item by using the mouse. The main event procedures are FILE, RUN, ANALYSIS, VIEW, OUTPUT, HELP, and EXIT (Figure 1). Other forms and/or procedures are contained under each of these main even procedures. Controls in the system are implemented using event-driven techniques. An event is executed by clicking a corresponding command button or an item in simulation windows, which is composed of an event procedure (Figure 2).

RUN Procedure

The RUN event procedure is the key part of the system (Figure 3). It contains a stand generator, a felling simulator, and an extraction (skidding or forwarding) simulator. These subsystems can be performed sequentially or independently.

The structure of data produced by the stand generator is consistent with the input needed for felling simulation. Either natural or planted stands can be generated by the stand generator for use in later felling simulation. Inputs for the stand generator are species, stand age, stand density, dominant height, minimum and maximum DBH, spatial pattern, and even or uneven age (for natural stands). Outputs of the stand generator are displayed on the computer screen and saved as an ASCII data file that includes X-Y coordinate, DBH, height, and volume of each tree in a specified square plot. Random, uniform, and clustered spatial patterns are modeled for natural stand. Random and uniform patterns are used for plantation.

Machine simulations are performed using several windows on the computer screen. The main window displays the stand map or tree piles, machine running paths, and the machine image in addition to the main event command menu bar. In this stand map window, each solid blue circle represents a tree of a given diameter during felling. When a tree is cut, a solid black circle is drawn to signify the stump and the machine can move forward from this point. Later, if the operator performs a cutting at this point, the program will indicate the "tree not found". During skidding or forwarding simulations, black circles represent the location of piles of felled trees. When a pile is grappled or loaded, a "+" symbol is drawn to identify the pile is loaded.

Machine images are rotated 360⁰ by transforming the coordinate system of the machine (27). The machine image detects obstacles such as remaining trees. When the machine collides with a tree, the program gives both sound and text warnings. The machine must then move in the opposite direction or shear the now "damaged" tree. Similarly, when the machine's holding capacity exceeds its maximum limit, sound and text warnings are also provided.

