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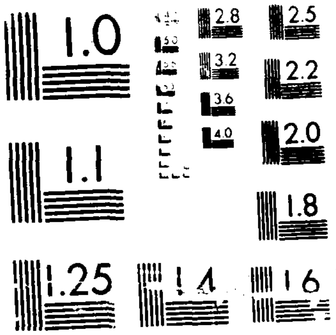

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Simulating Cable Logging in the Allegheny Region of Pennsylvania: A Case Study

by

Peter William Hodes

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A Division of CNA Hudson Institute

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Simulating Cable Logging in the Allegheny Region of Pennsylvania: A Case Study

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ABSTRACT

The eight-county Allegheny Region of Pennsylvania is 84% forested and comprises one of the state's most valuable timbersheds. Much of this area is inaccessible to conventional logging equipment due to steep slopes, poor drainage, and high erodability. For this reason, there has been a recently growing interest in using cable yarders to harvest these areas.

A computer simulation model was developed to aid in investigating the feasibility of cable logging on a particular site in the region. Data used were those collected from a cable logging operation that was conducted on the Allegheny National Forest in October of 1986.

The simulation model utilizes the SIMAN simulation language and simulates the functional elements of a cable yarding operation. The utility of the model was highlighted by comparing two plausable harvest unit configurations for a given site. The alternative with the shortest total harvesting time was then chosen.

Several design features will aid in the expansion of the model as more detailed data are collected. In particular, the model is modularized by harvesting function, contains complete line-by-line documentation of the SIMAN source code, and contains a thorough discussion of the statistical methodologies used. Recommendations were made for further data acquisition and model refinement.

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Chapter I

INTRODUCTION

Study Rationale

The eight-county Allegheny Region (Figure 1.1) is located along the northern tier of Pennsylvania and comprises one of the state's most valuable timbersheds. The region is 84% forested and contains the highest per acre and total growing stock volume of any region in Pennsylvania (Powell and Considine 1982). It contains 3.3 million acres, over 20% of the state's commercial forest land (Lord 1985). Most of this is of the valuable northern hardwood forest type consisting of high quality black cherry, white ash, and sugar maple.

Much of this acreage is characterized by steep slopes, poor drainage, and high erodibility. On the Allegheny National Forest alone, it is estimated that 25,000 to 40,000 acres are eligible for cable yarding, due to drainage and/or slope problems (Hockinson 1986). Environmental concerns over high soil erosion and stream sedimentation have precluded the use of conventional logging equipment, such as rubber-tired skidders, to remove timber from these sites.

Cable yarding systems were used to skid timber in the eastern United States in the early 1900's. Their use died out as the old growth stands disappeared. In the 1970's, cable yarders were reintroduced to harvest steep terrain

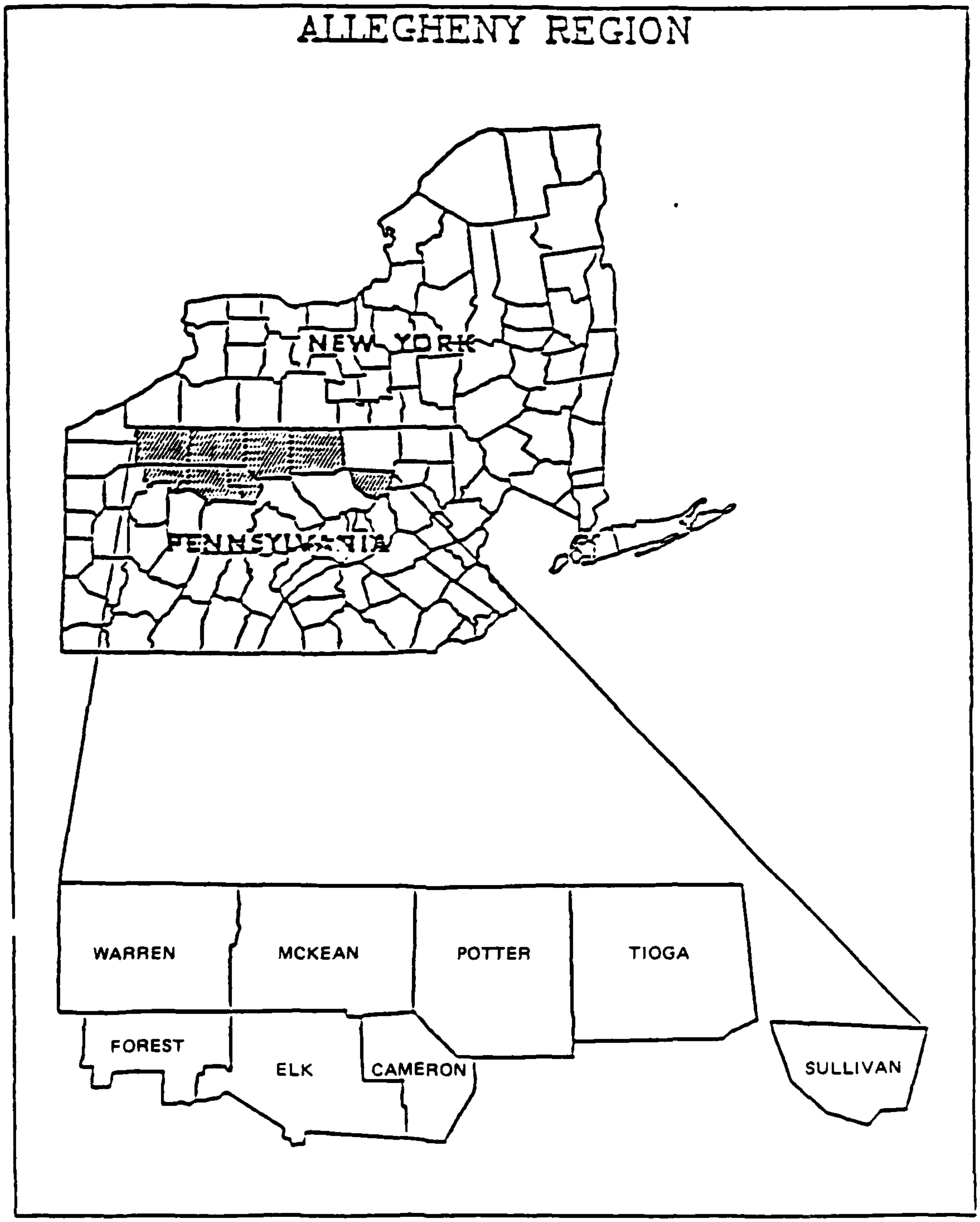

Figure 1.1: The Allegheny Region of Pennsylvania.

and environmentally sensitive areas (Peters 1984). Cable logging has a less detrimental impact on the environment (primarily by reducing the number of haul and skid roads) than conventional systems. For this reason there has been a recently growing interest in using cable yarders to log environmentally sensitive areas within the Allegheny National Forest.

Using cable logging to harvest eastern hardwood logs on steep terrain, however, can result in low production rates and high costs per unit of wood produced (LeDoux 1985). Logging managers can improve productivity and profitability by knowing how site-specific variables interact with cable logging equipment. Carrying out this investigation by field study or trial and error alone can often be an expensive proposition. One tool that can aid in the decision-making process is computer simulation. Computer simulation provides the logging manager with a low cost means of exploring various system alternatives before they are carried out and thus provides a valuable tool in the decision-making process.

Objectives

This study is the first phase in the development of a simulation model that logging planners could use to investigate the feasibility of cable logging on a particular site and under particular operating conditions. The basic model proposed here does not examine the interaction between logging equipment and site specific variables but can be refined to do so as more data are collected in the future.

In October of 1986, a cable logging operation was performed on the Allegheny National Forest to investigate the feasibility of its use on a large scale in the region. The data used in the development of this model are limited to those obtained from this one time and motion study. The small data base will limit the actual use of this particular model to plan cable-logging operations on the Allegheny National Forest.

