A Mechanized Harvesting System Simulation: Input, Output, Limitations and Capabilities

by

Darío M. Aedo-Ortiz

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Oregon State University

in partial fulfillment of
the requirements for the
degree of

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This study concerns the use of a discrete-event simulation model for analyzing the production of a mechanized forest harvest system. The simulation models a field collection data set of a harvester-forwarder system which was previously collected by the Forest Engineering Department of Oregon State University. The computer software consisted of the statistical package Statgraphics and the simulation package Promodel PC.

Special emphasis is given to the use of statistical distributions and linear regressions as simulation input data. The simulation model was built in productive machine time. Input quality and output capabilities of the simulation language Promodel PC produced realistic output

of weekly predicted production of the system. Also, linear regressions of average yarding distance and unloading time of the forwarder estimated the production of the harvest system. The unloading time regression was used to develop a cost evaluation of the possibility of adding a loader to the harvest system.

"Group" and "ungroup" functions of Promodel PC are powerful tools for generating a simulation model of a harvest system. These functions allow an easy programming transition despite the different system products. On the other hand, animation produced more model building difficulties than output benefits.

It is advisable for future field studies to be designed in a different manner. Variables should be collected according to the input needs of the simulation model.

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To my parents Darío Aedo San Martín and Luisa Edith Ortiz Aedo: I hope that this accomplishment gives you the greatest happiness.

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A MECHANIZED HARVESTING SYSTEM SIMULATION: INPUT, OUTPUT, LIMITATIONS AND CAPABILITIES

CHAPTER 1
INTRODUCTION

The Forest Engineering Department at Oregon State University has been actively involved in field research of harvesting systems over the past two decades. Recently a portion of the research has focused on mechanized systems. Since many mechanized systems involve the close coordination of several machines, the analysis of production and cost becomes more complex. Subtle interactions among the harvesting machines along with changes in the working environment can result in widely varying system production rates.

Since field production studies only capture a sample of the production rates that occur during the unique conditions of each study, a more extensive analysis procedure was desired. One way to achieve the more extensive analysis is to build a simulation model. The simulation model can be run repeatedly under slightly different equipment interaction and working conditions to produce a realistic range of production rates.

The timing sequence between field production studies and the simulation modeling is somewhat circular. The field studies are the source of the simulation input. On the other hand, the simulation results help to determine how the field study should be designed. This study will explore the relationship between field studies and simulation modeling so that both techniques are enhanced to produce the best possible overall analysis.

A fairly simple two machine system was chosen for this study. Data from a prior field study was available as input data. The researchers associated with the prior field study had several questions about how the production rates would be affected with changes in the operating conditions. This paper investigates the ability of a simulation model to do this type of sensitivity analysis.

There are three main starting points of this study. The first is a field production study of a single-grip harvester and a forwarder developed by the Forest Engineering Department at Oregon State University (Kellogg and Bettinger, 1994). The second is a simulation language package for developing discrete-event simulation models, Promodel PC for Windows, version 1.1, which was made available in 1993. This package has animation capability and has never been used before in the modeling of forest harvest systems. The third is a statistical package (Statgraphics for DOS, version 6.0) which is easy to use with data stored in spreadsheets.

The above scenario gave the framework for specifying the main objectives of this study. These objectives are:

1.- To build a simulation model of a harvester-forwarder system giving special attention to input data treatment and the calculation of a set of realistic output.

2.- To determine the limitations and capabilities in using Promodel PC and Statgraphics.

3.- To develop a set of guidelines for analysis of harvesting production using both field data collection and simulation model building.

This paper has been divided into six main chapters. The Theoretical Review chapter gives a general review of the basic concepts associated with simulation analysis. The Methodology chapter presents a detailed description of the main stages required for doing an analysis. These stages are input determination, simulation model building, transient period calculation, and final run execution. The Findings chapter gives all the results obtained for each of the main stages of the Methodology in the specific case of a harvester-forwarder system. The Discussion and Conclusions chapters present and discuss the main findings related to input, output, limitations and capabilities of using a simulation technique. The appendices contain the simulation model code, possible statistical distributions to use as input of simulation models of harvesting systems, the basic statistics of the main input variables, and a sequence of steps to follow in obtaining statistical distributions.

This study intends to be helpful in two ways for developing production studies of harvesting processes. First, it clarifies the way in which field studies and simulation studies can work together effectively. Second, it intends to guide future simulation analysis that uses Promodel PC and Statgraphics.

CHAPTER 2
THEORETICAL REVIEW

Consistency in productivity and cost studies in forest harvesting systems is difficult because of the considerable variability related to harvest operations. As Blinn et al. (1986) say, "the dynamic nature of harvesting operations has made it difficult to evaluate the effects ...". Variability not only occurs between two different harvest operations, but also within each operation itself.

The varying situations found in the comparison of harvest operations are almost limitless. When harvest operations are analyzed, it becomes evident that no two operations are alike. The variations between operations can be caused by difference in sites (slope, soil, exposition, etc.), characteristics of the forests (number of species, age, density, etc.), number and kind of machines used (skidders, yarders, loaders, harvesters, forwarders, processors, helicopters, etc.), intensity of the harvest operation (partial, or clear-cut), and products to be extracted (sawlogs, pulpwoods, full tree, fuelwood, etc.) (Blinn et al., 1986).

Production variability is also found within a specific harvest process. For instance, a feller-buncher does not always require the same amount of time to fall a tree. The time variation can be caused by the size of the tree (diameter, height, size of branches), local slope, local tree density, wind (speed and direction), etc. The same is true of every machine used in harvest operations. Moreover, there are variations in the production due to the interaction of the system machines (Geddes et al, 1985). Sometimes in the felling stage, the wood is piled in bunches, while other times it is spread out due to specific requirements or limitations of the machine in the field. These variations in the felling process cause different rates of production at the skidding stage. For example, sometimes the skidder will have only one stop and can have a trip load ready quickly, but in other cases it will need to make more than one stop. Then there are also random variations in the production rate of an individual harvest operation itself.

In summary, the large variability found between harvest operations and in the development of each of them, clearly justifies the needs for productivity and cost studies.

2.1 Simulation

Another point that becomes immediately apparent is which alternative techniques are available to develop these studies. In the first stage, a productivity and cost study must be developed for the field. In the next stages, the original field study can be followed by one of two options: (1) new field studies examining the specific harvest system under other field situations, or (2) a computer simulation analysis of these new situations. At this level, a simulation analysis is usually justified due to the savings in money (Block and Fridley, 1990).

What is simulation? "Simulation is the technique of constructing and running a model of a real system in order to study its behavior without disrupting the environment of the real system" (Matko et al. citing Kosskossidis and Brennan, 1992). This definition presents several ideas that require discussion.

To begin with, "simulation is the technique of constructing and running a model of a real system ...".

Here two main points appear. First, the idea of constructing and running implicitly requires the use of computers due to the amount of calculations. Second, what kind of model is this "model of a real system"? Matko et al. (1992) say that there are three types of models in general: physical, mental and symbolic. According to the nature of a harvesting operation, a symbolic model can represent it best. More specifically, a harvesting system may be represented by a stochastic model, where the relations between variables are given in terms of statistical values.

Another point about simulation models is that each simulation model is representing a system (Law and Kelton, 1991). A system or real system "is a combination of elements or components interrelated to each other and to the whole which act together to achieve a certain goal" (Matko et al., 1992). There is a one to one relationship between simulation model and system. If any of the system components is changed, a new system is created and a new simulation model is required. For instance, a harvest system can consist of a harvester and a forwarder that work together to produce logs. If the forwarder is replaced by a skidder, then, despite the final goal being the same, the result is not a modified system, but instead a new harvest system that needs to be modeled with new functions. On the other hand, if the forwarder needs to be studied under different slope conditions, then just slight modifications in the parameters of the functions are required and the same simulation model is a valid representation of the system. Therefore, a simulation model can accept only slight modifications, otherwise the system and the simulation model need to be changed.

Also, Greber (1985) specifies other important characteristic of simulation; he says, "the primary purpose of simulation models is to answer what-if questions; in and of themselves, they cannot answer what-is-best."

In summary, a simulation technique can be used to answer what-if type questions of a specific harvest system through the building of a stochastic model using a computer.

2.2 Discrete-Event Simulation

What kind of simulation is the most adequate to use in the study of mechanized harvesting systems? Due to the nature of the harvest production systems, a discrete-event simulation is the best one to apply (Johnson, 1986). A discrete-event simulation models a system as it evolves over time. It is a representation in which the state variables change at only a countable number of points in time (Law and Kelton, 1991). In a harvest system, changes occur in the felling, delimbing, bucking, and yarding activities. There is a countable number of points in time where variables of a harvest system change, so a discrete-event simulation applies well to these systems (Johnson, 1986).

2.3 Input Requirements

In order to have credible simulation output, the quality of input data is the key (Kellogg et al., 1992). Good simulation input is determined from an accurate definition of the events, and from a set of statistical distributions and linear regressions.

Why are statistical distributions and linear regressions required in a forest harvest simulation model? As was established before, a stochastic model can represent the variability of a harvest system. The variability is introduced through the generation of randomness using statistical functions (Ross, 1990). The set of statistical distributions and linear regressions generates this necessary randomness for the important variables of a harvest system in a simulation model. In the past, the statistical functions were assumed rather than determined. The reason for this was the high cost of statistical software and the skill required to use it. For example, the use of the Weibull distribution was justified in the modeling of time variables of machines (Hawkins et al., 1993). However, if these required functions in a simulation program are assumed, it is not possible to be entirely confident of the output. On the other hand, if the statistical functions of the system are determined, there is no doubt that the actual variability of the system is being expressed. Therefore, as a general guide for any simulation, it is better not to assume statistics functions, but instead to determine as many of them as possible in order to have confidence in the results. Moreover, the latest statistical software packages make these calculations easier.

After determining that the application of actual statistical distributions and linear regressions are necessary and easy to use in a simulation, it is necessary to decide the requirements for the simulation. The field data collection process must satisfy the input requirements of the simulation program. The field data and simulation input data process need to work together. The field study not only needs to be a collection of time variables, but also a collection of other system variables that allows the full configuration of the simulation model.

2.3.1 Statistical Distributions

In an attempt to find the best technique for determining statistical distribution in a forest harvesting simulation scenario, it is necessary to review the characteristics of the variables that can be a part of the simulation. Nearly all the variables are continuous, such as diameter at breast height (DBH), slope, machines production times, etc. Chi-square tests working with continuous variables present difficulty, principally in the specification of the intervals (Law and Kelton, 1991). Thus, the decision is restricted to one goodness-of-fit test adequate for continuous variables based on an empirical distribution function (EDF). EDF tests are based on the differences between the empirical and theoretical accumulative distribution functions. The most well known of these tests was introduced by Kolmogorov and Smirnov in 1933 and is commonly called the K-S Test (Stephens, 1986). K-S tests present three advantages in comparison to chi-square tests. First, K-S tests do not require grouping the data in any particular way. Second, tests are valid (exactly) for any sample size n (in the all-parameters known case), whereas chi-square tests are valid in an asymptotic sense. Finally, K-S tests tend to be more powerful than chi-square tests against many alternative distributions (Law and Kelton, 1991). The K-S tests were chosen because they present more advantages than the chi-square tests and can be calculated with Statgraphics.

2.3.2 Linear Regressions

The quality of a linear regression is based on the accomplishment of the assumptions of linearity, constant variance, normality and independence. Exact justification of confidence intervals and t-tests for the parameters or functions of the parameters depends on these assumptions (Ramsey and Schafer, 1992). In other words, a model is robust if it accomplishes these features. These assumptions are more important than the value of any output measure, such as coefficient of determination. The coefficients of determination (simple or adjusted) are only statistical values that express what fraction of the total response variation is associated with variation in the explanatory variable (Ramsey and Schafer, 1992). The analysis of the basic assumptions of a linear regression, on the other hand, allows us to have confidence that the model is valid.

There are statistical and visual tests for verifying the assumptions of a linear regression. A visual analysis is easier and faster. This consists of a review of the scatterplot, residual plot, and normal probability plot of the data. The linearity assumption can be checked by looking at the scatterplot. A residual plot shows whether or not the linear regression accomplishes the assumption of constant variance. Residuals, also called errors, are the differences between the observed and estimated values (Chase and Bown, 1986). Finally, a normal probability plot checks the assumption of normality.

2.4 Software Choice

An important decision related to the design of a simulation model is what kind of software is the best for the model construction. There are two alternative sets of software to choose from: general-purpose languages (GPL), or simulation languages (SL). GPL present just one main advantage in comparison with SL; GPL require less execution time because an SL is designed to model a wide variety of systems with one set of building blocks, whereas a general-purpose software (Fortran, C, etc.) can be tailored to the particular application (Law and Kelton, 1991). On the other hand, some of the advantages of SL against GPL are:

1.- SL automatically provide most of the features needed in programming a simulation model, resulting in a significant decrease in programming time.

2.- SL provide a natural framework for simulation modeling.

