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A COMPUTER SIMULATION OF FULL-TREE FIELD CHIPPING AND TRUCKING

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A COMPUTER SIMULATION OF FULL-TREE FIELD CHIPPING AND TRUCKING

Dennis P. Bradley, Frank E. Biltonen, and Sharon A. Winsauer

Loggers and wood users have shown continuing interest in full-tree field chipping from its conception, but its complexity, high costs, and mill use problems have discouraged acceptance. A key factor in the slow pace of adopting this or any other new harvesting technique is the fact that "trial and error" is the dominant form of learning how to use new harvesting methods. This may have been adequate before but certainly not now. Loggers, landowners, and consumers all lose when logging methods are inefficient. Better methods of planning to improve harvesting efficiency are urgently needed.

PURPOSE

This paper describes the principal features of a computer simulation of a full-tree chipping system that can help loggers increase production and lower costs. The purpose of this work, in addition to improving the efficiency of field chippers, is to demonstrate the flexibility and realism that can be achieved with simulation for the improvement of any harvest system.

Only the larger companies and loggers have the resources to put simulation to immediate use, but the spin-off of improved techniques and methods will benefit all loggers. Future publications will include a more detailed description of the model as well as specific examples of how this simulator has been used by loggers to direct changes in their operations.

Simulation or modeling is actually an old tool: the value of model bridges and aircraft is familiar to all. However, a computerized abstraction of a harvesting system seems quite different. How can numbers in a calculator express the complex relations between men, machines, and work rules? Although the process sounds mysterious and uselessly hypothetical, computer simulation has nevertheless proved to be an extremely powerful approach to system design in many other problem areas. And there is every reason to expect a similar contribution to logging.

WHAT THE SIMULATOR IS AND DOES

This simulator is a computer program whose instructions represent (a) the resources used by the real system, such as men and machines; (b) the actions performed by these resources; and (c) the operating rules that determine what will happen next when decisions are necessary. In addition, a simulated clock provides the background in which all the resources, actions, and rules interact.

The real system is simulated by telling the computer to symbolically set the resources to work for a desired period of simulated time. At the end of this simulated time, which may represent months of real activity, the computer tells the user how the model performed. For example, how much wood was produced, how much did it cost, where did one machine interfere with another, etc.? This report or history of the model is the payoff. If the user is confident that the model is a realistic copy of the real system, (more will be said about model realism later) he can draw conclusions about how to operate the real equipment. Should he add or remove equipment, or change operating rules, or alter work schedules?

Because computers are so fast, time, in effect, can be compressed and months or years of activity can be summarized in a few milliseconds of computer time. And therefore, many system alternatives can be examined realistically in a fraction of the time and cost required for an actual field test. Simulation does not eliminate the need for field testing but a great deal of wasted effort can be avoided.

The simulator is written in GPSS/360, an extremely popular and powerful general purpose simulation language. Developed by IBM,[1] this language has now been implemented on the machines of several manufacturers.

[1] International Business Machine Corporation. General Purpose Simulation System V Users' Manual. SH20-0851-1. White Plains, New York. 422 p. Illus. 1973.

DESCRIPTION OF THE SIMULATOR

The simulator duplicates the major features found in a real system (fig. 1):

1. A stand of trees.
2. Feller-bunchers.
3. Skidders.
4. A chipper with loader.
5. Trucks and vans.
6. One or two optional setout trucks.
7. Mill yard scale and chip dumper.
8. Other trucks (provide realistic competition at the mill scale and dumper).
9. A master timer.

The following descriptions of each segment include the processes being simulated, the data to be provided by the users, the kinds of events that result in decisions, and the quantifiable criteria for making each decision.

A realistic correspondence between the real system and its model is essential in establishing a user's confidence in the model. On the other hand, it should also be apparent that not all detail is equally relevant. For example, we feel that the feller-buncher's travel and harvesting actions in this model are very realistic.

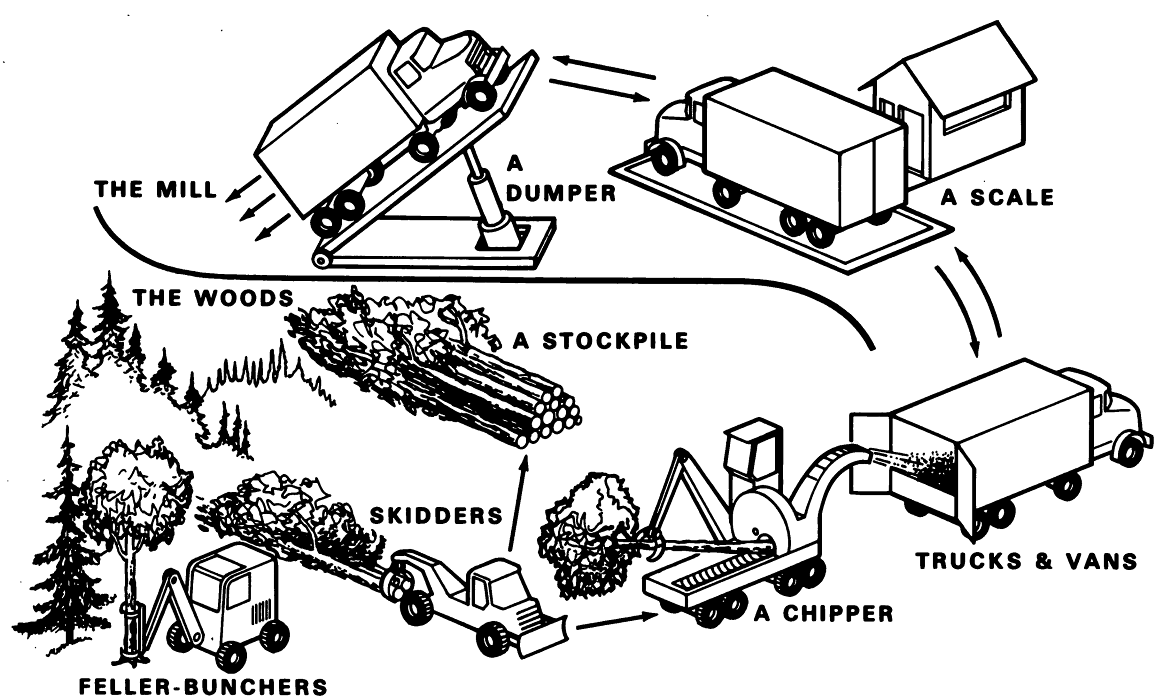

Figure 1.--The full-tree field chipping system.