For a felling simulation, the user inputs the stand data file name generated earlier, machine running path name (for later storing), felling machine type, and plot size for a felling simulation. Plot size is variable, but the default plot size for felling simulation is a square plot of 0.16-ha (0.4-
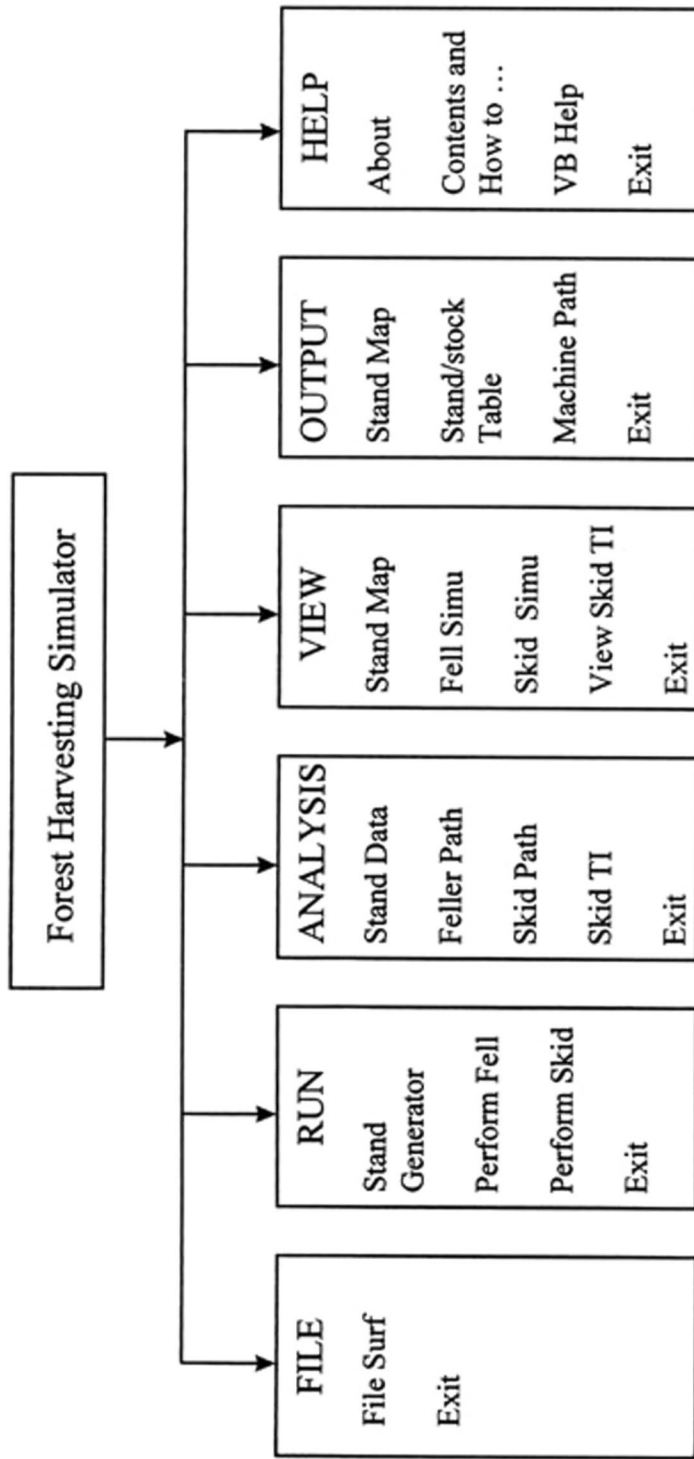
Figure 1. System structure of interactive forest harvesting simulator.
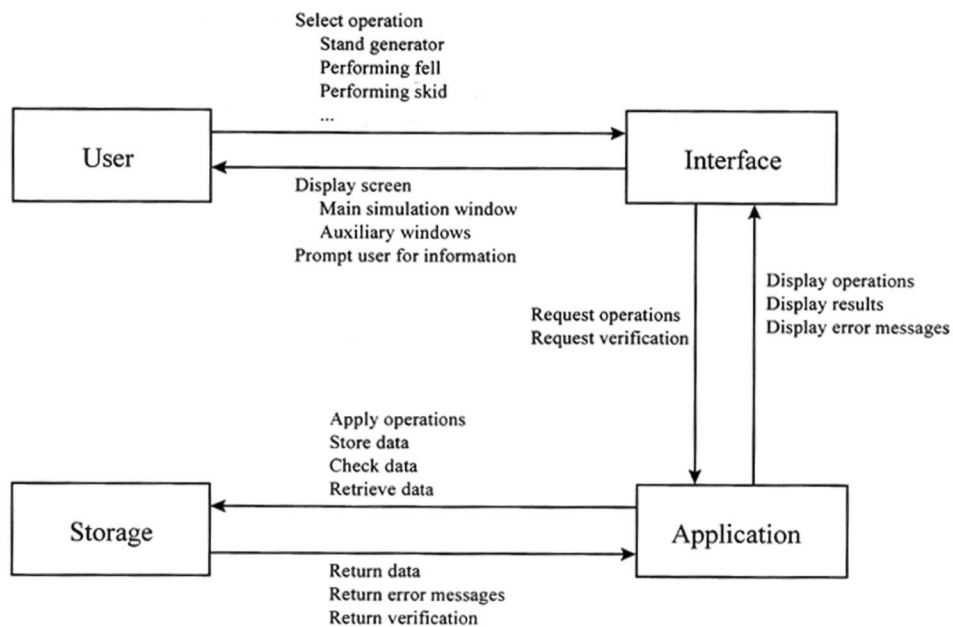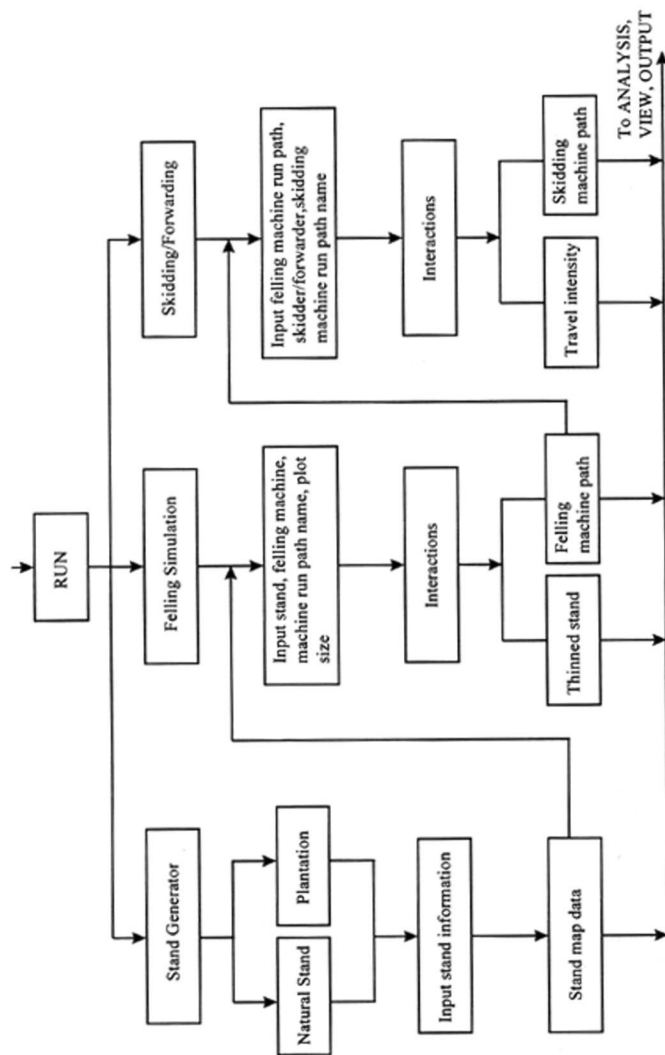
Select operation
   Stand generator
   Performing fell
   Performing skid
   ...

User → **Interface**

Display screen
   Main simulation window
   Auxiliary windows
Prompt user for information

Display operations
Display results
Display error messages

Request operations
Request verification

Apply operations
Store data
Check data
Retrieve data

Storage → **Application**

Return data
Return error messages
Return verification

Figure 2. Event flow diagram of the system.

Figure 3. Flowchart of RUN procedure in the system.

acre) that measures 40 m by 40 m (132 feet by 132 feet). The interactive simulation results are shown on the computer screen. When ending a felling simulation run, two ASCII files are saved. One file contains the residual stand data while the other contains the coordinates of the machine path through the stand. Data in both files can be used in later analyses or to form the basis of extraction simulations.