3.- Simulation models are generally easier to change when written in an SL.

4.- Most SL provide dynamic storage allocation during execution.

5.- SL provide better error detection because many potential types of errors have been identified and are checked for automatically (Law and Kelton, 1991).

Therefore in most cases, SL software is the best choice in the construction of a harvesting simulation model.

There is a large list of SL software available: SIMAN, SIMSCRIPT II.5, SLAM II, SIMNET, GPSS/H, GPSS/PC, Promodel PC, and so on. In this study Promodel PC version 1.0 for Windows was chosen. Law and Kelton (1991) classify Promodel as a manufacturing package for manufacturing applications in its DOS version. Promodel in its Windows version presents more animation capabilities and one of the goals of this study is to determine its capabilities in forest harvesting modeling.

2.5 Verification and Validation

There are two other points to be considered in the use of a simulation model: its verification and validation. To verify a simulation model is to check that it is free of errors, using all the "standard" techniques of debugging computer programs (Ross, 1990). An effective and simple debugging technique is to calculate the output from both the simulation model and a hand calculation and compare them (Ross, 1990). This verification stage defined by Ross (1990) is the second stage of validation defined by Law and Kelton (1991). There are two other validation stages (first and third in time) considered by Law and Kelton (1991). The first validation stage contrasts the conceptual model with the real system. The third one establishes the credibility between the "correct" results available from the simulation model and the results implemented in future situations. The first and second (verification) stages of validation will be part of the methodology of this study.

The third stage of validation is an important stage, but time restrictions prevent its development in this study.

CHAPTER 3
METHODOLOGY

Two software packages are used in this research. Statgraphics for DOS version 6.0 is a statistical package that is used to develop and analyze the frequency distributions and linear regressions which are required as input for the simulation model. Promodel PC for Windows version 1.10 is a simulation language package with animation capabilities. It is used in the building and analysis of the harvesting model.

This methodology gives the steps required to calculate productivity output using the simulation technique. The starting point is a productivity data set collected in a field study of a harvester (Appendix A) and a forwarder (Appendix B). This data needs to be organized in a systematic way in order to build a simulation model. When all the input data is processed and the simulation model built, a verification of the output of the model needs to be done. Then the transient period and the number of runs can be calculated to determine when the simulation data has reached a steady state and can be summarized.

Below, each step of the methodology is explained in detail.

3.1 Simulation Input

Simulation data input is divided into four stages: the system definition, study goals, statistical distributions, and linear regressions calculations. Each of these stages will be discussed below.

3.1.1 System Definition

System definition in the development of a simulation involves several factors. The first is to establish the kinds and number of machines that are used in the system. The second factor is the definition of the elements that are part of the cycle time of each machine with consideration given to which elements will routinely occur and which elements will occur only under special circumstances. For instance, a cutter always needs to spend time in each cycle felling a selected tree, but only occasionally does he need to spend time eliminating a hazard tree in the falling area. The last factor is the specification of the products that flow through the system. Obviously, trees and logs are system products because they are the raw materials and the final output of the system respectively. However, it is not so obvious that the number of logs cut from a tree, or the set of logs loaded during each stop of a forwarder, are also intermediate system products.

3.1.2 Productivity Study

Another important point is the clear specification of the intended goals of the simulation analysis. These goals determine whether to construct a discrete event simulation in real time (scheduled machine hours, SMH), or in productive time (productive machine hours, PMH). A productive time simulation has less randomness than a real time simulation. In a productive time simulation, randomness comes from independent variables that express the variability of system inputs and products. It is preferable to omit the additional randomness that comes from delays or interaction variables related to real time simulation.

Real time simulation (SMH based) is recommended in two instances. First, when the goals of the study are related to times outside of the productive time, and second, when these goals are concerned with physical constraints, such as buffer sizes. For example, if the researcher is interested in the breakdown time that a system can tolerate without dropping below a certain minimum productivity level, clearly the simulation needs to be developed in real time (SMH). Also, if the goal is to determine the minimum size of a landing without producing bottleneck delays, the SMH simulation is the best choice. In this research, however, these were not important considerations. Also, there is inadequate field data available referring to physical constraints and delays. Therefore, this study is limited to production time (PMH) only.

3.1.3 Statistical Distributions Findings

Fitting the field data to standard statistical distributions will be done in the Statgraphics package.

There are three categories of variables that require statistical distribution calculations. The first is operating-time variables. For example, it is necessary to calculate the statistical distribution of the unloading time. The second kind are the system product variables.

For instance, sometimes the diameter at breast height (DBH) represents the tree. Its distribution must be calculated because it is an independent variable that defines the volume of the tree, the number of logs that can be extracted, and the felling time required. The third and last kind of variables are related to the independent variables that define time elements. For example, in order to know the cycle time of a skidder under different average yarding distance (AYD), the distribution of the yarding distance must be determined. Knowing (1) the distribution of the yarding distance and (2) the linear regression between yarding distance and skidder cycle time, the simulation of a slightly different situation can be developed with the generation of random yarding distances.

3.1.4 Linear Regression Calculations

Some of the operating times change with the characteristics of the products; others only change due to the variability of the environment. In the second case, this environmental variability is expressed through the statistical distributions of these times. But when the characteristics of the products alter an operating time, multiple linear regression can express this change. For instance, in a real time simulation the delay times of a machine are directly dependent upon the amount of time that this machine was working without stops. Therefore, the delay time must be expressed through a linear regression with the amount of time worked.

The development of linear regression equations is done with Statgraphics. The most important point to be considered for accepting a model is that the linear regressions have acceptable residual and normal probability plots. These plots verify that the basic assumptions of equal variance and normal distribution are being met. A residual plot is a scatter diagram graph that shows the predicted values of the linear regression versus its residuals. An acceptable residual plot is completely random with no patterns present. In other words, the data set looks like a cloud. A normal probability plot shows the residuals in the X-axis and a normal probability scale in the Y-axis. The cumulative probability is calculated and plotted. A straight line is drawn through the points. An acceptable normal probability plot has the data distributed randomly along the straight line. Hypothetical examples of good residual and probability plots are given in Figures 1 and 2 below.

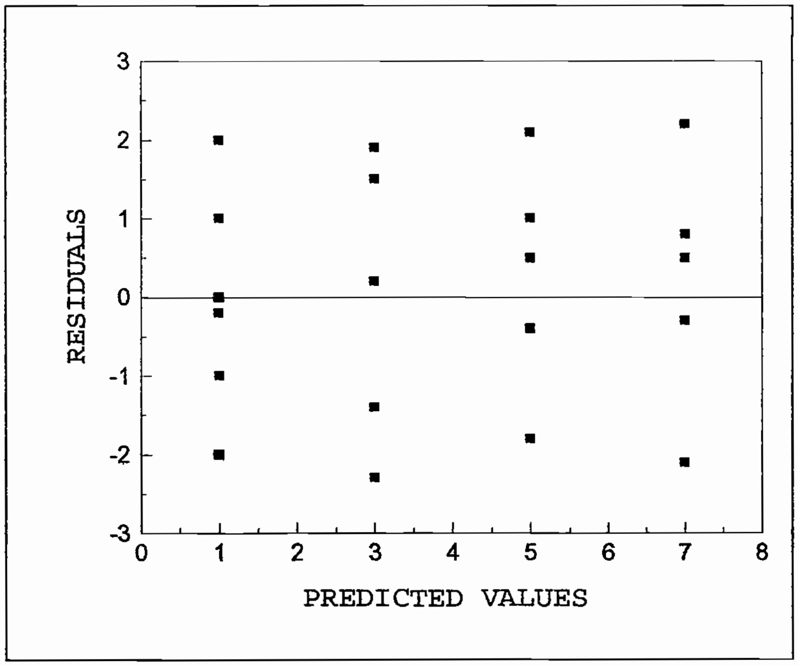

Figure 1. Sample residual plot.

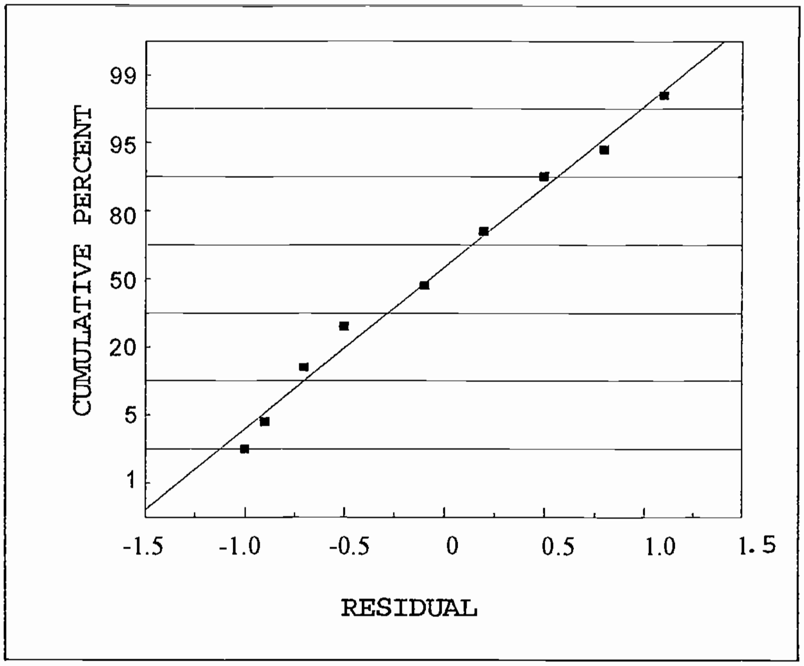

Figure 2. Sample normal probability plot.

Because a simulation must use linear regressions as a tool for prediction, it is advisable to report some basic statistical calculations. Some of them are: the mean square error (MSE), the size of the sample (n), the mean and variance of the independent variables (x_m and s_x^2), the standard errors (St. Error) and p-values of the estimated parameters, and the adjusted coefficient of determination ($R^2_{(ADJ)}$).

3.2 Simulation Model Building

The simulation model building using the 1.1 version of Promodel PC for Windows needs to follow some main steps. The animation portion of a simulation model can be separated from the rest of the model building. More specific information can be found in the user software manuals. A general description of the model building procedure follows.

3.2.1 First Settings

In this first step, it is necessary to select the time units that will be used in the simulation runs. Given the production goals and the precision of the field data, the following choices must be considered: (1) real or productive time, (2) time unit (seconds, minutes, hours) and (3) time measurement precision (one, two or more decimal places).

Also, it is convenient in the first step to build the graphic library of the products and machines of the system. The graphic library gives animation capability to the simulation. The graphic editor performs figure design and storage.

3.2.2 Locations

This next step defines and establishes the required locations of the processing and storage sites within the system. There are no rules related to the definition of a location or the determination of the number of locations required. However, two important points to be considered are that (1) a location is principally related to a physical space where a system-product will be modified, and (2) a location can also be established only for animation reasons.

Another main determination is the size of each location. The size is dependent on the real situation and the sizes and frequency of the tree arrivals. This determination is independent of the kind of simulation selected, with PMH or SMH time. In a SMH simulation this determination is obvious; but in a PMH simulation, the location size needs to be a value that will not produce unrealistic bottlenecks.

3.2.3 Entities

Entities of the simulation model are synonymous with system products. At this point it is necessary to define each of the system products and choose an icon from the library to represent it.

3.2.4 Resources

Resources refer to the machines of the system. Similar to the treatment of entities, it is necessary to define each of the machines and choose an icon that can represent it. Also, the machine routes need to be defined at this time.

The amount of time and effort required to spend at this level of the simulation model building depends on the desired visual quality of the animation.

3.2.5 Processing

Processing is the main section of the simulation. In this section the logic of the system is defined and the simulation variables are quantified. The logical links between the variables of the system are defined. The following must be specified: (1) the sequence order of the locations, (2) the machine use at each location, (3) the sequence order and transformation order of the system products, and (4) the numerical values and randomness of the system.

In this stage, all the computer programming is developed. The constructs used are: if-then instructions, group and ungroup functions, statistical distributions of system variables, and linear regressions between variables of the system.

3.2.6 Arrivals

At this stage it is necessary to define both the number of system products that are entering each time and the frequency of these arrivals. Since a preload of the system is not possible, this stage is important for the next stages, especially for the transient period calculation.

3.2.7 Simulation Variables

All the programming variables (global variables or attributes) used in the processing stages need to be defined. Each variable will be designated as an integer or real variable, given an initial value, and the level of statistical output specified.

3.3 Transient Period

There are several methods for determining the length of the transient or warm-up period of a real time simulation. Usually these methods involve the use of empirical knowledge of the reasonable expected variation for the system. This variation is evaluated using the average value per time of an important output variable, such as produced volume. The transient data is determined by analyzing the graph of these values and estimating when the system reaches its steady state. One easily understood method which follows a graph principle has been presented (Taha, 1990).