The feller-buncher travels to each tree, fells it, and leaves it or carries it along. Each tree has a unique location, diameter, and volume. Average felling rates or average tree sizes or average travel distances are not used. Yet, the model does not include refueling stops. In other words, we felt that unique tree positions and volumes were very important details but that refueling was not.

The same point can be made for every other segment; we feel that we have included the relevent realistic detail. The degree of detail described here and how well it fits a user's own conceptions and needs will determine, in large part, how useful this model will be for him. In any event, we hope that the general approach described here will be valuable. Certainly, the simulator can be modified if necessary.

This simulator has been designed to be as independent of specific machines as possible. That is, the nature and the order of the processes performed by each machine are the same regardless of the brand name or size of the machine. Differences in machine speeds and capacities can then be changed by the user to fit the specific machines he wishes to observe.

Feller-Bunchers

Feller-Buncher--Stand Interaction

The number of feller-bunchers, stand character, and terrain are the main factors affecting feller-buncher production.

The feller-bunchers harvest a stand based on an arbitrarily selected basic plot of 1 or 2 acres. The basic plot data, provided by the user, consists of unique tree locations (x and y coordinates) and volumes for each tree in the stand. Prior to the simulation, the user prepares a two-dimensional plot of the test stand and manually selects a tree felling order for every tree in the basic plot. This felling order is selected in a way, logically and practically similar to the order an actual feller-buncher would use. Although this felling order is followed precisely by all feller-bunchers, bunch composition and the actual travel path are established independently and may differ considerably. This process is described below.

To achieve a harvested area of the desired size for simulation, since 1 or 2 acres may not be an adequate test, the basic plot can be harvested as many times as necessary. The total harvest area desired is divided equally among the feller-bunchers into as many basic plot units as necessary. (This process of harvesting the same plot many times is dictated primarily by computer core memory limitations. It may be possible to replace it with one large plot if the data and core space are available.)

Thus, each feller-buncher will harvest this basic plot several times in order to achieve the desired harvest area for all feller-bunchers. A Basic plot is hereafter called a subregion. The total number of subregions assigned to each feller-buncher is called a region.

This segment permits a user to choose two basic methods to prepare bunches for skidding. First, trees may be cut and carried one at a time to a bunch on the ground until the desired bunch size is reached. Second, several trees may be cut and carried along in an accumulator. When full, this accumulation or bouquet will be deposited on the ground as a complete bunch by itself, or it may become a partial bunch to which other bouquets are added. Desired bunch size, accumulator limits, feller-buncher to tree distance limit, and partial bunch to tree distance limit, can all be set by the user.

For the feller-buncher and all other segments, the times consumed in carrying out the specific processes must be provided by the user. An important point to note here is that all segments in the model can accomodate not only constant data but also data with random variation, or any mixture of the two at the user's discretion. For example, the user may decide to have each feller-buncher travel at precisely the same speed all the time or he may permit machines to vary their speed at random, around some mean speed. This ability to reproduce random variation is extremely important in achieving realism, although it also raises some data collection and analysis problems, to be discussed later.

Another feature of this model that requires emphasis is that individual trees maintain their identity from the time they are cut until they are chipped and blown into the van. This consistency is extremely important but has not been a part of other harvesting simulators.

Feller-Buncher--Feller-Buncher Interaction

If by chance a feller-buncher completes the felling and bunching of all assigned subregions, it may assist any other feller-buncher who has not completed all of his. However, the subregion or basic plot is the smallest unit that a feller-buncher can work in; that is, only one feller-buncher is allowed in a subregion at a time while several feller-bunchers can work in the same region.

When all subregions and regions have been felled, the feller-bunchers quit; presumably they go to another logging chance independent of the area under simulated harvest.

Each bunch, when completed by the feller-buncher, possesses all the information necessary to affect skidding and chipping operations on it. For example, each bunch includes 1) a record of each individual tree volume as well as their sum; 2) its skid distance to the landing; 3) the feller-buncher that produced it; and 4) the subregion in which it was felled.

Feller-Buncher--Skidder Interaction

One additional feature is provided in the case of a skidder catching up to a feller-buncher and deciding (these rules will be described later) to take the partial bunch, that is, a bunch not complete in the feller-buncher's opinion. Of course, if the skidder takes this partial bunch, the next tree felled or the next bouquet to be completed will be the next partial bunch.

Skidders

Skidders convey complete bunches (complete in their opinion) from the bunches' locations in the woods to the landing and chipper. Numbers of skidders, skid distances, terrain, and bunch size are the principal factors affecting skidding production.

Skidder--Feller-Buncher Interaction

The user must initially assign one or more skidders to work with each feller-buncher. Each skidder can be thought of as following a trail of completed or partially completed bunches unique to its feller-buncher assignment.

As long as the skidder does not catch up to the feller-buncher, that is, as long as fully completed bunches exist on its unique trail, the skidder stays with its initial feller-buncher. However, if it does catch up, a change in feller-buncher assignment may be necessary. To provide the model with this power, a set of tests is available to the user.