The specific objectives of this study were the following:

1) design a model that simulates the cable yarding operation that was performed;

2) construct such a model, using SIMAN, with field data that was collected during the operation;

3) evaluate the model with regard to several criteria, including acceptability of model design, appropriateness of regression equations, theoretical distributions, and empirical distributions used, and ease of expanding the model as more data are collected;

4) make recommendations for further data acquisition and model refinement.

Chapter II

REVIEW OF LITERATURE

Introduction

This chapter will present a review of the literature on the following topics: (1) how elemental cycle times of skyline logging operations have been defined in the past for eastern harvesting operations, (2) the development of timber-harvest simulation models in the past, and (3) the validation and verification of simulation models. This chapter will serve primarily as background and support for the methods to be used in the study.

Elemental Cycle Times

Since 1971, the USDA Forest Service Engineering Research Unit in Morgantown, West Virginia has been active in studying eastern cable logging operations. As a result, turn time predicting equations for various cable yarding systems are abundant and well documented in a number of publications: Cubbage and Gorse (1975), Fisher et al. (1980), Rossie (1983), Biller and Peters (1982 and 1984), Peters (1984), Fisher et al. (1984), Biller and Fisher (1984), Peters and Baumgras (1984), Baumgras and Peters (1985), LeDoux (1985), and LeDoux and Starnes (1986). In all of the studies, total turn time was broken down into five elements, and delay-free elemental yarding prediction equations were developed. These five elements were outhaul, hooking, lateral inhaul, inhaul, and unhooking.

Additionally, a delay-free total cycle time equation was provided in each of the studies. This equation was developed independently of the five elemental equations and was not simply the sum of the parts. Since some of the independent variables were highly correlated, they would not all be needed to predict total cycle time. Thus, an independent equation was developed.

Timber Harvest Simulation Models

Many different timber-harvest simulation models have been developed over the past two decades, and they represent a number of modeling viewpoints. Some, such as those presented by Stark (1968), Bussell et al. (1969), American-Pulpwood Association (1972), Martin (1975), Killham (1975), and Johnson (1976) model a variety of systems.

Others pertain to specific systems: Johnson (1970) modeled the loading and hauling subsystems of a logging system; Johnson and Biller (1973) modeled a wood chipping system; Bradley et al. (1976) and Bradley and Winsauer (1976) modeled a whole tree field chipping operation and; Bare et al. (1976) modeled a logging residue handling system.

Goulet et al. (1980) evaluated five of these models: Simulation Applied to Logging Systems (SAPLOS) (Johnson 1976), Timber Harvest and Transport Simulator (THATS) (Martin 1975), Full Tree Field Chipping and Transport Simulator (FTFC) (Bradley et al. 1976 and Bradley and

Winsauer 1976), Forest Harvest Simulation Model (FHSM) (Killham 1975), and Harvest System Simulator (HSS) (American Pulpwood Association 1972). They found that while many user implementation problems exist, the models still present a good picture of state of the art in timber harvesting computer simulation. The salient features of each of these models are presented in Appendix A; Goulet's conclusions are presented below.

Implementation Problems

Goulet et al. (1980) installed the five models on Auburn University's IBM S 370/158 computer and ran them with test data. In summarizing their study, Goulet concluded the following:

1) Each model operates under a slightly different set of rules and assumptions according to the philosophy of the model builder. Users are advised to proceed with caution when choosing and using a model and to be aware of the assumptions made so that output can be analyzed in this light.

2) The models are not easy to use, and in general, close coordination between a computer specialist and the user will be necessary.

3) The models FHSM, FTFC, SAPLOS, and THATS would require extensive design and reprograming to simulate systems not covered in the basic model.

Despite these problems the authors concluded that the models represented a very good picture of state of the art in timber harvesting simulation. Furthermore, much learning occurred in the generation of these models and many problems were uncovered in modeling and model implementation.

They stressed that continued development and refinement of timber harvesting simulation models were needed to effectively analyze current and proposed harvesting strategies. They suggested that the results of the research and the learning derived from the present models be incorporated in a new model that:

a) is designed and written from the user's point of view;

b) faithfully reproduces the harvesting operations to be modeled;

c) maintains a level of detail that is uniform across all functions;

d) collects model statistics to estimate both the mean and the variance of each performance variable;

e) defines performance variables which can be used to study the balance/imbalance of the system, measure the complex interaction of personnel and machines, and effectively measure marginal and total costs;

f) allows flexibility for tailoring to existing systems and for the creation of new systems; and

g) is usable without extensive computer training.

A Second Generation Model

Work by Hines et al. (1981) established further design criteria for a second generation harvesting simulation, particularly modularization by harvesting function within an overall simulation framework established by the SLAM (Pritsker 1984) simulation language. The modular design strategy proposed by Hines et al. (1981) envisioned separate modules, or building blocks, each modeling a unique harvesting function. A simulation run would involve assembling the appropriate modules and executing a control program that would pass resources between modules and collect model statistics.

To date, three modules have been completed. Webster et al. (1983) reported the development and general features of a feller/buncher module that simulates the operation of one or two small, skid-steer machines. A highly detailed description of the feller/buncher module is given by Padgett (1982). Hines et al. (1983) reported the general features of a grapple skidding module that can model one or two grapple skidders. Liu (1981) provided a detailed description. An input data pre-processor module has also been developed (Rogers 1984) to assist the user in entering data for the feller/buncher modules. Personal communication with Rummer (1986) suggested that further model refinement was necessary before the model could be used for planning actual logging operations.

Validation and Verification

One of the most important phases in the development of a computer simulation model is determining whether the model is an accurate representation of the real-world system being studied. Model developers address this concern through model verification and validation. Law and Kelton (1982) described verification as the determination of whether a simulation model performs as intended, i.e., debugging the computer program. They defined validation as the determination of whether a simulation model is an accurate representation of the real-world system.

Validation

A model should be developed for a specific purpose or use, and its validity should be determined with respect to that purpose. A model may be valid for one set of experimental conditions and invalid for another. A model is considered valid for a set of experimental conditions if its accuracy is within the acceptable range required for the model's intended purpose (Sargent 1984).

Below is a description of some of the validation techniques (and tests) used in model validation.

1) Face validity: Face validity is asking people knowledgeable about the system whether the model and/or its behavior is reasonable. This technique can be used in determining if the logic in the model flowchart is correct and, if a model's input-output relationships are reasonable (Sargent 1984).

2) Comparison to other models: Computer output from the simulation model being validated is compared to the output of other (valid) models (Shannon 1975).

3) Turing Tests: People who are knowlegeable about the operations of a system are asked if they can discriminate between real-world system data and model output. A statistical procedure for Turing Tests is given in Schruben (1980).

4) Historical methods: Naylor and Finger (1967) proposed the three historical methods of validation: rationalism, empiricism, and positive economics. Rationalism assumes that everyone knows whether the underlying assumptions of a model are true. Then logic deductions are used from these assumptions to develop the correct (valid) model. Empiricism requires every assumption and outcome to be empirically validated. Positive economics requires only that the model be able to predict the future and is not concerned with its assumptions or structure.

5) Traces: The behavior of different types of specific entities in the model are traced through the model to determine if the model's logic is correct and if the ecesary accuracy is obtained.

Some of the comments on validation, found in the documentation manuals of the models that were reviewed, are instructive in showing the approach to validation that has been taken in these models, and so will be repeated here. Johnson et al. (1972, p. 361) say of SAPLOS,

> The model needs further validation from studies of a variety of logging systems in different locations. This validation process will be performed in conjunction with the expansion of the data base.

Martin (1975, p.31) says of THATS,

> The methodology of the model and its structure need little validation because the simulator simply duplicates the process of logging as it is normally performed in Appalachia. The sequence of operations is the same in both.

Bradley et al. (1976, p.11) caution the user of FTFC,

> The user must test the simulator on an actual logging operation. The test is required to detect errors in either concept or model.