The extraction simulation procedure is well implemented to fulfill the skidding or forwarding simulation. With this procedure, the user is required to enter the felling machine running path file, felling plot size, number of replications of the felling plot to use, and skidder or forwarder. The skidding or forwarding simulation is based on the results of felling simulations, which is performed in a larger area (default 49 replications of the default felling plot = 7.84 ha. (19.6 acres)). The felling plot can be replicated 36, 49, 64, 81, or 100 times in the system to create an extraction plot. Then the system will replicate the requested numbers of the felling plot to create a larger area for skidding or forwarding. Simultaneously, tree or log piles identified by location, number of trees or logs, and volume are displayed on computer screen. As with felling, the interactive skidding or forwarding simulation results are also shown on the computer screen and updated as the activities occur. When ending this simulation, two ASCII files are also saved. Those two files have the same name as the felling machine path but different extension names. The skidder or forwarder running path file has the extension ".skd", with a data structure including X-Y coordinates of skidding machine path, machine actions, trees or logs per turn, and volume per turn. This file can be used for later analysis in the ANALYSIS procedure. The skidder/forwarder travel intensity file has an extension of ".sti", whose data structure contains the indexes of a felling plot array plot(i,j), number of pass loaded, and travel intensity category.

While performing skidding or forwarding simulations, the travel intensity category within each felling grid is shown on the screen with a little square in four different colors. Four travel intensity categories of skidder or forwarder are defined in the system as follows (6):

TI1 - Trees on the plot have been felled.

TI2 - Trees which stood on the plot have been re-

moved and no other traffic has passed through the plot.

TI3 - Trees which stood on the plot have been removed and trees outside the plot have been skidded through the plot. Passes with a loaded machine are between three and ten.

TI4 - More than ten loaded machine passes have been made through the plot.

Two smaller auxiliary windows are provided to display machine summaries and action command buttons that vary with different harvesting machines. The left mouse button invokes the action commands and loads the machine image at the beginning of the simulation. The right button is used to move the machine image. Simulations are performed by moving the machine image with the mouse in the stand map displayed on the computer screen.

The system can compare the original stand to the residual stand in the format of stand and stock tables. Since partial cuts alter the diameter distribution of the stands, histograms of diameter distribution are provided in auxiliary windows along with stand and stock tables. The machine running paths can be also analyzed statistically and economically.

A simulation performed earlier can be viewed again with the system. The stand map, a histogram of DBH distributions, stand and stock tables, elemental time, machine summary by work cycles, a machine production summary, a summary for the harvested stand and logging site, and the machine running path files can be displayed on screen or printed on paper.

FILE Procedure

File Surf is implemented as an independent procedure under FILE. By using it, the user can browse the files under a specified directory in a specified drive as in a typical file browser. This allows the user to browse and find files created while performing simulations without exiting the system.

ANALYSIS Procedure

This is a routine statistical analysis procedure providing stand and stock tables and histograms of trees per acre by DBH class. Activities of fell-

ing and skidding machines are also analyzed with four summaries provided: (1) elemental time summary, (2) machine summary by cycle, (3) summary of harvested stand or extracting site, and (4) production summary. At the same time, the operating costs of the machines can be calculated by using the machine rate method if desired. Another procedure is available to summarize the proportion of felling grids in each travel intensity category after skidding or forwarding over the whole logging area.

VIEW Procedure

Three procedures are implemented under VIEW to retrieve and view the stand map, felling operations, and skidding operations. The user inputs stand map data file and felling machine running path file for viewing felling simulation, and skidding or forwarding machine running path file, felling plot size, number of replications of felling plot for viewing skidding or forwarding simulation. Since four categories of travel loaded intensity of skidder or forwarder are defined based on the number of travel loaded passes on a felling plot, the layout of travel intensity represented by four different colors can be viewed by invoking another subprocedure under VIEW.

OUTPUT Procedure

Seven procedures are implemented under OUTPUT. Either ASCII data files or screen outputs in RUN and ANALYSIS procedures can be reproduced on the paper by invoking the event procedures under OUTPUT.

HELP Procedure

The structure and contents of this simulation system are well documented in HELP procedure. The system is also designed to load the Visual Basic online helps automatically even without installing the Visual Basic software on a user's computer.

SIMULATION EXAMPLE

Felling Simulation

To illustrate the use of this program, suppose a southern pine plantation was first generated by the system using user inputs. The stand contains 975 trees/ha (390 trees/acre). We will simulate felling in a 40 m by 40 m square plot containing 0.16 ha using a drive-to-tree feller-buncher.

To begin the felling simulation, the user enters the stand map file, the felling machine run path file name, type of the machine, and plot size. Three windows are then displayed on the computer screen. The largest window contains a copy of the stand map. The two smaller windows display a machine summary and the machine action command buttons. At this point, the user may mark the trees to be cut or left. Trees can only be marked by DBH class with marked trees represented by a red circle around them.