When a skidder catches up, it checks to see if the partial bunch is big enough to (a) *take* as it is, (b) *wait* for it to get bigger, or (c) *look* for work elsewhere with another feller-buncher. Whether the bunch is big enough determines the change, and the user can set these limits as he sees fit.

Skidder--Chipper Interaction

Once at the landing, each skidder has more decisions to make. There are two places to take the wood--directly to the chipper, or to the stockpile. The reasons for the two spots are:

1. If the skidders begin work before the chipper arrives on the job, they must have a place to deposit bunches.
2. After the chipper is on the job, the limited capacity of the area within reach of the chipper's integral loader may require a skidder to wait to deposit a bunch directly at the chipper.

Since the whole objective is to eliminate inefficiency, the model provides two sets of rules to achieve efficient routing. These rules can be changed by the user to find the best rules for each situation.

Case I--A skidder is approaching the landing with a bunch and the chipper is on the job (fig. 2). The skidder can either (a) deposit bunch at chipper or (b) deposit bunch in stockpile. There are two costs dependent on the decision:

1. If deposited at chipper, the skidder *may incur* waiting costs.

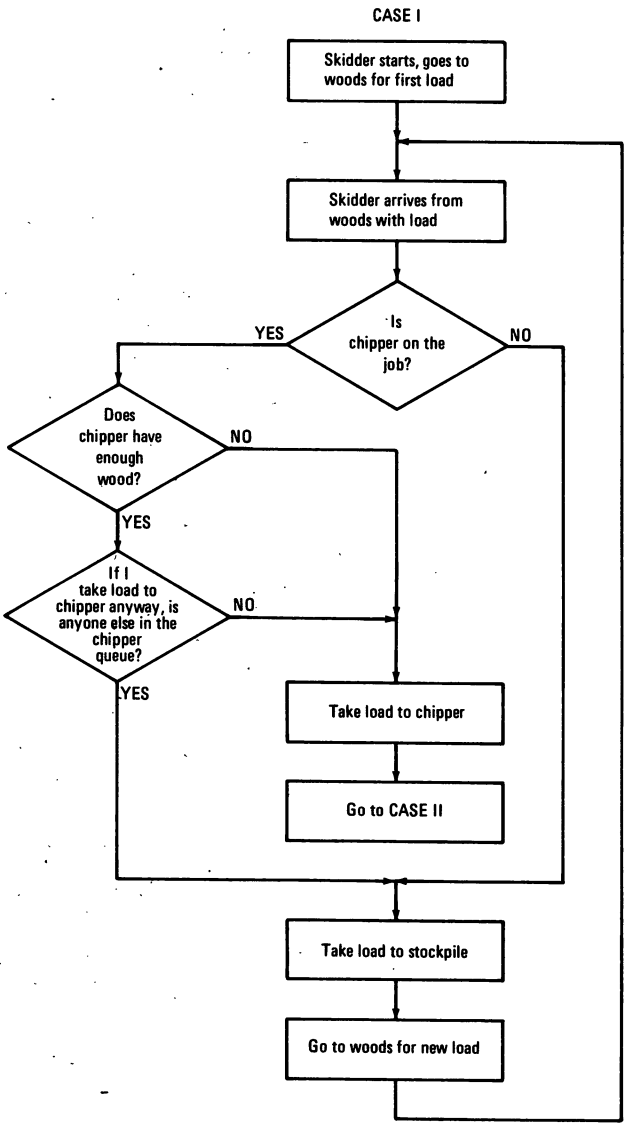

Figure 2.--Skidder logic employed for Case I.

2. If deposited at the stockpile, the skidder *will unavoidably incur* double handling costs.

A skidder asks two questions to reach a decision. First, does the chipper need wood? If it does, take the bunch to the chipper. On the other hand, even if the chipper does not immediately need wood, the skidder would still like to drop its bunch at the chipper to avoid unnecessary stockpiling if the estimated skidder wait is short. Thus, the second question is: are other skidders ahead of him to cause excessive waiting? If not, take the bunch to the chipper. Otherwise, take the bunch to the stockpile. The minimum amount of wood needed by the chipper and the limit on the number of skidders waiting to drop bunches at the chipper can be changed to arrive, by repeated trials, at the correct tradeoff.

Note in fig. 2 that when a skidder drops a bunch at the stockpile it categorically goes back to the woods for a new bunch.

Case II--From Case I, the skidder has dropped its bunch at the chipper (fig. 3). It can either (a) get a new one from the woods, or (b) bring a bunch from the stockpile. Three potential costs are associated with this decision:

1. If the skidder goes back to the woods, the chipper may run out of wood.
2. If it decides to bring another bunch from the stockpile just as another skidder is coming from the woods, it might cause this other skidder to drop its bunch in the stockpile with a net loss of effort due to (a) double handling two bunches instead of one and (b) a disruption of skidding operations.

The skidder asks three questions to reach a decision:

1. Does the chipper still need wood?
2. How many other skidders are waiting to drop bunches at the chipper?
3. Is any other skidder "near" the landing?

The minimum amount of wood required by the chipper, the limit on the number of skidders waiting at the chipper, and distance from the landing at which skidders on the landing can "see" an approaching skidder, can all be changed to test their effect on skidding costs. Figures 2 and 3 are not complete in detail but serve to show the logic employed.

When all bunches have been skidded, one or more skidders are assigned the job of emptying the stockpile for the chipper or the chipper can be brought to the stockpile.