There is no known method for determining the transient period of a productive time simulation. For this reason, one was designed. In a productive time simulation, each of the system machines works without interfering with the other. Therefore, the key for determining the transient period is to detect the simulation running time when idle times of all the machines reach a zero value. This means that there is no remaining start-up effect in the system and that the transient period has passed. After completing several runs with different transient periods, and observing the reduction of idle time for each machine in the resulting file, a reliable estimation of the actual transient period can be made. The transient period used in the final runs should include a safety margin to protect against modified situations which can take longer to reach a steady state.

3.4 Verification

Verification is the process by which the results given by the simulation model are compared with the field data. At this step in the simulation building, it is possible to detect inconsistencies and errors and correct them.

After the verification is completed, the minimum duration of each run must be determined. Each run consisted of a certain number of replications or iterations. There are two main points to consider. The first is the computer time required for a complete run. The second is the width allowed for the confidence intervals of the results. The longer the simulation is run, the smaller the width of the confidence intervals will be.

3.5 Productivity Objective Findings

After the first four steps are completed the results can be calculated. The results can be obtained through either of two methods, depending on the manner in which the variables in the study are expressed.

In the first method, when the mean of a variable (described by a statistical distribution) changes, the coefficient of variation (standard deviation/mean*100) and distribution remain the same. For example, the delimbing time of a processor has a normal distribution, and its parameter values has a mean of 20 seconds with a standard deviation of 4 seconds. The analytical question to be asked is, "How much can production increase if the delimbing time decreases to an average of 10 seconds?". In this situation the same normal distribution is used. The standard deviation will change to 2 seconds because the new mean is 10 seconds, and the coefficient of variation of the original situation is 20 percent.

The second method for obtaining the production results is used when the changing variable is expressed through a function in the model. In this case, the variable in the study is a dependent variable of a mathematical relation, and the change needs to be made in the independent variable of the relation. For instance, taking the same time variable and question as above, if the delimbing time of the processor is expressed by a simple linear regression where the delimbing time is the dependent variable and the branch diameter is the independent variable, then an indirect change from a mean of 20 seconds to a mean of 10 seconds in the delimbing time is made. The value of the branch diameter related to the 10 seconds delimbing time needs to be calculated. Finally, the parameters of statistical distribution related to the branch diameter are modified as in the first case.

In summary this methodology has established the main steps required to develop a productivity analysis using a simulation technique.

CHAPTER 4
FINDINGS

4.1 Simulation Input

The field data used as the input to the simulation came from a study developed by Loren Kellogg and Pete Bettinger of a cut-to-length harvester/forwarder system.

4.1.1 System Definition

The system is composed of two machines, a Timberjack 2518 single-grip harvester and an FMG 910 forwarder. The operation consisted of thinning a 47-year-old Douglas fir (Pseudotsuga menziesii) and Western hemlock (Tsuga heterophylla) stand (Kellogg and Bettinger, 1994). The important operating times of the harvester and forwarder cycles are listed in Tables 1 and 2. Also, in Figures 3 and 4 the schemes of the cycles of these machines are given.

The original definition of operating times classified Brushing, Piling and Planning into different categories. For simulation purposes just one statistical distribution was calculated for these three operating times combined.

TABLE 1. Harvester operating times.

TIME	DESCRIPTION
Moving Machine	Begins when the harvester tracks start moving, ends when the harvester stops moving to perform some other task.
Positioning to Cut	Begins when the boom starts to swing toward a tree, ends when felling head rests on a tree.
Felling and Dropping	Begins when the felling head is attached to a tree, ends when the tree hits the ground, or when processing begins.
Processing	Begins when the tree hits the ground, or when the felling head begins to pull the tree through the delimbing knives, ends when processing is complete.
Brushing	Removal of saplings and brush and felling of unmerchantable trees.
Piling	Piling or sorting logs in the woods.
Planning	Assessment by the harvester operator of area or trees to cut, while remaining in the stationary machine.

Source: Kellogg and Bettinger, 1994.

TABLE 2. Forwarder operating times.

TIME	DESCRIPTION
Traveling Empty	Begins when the forwarder leaves the landing area, ends when the forwarder stops to begin loading or some other task.
Loading	Begins when the forwarder starts to load logs, ends when the boom is rested in a stationary position, ready for a machine move.
Moving Between Loading	Begins when the boom is rested stationary on the bunk, ends when the forwarder stops moving.
Traveling Loaded	Begins when the boom is rested stationary on the bunk, ends when the forwarder stops at the landing area.
Unloading *(includes sorting into decks)*	Begins when the forwarder raises the boom for unloading, and ends when the boom is rested stationary on the bunk for a return trip to the woods or some other task.

Source: Kellogg and Bettinger, 1994.

The output product of the harvester cycle is Logs, but the input product of the forwarder cycle is Group, which is several logs. At each stop of the forwarder for loading, more logs are usually loaded than came from one tree.

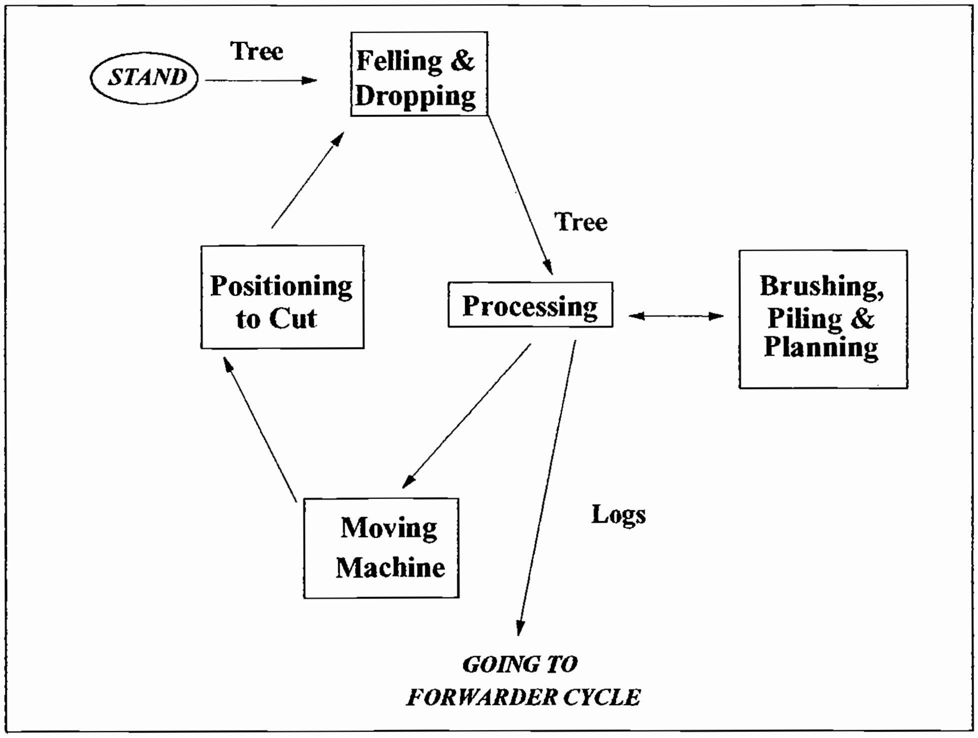

Figure 3. Harvester cycle

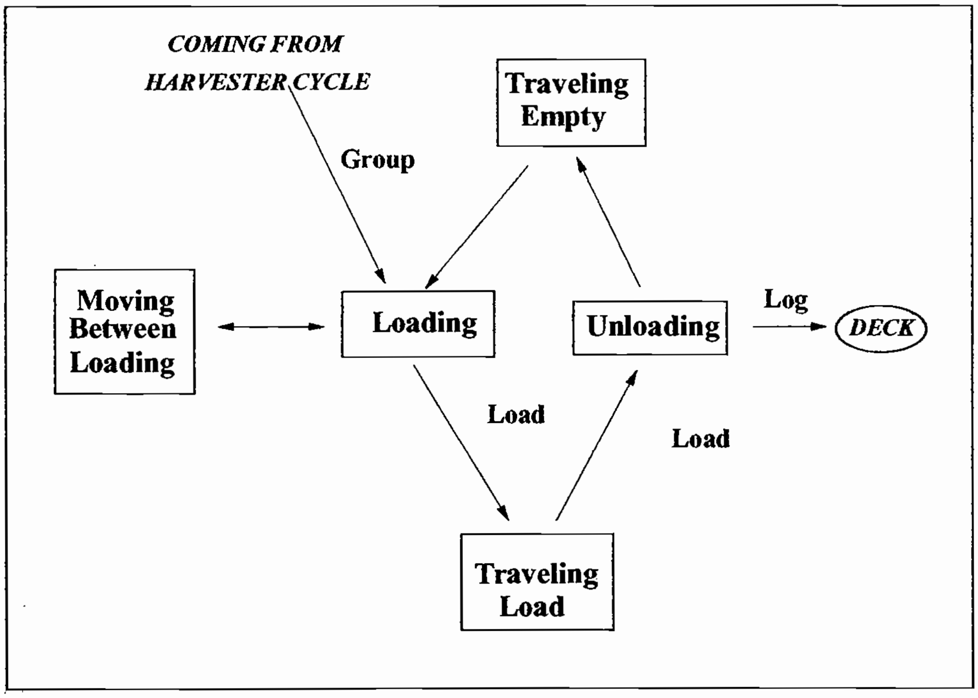

Figure 4. Forwarder cycle.

There are five products in the harvester - forwarder system. Their definitions are given in Table 3.

TABLE 3. System products.

ENTITY	DEFINITION
Tree	Each of the trees to be cut in the thinning operation.
Logs	Set of logs located at the stump that is produced from a tree.
Group	Set of logs that can be loaded for the forwarder in just one stop.
Load	Set of logs that can be transported by a forwarder in each trip.
Log	Final product of the system, located at the landing deck.

4.1.2 Productivity Study

The two main forwarder situations we have chosen to study are the responses under variations in (1) AYD and (2) unloading time. Both situations intend to model the changes in the total production per PMH of the system.

The study of yarding distance quantifies the effect of this variable on the total production of the system. There are three variables related to the yarding time that must first be defined and measured. One relates to the distance traveled by the forwarder from the landing yard to the first loading location in the forest (distance out). Another relates to the travel distance within the loading area. The last is the distance between the place where the forwarder finishes loading and the landing (distance in).

If a loader is added to the system, the forwarder does not need to sort the logs during unloading. The forwarder unloading time is reduced. Moreover, if the forwarder is the bottleneck machine in the system, the PMH production of the system will be improved in direct proportion to the reduction in unloading time.

This simulation will be developed using only productive time because the goals are not concerned with possible interference variables such as delays or landing sizes.

4.1.3 Statistical Distributions Findings

The statistical distributions required in the simulation model for building the harvester, forwarder and interaction behavior are given in tables 4, 5, and 6 respectively. The results were calculated using the K-S

Goodness of Fit Test (D'Agostino and Stephens, 1986). The selection criteria are the p-values found for each of the statistical distributions (Erlang, Exponential, Gamma, Lognormal, Normal and Weibull). High p-values are better than low ones because the null hypothesis of the K-S Test says that the theoretical distribution fits the field data. If more than one statistical distribution fits the data of one variable; the alternative statistical distribution is given in brackets. An explanation of how a statistical distribution can be found using the K-S Test is given in Appendix C. Also. Appendix D gives the main formulas related to the statistical distributions founded.

The positioning-to-cut variable had low p-values for both acceptable statistical distributions. Despite the fact that the Lognormal statistical distribution had a lower p-value, it was chosen because it is a simpler to work distribution.

Table 4. Harvester statistical distributions

VARIABLE	STATISTICAL DISTRIBUTION	UNIT	PARAMETERS	P-VALUE
Moving Machine	Lognormal (Gamma)	[cmin]	mean =14.77 st.dev.=14.99	0.49 (0.10)
Positioning to Cut	Lognormal (Gamma)	[cmin]	mean =19.59 st.dev.= 8.96	0.06 (0.12)
Processing	Lognormal (Gamma)	[cmin]	mean =34.24 st.dev.=21.51	0.37 (0.07)
Brushing, Piling & Planning	Lognormal (Gamma)	[cmin]	mean =59.32 st.dev.=50.45	0.15 (0.06)

Table 5. Forwarder statistical distributions

VARIABLE	STATISTICAL DISTRIBUTION	UNIT	PARAMETERS	P-VALUE
Traveling Empty	Weibull	[cmin]	shape = 1.97 scale =503.45	0.76
Loading	Weibull (Normal)	[cmin]	shape = 3.73 scale =1931.7	0.98 (0.97)
Moving Between Loading	Weibull (Gamma)	[cmin]	shape = 1.76 scale =211.9	0.94 (0.91)
Traveling Loaded	Weibull	[cmin]	shape = 2.35 scale =407.3	0.98
Unloading	Lognormal	[cmin]	mean =912.9 st.dev.=724.5	0.47

Table 6. Other statistical distributions

VARIABLE	STATISTICAL DISTRIBUTION	UNIT	PARAMETERS	P-VALUE
DBH	Normal (Gamma)	[inch]	mean =8.838 st.dev.=2.738	0.63 (0.79)
Group	Lognormal	[log]	mean =10.984 st.dev.=5.304	0.08
Stops	Weibull (Normal)	[#]	shape =2.672 scale =9.523	0.27 (0.15)
Distance Out	Lognormal (Normal)	[feet]	mean =919.1 st.dev.=448.1	0.68 (0.27)
Distance In	Lognormal (Normal)	[feet]	mean =862.4 st.dev.=631.5	0.71 (0.21)

4.1.4 Linear Regression Calculations

Four linear regressions were needed in the simulation model. The following screening steps were followed to accept a linear regression.