Martin's (1975) comment suggests that he used face validity in the validation of THATS. From the literature reviewed, it is uncertain if any formal types of validation were used in the development of the two other models.

Webster et al. (1984) suggested that trying to develop a valid model involves a multitude of compromises which embrace design, practical, logical, economical, computer, language, implementation, and philosophical difficulties. At the heart of the problem of developing simulation models is the question of complexity of the model. To be highly realistic, a model may need to be complex, since by including more of the factors and variations of the system the model becomes more capable of duplicating the system's response. But complex models take more time to develop, are more difficult to analyze, require more computer resources, and cost more overall than simple models. Simple models, on the other hand, will not always provide the user with the quality or variability of results that are naturally inherent within the system and may lead him into erroneous conclusions.

Verification

Law and Kelton (1982) describe five techniques which can be used for debugging the computer code of a simulation model.

1) In developing the simulation model, write and debug the computer program in modules or subprograms.

2) Structured-walk-through: All people involved in the model development are assembled in a room. They go through the computer code and do not proceed from one statement to another until everyone agrees that the statement is correct.

3) Trace: In a trace, the state of the simulated system, i.e., the contents of the event list, the state variables, certain statistical counters, etc., is printed just after each event occurs in order to see whether the program is operating as intended. These traces should be examined in order to see if the model logic is correct. Most major simulation language packages provide the capability to perform a trace.

4) The model, when possible, should be run under simplifying assumptions for which the expected model output can easily be computed. The expected output should then be compared to the actual output.

5) With some types of simulation models, it may be helpful to display the simulation output on a graphics terminal as the simulation actually progresses.

Chapter III

DESCRIPTION OF THE SIMULATION STUDY

Introduction

A computer model to simulate the harvesting actions of a cable yarder in the Allegheny Region of Northwestern Pennsylvania was constructed using field data collected from that region. The model predicts time to harvest a given site and volume harvested per unit time. The discrete event model employs the SIMAN simulation language. This chapter describes the "real-world" system that was observed and the simulation model that was constructed.

The "Real-World" System

The focus of this section is the description of the logging site, the logging machine, the logging operation that was conducted, and the time study that was performed.

The Test Area

The logging operation was conducted on the Bradford Ranger District of the Allegheny National Forest in Northwestern Pennsylvania. The total area harvested was 11 acres. The primary tree species were black cherry, white ash, sugar maple, and basswood. The clearcut harvest yielded an average of 12.3 MBF/acre of sawtimber and 9.7 cords/acre of pulpwood (Table 3.1), contained in an average of 66 trees/acre (Table 3.2).

Table 3.1: Total volume by species, product, and diameter class.

	DIAMETER CLASS									
SAWTIMBER (MBF)	12"	14"	16"	18"	20"	22"	24"	26"	28"	TOTAL
Hickory	0.13									0.13
Basswood	1.46	7.15	6.01	7.67	0.96	0.65				23.89
Yellow Birch	0.07	0.15		0.15						0.36
Sugar Maple	0.52	3.56	1.72	9.07	14.48	4.78	2.72	7.81		44.65
Red Maple	0.07		0.52	0.28					0.52	1.4
Black Cherry	0.92	2.56	5.09	7.48	8.19	8.07	4.09	1.05		37.41
White Ash	0.61	2.07	4.56	4.04	3.23	0.97				15.5
Beech	0.15	2.39	3.03	3.14	2.08	1.07	0.71			12.18
All Species										135.5
PULPWOOD (CORDS)										51.37
TOPWOOD (CORDS)										55.2

Table 3.2: Total number of trees by species, product, and diameter class.

	DIAMETER CLASS									
SAWTIMBER	12"	14"	16"	18"	20"	22"	24"	26"	28"	TOTAL
Hickory	2									2
Basswood	25	60	31	28	3	2				149
Yellow Birch	1	2		1						4
Sugar Maple	9	31	12	37	50	13	6	14		172
Red Maple	1		4	1					1	7
Black Cherry	15	20	29	30	27	17	8	2		148
White Ash	10	19	28	17	10	2				86
Beech	2	24	17	16	7	3	1			70
										346

PULPWOOD	DIAMETER CLASS						
	6"	8"	10"	12"	14"	16"	TOTAL
	38	121	158	43	16	5	381

Machine Specifications

The cable machine used was a slacking (live) skyline (Figure 3.1) with a Christy carriage. The yarder, used to transport whole trees from the stump to a landing, was not a commercial design, and would cost about $50,000 if built to order. It is owned and operated by Bess Skyline Logging of Virginia. It was a single-drum yarder, powered by a six cylinder Industrial Waukesha gasoline engine. Tower height was 40 feet; the skyline was 3/4-inch IWRL regular-lay wire rope; the mainline was 1/2-inch IWRL regular-lay wire rope; maximum mainline pull was 15,000 pounds.

The Yarding Operation

The layout of the harvesting area is illustrated in Figure 3.2. Two log landings were constructed for the operation (see Figure 3.2). The yarder was positioned at the first landing. The tower was raised and guyed to stumps or trees above the landing. The skyline was tied off to a tailtree downhill from the yarder. The area from which logs were harvested, at any one of these particular setups, is termed a logging corridor. Logs were harvested from several corridors at each of the two landings. Changing logging corridors consisted of anchoring the skyline to another tailtree so that the skyline would be situated over an area that had not yet been harvested. This particular type of harvesting pattern is described by Peters (1985) as a reverse fan type; the cable yarder being