A feller-buncher image is loaded in main simulation window using the left mouse button. The operator chooses the appropriate action by clicking the command button in machine action window. The machine is moved to the tree to be cut or a desired location by pointing to the position and clicking with the right mouse button in main simulation window. After the tree is cut, a solid black circle is drawn at the location of cut tree and the machine summary is updated and displayed in its window. The above procedures are repeated until the head is full. The operator then moves the machine image to the location of the bunch to be built and drops the trees. The machine summary window is then cleared, showing an empty head on the machine, and the dropped trees are drawn to scale in the direction they fell on the screen (Figure 4). After the stand is cut, only residual trees, stumps, and bunches of felled trees remain (Figure 5).

Chainsaw felling is also supported (Figure 6). First, the user draws a line segment to indicate the desired felling direction in the chainsaw felling action window. If the mirror-image felling direction is later preferred, the user can switch to this direction using the "Options" button. Notice that the first two trees were felled in the initial direction defined in action window while the last two were felled in the mirror-image direction.

Felling and processing by a cut-to-length harvester can also be simulated (Figure 7). The harvester boom can reach several trees from each machine location. A circle drawn around the harvester indicates the potential reach of the boom. This circle moves as the harvester moves. Trees on any side of the machine within the boom reach can be removed based on the user's choice or harvest methods. The processed trees are then dropped where desired for later forwarding.
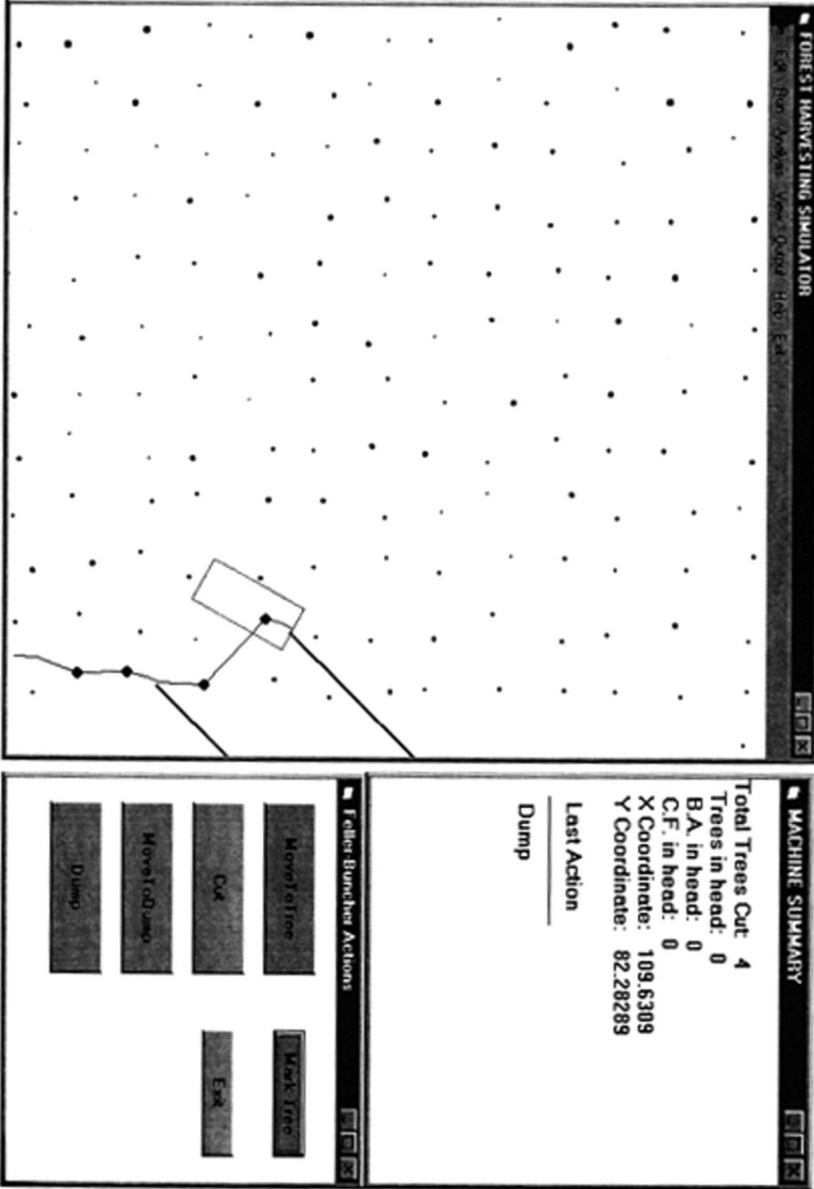
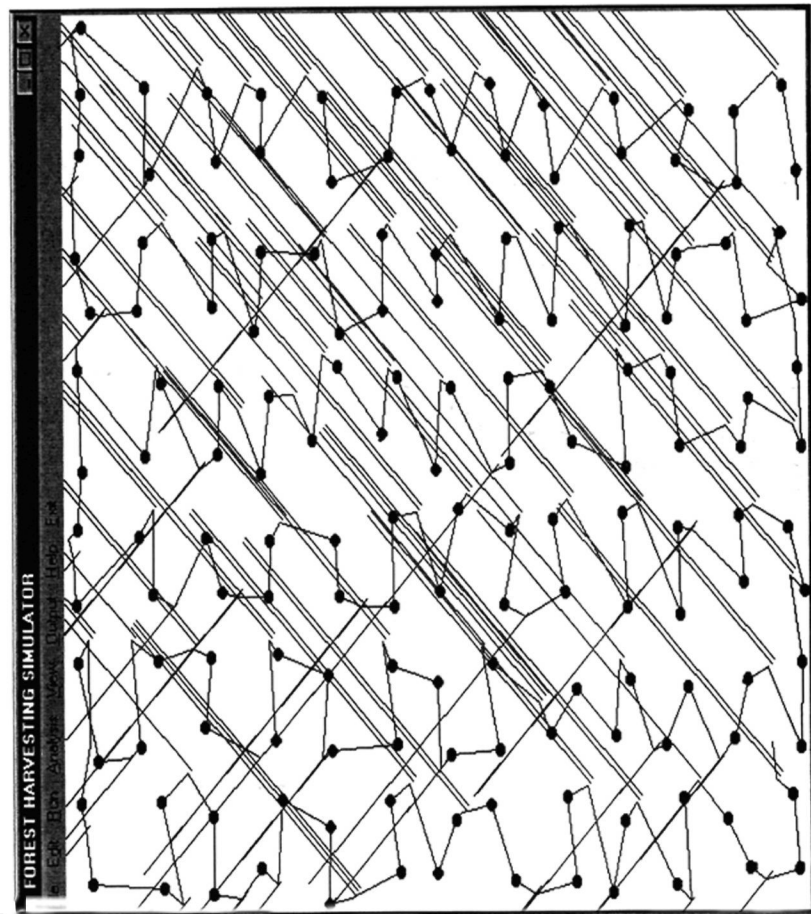Figure 4. Simulation display of a feller-buncher after cutting four trees and building two bunches.