1.- The variables were defined.

2.- A linear regression was calculated.

3.- The p-values of the parameters were checked to see if they were lower than 0.05.

4.- The residual plot was observed for an acceptable shape (see Methodology Section). Otherwise, a non-linear regression was tried and the third step above was repeated.

5.- The normal probability plot was cheked for an acceptable shape (see Methodology Section).

Each of the linear regressions achieves these requirements. For reference of the range of values, minimum, maximum and other statistical values related with the independent variables of the linear regressions are given in Appendix E.

No acceptable statistical distribution was found for the felling time of the harvester. Therefore, the following linear regression was substituted for the following distribution, where LN is the natural logarithm (base e).

LN(Felling) =	1.907034 +	0.084261 * DBH
[LN(cmin)]		[inch]
St. Error	0.070859	0.007579
P - Value	<=0.0000	<=0.0000
$R^2_{(ADJ)}$	0.2449	

Because of the way the field data was collected, the only way that the number of logs per tree (a discrete variable) can be predicted is through a linear regression with the DBH. The continuous linear regression result is rounded to an integer.

$$\underset{[\#]}{\text{LogsPerTree}} = 0.557665 + 0.257050 * \underset{[\text{inch}]}{\text{DBH}}$$

St. Error	0.14442	0.015528
P - Value	0.0001	<=0.0000
$R^2_{(ADJ)}$	0.4207	

In the AYD study the time variables, traveling empty and traveling loaded, need to be expressed through linear regressions.

$$\underset{[\text{cmin}]}{\text{Traveling Empty}} = 0.468877 * \underset{[\text{feet}]}{\text{Distance Out}}$$

St. Error	0.014446
P - Value	<=0.0000
$R^2_{(ADJ)}$	0.8985

The traveling empty is only dependent on the distance out; but the traveling loaded time is dependent on the distance in, and the number of stops required for a full load.

$$\underset{[\text{cmin}]}{\text{Traveling Loaded}} = 0.202448 * \underset{[\text{feet}]}{\text{Distance In}} + 0.592679 * \underset{[\#]}{\text{Stops}}$$

St. Error	0.024694	0.074389
P - Value	<=0.0000	<=0.0000
$R^2_{(ADJ)}$	0.8829	

4.2 Simulation Model Building

A simulation model was built that runs in productive machine time. A printout of the code of the main model is given in Appendix F. For animation purposes, a basic graphic library was also built.

4.3 Transient Period

Four hours of simulated operation time was enough to reach a steady state. At this point, idle times no longer occur on the machines. Because the simulation will be modified in the sensitivity analysis, a conservative (longer) transient period was established at eight hours, twice the original period calculated. Therefore, each of the replications will consist of eight hours of warm up or transient period and forty-eight hours of effective simulation.

4.4 Verification

In this stage, a problem was found with the use of the Gamma distribution for modeling the DBH. The Gamma distribution was overestimating the DBH, and as a result the total system production was overestimated. Therefore, the Gamma was replaced with the Normal distribution, and the resulting production given for the hand calculation was now in the range of the simulation output.

The number of replications per run was established at five for two reasons; (1) the time required per computer run was approximate one hour, and (2) the width of the confidence interval of the average production per PMH was less than 3 m^3.

4.5 Productivity Objective Findings

A linear regression between the production per PMH of the system and the AYD of the forwarder (Figure 5) was developed using the simulation results.

The simulation model was repeated five times at each AYD. Each data point in Figure 5 represents forty-eight hours of system performance.

The calculation of these linear regressions followed the same steps as was followed in the calculation of the linear regressions required for the input to the simulation model.

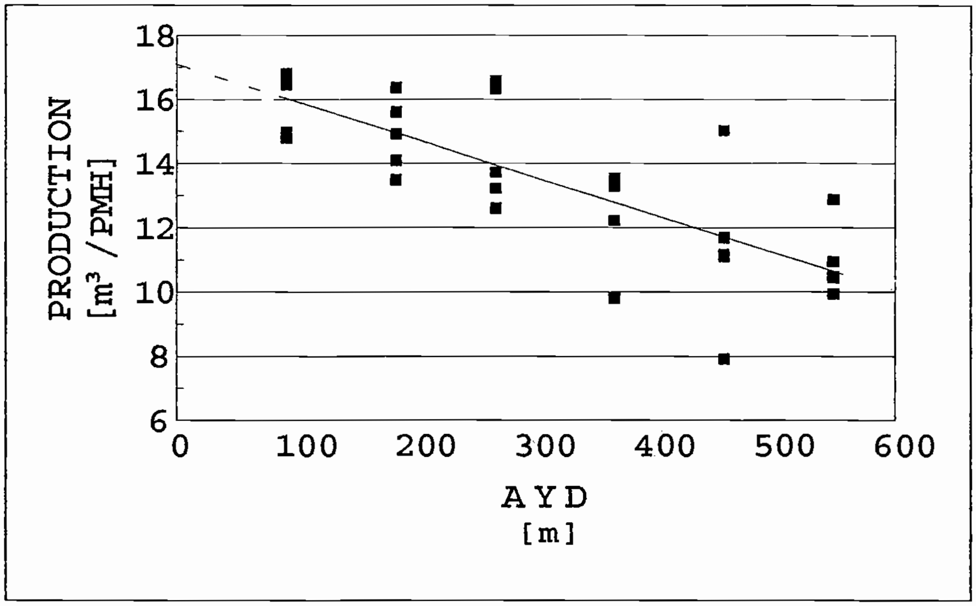

Figure 5. Production under different AYD.

Production = 17.094525 - 0.011768 * AYD
[m³/PMH] [m]

St. Error 0.636906 0.001793

P - Value <=0.0000 <=0.0000

$R^2_{(ADJ)}$ = 0.5919 MSE = 2.36447 n = 30

In a similar way, a linear relation between the unloading time of the forwarder and the production per PMH of the system (Figure 6) was established.

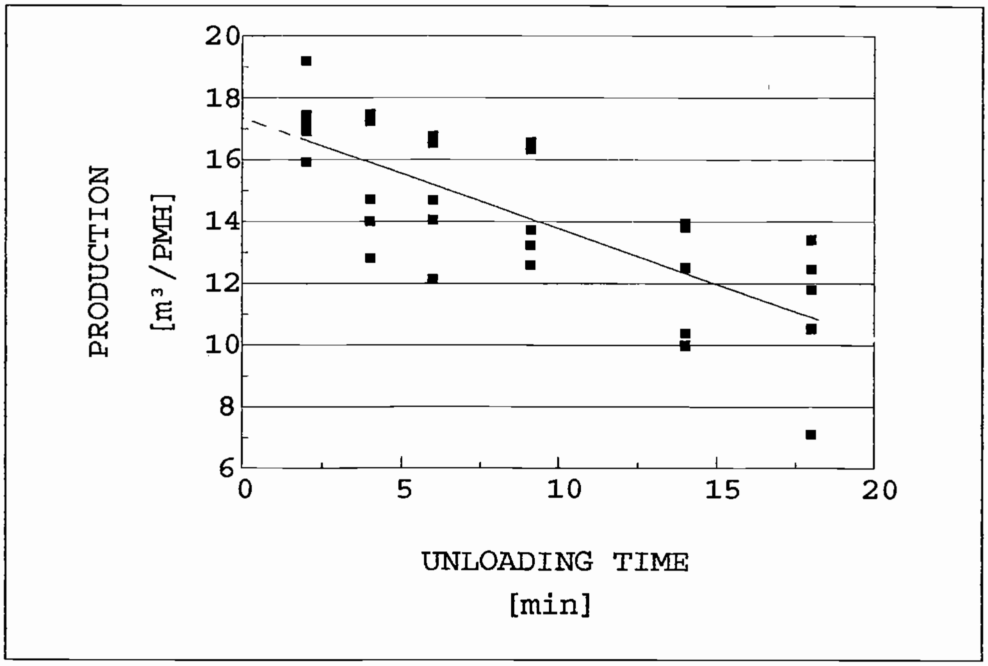

Figure 6. Production under different unloading times.

Production = 17.348911 - 0.358599 * Unloading Time

[m^3/PMH] [min]

St. Error 0.627232 0.059834

P - Value <=0.0000 <=0.0000

$R^2_{(ADJ)}$ = 0.5463 MSE = 3.38126 n = 30

As in the AYD study, the unloading study was repeated at six different levels with five replications at each unloading time.

CHAPTER 5
DISCUSSION

5.1 Input

When a productivity study of a system uses simulation as an analysis technique, the first thing to do is to clearly define the productivity questions. Then a draft of the simulation model can be built which is capable of answering these questions. Next, design a field study in a way that all the data required for the simulation can be collected.

Statistical distributions and linear regressions are the input data for a simulation that represent the variables in the model. For example, in the harvester-forwarder system the average and standard deviation of the DBH are not sufficient information; instead the statistical distribution that fits the DBH and its parameters is required. This statistical distribution generates random values for this variable.

The first draft of a simulation model will help define which variables to collect in the field and the quality of information that is required for each variable. Depending on the productivity questions being asked in the study, sometimes only the statistical distribution of the total cycle of a machine is needed. In other cases it will be necessary to collect information on each element of the work cycle of the machine. Moreover, sometimes data on operational variables that are related with these time variables will also need to be collected.

In a situation when the field data was collected previously, a simulation analysis is severely limited. The most important example related to the harvester-forwarder system that was studied is the amount of output. Originally, the field data tried to capture information on each kind of output product (sawlogs, pulpwood and logs in general); but the identity of these individual products was not tracked successfully. The number of logs cut per tree was collected, but the logs were not identified as sawlogs or pulpwood logs.

In summary, a simulation model needs as input all the statistical distributions and linear regressions for each of the important variables of the system. After a first draft of the simulation model is constructed, the field data needs can be specified. Then a field data collection procedure can be designed.

When the field data have been collected in a spreadsheet format, it is easy for a person working with a statistical software package such as Statgraphics to process the data.

After a linear regression is calculated, the graphical output features of the software allow for a fast and easy inspection of the basic assumptions. Residuals and the normal probability plots are examples of the tools available. Also, current reports are available of the linear regression display output such as the number of data points, standard errors, p-values of the coefficients, as well as model and lack-of-fit tests.

When a specific statistical distribution needs to be found, Statgraphics has a Kolmogorov-Smirnov test option that allows analysis of eighteen different distributions. Also, it allows sensitivity analysis on the parameters of the distribution.

5.2 Output

The most important feature related to simulation output is the capability to reproduce the randomness of the actual harvest system. Using statistical distributions in the simulation, production variations due to realistic randomness can be generated.

Figures 5 and 6 (see Findings Chapter) show the graphs that are related to the variations in production due to changes in AYD and unloading time. Each of the dots represents approximately one week of operation. The difference in production between two given weeks can easily be 4 [m^3/PMH]. This variation is due solely to the statistical distribution of the simulation model.

The simulation was built using a productive hour time basis. The actual field performance will vary even more due to delays, interference, and site conditions.

What are the important results of this finding? First, the regression line established the average production that could be expected over many weeks of operation. Second, if we would like to predict the specific production of a week, we need to calculate a valid statistical prediction. For example, let us say that we have an operation with similar conditions to the situation in this study. How much production can we expect in any given week of operation? From a statistical point of view, we need to find limits of prediction for the production in [m^3/PMH] for a given AYD.

The general equation for calculating these limits of prediction is given below.

$$PRED\{y/x_h\} = \beta_0 + \beta_1 \times x_h \pm t_{\left(1-\frac{\alpha}{2},\, n-2\right)} \times \sqrt{MSE \times \left(1 + \frac{1}{n} + \frac{(x_h - x_m)^2}{(n-1)s_x^2}\right)}$$

Where:

$PRED\{y/x_h\}$= prediction interval of y when x=x_h.

β_0, β_1= coefficients of the linear regression.

$t_{\left(1-\frac{\alpha}{2},\, n-2\right)}$ = t-student value with 1-α confidence and n sample size.

MSE = mean square error.

x_m = sample mean.

s_x^2 = sample variance.

(Ramsey and Schafer, 1992)

The sample size n is 30. The t-value at 95% confidence level and 28 degrees of freedom is 2.048 (Wine, 1964). The mean square error is equal to 2.36447. The sample AYD mean is equal to 318.797 [m] and the sample AYD variance is equal to 25353.51605 [m^2].