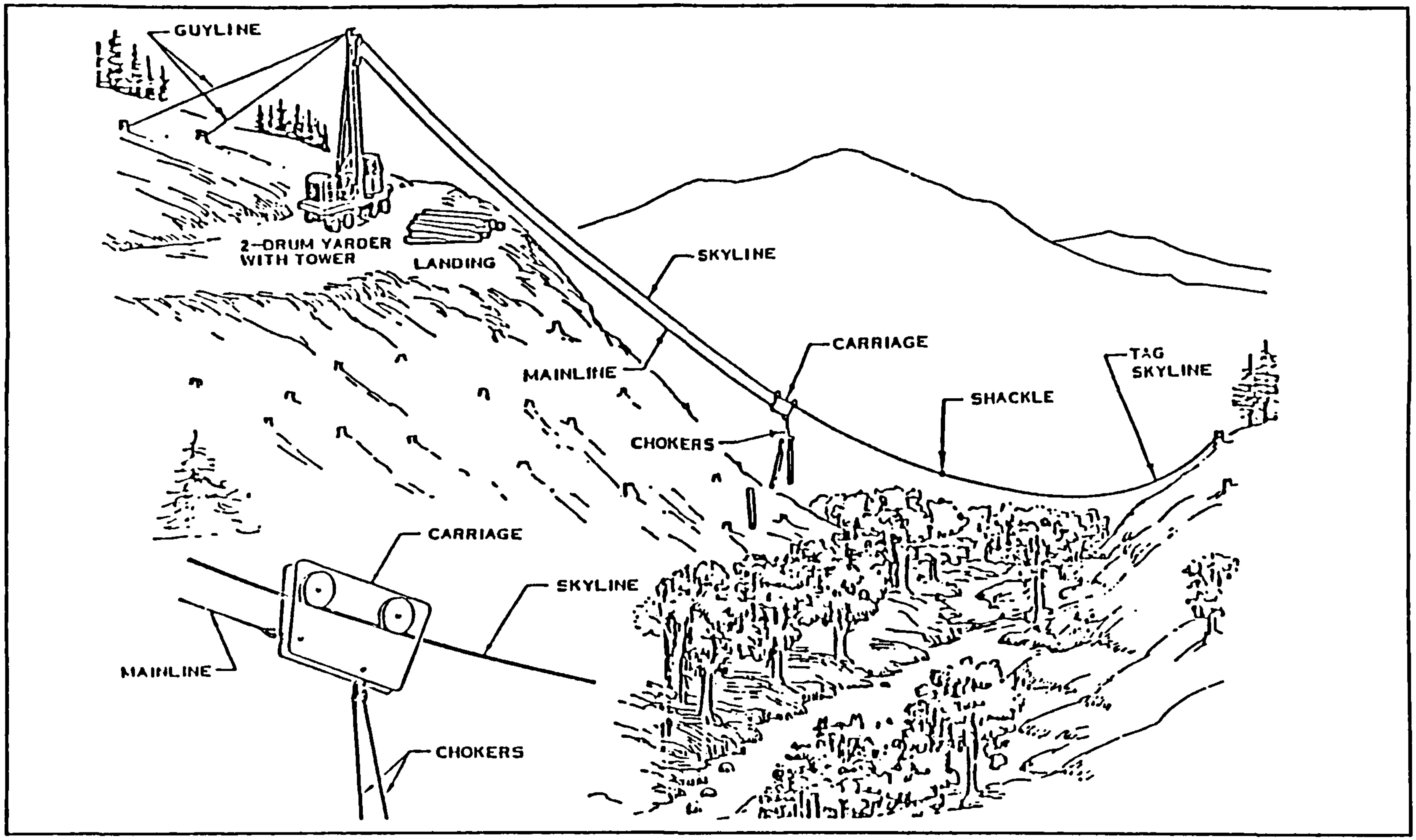

Figure 3.1: Schematic diagram of a cable logging operation.

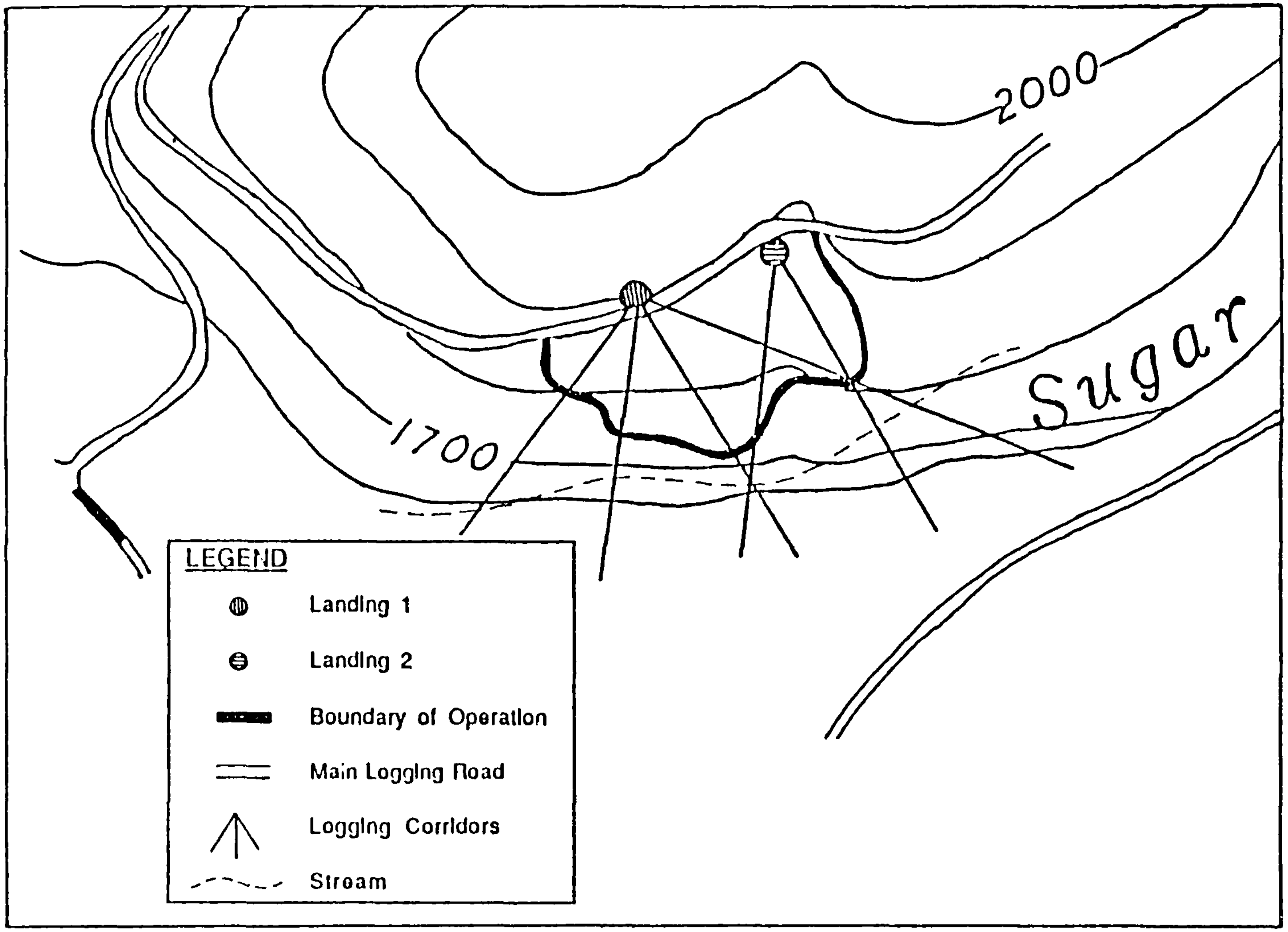

Figure 3.2: Diagram of cable logging area.

the point of common pivot and the tailtrees creating the arc of the fan.

After a corridor was set up, the Christy carriage traveled down the tight skyline until it engaged a stop, which released the mainline from the carriage. Three chokesetters took the mainline out and attached the logs, then signaled the yarder operator to winch in the load. When the load reached the carriage, a ball on the mainline unlocked the carriage from the stop. The load traveled uphill to the yarder at the log landing, where the skyline was slackened and the logs were unhooked by a single unhooker. These six elements (outhaul,lateral outhaul, hooking, lateral inhaul, inhaul, and unhooking) comprise one yarding cycle. For each corridor change, yarding started at the top of the hill and progressed toward the bottom. Maximum slope yarding distance was 425 feet. One stem was usually landed per turn and occasionally two if the trees were small.

Logs that accumulated at the landing area were intermittently transported (by means of a rubber-tired skidder) to a main loading area. It was necessary for the cable yarder to cease operation while the skidder was at the landing.

When all corridors were harvested at landing 1, the guy lines were disconnected, the tower was lowered, and the mainline and skyline were wound on the drum. The cable yarder was then transported to landing 2 where it was assembled by reversing this process.

The conditions at landing 1 differed from those at landing 2 in several ways. Landing 1 was situated in such a way that the skyline crossed over the main logging road (see Figure 3.2). On several occasions, yarding was suspended in order to allow a logging truck to pass; this was not the case for landing 2. The slopes were much more gentle at landing 2. This caused the logs to drag on the ground on the inhaul phase. This, combined with the fact that the part of the unit harvested from landing 2 was much brushier, caused logs to get hung up in the slash more often on the inhaul phase. Separate service time equations, for some of the yarding cycle elements, were developed for each landing in order to explain some of this variability.

Timing the Operation

Time and motion study data were collected over a two week period in October of 1986. Statistics were collected on 183 yarding cycles from five corridors at two landings; three corridors at the first landing and two at the second. Throughout the study, continuous timing was used to document elemental cycle times and delay times to the nearest one hundredth of a second.

Most of the sampling was devoted to timing the productive yarding elements so that elemental time predicting equations could be developed for each of the six phases of a yarding cycle, or turn (outhaul, lateral outhaul, hooking, lateral inhaul, inhaul, and unhooking). Additionally, all hauling distances as well as number of stems yarded per turn were recorded.

Four non-productive delay times were also recorded: time to change landings, time to change corridors, time needed to clear the landing of accumulated logs, and time required to free logs hung up in the slash on the inhaul element. The statistics collected are provided in Appendix C, and their definitions are in Table 3.3.