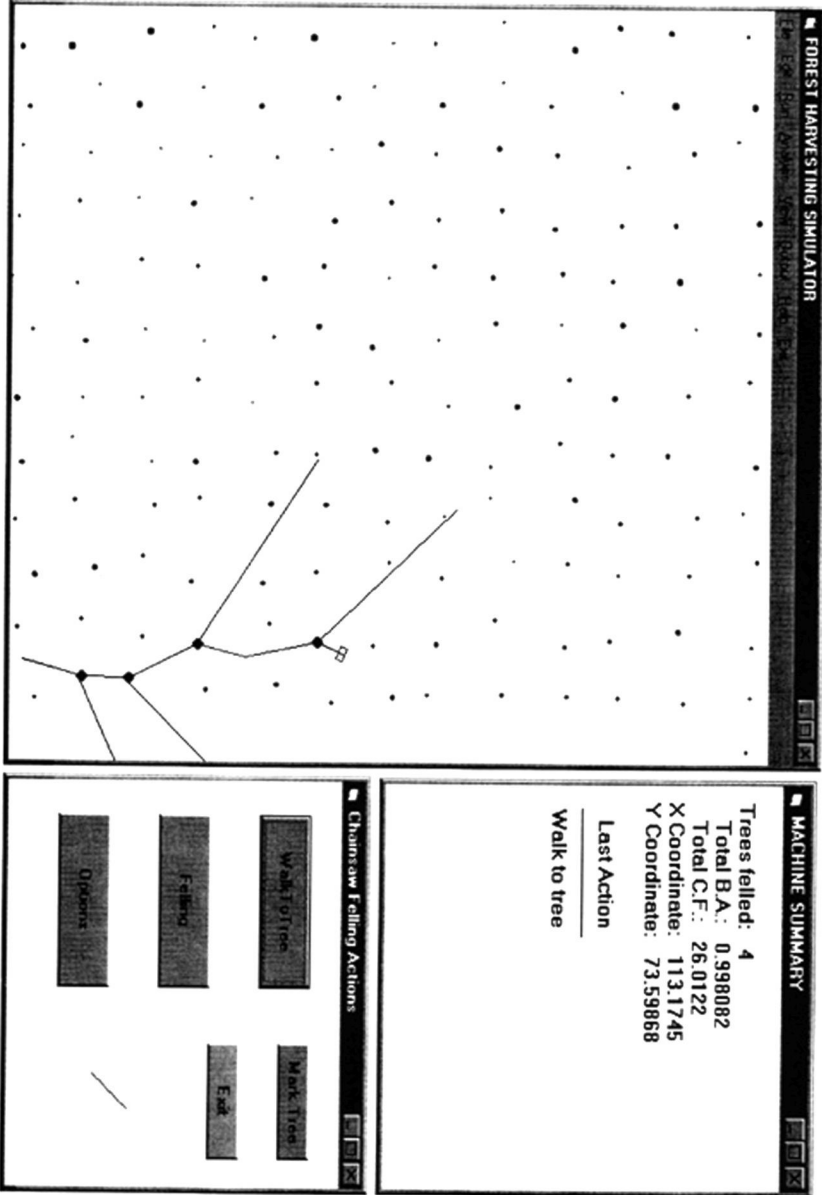Figure 5. Simulation display of a feller-buncher after cutting the entire plot.