Therefore, the limits of prediction for an AYD of 266.86 [m] (field AYD mean) with 95% of confidence will be between 10.747 and 17.161 [m^3/PMH]. In other words, if a harvester-forwarder system is operating in a situation with an AYD of 266.86[m], we can expect that the production of any week will be between 10.747 and 17.161 [m^3/PMH] with a 95% of confidence. This range is large (6.414 [m^3/PMH]) and it is due to the randomness of the system.

There are two other important considerations in the prediction of values. First, the confidence interval for prediction is a minimum at the sample mean. It is a good practice to match the average value of the field sample with the sample mean of the regression. Second, the width of the interval can be decreased if we increase the number of replications per run.

5.3 Limitations and Capabilities

The most important limitation of a simulation model is that its quality depends directly on the field data collected. We can not expect to have a credible simulation if we have an inadequate set of data. The best way to control this limitation was discussed in section 5.1.

Promodel PC is a simulation package which is easy to use and capable of modeling harvesting operation systems. There are four main points that make Promodel PC a powerful tool for productivity studies of harvest process.

First, the set of statistical distributions available is large; all eighteen of the statistical distributions tested by the Goodness-of-Fit test in Statgraphics are available. There is also the option of defining user distributions.

Second, Promodel has prebuild functions that allow grouping and ungrouping of system products without losing the information of the original products. This characteristic is important because the harvest operations are always related to these functions. For example, a tree needs to be ungrouped in logs; logs need to be grouped in bunches; bunches are subsequently redefined as different kinds of system-products loads according to the skidding or yarding machine being used, and so on.

Third, the output of Promodel allows further analysis. It is possible to keep track of many kinds of variables through each replication and for the whole run. In this way, each replication of a run can be a full set of data available for analysis.

Finally, the structure of the simulation-building-and-run menu is easy to use. A basic knowledge of simulation and programming is required; but the most important parts in the construction of a simulation model are systematized in a didactic way.

The animation characteristic of this simulation package has good and bad sides. The positive consequence is that animation can display analysis to people who are not familiar with simulation. The bad consequence is that animation makes a program more difficult to build, to modify, and to follow its logic. With animation it is necessary to build a bigger graph library, to create artificial locations and an artificial path network. The processing steps are also less clear and the computer run time takes longer. In general, avoid animation if possible.

5.4 Considerations About Adding a Loader

In this system the bottleneck is the forwarder. To achieve more production a reasonable alternative could be to add a loader to the system. In this way the forwarder can spend less time sorting during unloading, and the production of the system would increase.

Adding a loader to the original harvesting system simulation model is a major change to the system procedures. In order to add a loader we need information related to (1) the amount of interference between the loader and the forwarder, (2) the statistical distributions related to the elements of the loader cycle, and (3) the size of the landing. None of these were available from the field study source.

As an alternative, a simple cost analysis can be developed (subject to some assumptions). The main assumption is that the loader can not interfere with the forwarder at the landing because the bottleneck is the forwarder. In addition, there are three other important conditions. First, the original unloading time of the forwarder included a sorting stage and this is no less than 20% and no more than 80% of the total unloading time.

Second, the landing is big enough for storing all the logs of the system. Third, the percentage of utilization of all machines is 75%.

The hourly owning and operating costs of a harvester and a forwarder are \$93.95/SMH and \$74.70/SMH respectively (Kellogg and Bettinger, 1994). For the loader costs, the OSU Mechanization Data Base gives operating and owner cost for 53 loaders. The average loader cost is \$64.02/SMH. The unloading time calculated in the field data is 9.13 [min] per load. This unloading time can be divided into two times, (1) self unloading time of the forwarder, and (2) sorting and loading time. If it is assumed that the sorting and loading time can varies between 1.83 [min] and 7.30 [min] (20 and 80% of the total unoading time), it can have a range of production and cost system that is given in Table 7.

The production under present conditions (without a loader), using the linear regression related to Figure 6 is

$$(17.348911 - 0.358599 * 9.13[\text{min}]) * 0.75 = 10.56\ [\text{m}^3/\text{SMH}].$$

Then the cost of the system is

($93.95/SMH + $74.70/SMH) / 10.56 [$m^3$/SMH] = $15.97/$m^3$.

Table 7. Production and cost with a loader added.

UNLOADING TIME	SYSTEM PRODUCTION	SYSTEM COST
[min]	[m^3/SMH]	[$/$m^3$]
7.30	11.05	21.06
5.48	11.54	20.16
3.65	12.03	19.34
1.83	12.52	18.58

From a cost point of view, adding a loader to the harvest operation is not a cost effective alternative although it increases the hourly output.

5.5 Considerations About Using Two Forwarders

Another possible solution to analyze for solving the unbalance problem of the system is to work with one harvester and two forwarders.

The main assumptions related with this alternative system are (1) the forwarders do not have interference between them in both the forest and the set-out trailers, (2) the harvester is starting its operation enough days ahead for avoiding lack of logs for the forwarders, and (3) the utilization rate of the machines are 75%.

As was established in the section 5.4 for doing a simple cost analysis, the harvester and the forwarder have hourly operating costs of \$93.95/SMH and \$74.70/SMH respectively. Using the linear regression related to Figure 5, the calculation of the forwarders production under extreme AYDs can be done.

$$(17.094525 - 0.011768 * 92[\mathrm{m}]) * 2 * 0.75 = 24.02[\mathrm{m}^3/\mathrm{SMH}]$$

$$(17.094525 - 0.011768 * 548[\mathrm{m}]) * 2 * 0.75 = 15.97[\mathrm{m}^3/\mathrm{SMH}]$$

On the other hand, the average production of the harvester in the simulation runs is $20.88[\mathrm{m}^3/\mathrm{PMH}] * 0.75 = 15.66[\mathrm{m}^3/\mathrm{SMH}]$. Therefore, under any AYD this machine configuration has the bottleneck in the harvester and the system cost is

$$(\$93.95/\mathrm{SMH} + 2 * \$74.70/\mathrm{SMH})\ /\ 15.66\ [\mathrm{m}^3/\mathrm{SMH}] = \$15.54/\mathrm{m}^3$$

This is only slightly less than the \$15.97/m^3 under present conditions. Then, some extra points need to be considered, such as (1) the utilization rates are just assumptions, (2) there is less chance to have all the machines busy all year long, (3) most of the forest conditions (species, slope, density, age) are constantly changing from forest to forest, and (4) there is some extra savings due to less road construction and transportation because of longer AYD. All these uncertainties due to lack of real data do not allow a conclusive decision about the best system to use.

CHAPTER 6
CONCLUSIONS

6.1 Study Summary

From this study it is possible to conclude the following.

1.- Statistical distributions and linear regressions obtained from field data are the type of input needed for a simulation that produces realistic output.

2.- The "group" and "ungroup" functions of Promodel are powerful tools for modeling harvesting systems.

3.- Animation is a Promodel capability that produces more inconvenience than benefits.

4.- The recommended sequence of activities for future production studies of harvesting systems using simulation as a tool is: establish production questions; create a rough draft of the simulation model; collect field data; calculate simulation input data; build a final version of the simulation model; verify the model; calculate its transient period, length of each replication and number of replications; and perform the simulation analysis.

6.2 Future Studies

Future researches can address the following needs.

1.- When the variables in the study do not have normal distributions, determine an algorithm which will specify a minimum sample size for field data.

2.- Develop a production study using the full recommended sequence of work. Mainly this study needs to address two main points: first, the effectiveness of field and simulation studies working together, and second, the quality of the output data.

3.- Establish a standarized procedure for collecting and processing field production data of harvest systems, having in mind future simulation studies. This standarized procedure needs to easily collect and store data, producing, for example, a public bank of data where it is possible to get useful statistical information for simulation. This would include statistical distributions fitted, parameters values, and a range of data of each of the important variables of each system.

4.- Evaluate other simulation language packages in the analysis of harvest systems. Promodel PC is a feasible simulation language to use in analysis of harvest operation. However, there are others SL packages that could be faster and easier to use.

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APPENDICES

A.- Field Data of the Harvester Machine

Table 8. Harvester field data.

Observ.	Moving Machine	Positioning to Cut	Felling and Dropping	Processing	Brushing, Piling & Planning	Logs Per Tree	DBH
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[inch]
1	0	13	18	63	0	4	12
2	0	22	13	38	20	3	11
4	9	13	13	7	0	1	7
5	12.5	22	13	13	0	2	6
5	10	15	22	25	45	2	10
6	12.5	15	8	23	0	1	15
6	10	18	28	28	0	3	10
7	20	15	17	38	0	3	10
7	47	30	18	50	72	3	12
8	15	17	17	15	0	1	7
8	30	8	18	17	97	2	6
9	15	13	12	10	0	1	6
9	22	8	17	25	0	3	9
10	7	17	13	13	33	2	6
12	18	13	12	40	0	4	11
13	4	12	10	20	67	1	6
13	11.5	10	15	22	0	3	8
15	4	22	7	12	0	1	6
15	38	20	15	50	63	4	10
17	6	25	17	45	0	4	12
17	10	23	17	52	59	2	12
18	9	35	23	12	160	1	7
18	4	15	10	45	98	4	10
19	9	32	25	42	0	4	12
21	8.3	13	15	38	35	3	9

Table 8. Continued.

Observ.	Moving Machine	Positioning to Cut	Felling and Dropping	Processing	Brushing, Piling & Planning	Logs Per Tree	DBH
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[inch]
22	47	15	10	13	237	1	8
22	8.3	17	13	12	0	1	5
23	8.3	8	17	43	18	4	12
23	11.5	12	15	37	0	3	8
24	7.7	17	13	27	30	4	9
24	11.5	32	18	75	0	4	14
25	2.3	10	55	63	62	4	13
25	7.7	13	13	18	69	3	7
26	2.3	40	7	18	0	2	5
27	2.3	33	7	20	0	3	7
28	2.5	10	33	85	60	4	14
28	22	13	10	17	0	2	6
29	2.5	37	13	54	0	3	14
29	2	10	13	27	67	3	10
30	3	20	12	27	0	2	6
30	15	18	22	57	131	5	14
31	13	20	12	35	22	4	10
31	3	22	18	57	0	4	10
32	22	28	15	33	138	4	9
34	3	28	17	40	0	3	12
35	3	18	15	25	0	4	9
35	17	23	7	45	0	2	8
36	71	20	13	20	92	3	8
36	17	20	13	22	0	2	7
37	11	7	8	7	38	1	5
38	11	8	13	10	98	1	6
39	15	35	12	23	0	3	9
39	30	15	7	10	35	1	5

Table 8. Continued.

Observ.	Moving Machine	Positioning to Cut	Felling and Dropping	Processing	Brushing, Piling & Planning	Logs Per Tree	DBH
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[inch]
40	15	15	122	45	38	4	13
40	17	15	10	13	23	1	5
41	70	25	10	25	188	4	10
42	12	12	22	23	17	4	10
42	12	20	25	83	0	5	14
43	20	15	28	25	0	4	10
44	25	20	13	37	0	4	10
44	7.7	22	12	28	206	4	8
45	10	20	13	65	89	4	10
45	7.7	28	10	38	0	4	11
46	10	22	17	17	0	3	8
47	8	17	23	22	118	2	9
47	19	17	13	38	25	4	11
48	27	25	17	70	83	4	12
48	37	35	15	37	17	3	11
49	12.5	18	8	13	22	2	5
49	45	32	10	90	17	3	8
50	9	25	18	25	63	1	6
52	11	30	15	40	55	4	12
53	11	17	10	10	76	1	4
54	1.5	30	15	48	0	3	10
55	23.5	30	13	75	41	4	14
55	8.7	15	20	52	76	5	11
56	23.5	22	13	35	20	3	10
56	8.7	15	18	25	0	4	8
57	10	12	18	55	100	4	13
57	4	7	8	15	42	2	18
58	3.8	7	17	22	65	3	8

Table 8. Continued.

Observ.	Moving Machine	Positioning to Cut	Felling and Dropping	Processing	Brushing, Piling & Planning	Logs Per Tree	DBH
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[inch]
58	4	38	17	35	50	3	11
59	24	5	15	27	131	3	9
60	3.8	15	15	33	0	4	11
60	24	13	8	13	15	1	8
61	3.8	28	20	58	0	4	11
62	6	13	18	53	70	4	11
63	39	12	7	7	192	1	5
63	6	37	28	37	0	4	11
64	5	8	12	8	49	1	5
65	3.2	20	23	30	0	4	9
66	6.5	18	5	20	20	1	7
67	3.2	27	11	27	68	4	8
67	6.5	15	7	15	24	1	5
68	22	30	15	70	28	4	12
68	6.5	12	8	15	0	2	5
69	6.5	12	7	12	44	1	5
69	20	20	27	20	0	3	7
70	18	15	37	27	18	4	10
70	18	7	12	12	0	1	18
71	25	15	15	74	149	2	7
72	20	13	15	27	0	4	9
72	8	17	15	15	52	2	6
73	35	7	28	22	48	2	12
74	21	12	22	28	0	4	9
74	7.5	8	12	13	0	1	14
75	4.2	18	15	23	18	2	6
76	21	15	12	25	13	3	7
77	32	15	53	95	22	5	16

Table 8. Continued.