The Simulation Model

This discussion will address four topics. First, the functional elements of the "real-world" system the model considers and their dynamic relationship will be presented. Two flowcharts will be employed for this purpose: the Main flowchart (Figure 3.3) and the Yarding Cycle flowchart (Figure 3.4). Attention is then directed to the development of random inputs which represent service times and incremental distance changes in the model. Following this, important features of SIMAN and of model construction will be pointed out. A section on model validation will follow.

A complete executable example that compares two system alternatives, output, and directions for modifying the model (e.g. such as changing the number of corridors, corridor lengths, etc.) is provided in Appendix B. This

Table 3.3: Definitions of model statistics collected.

Outhaul time and distance: Outhaul ends when the carriage hits the stop.

Lateral outhaul time and distance: Lateral outhaul ends when the chokers reach the stems.

Lateral inhaul time: Lateral inhaul time ends when the carriage begins to move uphill.

Hooking time: Hooking time ends when the signal is give to haul in.

Inhaul time: Inhaul time ends when the stems are on the ground at the landing.

Unhooking time: Unhooking time ends when the outhaul begins.

Total cycle time: Total cycle time begins and ends at the start of the outhaul.

Number of stems landed: This is the number of stems per turn that are successfully yarded to the landing.

System delays (frequency and duration): System delays are defined as any event that disrupts the "normal flow" of activity. System delays that were recorded are as follows:

* Delay to clear landing: This time begins when unhooking ends and ends when outhaul begins. The duration of this delay is 0.00 unless logs are actually cleared from the landing on that cycle.

* Delay to change corridors: This time begins when unhooking ends at the previous corridor and ends when outhaul begins at the new corridor.

* Delay to change landings: This time begins when unhooking ends at the previous landing and ends when outhaul begins at the new corridor.

* Logs hung up in slash on inhaul element: This time beings when carriage motion stops on the inhaul element and ends when motion of the carriage resumes (i.e. after log is freed from slash).

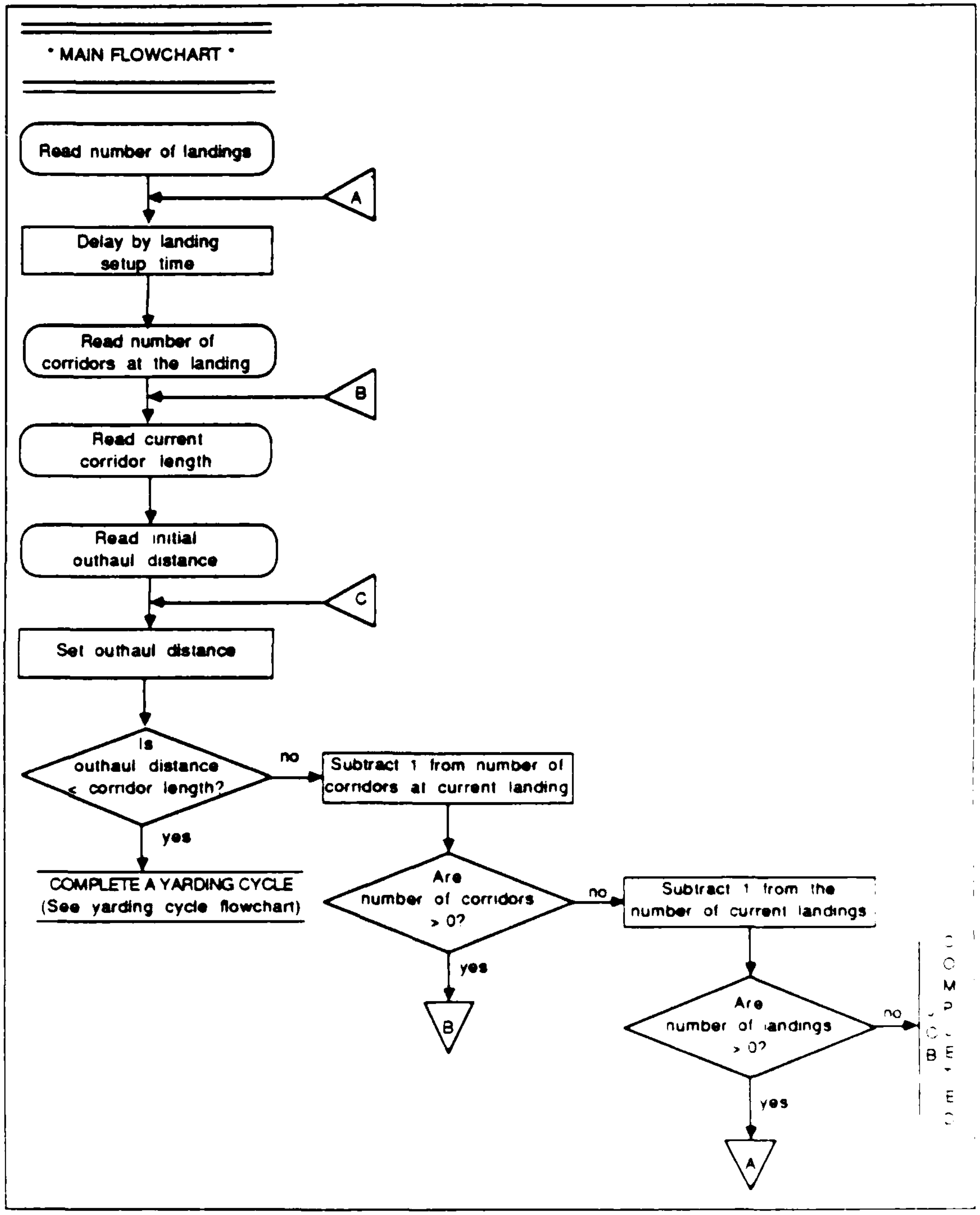

Figure 3.3: Main flowchart.