Figure 6. Simulation display of chainsaw felling after cutting four trees.
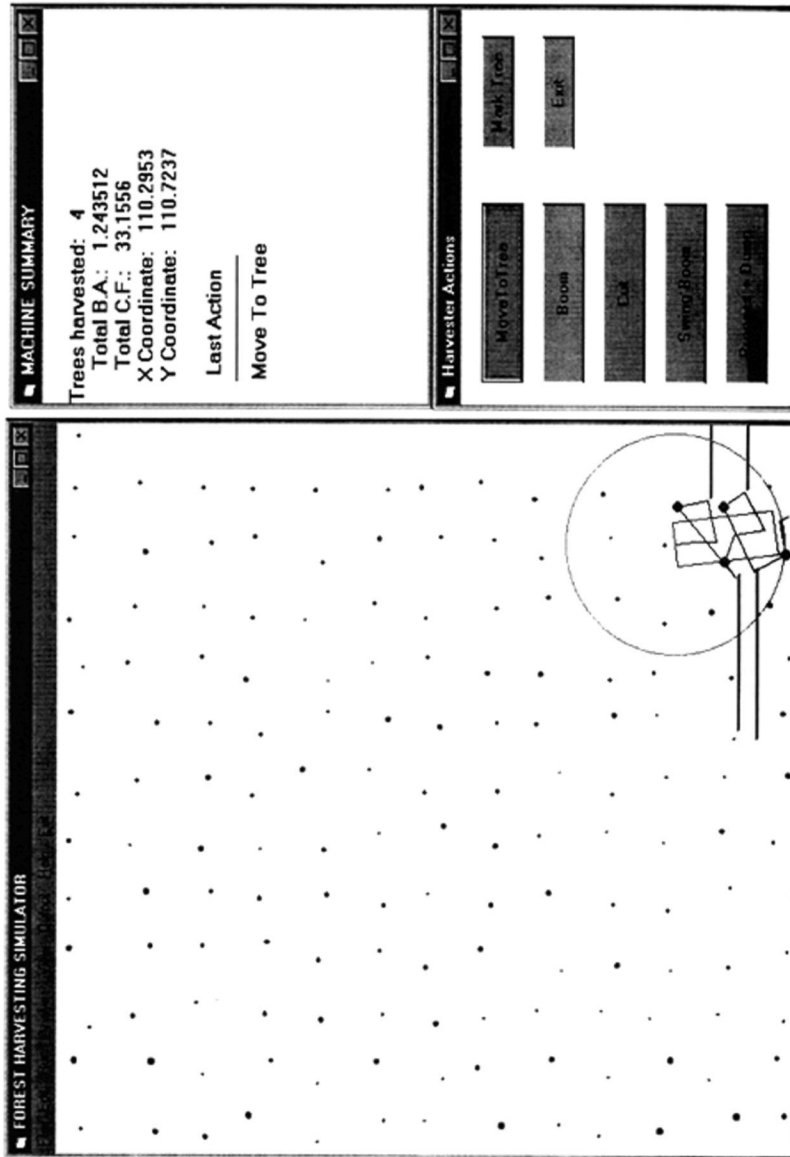
Figure 7. Simulation display of a cut-to-length harvester after cutting four trees.

When ending a felling simulation, two general types of summaries are provided: (1) stand summaries and (2) machine summaries. The stand summary compares the original stand to the residual stand and computes the trees, basal area, and volume removed per unit area in partial cuts. This is provided in the stand and stock table format commonly used by foresters to report stand information and in histograms. Machine summaries are provided in four parts: (1) an elemental time summary, (2) a summary by cycle, (3) a summary of harvested stand, and (4) a production summary.

Skidding/Forwarding Simulation

To perform a skidding or forwarding simulation, the user enters the felling machine path file, felling plot size, number of replications of the felling plot, number of trees pre-piled, skidder or forwarder, and the skidding machine run path name. Three windows are displayed on the computer screen similar to those used in felling.

The simulation of a grapple skidder with 49 replications of felling plot (7.84 ha) is shown in Figure 8. Each grid in the bigger window represents a felling plot (0.16 ha). Each black circle represents a bunch of felled trees (or processed stems if felling was peformed by a harvester). The two smaller windows display the skidding machine summary and action command buttons.

The user first locates the landing using the left mouse button. A larger red "+" is drawn at the center of the landing. The machine is moved to the bunch to be grappled by pointing to its position and clicking the right mouse button. The user then selects the appropriate action by clicking a button in action window. When the machine reaches the maximum holding capacity, the user will be given both sound and text warnings. After grappling the bunch, a smaller blue "+" is drawn at the bunch location to indicate that the bunch was loaded. A small color square is also displayed in this grid to represent the intensity of travel within the grid. The above procedures are repeated until all bunches in the skidding site are extracted to landing (Figure 9). Forwarders are simulated in a similar manner (Figure 10).

After a skidding or forwarding simulation, a machine summary and travel intensity summary are provided. The machine summary is provided in four parts: (1) an elemental time summary, (2)

a summary by cycle, (3) a summary of logging site, and (4) a production summary. The travel intensity summary provides the proportion of the logging site in each travel intensity category.

DISCUSSIONS AND FUTURE WORK

Interactive simulation is a viable method for examining the operation and working patterns of machines in forest stands. The method can be used on relatively inexpensive computer equipment with simple graphics capability without sacrificing excessive detail. Such a method offers potential for studying and improving the work methods of operators and machines in a variety of harvest prescriptions. Since the program requires user decisions as input, the results obtained through the simulation are more easily accepted. The user immediately sees the effects of his decisions while running the program. No programming skills or specific computer knowledge are required to use this simulation system. The graphical user interface (GUI) allows the user to easily access any part of the system.