Observ.	Moving Machine	Positioning to Cut	Felling and Dropping	Processing	Brushing, Piling & Planning	Logs Per Tree	DBH
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[inch]
77	4.2	20	12	30	22	3	7
78	35	10	18	12	95	2	5
78	4.2	33	7	33	0	2	5
79	6.5	7	12	17	37	2	8
80	6.5	13	10	18	0	2	10
81	5.7	23	30	43	65	3	11
81	6	15	17	13	30	1	5
82	6	15	10	37	0	2	5
82	30	28	17	72	22	4	11
83	11.7	27	17	52	70	4	13
84	11.7	25	8	23	49	2	10
84	8.3	22	10	8	35	1	9
85	8.3	25	12	15	0	2	8
85	11.7	12	12	18	0	3	8
86	8.3	22	8	42	23	4	13
87	15	13	12	33	0	3	9
88	6	13	15	18	78	2	7
89	26.5	23	18	15	145	1	8
89	6	17	10	8	0	1	9
90	6	12	13	33	33	2	9
91	11	17	10	12	0	1	11
93	10.7	17	23	88	32	4	14
94	11.5	15	22	18	23	1	6
95	11.5	15	8	30	0	3	8
96	16	8	12	70	244	3	14
97	18	12	13	42	39	2	12
98	25	22	13	37	0	3	11
98	16	10	8	20	38	2	6

Table 8. Continued.

Observ.	Moving Machine	Positioning to Cut	Felling and Dropping	Processing	Brushing, Piling & Planning	Logs Per Tree	DBH
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[inch]
99	23	13	10	12	0	1	6
99	11	13	20	13	222	2	8
100	11	18	5	7	0	1	4
101	60	5	12	12	51	1	5
101	65	7	8	13	0	1	6
102	3.4	12	13	20	20	1	5
103	3.4	27	27	25	36	2	13
104	3.4	8	20	40	43	2	9
104	12.5	25	8	25	0	2	6
105	28	18	32	35	0	3	11
106	15	12	20	40	39	4	12
107	18	30	7	32	0	3	9
108	14	18	15	33	0	3	8
109	7.6	17	8	13	0	1	6
109	14	28	12	43	0	3	10
110	7.6	12	10	48	0	4	10
110	3.3	25	10	30	61	3	9
111	3.3	28	10	30	0	3	10
111	7.6	18	330	62	23	3	10
112	3.3	38	15	30	0	3	8
112	7.6	18	10	38	0	3	10
113	22	17	15	23	37	2	6
113	38.5	10	18	40	129	3	10
114	4.3	12	12	12	21	2	6
115	7.3	27	15	20	0	2	9
115	4.3	30	8	22	0	2	6
116	4.3	13	13	37	28	4	10
116	7.3	25	17	35	0	3	10

Table 8. Continued.

Observ.	Moving Machine	Positioning to Cut	Felling and Dropping	Processing	Brushing, Piling & Planning	Logs Per Tree	DBH
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[inch]
117	33	33	12	53	15	4	9
118	6	7	8	17	0	2	6
119	13.5	13	20	95	65	5	15
120	6	23	12	33	0	2	7
120	9.5	27	13	23	147	3	8
121	13	30	27	55	18	4	12
121	9.5	18	13	22	18	2	8
122	6.5	18	23	37	25	4	10
123	6.5	18	15	28	25	3	10
123	9.5	73	18	223	0	7	16
125	17	10	10	60	0	3	8
125	4	20	10	38	0	4	10
126	4	17	8	23	0	3	8
126	17	23	15	38	0	4	10
127	6.5	17	18	24	0	3	6
127	17	22	23	38	12	4	11
128	6.5	20	17	23	25	3	8
128	8.5	10	18	58	57	4	11
129	8.5	28	7	35	0	3	8
129	10	32	12	60	42	4	9
130	16.5	18	12	27	24	3	7
130	32	13	17	32	22	4	10
131	10	17	12	33	56	4	9
131	16.5	15	15	29	17	3	7
132	25	23	40	80	0	5	14
132	43	22	22	37	106	4	11
133	43	35	18	33	0	3	7
133	12.5	17	12	43	30	3	9

Table 8. Continued.

Observ.	Moving Machine	Positioning to Cut	Felling and Dropping	Processing	Brushing, Piling & Planning	Logs Per Tree	DBH
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[inch]
134	12.5	27	8	57	0	4	11
134	6.2	17	15	75	209	4	12
135	18	20	12	28	164	4	10
135	6.2	22	12	60	25	4	11
137	3	12	8	8	0	1	4
137	6.2	22	10	23	35	3	7
138	3	13	18	32	0	2	8
138	7.5	20	20	37	18	3	10
139	7.5	33	17	93	30	5	14
139	3	15	7	20	0	2	6
140	3	18	15	50	0	4	10
140	18	23	15	53	0	3	9
141	3	32	13	42	0	4	9
142	8	23	10	38	23	4	10
142	9	15	25	35	45	4	10
143	9	28	13	37	0	4	8
143	20	20	8	25	0	2	6
144	23	7	13	32	167	3	7
144	12	28	18	23	0	3	7
145	17	15	23	42	87	3	6
146	4.5	17	13	40	0	3	9
146	7.5	25	20	40	95	4	11
147	7.5	62	35	93	45	3	11
147	4.5	28	18	22	0	3	7
148	20	12	8	20	75	2	8
148	4.5	20	22	27	82	3	9
149	26	20	10	33	129	2	8
149	4.5	25	17	20	0	3	7

Table 8. Continued.

Observ.	Moving Machine	Positioning to Cut	Felling and Dropping	Processing	Brushing, Piling & Planning	Logs Per Tree	DBH
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[inch]
150	17.5	28	13	33	55	3	9
150	26	37	5	22	0	1	6
151	17.5	7	15	25	96	3	7
152	10	18	22	20	30	2	5
153	10	23	15	42	0	4	11
154	33	22	15	98	112	4	14
155	8	18	25	62	50	4	16
156	13.2	38	12	38	46	4	10
156	11	22	12	27	28	3	7
157	11	25	23	89	0	4	12
158	13.2	27	15	35	35	3	9
158	16.5	22	22	30	65	3	11
159	16.5	25	22	35	0	4	11
159	13.2	12	77	113	28	4	13
160	7.3	10	10	37	0	3	7
160	72	33	18	58	885	3	10
161	7.3	27	20	28	27	3	9
161	3.8	5	12	50	103	4	9
162	3.8	18	13	55	0	3	5
162	7.3	27	27	55	0	4	11
163	15	13	17	22	37	2	8
164	3.8	13	12	27	48	0	8
164	15	32	10	42	0	3	11
165	6	8	7	17	0	2	6
165	3.8	8	7	13	28	1	4
166	3.8	18	13	37	0	4	11
166	6	20	8	18	17	2	8
167	6	25	15	17	0	3	6

Table 8. Continued.

Observ.	Moving Machine	Positioning to Cut	Felling and Dropping	Processing	Brushing, Piling & Planning	Logs Per Tree	DBH
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[inch]
167	25	53	25	28	148	4	10
168	25	33	15	30	0	4	11
169	30	12	7	15	0	2	4
169	65	17	22	28	86	3	9
170	24	47	12	57	260	2	13
171	25	15	8	22	17	2	6
172	23	30	23	38	91	4	14
173	1.7	13	12	22	28	3	7
174	1.7	15	10	17	0	2	6
174	11	15	13	52	0	4	12
177	16.5	27	5	12	0	1	5
178	3	60	85	178	57	4	20
178	7.7	18	17	58	0	4	10
179	8	10	13	18	55	2	13
179	7.7	37	13	28	0	4	11
180	44	12	13	30	93	3	9
180	7.7	12	10	30	20	3	8
181	38	30	23	30	115	3	9
182	3.3	23	10	28	36	3	8
183	20.5	10	17	20	27	3	7
184	20.5	13	12	15	20	2	6
185	8.5	18	5	5	0	1	4
185	2.3	20	28	117	75	5	16
186	2.3	22	12	40	22	4	12
187	7.5	10	18	17	18	2	8
187	2.3	40	22	27	0	3	13
188	7.5	23	10	25	0	2	8
188	7.3	8	12	30	0	3	7

Table 8. Continued.

Observ.	Moving Machine	Positioning to Cut	Felling and Dropping	Processing	Brushing, Piling & Planning	Logs Per Tree	DBH
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[inch]
189	7.3	18	7	18	43	2	6
190	7.3	25	12	38	0	3	9
190	7.5	27	8	23	0	2	8
192	8.5	23	7	13	0	1	6
193	8.5	23	17	40	0	4	9
193	11.5	25	12	48	20	4	14
194	12.5	25	12	32	0	3	8
194	37	32	30	77	102	5	16
195	22.5	17	30	45	148	4	11
195	12.5	17	12	35	0	4	7
196	27	13	5	12	0	1	4
197	18	17	15	45	0	2	7
198	13.5	15	13	17	0	2	6
199	6.2	18	25	38	0	3	9
199	13.5	32	45	28	0	4	10
200	17.5	15	15	32	93	3	8
201	6.2	25	17	57	0	4	12
201	17.5	13	30	62	27	4	10
202	6.2	15	23	15	107	2	7
202	20	37	13	33	61	3	9
203	32	12	25	60	0	4	12
204	9.3	5	15	23	66	3	9
205	9.3	17	8	33	0	3	8
205	3	17	15	32	38	4	10
206	9.3	13	12	37	28	3	8
206	3	23	13	45	0	4	11
207	3	22	40	50	44	4	12
207	18	7	22	28	75	4	11

Table 8. Continued.

Observ.	Moving Machine	Positioning to Cut	Felling and Dropping	Processing	Brushing, Piling & Planning	Logs Per Tree	DBH
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[inch]
208	17	28	10	42	0	4	10
208	3	23	12	25	18	3	6
209	20	32	15	40	12	4	8
209	4	10	15	18	0	3	4
210	17	5	17	30	18	3	8
211	20.5	28	30	37	115	3	9
211	6.2	8	17	20	145	2	6
212	8.5	17	27	22	0	3	9
212	6.2	20	13	25	0	3	8
213	6.2	23	30	45	0	3	8
214	6.2	10	10	12	58	1	6
215	6.2	7	8	15	0	1	7
216	6.2	7	7	27	37	2	7
217	11.5	23	23	33	0	3	6
219	30	19	18	30	22	3	8
219	7.5	18	12	20	47	2	5
220	13	18	10	28	48	2	6
220	7.5	22	10	28	0	3	8
221	7.5	30	12	30	0	3	9
221	5	13	15	20	28	2	8
222	5	28	37	40	0	4	12
222	10.5	18	7	23	25	3	8
223	10.5	22	10	22	17	3	7
224	12.5	8	13	25	0	2	8
224	9	23	35	28	0	2	5
225	12.5	25	10	28	18	3	9
226	15	18	17	33	119	4	12
226	20	20	70	48	156	4	13

Table 8. Continued.

Observ.	Moving Machine	Positioning to Cut	Felling and Dropping	Processing	Brushing, Piling & Planning	Logs Per Tree	DBH
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[inch]
227	15	15	10	17	13	2	9
227	8.5	18	68	52	79	4	9
228	8.5	25	10	13	57	2	10
228	18.5	10	10	32	0	3	9
229	18.5	47	30	261	0	8	17
230	7.7	23	10	47	0	3	9
231	7.7	17	13	8	23	1	5
232	7.7	22	12	15	0	1	5
235	7.3	12	13	55	28	3	9
238	22	13	8	13	53	1	4
239	3.6	18	10	10	0	1	7
240	3.6	12	7	15	12	1	4
243	3.6	25	20	15	0	1	7
244	11	8	10	12	0	1	4
246	4.3	12	10	18	50	2	6
247	4.3	22	13	17	0	1	7
248	4.3	25	12	18	0	2	7
249	40	15	8	32	0	3	8
251	3.8	7	13	23	42	3	7
253	3.8	13	13	23	0	3	7
256	13.3	10	18	12	0	1	4
257	13.3	10	30	30	0	3	9
258	13.3	25	17	72	43	4	14
262	19	22	12	27	0	3	6
263	19	18	12	33	0	3	10
265	40	27	15	48	38	4	9
268	42	12	38	38	67	3	12
270	21.7	8	13	25	119	3	7

Table 8. Continued.

Observ.	Moving Machine	Positioning to Cut	Felling and Dropping	Processing	Brushing, Piling & Planning	Logs Per Tree	DBH
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[inch]
271	21.7	18	12	40	0	4	10
272	21.7	23	17	78	127	4	13
273	5.5	20	13	42	15	3	9
275	5.5	45	27	47	99	4	11
276	5.5	28	23	37	0	4	11
277	13.3	18	25	27	418	3	10
278	13.3	20	17	27	15	2	7
279	13.3	12	18	55	0	4	10
280	15	3	12	28	0	3	7
281	10	18	22	30	77	4	9
282	11	13	7	10	20	2	5
283	11	17	13	17	0	2	8
285	13	10	15	60	10	3	11
286	13	33	28	47	0	4	10
287	27	8	10	7	38	1	4
288	2.4	10	12	7	0	1	5
292	2.4	12	12	42	49	3	10
294	5.7	12	8	12	0	1	5
295	5.7	17	8	18	0	2	8

B.- Field Data of the Forwarder Machine

Table 9. Forwarder field data.