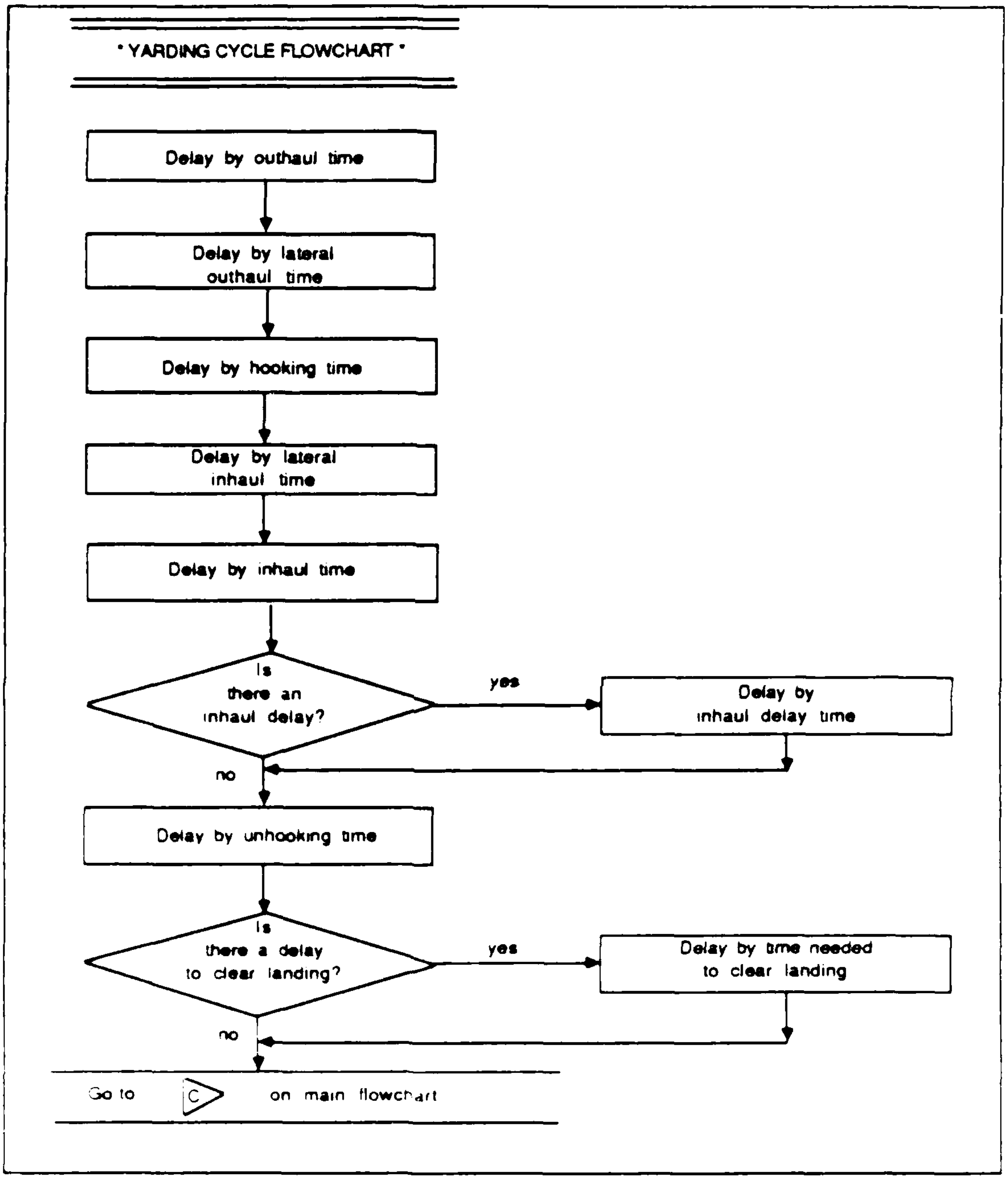

Figure 3.4: Yarding cycle flowchart.

example serves to illustrate the potential usefulness of a model of this type.

The Main Flowchart

The Main flowchart (Figure 3.3) contains the model logic that represents movement between corridors, and between landings. The static and dynamic relationships are illustrated.

The number of landings in the harvesting unit are read into the model and a delay to set up a landing is executed. The number of corridors at the current landing, the current corridor length, and initial outhaul distance (all specified by the user) are set. A yarding cycle is then completed.

The number of cycles to be completed at the current outhaul distance is then sampled from the user-defined empirical distribution. When all cycles are completed at that distance, outhaul distance is increased by an increment that was specified by the user.

If the outhaul distance is less than the current corridor length, more yarding cycles are performed. If this is not the case, a check is made to determine if there are any unharvested corridors at the current landing. If there are, a delay to set up a new corridor is executed and the corridor is harvested in the same manner as described above.

If there are no more unharvested corridors at the current landing, than a check is made to determine if there are any more landings in the harvesting unit. If there are, a delay to set up the new landing is executed; if not, the simulation is terminated.

The Yarding Cycle Flowchart

The Yarding Cycle flowchart (Figure 3.4) contains the model logic that represents a yarding cycle. The static and dynamic relationships are illustrated.

The six productive elements of a cable yarding cycle have been considered; outhaul, lateral outhaul, hooking, lateral inhaul, inhaul, and unhooking. Additionally, two nonproductive delays have been considered: inhaul delays, and a delay time to clear the landing of accumulated logs. Two other nonproductive delays (delay to change corridors and to change landings) are included in the Main flowchart.

Statistical Analysis

This section describes how the data collected were used to specify random inputs in the simulation model. Theoretical distributions, empirical distributions, regression equations, and median values were used.

Theoretical Distributions

Standard techniques of statistical inference were used to fit a theoretical distribution to the data for some of the cycle elements. After a theoretical distribution was hypothesized, maximum likelihood estimates of the distribution parameters were calculated using the Statgraphics statistical package (STSC, Inc. 1985). The Chi-square goodness-of-fit test and Kolmogorov-Smirnov test were employed to determine if an acceptable fit was obtained. Random numbers were sampled directly from these theoretical distributions in the simulation. Probability density functions, of the theoretical distributions used, are provided in Table 3.4.

Service time distribution results for hooking (Figure 3.5 and Table 3.5), unhooking (Figure 3.6 and Table 3.6), lateral outhaul for landing 1 (Figure 3.7 and Table 3.7), and lateral outhaul for landing 2 (Figure 3.8 and Table 3.8) are provided.

Empirical Distributions

When a theoretical distribution form could not be found to adequately fit the data, the data were used directly to define an empirical distribution. In the simulation, random numbers were sampled directly from this empirical distribution. This method was employed to describe lateral inhaul time (Table 3.9) and number of yarding cycles to be performed at a given outhaul distance (Table 3.10).

Regression Equations

When two yarding cycle elements were highly correlated, their relationship was described through standard regression techniques. A linear relationship was found to exist between outhaul distance and outhaul and inhaul service times. In the simulation, outhaul distance is used to predict outhaul time and inhaul time in two separate regression equations. Outhaul distance is highly

Table 3.4: Probability density functions of two theoretical distributions.

Weibull Distribution

$$f(x) = \alpha\beta^{-\alpha} x^{\alpha-1} e^{-(x/\beta)^{\alpha}} \qquad x>0$$

Lognormal Distribution

$$f(x) = \frac{1}{x/\sqrt{2\pi}\sigma} e^{-(\ln x - \mu)^2/2\sigma^2} \qquad x>0$$

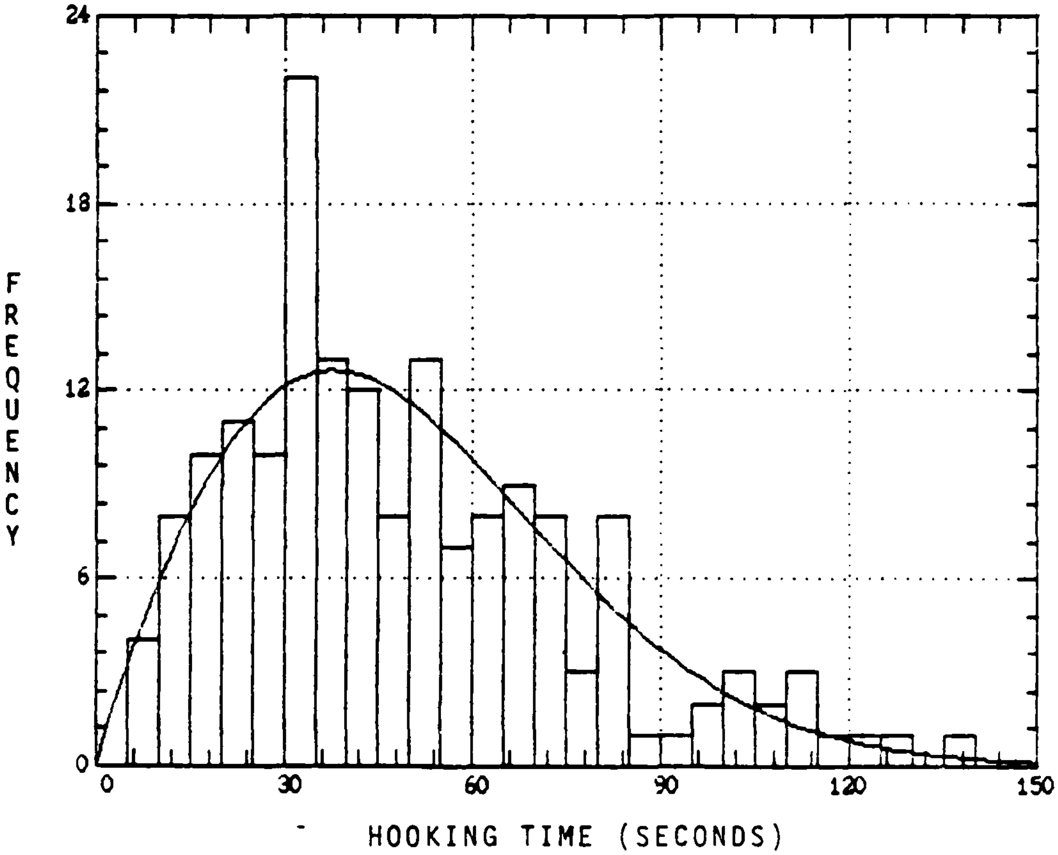

Figure 3.5: Frequency distribution of hooking time with fitted Weibull curve superimposed.