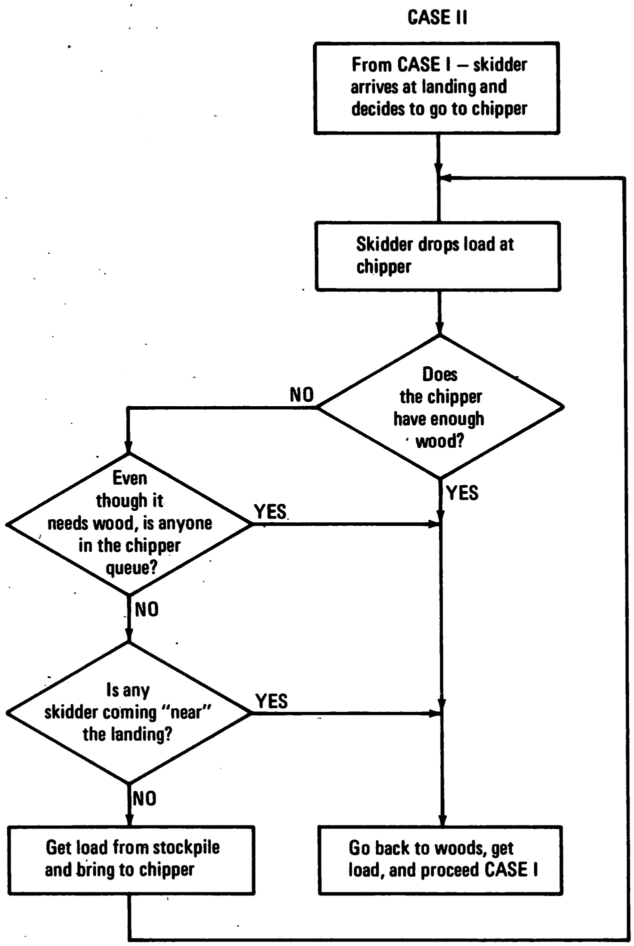

Figure 3.--Skidder logic employed for Case II.

Chipper

This segment duplicates the operation of a portable chipping machine with an attached or separate loader. Chipper production is dependent primarily on tree size, loader capacity, chipper capacity, and the number of vans that can be positioned in front of the chip spout.

Chipper--Skidder Interaction

Bunches of trees are brought by skidders to an area within reach of its loader where the bunches are "broken up" by the loader to construct chipper loads. The size of each load is dependent on the capacity of the loader's grapple and the chipper's mouth and the user can specify this load size in terms of number of stems and/or total volume.

After picking up the load, the loader places it on the feed conveyor and assists the chipper feeding process. When this assistance is completed, the loader gets another load from the trees in the buffer. The simulator records chipper delays due to the skidders not bringing enough wood.

Chipper--Van Interactions

The number of slots for empty vans, dependent on the size of the landing area, and on the flexibility of the chipper spout, is set by the user.

Once chipped, the load's volume is added to the van and a test is performed to see if the van is filled. If not, another load is chipped. When the van is filled, it is closed, the spout is moved to the next empty van and chipping resumes. Of course, if there are no empty vans in slots, or if there are no more trees in the chipper buffer, chipping will stop and the delay will be recorded.

Trucks, Vans, and Setout Trucks

This segment has the job of moving full vans to the mill. The number of trucks, setout trucks, vans, and hauling distance are the major factors affecting productivity.

Three different trucking situations are identified in this model.

Situation 1.

a. There are no terrain and road problems; highway tractors with vans can drive directly to the chippers without assistance.
b. Setout trucks for handling empty and full vans are not required, because either
   (1) There are *no* extra vans or
   (2) There are extra vans *but* the number of slots at the chipper equals or exceeds the total number of vans.

Situation 2.

a. There are still no terrain or road problems; highway tractors can get to the chipper without assistance, but
b. One or more setout trucks *are required some of the time* because both of the following conditions are true:
   (1) There are extra vans *and*
   (2) The number of slots at the chipper is less than the total number of vans.

Situation 3.

a. Terrain and/or road problems prohibit the highway trucks from bringing empty vans to the chipper. They must drop empties and pick up full vans a considerable distance away.

b. One or more setout trucks must therefore do all the work of moving empty and full vans to and from the chipper. Setout trucks in this situation are probably specially modified dozers or skidders with a fifth wheel.

The three situations are distinguished primarily on how any setout trucks, if used, interact with the highway trucks. In situation 1, a setout truck is never used; in 2, they are used only when necessary because the incoming highway trucks can do much of the handling; and in 3, they are used exclusively for van handling. In addition, the trucking segment distinguishes between a chipper having one slot in front of the spout and two or more slots.

The following detailed description of truck, van, and setout truck interactions for two or more slots seems to concentrate on situation 2, but it works the same for situation 1. Situation 3 can also be handled but with slight modification.

Truck and Setout Truck Logic for Situation 2--Two or More Slots

As already summarized, highway tractors have no trouble reaching the chipper, but one or more setout trucks are required because there are more vans than trucks, *and* the space for vans at the chipper is less than the total number of vans.

Thus, area must be provided within a short distance of the chipper for incoming trucks to drop empty vans when no slots at the chipper are open.

Also, a similar (if not the same) area must be provided for full vans completed before highway tractors return from the mill. Obviously, this movement of empty and full vans in the absence of highway tractors (HT) is done by a setout truck (SOT) in order to keep the chipper working and to reduce truck turnaround time.

The HT's and the SOT's cooperate to avoid unnecessary van handling. If possible, incoming HT's drop empty vans directly in a slot at the chipper *and*, secondly, they also try to pick up a full van or attach themselves to a partially full one in another slot.

Correspondingly, but with the subservient role, the SOT's move empty vans only when the chipper needs one and remove full vans only when no HT's are around. They never hook up to a partially full van.

At the instant an HT reaches the landing with an empty van, the location of empty slots and full or partially full vans is determined. Based on this status, the complete route of this HT into and out of the landing is determined at this time. Then it proceeds to drop its van somewhere and to pick up a full one or attach itself to a partial van somewhere else. Or perhaps the HT may remain attached to its original van until a slot is open and its van can be filled. But in any event, once it is on its way into the landing, no other HT or SOT can disrupt or change its route. This is done by permitting the HT to "reserve" the best path for entering and leaving the landing that it saw at the outset.