Observ.	Traveling Empty	Loading	Moving Between Loading	Traveling Loaded	Unloading	Stops	Load	Distance Out	Travel Distance	Distance In
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[#]	[feet]	[feet]	[feet]
1	225	2,627	135	267	650	9	71	1,909	239	1,670
2	587	1,782	154	217	547	12	85	1,346	73	1,652
3	751	2,583	118	395	565	6	60	976	85	891
4	617	2,167	140	355	662	6	65	886	115	1,385
5	785	1,943	305	452	622	8	72	1,345	354	1,559
6	861	2,257	188	385	607	9	72	1,753	232	1,521
7	1,007	2,440	362	272	657	13	80	1,664	347	904
8	608	1,463	80	290	598	7	60	894	33	861
10	825	3,452	346	697	483	11	111	976	170	1,661
11	783	1,873	253	193	532	10	89	1,661	256	1,455
13	1,290	1,795	57	589	1,915	4	93	2,008	35	1,224
14	636	1,407	62	502	1,790	4	85	1,164	87	1,077
16	810	1,904	125	557	1,724	8	87	1,243	124	1,119
18	254	1,166	147	575	2,164	6	71	1,104	80	1,024

Table 9. Continued.

Observ.	Traveling Empty	Loading	Moving Between Loading	Traveling Loaded	Unloading	Stops	Load	Distance Out	Travel Distance	Distance In
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[#]	[feet]	[feet]	[feet]
19	757	1,521	37	642	1,529	4	78	1,639	243	1,983
20	683	1,945	134	424	287	8	106	1,759	132	1,627
21	740	1,927	128	575	2,090	6	83	1,165	75	1,705
22	572	1,620	119	488	2,068	6	80	1,050	50	1,615
23	683	1,430	30	407	1,180	3	60	1,615	50	950
24	648	1,406	65	432	1,554	4	68	1,162	83	1,674
27	695	2,269	393	573	978	14	78	1,356	232	1,124
28	742	1,760	232	538	915	9	69	1,264	180	1,084
29	758	2,240	203	568	458	9	129	821	582	1,912
30	908	2,217	195	658	600	10	109	2,075	396	1,974
31	638	2,352	106	557	2,033	8	111	1,290	80	1,210
32	573	1,846	125	383	1,680	4	111	1,275	99	1,176
33	636	2,346	268	267	899	13	77	1,404	238	1,362
34	513	2,065	197	230	615	9	69	1,174	265	809
35	630	1,616	156	355	470	8	53	1,102	177	1,424
36	862	2,417	247	615	767	12	137	1,975	286	1,889
37	743	2,465	273	317	397	16	123	1,874	682	731

Table 9. Continued.

Observ.	Traveling Empty	Loading	Moving Between Loading	Traveling Loaded	Unloading	Stops	Load	Distance Out	Travel Distance	Distance In
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[#]	[feet]	[feet]	[feet]
38	778	1,945	211	428	1,471	7	68	1,222	409	2,078
39	319	2,434	149	468	1,342	8	71	2,387	179	2,108
40	188	980	129	110	303	8	35	312	90	222
41	290	2,437	213	297	591	10	155	554	204	1,007
42	220	2,119	100	283	490	9	126	440	125	983
43	410	1,127	143	70	250	8	50	937	247	63
44	345	1,732	46	268	2,965	5	102	595	85	510
45	630	2,441	276	635	988	13	88	761	218	689
46	353	2,418	362	353	905	11	85	716	278	573
47	345	2,509	242	257	814	11	151	638	465	1,872
49	725	2,196	225	405	830	11	66	794	312	784
50	445	2,185	451	618	827	8	83	752	557	811
51	585	1,528	300	362	716	8	60	950	264	686
52	202	1,452	166	278	1,905	5	95	428	100	420
53	240	1,601	52	205	1,790	4	83	450	50	400
54	158	690	58	142	1,606	4	47	390	97	293
55	530	1,953	230	220	392	12	114	908	193	573

Table 9. Continued.

Observ.	Traveling Empty	Loading	Moving Between Loading	Traveling Loaded	Unloading	Stops	Load	Distance Out	Travel Distance	Distance In
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[#]	[feet]	[feet]	[feet]
56	610	2,179	193	430	582	11	116	952	452	830
57	447	2,276	97	535	420	11	118	797	633	994
58	569	1,292	163	337	320	9	81	965	281	684
59	730	2,120	176	412	802	10	75	965	474	781
60	617	1,513	140	210	435	10	64	632	676	514
61	213	545	60	152	158	6	25	514	90	424
62	448	1,771	419	205	607	9	56	734	195	559
63	510	1,578	173	698	1,882	4	93	854	55	821
64	380	1,323	47	412	1,460	3	82	799	25	796
101	392	1,593	71	380	1,310	5	91	764	143	749
102	567	1,487	137	525	1,513	5	97	980	60	876
103	576	2,023	108	23	1,627	5	97	958	45	935
104	455	1,681	95	553	1,855	5	110	903	55	910
105	478	1,981	704	339	1,930	14	107	899	1,376	314
106	567	1,582	178	836	1,679	2	86	1,036	75	983
107	452	1,653	413	615	1,987	8	112	959	491	1,012
108	530	1,382	121	603	1,740	6	100	1,010	70	1,022

Table 9. Continued.

Observ.	Traveling Empty	Loading	Moving Between Loading	Traveling Loaded	Unloading	Stops	Load	Distance Out	Travel Distance	Distance In
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[#]	[feet]	[feet]	[feet]
109	475	2,206	169	255	728	13	109	990	766	574
110	382	2,070	226	172	457	17	128	674	280	514
111	263	755	74	128	128	6	33	494	185	309
112	285	1,977	237	670	2,240	7	102	661	71	612
113	251	1,538	216	371	1,199	9	77	612	135	499
114	357	1,795	160	503	598	7	72	822	132	502
115	272	1,918	140	305	685	7	63	592	120	372
116	205	1,185	380	296	1,258	6	66	670	191	501
117	224	1,712	324	257	1,500	8	101	604	170	456
118	140	1,149	108	398	1,434	6	102	419	150	404
119	212	1,045	296	208	460	7	44	573	252	343
120	172	690	343	318	695	4	48	408	175	233
121	405	2,210	376	201	1,172	10	89	989	302	271
122	184	1,409	236	85	907	9	71	446	405	63
123	124	1,193	371	246	1,390	3	74	511	208	325
124	191	973	85	295	733	3	50	423	30	415
125	140	978	187	307	1,355	8	65	378	140	342

Table 9. Continued.

Observ.	Traveling Empty	Loading	Moving Between Loading	Traveling Loaded	Unloading	Stops	Load	Distance Out	Travel Distance	Distance In
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[#]	[feet]	[feet]	[feet]
126	315	2,139	310	227	437	13	105	600	209	391
127	255	2,002	220	378	782	11	70	538	434	548
128	178	1,914	244	175	652	10	71	548	146	402
129	281	738	25	292	375	3	30	665	180	605
130	132	998	124	127	318	6	42	339	149	212
131	132	887	113	147	205	9	41	252	295	155
132	232	1,705	258	230	505	13	71	586	536	386
133	366	926	90	213	555	10	43	692	468	462
134	137	2,593	297	193	513	13	81	271	404	215
135	167	1,746	364	327	690	12	122	576	198	442
136	192	1,935	227	328	617	9	111	668	144	564
137	205	1,721	104	329	532	9	103	642	560	666
138	147	861	44	172	315	9	41	392	453	491
139	683	2,404	116	573	580	8	72	1,252	90	1,140
140	483	1,620	375	442	707	11	64	1,175	291	954
141	480	1,723	126	488	605	9	70	1,133	110	1,023
143	214	1,370	111	464	1,518	7	85	743	222	663

Table 9. Continued.

Observ.	Traveling Empty	Loading	Moving Between Loading	Traveling Loaded	Unloading	Stops	Load	Distance Out	Travel Distance	Distance In
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[#]	[feet]	[feet]	[feet]
144	437	1,738	130	210	675	9	68	1,035	350	412
145	278	1,379	339	90	670	13	65	392	255	237
146	437	1,220	141	148	629	7	51	574	190	481
147	252	1,732	78	200	527	5	58	481	112	369
148	435	1,004	30	299	360	2	35	646	60	586
149	451	1,656	193	207	562	9	57	661	140	471
150	213	660	17	230	303	3	22	501	208	404
151	222	1,679	233	390	548	8	68	501	85	940
152	293	1,677	192	349	662	9	68	938	431	747
153	210	1,529	130	535	622	8	60	858	498	803
154	160	1,300	107	308	343	7	55	827	240	668
155	210	478	22	303	135	3	16	753	15	738
156	490	2,185	174	428	518	11	123	1,140	426	1,060
157	342	2,240	196	420	395	13	117	1,060	430	1,063
158	378	2,334	188	390	617	15	119	1,038	440	948
159	462	1,796	143	328	1,296	10	82	1,055	237	773
160	450	2,080	185	415	377	14	99	1,195	255	940

Table 9. Continued.

Observ.	Traveling Empty	Loading	Moving Between Loading	Traveling Loaded	Unloading	Stops	Load	Distance Out	Travel Distance	Distance In
[#]	[cmin]	[cmin]	[cmin]	[cmin]	[cmin]	[#]	[#]	[feet]	[feet]	[feet]
161	503	1,972	367	372	518	19	117	1,170	387	823
162	363	1,791	337	468	472	9	125	1,044	254	873
163	308	2,185	157	287	508	14	124	943	532	621
164	297	1,975	182	202	347	14	108	853	650	703

C.- Step Sequence for the Finding of a Statistical Distribution

This appendix gives the sequence of steps that are required to find the statistical distribution of a variable when the data is given in a spreadsheet and the statistical software in use is Statgraphics. More detailed information can be found in the Examples, Reference or User Manuals of Statgraphics (Manugistic, Inc., 1992).

D.1 Importing File to Statgraphics

First, the file needs to have its name in the first column of the variable and be saved in the spreadsheet with extension "WK1". For example, the variable ***VAR*** is saved under the name ***FILE.WK1***.

The following steps are required to follow in this importing stage.

1.- Start Statgraphics with the full screen menu option.

2.- Select ***Data Management*** option.

3.- Select ***Import Data Files*** option.

4.- At the import directory entry, write the directory where the file to import is located. Let us say ***B:***.

5.- At the input file type entry, press the space bar key and select Lotus.

6.- Select the input file name. For example ***FILE.WK1***.

7.- Press the F6 key.

The importing file procedure has been completed and a Statgraphics file with name ***FILE.ASF*** is available with just one variable named ***VAR***.

D.2 Statistical Distribution Finding

This sequence explains how to calculate the parameters of a given statistical distribution and determine the level of significance of this fitting (p-value) using the Kolmogorov-Smirnov test of goodness-of-fit. This procedure is iterative, and needs to be repeated until all the possible statistical distributions are tested. The best fitting is given by the statistical distribution that attains the highest p-value.

For example, let us say that we would like to calculate the level of fitting of the variable ***VAR*** to a Normal distribution. The steps are:

1.- Select ***Distribution Functions*** option.

2.- Select ***Distribution Fitting*** option.

3.- Press **F7** key and select the variable ***VAR*** to analyze.

4.- Select distribution option number 14 for testing a Normal distribution.

5.- Press **F6** key and you will get the estimating values of the parameters, in this case the mean and the standard deviation.

6.- Select from the pop-up menu the ***K-S test*** option.

The approximate significance level (p-value) will be displayed. It is possible to follow the same steps presented above for testing any of the eighteen statistical distributions available in the menu.

D.- Statistical Distributions Used in the Simulation Model

This appendix gives the main statistics for each of the statistical distributions tested successfully in this study. Hasting and Peacock (1975), and Rothschild and Logothetis (1986) are the references for all the formulas.