Table 3.5: Estimated values of hooking time distribution parameters and goodness-of-fit statistics.

```
==============================================================
==============================================================

DISTRIBUTION                PARAMETER           ESTIMATED VALUE
============                =========           ===============
  Weibull                     alpha                  55.81
                              beta                    1.90
==============================================================

Chi*2 Goodness-Of-Fit Statistic = 20.07 with 15 df
Probability Of A Larger Value = 0.16549

Estimated Kolmogorov-Smirnov Statistic  DPLUS = 0.056  DMINUS = 0.030
Estimated Overall Statistic  DN = 0.0559
Approximate Significance Level = 0.9997
==============================================================
```

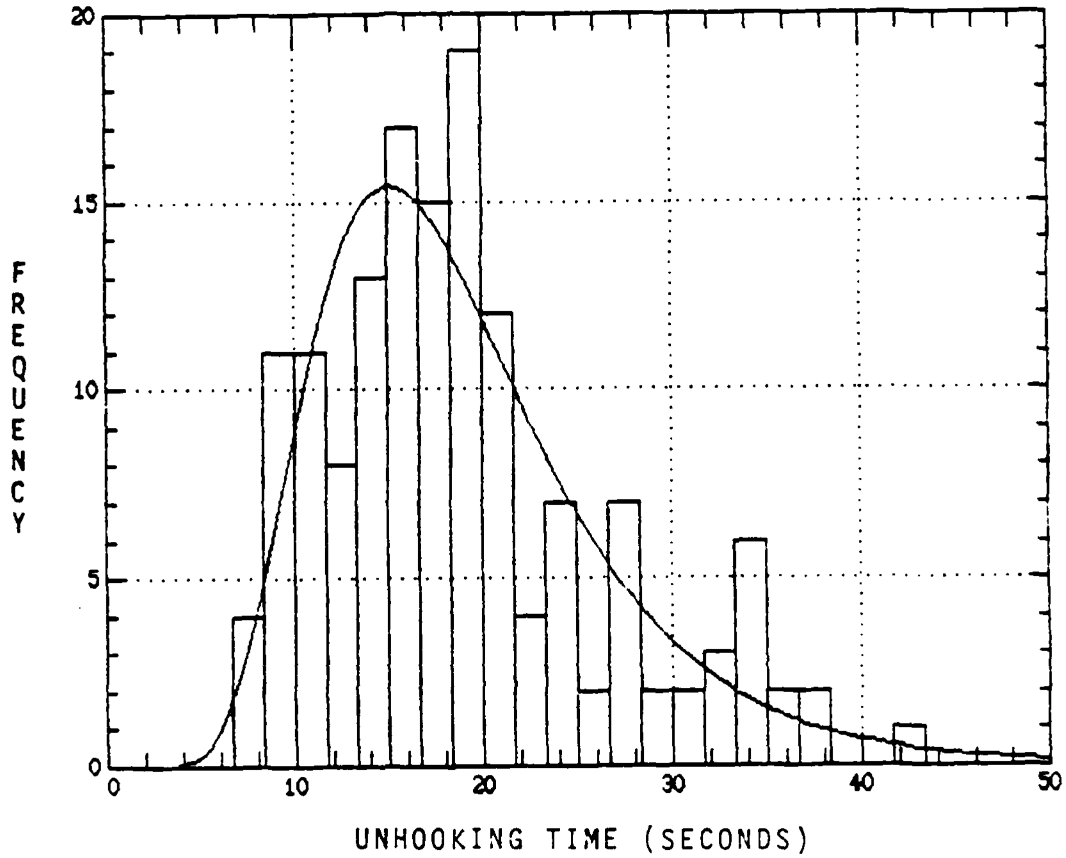

Figure 3.6: Frequency distribution of unhooking time with fitted lognormal curve superimposed.

Table 3.6: Estimated values of unhooking time distribution parameters and goodness-of-fit statistics.

```
===========================================================================
===========================================================================

DISTRIBUTION                    PARAMETER                ESTIMATED VALUE
============                    =========                ===============
 Lognormal                        mu                           18.98
                                  sigma                         7.37
===========================================================================

Chi*2 Goodness-Of-Fit Statistic = 15.32 with 11 df
Probability Of A Larger Value = =.16833

Estimated Kolmogorov-Smirnov Statistic  DPLUS = 0.062  DMINUS = 0.039
Estimated Overall Statistic  DN = 0.0615
Approximate Significance Level = 0.9995
===========================================================================
```

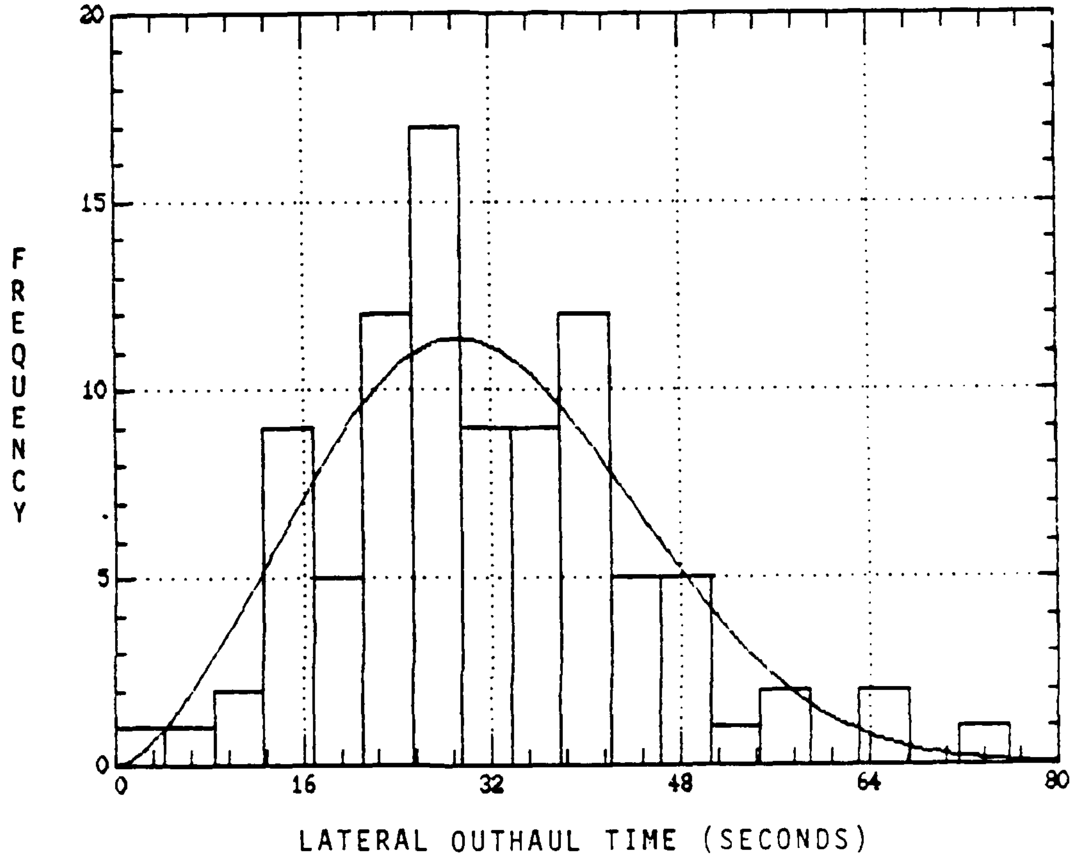

Figure 3.7: Frequency distribution of lateral outhaul time for landing 1 with fitted Weibull curve superimposed.