Some things still need to be improved in the system. Slopes on forest sites are not currently considered in the program. The system also does not consider or simulate tree damages during partial cuts. Machine productivity is estimated using production models from previous time studies. This limits use of the system to machines for which some field data are available. Validation of simulated travel patterns with actual field studies is needed and is currently being planned.

The interactive simulation system is relatively labor-intensive, especially for simulating skidding or forwarding. Interactive simulation of felling on a 0.16-ha (0.4 acre) plot takes 10 to 35 minutes depending on stand density and harvest method. Simulating skidding on the 7.84-ha skiddding area took 40 to 190 minutes depending on stand, harvest, and machine factors. Numerical simulation has recently been added to the system to allow simulation of skidding and forwarding without the time commitment. The interactive system, however, is designed to allow the user to perform part of a simulation at one time and continue the work at the other time. For many potential users, the improved accuracy and low cost of the method may more than offset the need for labor.
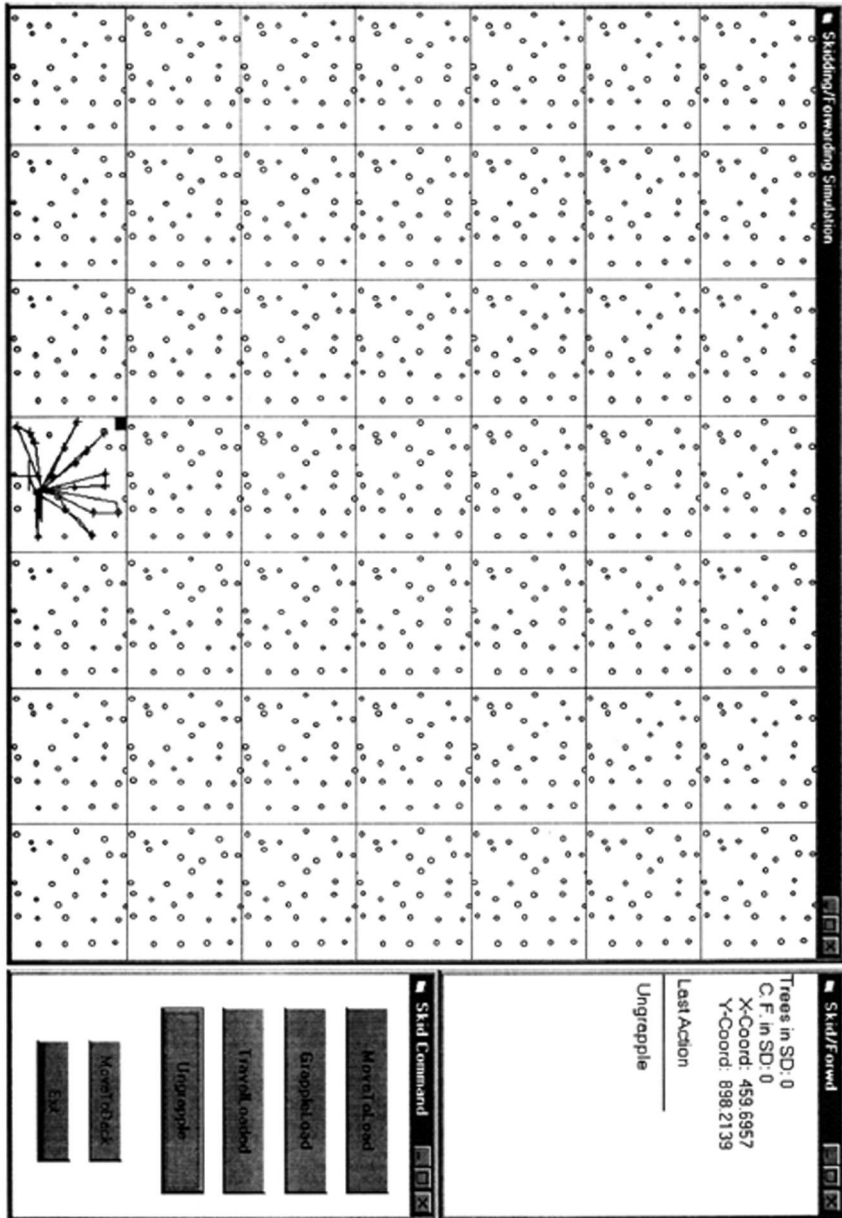
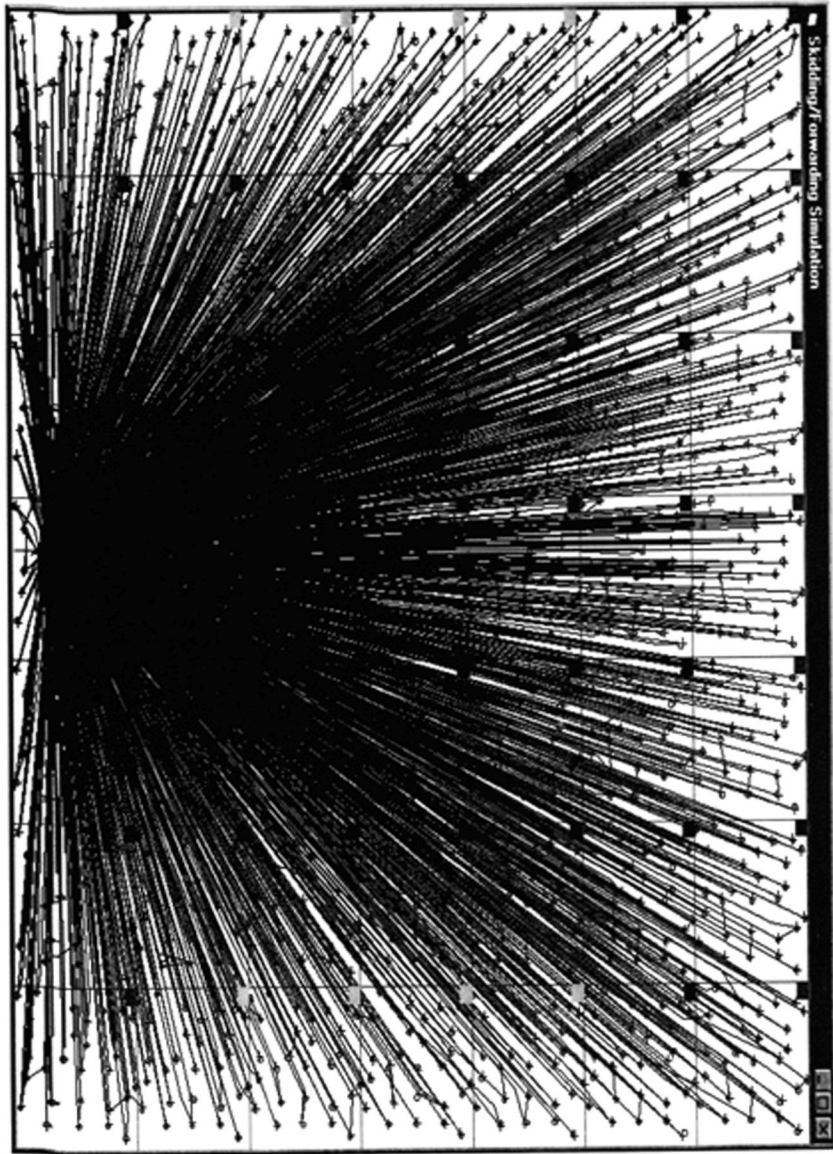Figure 8. Simulation display of a grapple skidder in extraction.