The purpose of SOT's is to increase the productivity of both the chipper and the HT's while minimizing their own work and interference. They move empty vans to the chipper from the empty van storage area and full ones from the chipper to the full van storage area only (1) when there are no HT's around and (2) when requested to by the chipper.

As described above, the HT's will always try to drop their empty vans directly in a chipper slot and will always try to pick up a full or partially full van at the chipper.

By taking empty vans to the chipper only when the chipper is about to run out of empties, the SOT's allow these slots to remain open as long as possible for the HT's. This minimizes the double handling of empties.

By picking up full vans at the chipper only when requested to do so, SOT's allow the returning HT the maximum opportunity to get a full van right at the chipper. This minimizes the double handling of full vans.

Truck and Setout Truck Logic for Situation 2--One Slot Only

When there is only one slot, the trucking segment becomes a bit simpler, the setout truck segment becomes more complex, and their interaction changes profoundly. For example, when there are two or more slots at the chipper, SOT's never hook up to a full van in a slot unless requested to do so by the chipper. The SOT's leave the full van there as long as possible in order to give an incoming truck a chance to haul it away. Similarly, they leave the slot open as long as possible for a truck and only bring empty vans when requested by the chipper. In addition, they always drop empty vans in the slot and *get out of the way*. These choices are relevent, because the chipper can keep producing while the SOT brings empties to or removes full vans from the other slots.

However, when there is only one slot, **SOT's must not** wait until the van is full **before reacting**. A SOT must be ready to **remove this** full van as quickly as possible **and** get another empty in its place because the chipper will be idle until it does (a costly alternative). Therefore, when only one slot exists, SOT's *stay attached* to the empty van after moving it into the slot. Then, when the van is filled, the SOT can immediately move it to the storage area and get another empty.

By staying attached, a single SOT can get the chipper producing in much less time than if it first had to move in and hook up. If a second SOT is available, efficiency can be improved further by having the extra SOT standing by with another empty ready to move in, as soon as the first SOT removes the full one.

However, what if a truck shows up at the landing while the SOT is attached to the single partially full van and there are no other full vans ready? This problem never occurred before under the SOT's rules for two or more slots.

In this new case, the incoming truck orders the attached SOT to disconnect from the van in the slot, while dropping its own empty van in the storage area. The truck then hooks up to the partially full van in the slot.

An additional feature of this modification for one slot occurs when the slot is open but a full van is also ready at the storage area. In this case the truck has the option of placing the empty van in the slot and waiting until it is full, or of dropping the empty van in the slot and picking up the already full van. The truck can compare the two series of estimated times in making this decision.

Other Trucks

This segment is included in the simulation to recreate the competition that captive chip trucks encounter at the mill yard. Regardless of how efficient the woods chipping operation is, its trucks are not the only ones using the mill yard. The user specifies not only how often other trucks arrive at the mill yard, but what proportion are chip trucks or roundwood trucks. As in the real world, other trucks and the captive chip trucks are served on a "first come" basis. But while all trucks compete for the service of the scale, only "other chip trucks" compete with the captive chip trucks for the use of the chip van dumper.

Other trucks' "inter-arrival times," that is, the time that elapses between the arrival of one "other truck" and the next, and the other time data must be gathered from the user's mill yard records at the scale or mill yard gate.

Master Timer

In any complex system, timing plays an important role--when does the system start, does each part start at the same time, when should each part stop working, do scheduled interruptions play an important part in the system, what about unscheduled interruptions, are multiple shifts in effect, and are there situations requiring overtime?

In this system simulator, we have concentrated on three principal areas: (1) system start-up, (2) working day length or production quota, and (3) exceptional situations to prolong the working day.

System Start-up

Except for the fact that segments of this system must perform in sequence to get the wood to the mill, the starting times of each segment are optional. The feller-bunchers start first, but the user can choose the number of days or hours at which each subsequent segment begins work. For example, feller-bunchers may start on Day 1, skidders on Day 3, and the chipper on Day 4. A day counter in the master timing segment triggers the initial start-up of each machine segment.

Working Day Length

Although the master timer controls the daily start cycle, each segment decides by itself when to stop. This stopping cue may be given by having a specific machine segment refer to the clock to see if the desired time has been reached or if a desired production quota has been achieved. Here, too, the user can choose the hours or quotas for each segment independently. If desired, interruptions for coffee, lunch, or preventive maintenance can be scheduled.

Exceptional Situations

In some situations overtime may be required. Because of the unusually long hauling times or other sources of unplanned delays, such as long waiting lines at the scale, the system may have to work longer to insure that trucks do not spend the night on the landing. For example, assume that trucks will not return to the landing for another load when they leave the scale empty after 4 p.m. Before 4 p.m., they usually have enough time to return to the chipper for one last load for the night. But because a particular return trip to the woods takes longer than expected, it arrives at the landing after the system would ordinarily quit. In this situation, the system knows the truck is on the way, and it will work overtime until a full van is ready. Many other options are possible, including daily work quotas.

Delays Due to Machine Breakdown

This model description has concentrated on delays caused by machine interactions but ignored delays caused by machine breakdowns. That is, all machinery is assumed to work perfectly. However, if a user has machine breakdown data, it can easily be included. At a minimum, a user needs to know how often specific machines fail and how long the repairs take. Given this data, at the start of each skidder trip, for example, the skidder would sample a "breakdown occurrence distribution." If no breakdown is due to occur this cycle, the skidder would be allowed to complete it. If a breakdown is due, the skidder transaction would then sample a "breakdown duration distribution" which would determine how long the machine would be out of operation.

The Simulator Report

Finally, this simulator gives a daily report of system production, cost, and interaction for each component. An example of the report (see Appendix) shows how much a system consisting of three feller-bunchers, three skidders, one chipper and loader, three trucks, six vans, and one setout truck, produced while operating in a stand having 2,915 cubic feet per acre and 200 trees per acre, etc. Keeping in mind the statistical problems to be discussed shortly, the user should interpret this information in much the same way that he would examine the records of a real system. The main difference is that the model's summary is probably a hundred times more detailed than any real system.