1.- Gamma Distribution

Parameters:

Scale = $1/\beta$

Shape = α

Probability density function:

$$f(x;\alpha,\beta) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} x^{\alpha-1} e^{-\beta x} \text{ if } x > 0; \alpha > 0; \beta > 0$$

where $\Gamma(\alpha) = \int_0^{\infty} e^{-u} u^{\alpha-1} du$

Mean = α/β

Variance = α/β^2

2.- Lognormal Distribution

Parameters:

Scale = m = the median

Shape = σ = the standard deviation of the log of x

Probability density function:

$$f(x; m, \sigma) = \frac{1}{x\sigma(2\pi)^{1/2}} e^{-\frac{[\log(x/m)]^2}{2\sigma^2}} \quad \text{if } x > 0; m > 0$$

Mean $= me^{\frac{\sigma^2}{2}}$

Variance $= m^2 w(w-1)$ where $w = e^{\sigma^2}$

3.- Normal Distribution

Parameters:

Location $= \mu$

Scale $= \sigma =$ the standard deviation

Probability density function:

$$f(x; \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad \text{if } \sigma > 0$$

Mean $= \mu$

Variance $= \sigma^2$

4.- Weibull Distribution

Parameters:

Scale = b

Shape = c

Probability density function:

$$f(x; b, c) = \frac{c}{b^c} x^{c-1} e^{-\left(\frac{x}{b}\right)^c} \text{ if } x > 0; b > 0; c > 0$$

$$\text{Mean} = b\Gamma[(c+1)/c]$$

$$\text{Variance} = b^2\left\{\Gamma[(c+2)/c] - (\Gamma[(c+1)/c])^2\right\}$$

E.- Statistical Values of Variables Related to Linear Regressions of the Simulation Input Data

This appendix gives the basic statistical values of linear regressions variables used as input or output of the simulation model.

Table 10. Basic statistical values of simulation variables.

VARIABLE	UNIT	AVERAGE	MINIMUM	MAXIMUM	MEDIAN	ST. DEVIATION
DBH	[inch]	8.93	4	19.8	8.7	2.78
Felling	[cmin]	16.25	5	122	13	10.94
LogsPer Tree	[#]	2.86	0	8	3	1.14
Traveling Empty	[cmin]	443.31	124	1,290	436	229.16
Distance Out	[feet]	915.73	252	2,387	872	423.01
Traveling Loaded	[cmin]	359.48	23	836	338	160.88
Distance In	[feet]	835.35	63	2,108	761	480.03
Stops	[#]	8.46	2	19	8	3.43
Unloading	[cmin]	903.81	128	2,965	659.5	579.8

F.- Formatted Listing of the Simulation Model Code

This appendix shows the formatted listing given by Promodel PC of the simulation model code. The actual font kind and size have been changed due to format requirements.

Some extra comments for clarifying the original code of the model are given with italic letters.

```
**********************************************************
               Formatted Listing of Model:
                   C:\PMWIN\HFMODEL.MOD
**********************************************************
     Time Units:                           Seconds
     Distance Units:                       Feet
**********************************************************
                        Locations
**********************************************************
Name        Cap    Units    Stats    Rules
----------- ----- -------- -------- --------------------
FOREST      2000    1       Detailed Rand, FIFO,
TRANSITION1 2000    1       None     Oldest, No Queue,

LOGS        2000    1       Detailed Rand, FIFO,
TRANSITION2 2000    1       None     Oldest, No Queue,
YARD        2000    1       Detailed Rand, FIFO,
```

```
**********************************************************
                    Entities
**********************************************************
 Name        Stats     Speed (fpm)
 ----------  --------  ------------
 TREE        Detailed  0
 LOG1        Detailed  0
 LOG2        Basic     0
 BUNCH1      Detailed  0
 BUNCH2      Detailed  0

**********************************************************
                   Processing
**********************************************************
                         Process        Routing
Entity   Location   Operation    Blk  Output   Destination  Rule  Move  Exit Logic
-------  ---------- ------------ ---- -------- ------------ ------ ------ ---- -------
#  TREE s arrive to FOREST  #
TREE    FOREST
           L1:
          # Generation of random dbh for each tree, with a minimum of 4 " #
          dbh=N(8.838,2.738)
           if dbh >= 4. then
           begin
            volumen=-3.511227+0.223713*dbh*dbh
            numlog=round(0.557665+.25705*dbh)
            vol=volumen*c/real(numlog
             L2:
            # Generation of random movetime #
```

```
           movetime=L(14.77,14.99)*60./100.
           if movetime<=0. then GOTO L2
            L3:
            # Generation of random swingtime #
           swintime=L(19.59,8.96)*60./100.
           if swintime>0. then use harvester for  swintime
            else GOTO L3
          end
          # If  dbh is less than 4" #
          else GOTO L1
                         1  LOG1    TRANSITION1 FIRST 1  USE HARVESTER
# Log processing station #
LOG1   TRANSITION1
          L4:
          # Generation of random processing time #
          proctime=L(34.24,21.51)*60./100.
          if proctime<=0. then GOTO L4
          azar=rand(1.)
          # 55.28..% of the times brushing, piling and planning time occur #
          if azar <= .5528455285 then
          begin
            L5:
            # Generation of random brushing, piling and planning time#
           brupilpla=L(59.3182,50.4473)*60./100.
            if brupilpla>0. then
            begin
              # Exponential regression for felling time #
             felltime=(6.73308881*exp(0.084261*dbh))*60./100.
              unittime= felltime+brupilpla
              # Use harvester for felling,brushing, piling, and planning #
```

```
                     use  harvester for unittime
                     split numlog as LOG2
                  end
                  else GOTO L5
                end
                else
                begin
                  felltime=(6.73308881*exp(0.084261*dbh))*60./100.
                   # Use harvester just for felling #
                   use harvester for felltime
                   split numlog as LOG2
                end
                              1   LOG2     LOGS        FIRST 1  USE HARVESTER
LOG2 TRANSITION1
                # Calculation of production for each period #
               if clock(hr)>=transient then
                begin
                  volh=vol/(6.*period)
                  totvolh=totvolh+volh
                  if clock(hr)<=(transient+period) then
                  begin
                    volday1h=vol/period
                    totday1h=totday1h+volday1h
                  end
                 else if clock(hr)<=(transient+2.*period) then
                       begin
                          volday2h=vol/period
                          totday2h=totday2h+volday2h
                       end
                      else if clock(hr)<=(transient+3.*period) then
```

```
                        begin
                          volday3h=vol/period
                          totday3h=totday3h+volday3h
                        end
                       else if clock(hr)<=(transient+4.*period) then
                              begin
                                volday4h=vol/period
                                totday4h=totday4h+volday4h
                              end
                             else if clock(hr)<=(transient+5.*period) then
                                    begin
                                      volday5h=vol/period
                                      totday5h=totday5h+volday5h
                                    end
                                  else if clock(hr)<=(transient+6.*period) then
                                         begin
                                           volday6h=vol/period
                                           totday6h=totday6h+volday6h
                                         end
          end
          # Generation of random number of logs to be loaded in each stop of the
            forwarder #
         bunchsize=round(L(10.9843,5.30427))
          0.000001
                        1   LOG2    LOGS
LOG2   LOGS
         # Grouping random number of logs #
         group  bunchsize as BUNCH1
BUNCH1 LOGS
         0.000001
```

```
          # Generation of random number of forwarder stops #
          loadsize=round(W(2.67242,9.52347))
                    1   BUNCH1   TRANSITION2 FIRST 1  USE HARVESTER
BUNCH1 TRANSITION2
           # Generation of random total number of logs per forwarder load #
          totalload=N(306.802,89.6307)
           L10:
           # Generation of random distance to be covered by the forwarder in unload
             trip #
          distanceout=N(915.725,423.012)
          if distanceout<=0. then GOTO L10
           L11:
           # Generation of random distance to be covered by the forwarder in load
             trip #
          distancein=N(835.35,480.027)
          if distancein<=0. then GOTO L11
           # Calculation of empty travel time #
          tripempt=.46887*distanceout*60./100.
          # Generation of random load and move time #
          load&move=(W(3.73,1931.7)+W(1.76,211.9))*60./100.
           # Calculation of loaded travel time #
          tripload=(.202428*distancein+.592679*totalload)*60./100.
          use forwarder for 0.000001
          group loadsize as BUNCH2
                    1   BUNCH2   YARD       FIRST 1  USE FORWARDER
BUNCH2 TRANSITION2
           #  Generation of random unloading time #
          funload=L(912.9,724.5)*60./100.
          use forwarder for funload
                    1   BUNCH2   YARD       FIRST 1  USE FORWARDER
```

```
BUNCH2   YARD
            # Ungrouping forwarder load into forwarder stop load size #
            ungroup
BUNCH1   YARD
            use forwarder for 0.000001
                        1   BUNCH1   YARD      FIRST 1
BUNCH1   YARD
             # Ungrouping forwarder stop load size into logs #
            ungroup
LOG2     YARD
            # Calculation of production per forwarder period #
           if clock(hr)>=transient then
            begin
              volf=vol/(6.*period)
              totvolf=totvolf+volf
              if clock(hr)<=(transient+period) then
              begin
                volday1f=vol/period
                totday1f=totday1f+volday1f
              end
             else if clock(hr)<=(transient+2.*period) then
                   begin
                     volday2f=vol/period
                     totday2f=totday2f+volday2f
                   end
                  else if clock(hr)<=(transient+3.*period) then
                        begin
                          volday3f=vol/period
                          totday3f=totday3f+volday3f
                        end
```

```
                        else if clock(hr)<=(transient+4.*period) then
                               begin
                                 volday4f=vol/period
                                 totday4f=totday4f+volday4f
                               end
                              else if clock(hr)<=(transient+5.*period) then
                               begin
                                 volday5f=vol/period
                                 totday5f=totday5f+volday5f
                               end
                               else
                               begin
                                 volday6f=vol/period
                                 totday6f=totday6f+volday6f
                               end
            end
            0.000001
                          # logs leave the system and  the program ends #
                         1   LOG2    EXIT      FIRST 1

***********************************************************
                               Arrivals
***********************************************************
Entity Location  Qty each               Occurrences   Frequency First Time
                                                                     Logic
-------- ---------- ----------  ----------------------------- --------- ---------------
TREE  FOREST   300      round((transient+6.*period)/3.) 10800      0
# 300 TREEs are arriving to the FOREST each time, this occurs round
(( transient +6.* period)/3) times with a frequency of 10800 seconds #
```

```
**********************************************************
                        Resources
**********************************************************
                              Res     Ent
Name      Units Stats   Search  Search  Path     Motion
--------- ----- ------- ------- ------- -------- -------
HARVESTER 1     Summary Closest Closest Net1     Empty:
                                        Home: N1 Full:
                                                 Accel:
                                                 Decel:
                                                 Pickup:
                                                 Deposit:
FORWARDER 1     Summary Closest Closest Net2     Empty:
                                        Home: N2 Full:
                                                 Accel:
                                                 Decel:
                                                 Pickup:
                                                 Deposit:


**********************************************************
                      Path Networks
**********************************************************
Name Queuing T/S   From  To  BI  Dist/Time Speed Factor
---- ------- ----- ----- --- --- --------- ------------
Net1 Yes     Time  N1    N2  Uni movetime    1
                   N2    N3  Uni proctime    1
                   N3    N1  Uni 0.000001    1
                   N3    N4  Bi  0.000001    1
Net2 Yes     Time  N1    N2  Uni tripempt    1
                   N2    N3  Uni load&move   1
```

```
                                N3     N1  Uni tripload   1

         ***********************************************************
                                     Interfaces
        ************************************************************
          Net        Node        Location
          ---------- ----------  -----------
          Net1       N1          FOREST
                     N2          TRANSITION1
                     N3          LOGS
                     N4          TRANSITION2
          Net2       N1          YARD
                     N3          TRANSITION2


         ***********************************************************
                                     Variables
        ************************************************************
          ID          Type         Initial value Stats
          ----------- ------------ ------------- --------
          bunchsize   Integer      0             None
          loadsize    Integer      0             None
          swintime    Real         0             None
          felltime    Real         0             None
          movetime    Real         0             None
          proctime    Real         0             None
          tripempt    Real         0             None
          load&move   Real         0             None
          tripload    Real         0             None
          funload     Real         0             None
```

volumen	Real	0	None
numlog	Integer	0	None
totvolh	Real	0	Basic
totday1h	Real	0	Basic
totday2h	Real	0	Basic
totday3h	Real	0	Basic
totday4h	Real	0	Basic
totday5h	Real	0	Basic
totday6h	Real	0	Basic
totvolf	Real	0	Basic
totday1f	Real	0	Basic
totday2f	Real	0	Basic
totday3f	Real	0	Basic
totday4f	Real	0	Basic
totday5f	Real	0	Basic
totday6f	Real	0	Basic
brupilpla	Real	0	None
azar	Real	0	None
unittime	Real	0	None
volh	Real	0	None
volday1h	Real	0	None
volday2h	Real	0	None
volday3h	Real	0	None
volday4h	Real	0	None
volday5h	Real	0	None
volday6h	Real	0	None
volf	Real	0	None
volday1f	Real	0	None
volday2f	Real	0	None

```
  volday3f    Real         0             None
  volday4f    Real         0             None
  volday5f    Real         0             None
  volday6f    Real         0             None
  c           Real         0.02831684659 None
  transient   Real         8.            None
  period      Real         8.            None
  totalload   Real         0             None
  distanceout Real         0             None
  distancein  Real         0             None

 *********************************************************
                        Attributes
**********************************************************
  ID         Type         Classification
  ---------- ------------ --------------
  dbh        Real         Entity
  vol        Real         Entity
```