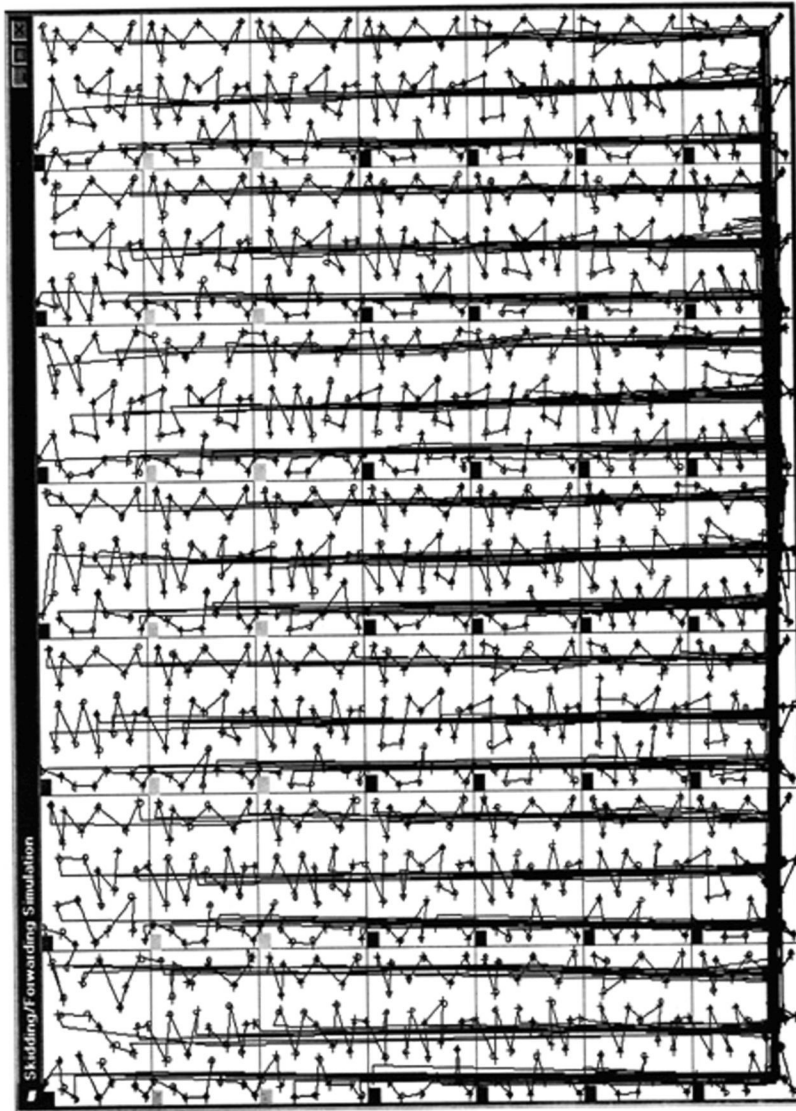Figure 9. Skidding simulation after extracting all tree piles to landing.

Figure 10. Forwarding simulation after extracting all log piles to landing.

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