Simulator Data Requirements

Stand data--Diameters, heights, volumes, and locations for each tree are necessary. There are a number of ways to acquire this data varying from field measurement to the use of computer generated data.

Machine speed--is the time required to travel or process. These times may be as simple as a constant or as involved as a function of many variables--terrain, distance, tree or load size. In any event, the simulator can take whatever data is available from constants, estimates of a mean and a variance, equations, or frequency distributions. In most every case, however, machine speeds can be expected to vary--even under fairly constant conditions--and the simulator can handle this very important facet of real systems.

Machine capacity is the maximum size load a machine can handle. In contrast to the case of machine speeds, the simulator must be provided with fairly rigid machine capacities. Providing a maximum limit in volume or stems does not mean that each load will always achieve the limit. For example, if the feller-buncher's accumulator could take 15 cubic feet more but the next tree has 50 cubic feet, the feller-buncher does not add this tree to the bouquet but drops what it has and starts to create another.

Decision making--The simulator must decide, as a real system does, what happens next in ambiguous situations. These decisions take place within a machine or process's own task or at the point where different machines interact. For example, one or more features of the system (a feller-buncher's current bunch size) is compared to some standard (the desired bunch size to meet the skidder capability) in order to decide what to do next (get another tree for this bunch or start another bunch).

Data Needed for the Stand and Each Segment

Any unit of measurement can be chosen by the user. The current program uses time in centiminutes, distance in feet, area in acres, volume in cubic feet, and machine costs in dollars per machine hour.

1. Stand data.
   a. Tree location in X and Y coordinates.
   b. Tree volume.
   c. Basic plot size.
   d. Total harvest area desired.
   e. Area to be harvested by each feller-buncher.
2. Feller-buncher.
   a. Number of feller-bunchers.
   b. Travel-empty speeds.
   c. Travel-full speeds.
   d. Shear speed including approach.
   e. Drop speed.
   f. Accumulator volume limit.
   g. Accumulator stem limit.
   h. Bunch volume limit.
   i. Bunch stem limit.
   j. Maximum travel distance limit.
   k. Machine and labor costs per hour.
3. Skidding segment data.
   a. Interaction with feller-bunchers.
      (1) Number of skidders.
      (2) Travel-empty speed.
      (3) Travel-full speed.
      (4) Position and grapple speed.
      (5) Drop speed.
      (6) For a partial bunch.
         (a) "Take it" volume limit.
         (b) "Wait for it" or "attempt to switch to another feller-buncher" volume limit.
   b. Interaction with chipper.
      (1) Minimum volume needed at the chipper to keep it from running out before another skidder arrives.
      (2) Maximum number of skidders waiting at chipper before the next skidder is sent to the stockpile.
      (3) Maximum distance that other skidders can be seen from the landing.
      (4) Machine and labor costs per hour.
4. Chipping segment.
   a. Loader speed including grapple, lift, swing, and feed assist.
   b. Chip spout moving speed.
   c. Number of slots for vans.
   d. Maximum number of stems in desired load.
   e. Maximum volume of stems in desired load.
   f. Machine and labor costs per hour.
5. Trucking segment.
   a. Number of trucks.
   b. Number of vans.
   c. Highway trucking speed--empty.
   d. Highway trucking speed--loaded.
   e. Van connect and disconnect time.
   f. Van closing time.
   g. Van capacity.
   h. Number of setout trucks.
   i. Highway and setout truck speeds on the landing.
   j. Morning truck scheduling.
   k. Machine and labor costs per hour.
6. Master timing and production summary segment.
   a. Number of days to simulate.
   b. Time lag for skidder start-up.
   c. Time lag for chipping and trucking start-up.
   d. Length of normal work day or daily trip quota.
7. Other trucking segment.
   a. Inter-arrival schedule for other trucks at the mill scale.
   b. Proportion of other trucks carrying chips.
8. Mill yard.
   a. Number of scales.
   b. Number of chip-van dumpers.
   c. Number of roundwood unloaders if required for realism.
   d. Truck weighing speed.
   e. Chip-van dumping speed.
   f. Roundwood truck unloading speed.
   g. Truck speeds on the mill yard.

Data Collection Problems

The stand and time study data gathered by the user can be as simple or complex as desired, or as time and budget permit. But the adequacy of data is a complex problem and only general considerations will be touched upon here.

The results generated by the simulator can be no better than the data going in; accurate data is obviously important. On the other hand, limited time and money force the user to be selective. But what criteria should he use?

Two factors are important. First, the random variation that characterizes all processes can result in statistical sampling problems. Secondly, some aspects of the system have more impact than others on efficiency. These two factors interact. For example, a large error in estimating the time to move the chip spout from one van to another will probably not have much effect on system productivity, whereas a very small error in estimating skidding time per 100 feet may have a profound effect. The user must therefore strike a difficult balance among accuracy, precision, relevance, and budget.

USING THE SIMULATOR

The general process of developing and using this simulator to improve a real logging system consists of several steps. We have already outlined the need to choose a relevant degree of detail in the model that not only corresponds to the real world but also to the user's needs. The choice of detail is largely intuitive but is a key step in establishing a user's confidence in the model's inherent reasonableness.

In the next step, the user must test the simulator on an actual logging operation. This test is required to detect errors in either concept or model. That is, the user's concept may have been inaccurate; if so the model would be incorrect as well. Or the concept may have been correct but was not translated into a correct model.

Finally, the user can proceed to cautiously test different changes, first with the model and then with the actual equipment. At best, simulation is an evolutionary process. That is, while it may be possible to arrive at the best system by making several major changes at once, it should be clear that simultaneous changes can be confusing.

We have already mentioned that a realistic simulator allows random variations to occur during some, if not all, machine functions. Each separate machine function is in itself variable, and the whole chipping operation may comprise 20 to 30 such functions operating simultaneously. To find the effect of changing a single function among all these interacting functions would be impossible without simulation.

For example, suppose a logger wants to see what effect adding another skidder has on production. Without simulation and using "trial and error", he uses the extra skidder for one or more days. He then compares production before and after using the extra skidder and asks whether the change was worth it. But no matter what numbers he compares, he has the nagging feeling that some unknown difference in weather, stand factors, attitudes, or a hundred other reasons, may have been the real cause for the observed difference. By trying his idea first on the simulator, however, the logger can even harvest the identical stand of trees twice; once with the usual number of skidders and the second time with the additional skidder. Because nothing else was changed, the difference in results can be attributed to the extra skidder.

But there are still complicating issues. Because random variation within limits is permitted, in the model as in the real world there is always the possibility of getting a bizarre series of random events. Thus, the user must also ask if each series was truly representative of the real system. To answer this question, the user can employ a variety of rigorous statistical techniques. These methods allow one to compare the variation within a given system, or between two or more different systems, in order to detect any real differences.

WHAT PROBLEMS CAN THIS SIMULATOR EXAMINE?

Computer simulation allows one to realistically manipulate a system in ways previously impractical, if not impossible. The following selection gives some idea of the tremendous range of factors that can be varied in simulation to learn their effects on the production and cost.

1. Stand characteristics.
2. Machine numbers and sizes.
3. Felling patterns.
4. Skidding patterns.
5. Acreage harvested per landing setup.
6. Truck scheduling.
7. Work day length.

8. The work rules affecting:
   a. Skidder--feller-buncher interaction.
   b. Skidder--chipper interaction.
   c. Chipper--loader interaction.
   d. Chipper--truck, van, and setout truck interaction.
9. The interaction of all of the above.

SUMMARY

Full tree field chipping is receiving a great deal of interest because of its many benefits, but its complexity, high cost, and mill use problems have discouraged acceptance. Using computer simulation, however, one can realistically analyze such complex harvest systems in a fraction of the time and cost of experimenting with real equipment. And as a result it is often possible to increase profits, reduce logging waste, allocate each tree to its best use, improve equipment design, and conserve fuel.

APPENDIX

Report Generated for One Day of a Possible Simulated Operation

I. STAND CHARACTERISTICS

30.00	Acres, total area to be harvested
2915.00	Cu. ft., average total volume per acre
9.53	Inches, average d.b.h.
65.00	Feet, average tree height
14.76	Feet, average tree spacing
200.00	Average number of trees per acre

II. SYSTEM CHARACTERISTICS

A. Feller-Bunchers.

3. Machines

Machine Limitations

The accumulator-shear can hold up to 50.0 cu. ft. or 5 stems, whichever comes first.

If the next tree is more than 50 feet from the feller-buncher, it is too far away to include in this bouquet.

If the next tree is more than 75 feet from the partial bunch, it is too far away to include in this bunch.

Bunch limitations dictated by skidder capacity.

The feller-bunchers try to achieve at least 100.0 cu. ft. or 10 stems in each bunch, whichever comes first.

B. Skidders

3. Machines

Interactions with feller-bunchers. When a 'catch-up' occurs, the skidder checks the partial bunch on the ground.

If the partial bunch has 75.0 cu. ft. or more, skid it as it is.

If the partial bunch has 50.0 cu. ft. to 75.0 cu. ft., wait for it to get bigger.

If the partial bunch has less than 50.0 cu. ft., attempt to switch to another feller-buncher.

Interactions with chipper. Should the skidder take the bunch direct to the chipper or to the stockpile?

If at least 15 trees are within chipper's reach or with other waiting skidders, take bunch to stockpile.

If 2 or more skidders are already waiting at the chipper take the bunch to the stockpile.

C. Chipper--Loader

The loader can take up to 35 cu. ft. or 5 stems, whichever comes first.

Interactions with the setout truck. Setout truck is used only when no highway trucks are around, and only when the chipper requests that a full or empty van be moved.

Setout truck brings an empty van if more than 2 slots are open.

Setout truck removes a full van if less than 2 slots are open.

D. Trucks, vans, and setout trucks

3 trucks
6 vans
1 setout truck
3 slots for vans at the chip chute

E. Daily production quotas

Fell and bunch	25,000.0 cu. ft. daily
Skid	16,000.0 cu. ft. daily
Chip	13 vans daily
Truck	13 vans daily

Feller-Buncher Production and Cost Summary

A. 3 Days worked by feller-buncher(s).
B. 3 Number of feller-bunchers.
C. $15.00 Feller-buncher cost per hour including labor.

D. 1611 Total accumulator cycles completed--all machines.
E. 48.10 Average volume per cycle, cu. ft.
F. 2.52 Average number of trees per cycle.
G. 711 Total bunches completed--all machines.
H. 108.99 Average volume per bunch, cu. ft.
I. 5.70 Average number of trees per bunch.
J. 2.26 Average number of cycles per bunch.
K. 4055 Total trees felled--all machines.
L. 77493.21 Total volume felled cu. ft.--all machines.
M. 20.28 Total acres felled--all machines.
N. 316,069 Total distance traveled ft.--all machines.

O. 17.90 Average number of accumulator cycles per machine hour.
P. 7.90 Average number of bunches completed per machine hour.
Q. 45.06 Average number of trees felled per machine hour.
R. 861.04 Average volume felled per machine hour--cu. ft.
S. .23 Average acreage felled per machine hour.
T. 3511.88 Average distance traveled per machine hour--ft.

U. .33 Feller-buncher cost per tree.
V. 1.74 Feller-buncher cost per 100 cu. ft.
W. 65.21 Feller-buncher cost per acre.
X. 3 Feller-bunchers still working.
Y. 9.72 Acres remaining to be felled.

Skidding Production and Cost Summary

A. 2 Days worked by skidder(s).
B. 3 Number of skidder(s).
C. $15.00 Skidder cost per hour, including labor.

D. 327.00 Bunches skidded--all machines.
E. 1721 Trees skidded--all machines.
F. 32866.77 Volume skidded, cu. ft.--all machines.
G. 8.61 Acres skidded--all machines.
H. 372126 Distance skidded, ft.--all machines.

I. 5.45 Bunches skidded per machine hour.
J. 28.68 Trees skidded per machine hour.
K. 547.78 Volume skidded per machine hour--cu. ft.
L. .14 Acres skidded per machine hour.
M. 6202.10 Distance skidded per machine hour.

N. 569.00 Average one-way skid distance per trip--feet.
O. 11.01 Average round trip time in minutes--all activities.
P. 8.54 Productive time--landing to woods and return.
Q. 1.73 Productive time--landing activity.
R. .50 Nonproductive time--waiting in the woods for a bunch.
S. .25 Nonproductive time--waiting to drop the bunch at the chipper.

Interactions with the chipper; number of trips that:

T. 15 Skidders caught up to a feller-buncher.

Of these "catch-up" trips, the number of trips that the skidders:

U. 10 Immediately took the bunch as it was.
V. 3 Waited for the bunch to get bigger.
W. 2 Attempted to switch to another feller-buncher.

Interactions with the chipper; number of trips that were:

X. 292 Skidded direct to the chipper.
Y. 35 Skidded direct to the stockpile.
Z. 17 Number of stockpile-chipper shuttle trips.

AA. $.53 Skidding cost per tree.
BB. $2.75 Skidding cost per 100 cu. ft.
CC. $104.53 Skidding cost per acre.
DD. 21.39 Acres remaining to be skidded.

Chipper-Loader Production and Cost Summary

A. 1 Days worked by chipper-loader.
B. $50.00 Chipper-loader cost per hour, including labor.

C.	252	Loads chipped.
D.	2.53	Average number of stems per load.
E.	48.27	Average volume per load, cu.ft.
F.	637	Trees chipped.
G.	12164.37	Volume chipped, cu. ft.
H.	13	Vans filled.
I.	19.38	Average number of loads per van.
J.	935.72	Average volume per van, cu. ft. solid wood.
K.	25.20	Loads chipped per machine hour.
L.	63.70	Trees chipped per machine hour.
M.	1216.44	Volume chipped per machine hour, cu. ft.
N.	1.30	Vans filled per machine hour.
O.	46.15	Average chipping time per van filled--all activities--minutes.
P.	29.13	Productive time per van--minutes.
Q.	17.02	Nonproductive time per van--minutes.
R.	6.60	Loader waiting for wood from skidders--minutes.
S.	10.42	Chipper waiting for vans to fill--minutes.
T.	$.78	Chipper-loader cost per tree.
U.	$4.11	Chipper-loader cost per 100 cu.ft.
V.	$38.46	Chipper-loader cost per van filled.

Truck, Van, and Setout Truck Production and Cost Summary

A.	3	Number of trucks.
B.	$25.00	Truck cost per hour, including labor, each.
C.	6	Number of vans.
D.	$15.00	Van cost per day, each.
E.	1	Number of setout trucks.
F.	$15.00	Setout truck cost per day, each.
G.	13	Vans hauled to mill--total.
H.	13	Average number of vans hauled per day.
I.	12164.37	Volume hauled to mill--total--cu. ft.
J.	138.46	Average round trip trucking time--all activities--minutes.
K.	97.20	Productive time--minutes.
L.	41.26	Nonproductive time--minutes. Waiting:
M.	12.19	For a slot to become available.
N.	4.47	In a slot for the van to be filled.
O.	0.00	At the storage area for the setout truck to bring a full van.
P.	12.57	To be weighed at the mill.
Q.	12.03	To be dumped at the mill.
R.	5.00	Average number of empty vans setout truck moved to chipper per day.
S.	3.00	Average number of full vans setout truck moved to storage area each day.
T.	$57.69	Trucking cost per trip.
U.	$6.92	Van cost per trip.
V.	$1.15	Setout truck cost per trip.
W.	$6.17	Truck cost per 100 cu. ft.
X.	$0.74	Van cost per 100 cu. ft.
Y.	$.12	Setout truck cost per 100 cu. ft.

Overall Production and Cost Summary

Number of machines.

A.	3	Feller-bunchers.
B.	3	Skidders.
C.	3	Trucks.
D.	6	Vans.
E.	1	Setout trucks.

Days worked by each segment:

F.	3	Feller-bunchers.
G.	2	Skidders.
H.	1	Chipper and trucks.

Volume produced by each segment to date, cu. ft.

I.	77493.21	Felled and bunched.
J.	32866.77	Skidded.
K.	12164.37	Chipped.
L.	12164.37	Hauled to mill.

Projected costs per 100 cu. ft. delivered to the mill and attributed to each segment.

M.	$1.74	Feller-bunchers.
N.	$2.75	Skidders.
O.	$4.11	Chipper-loader.
P.	$6.17	Trucks.
Q.	$0.74	Vans.
R.	$.12	Setout trucks.
S.	$15.63	Total cost per 100 cu. ft.
T.	$28.25	Chip price per 100 cu. ft. delivered to mill.
U.	$12.62	Projected net revenue per 100 cu. ft. delivered to mill.

Bradley, Dennis P., Frank E. Biltonen, and Sharon A. Winsauer. 1976. A computer simulation of full-tree field chipping and trucking. USDA For. Serv. Res. Pap. NC-129, 14 p., illus. North Cent. For. Exp. Stn., St. Paul, Minn.

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