Table 3.7: Estimated values of lateral outhaul time distribution parameters and goodness-of-fit statistics for landing 1.

```
==========================================================================
==========================================================================

DISTRIBUTION                   PARAMETER              ESTIMATED VALUE
============                   =========              ===============
  Weibull                        alpha                     35.50
                                 beta                       2.56
==========================================================================

Chi*2 Goodness-Of-Fit Statistic = 9.44 with 11 df
Probability Of A Larger Value = 0.30617

Estimated Kolmogorov-Smirnov Statistic  DPLUS = 0.063  DMINUS = 0.065
Estimated Overall Statistic  DN = 0.0655
Approximate Significance Level = 0.9999
==========================================================================
```

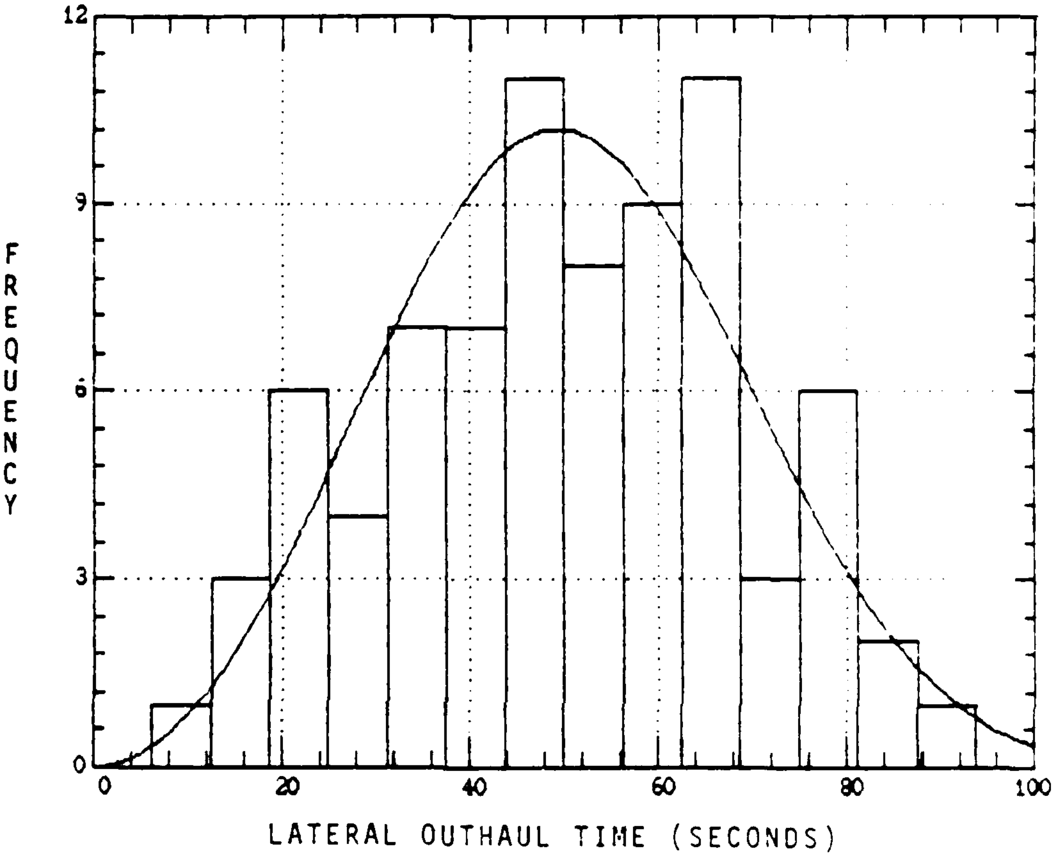

Figure 3.8: Frequency distribution of lateral outhaul time for landing 2 with fitted Weibull curve superimposed.

Table 3.8: Estimated values of lateral outhaul time distribution parameters and goodness-of-fit statistics for landing 2.

```
=================================================================
=================================================================

DISTRIBUTION                PARAMETER             ESTIMATED VALUE
============                =========             ===============
  Weibull                     alpha                     56.59
                              beta                       2.98
=================================================================

Chi*2 Goodness-Of-Fit Statistic = 6.57 with 7 df
Probability Of A Larger Value = 0.47461

Estimated Kolmogorov-Smirnov Statistic  DPLUS = 0.049  DMINUS = 0.069
Estimated Overall Statistic  DN = 0.0692
Approximate Significance Level = 0.9999
=================================================================
```

Table 3.9: Continuous empirical distribution for lateral inhaul time.

CUMULATIVE PROBABILITY	CUMULATIVE VALUE
0.01	4
0.10	11
0.20	14
0.30	17
0.40	22
0.50	30
0.60	40
0.70	68
0.80	92
0.90	136
1.00	387

Table 3.10: Discrete probability distribtion for number of cycles to complete at a given distance.

CUMULATIVE PROBABILITY	DISCRETE VALUE
0.24	1
0.34	3
0.48	4
0.55	5
0.58	6
0.69	7
0.72	8
0.76	9
0.79	10
0.82	11
0.86	12
1.00	20

correlated to inhaul time because the value of outhaul distance will always be equal to inhaul distance. Regression results for inhaul time for landing 1 and landing 2 (Table 3.11 and Table 3.12 respectively) and outhaul time for landing 1 and landing 2 (Table 3.13 and Table 3.14 respectively) are provided.

Non-parametric Methods

When there was a low sample size on a particular element of interest, these elements were represented in the simulation model by using the median value of the data points that were collected. Median values were used to explain the frequency and duration of the four nonproductive delays that were modeled. Results for inhaul delays, delays to clear the landing, delays to change corridors and to change landings are provided in Table 3.15.

Selection of the Simulation Language

The following criteria were used in the selection of a simulation language:

1) The completed model must run on a microcomputer.
2) The language must possess characteristics that will aid in model modification.
3) The language must allow the collection of statistics during the simulation run.
4) The language must be flexible enough to adequately model the system under study.

The SIMAN simulation language (Pegden 1985) meets all these criteria. It is a combined discrete-continuous event simulation analysis language for modeling general systems. Developed in 1982 and under constant revision, it is

Table 3.11: Regression results for inhaul time predicting equatio. for landing 1.

```
=======================================================================
=======================================================================
VARIABLE                    COEFFICIENT    STND. ERROR    T-VALUE   PROB(>T)
========                    ===========    ===========    =======   ========
Outhaul Distance                  0.283          0.003      82.87      0.000


                              ANALYSIS OF VARIANCE
                              ====================
SOURCE         SUM OF SQUARES       DF    MEAN SQUARE    F-RATIO   PROB(>F)
======         ==============       ==    ===========    =======   ========
Model               558220.68        1      558220.68    6865.27      0.000
Error                 6748.79       83          81.31

Total               564969.47       84
=======================================================================
R-SQUARED = 0.988
R-SQUARED (ADJ. FOR df) = 0.988
STANDARD ERROR OF ESTIMATE = 9.017
=======================================================================
```

Table 3.12: Regression results for inhaul time predicting equation for landing 2.

```
========================================================================
========================================================================
VARIABLE               COEFFICIENT    STND. ERROR    T-VALUE   PROB(>T)
========               ===========    ===========    =======   ========
Constant                    24.685         3.34         7.39    2.03E-7
Outhaul Distance             0.101         0.02         6.38    7.87E-8

                            ANALYSIS OF VARIANCE
                            ====================
SOURCE        SUM OF SQUARES     DF   MEAN SQUARE    F-RATIO   PROB(>F)
======        ==============     ==   ===========    =======   ========
Model             9002.59         1       9002.59     40.779      0.000
Error            15674.08        71        220.76

Total            24676.67        72
========================================================================
CORRELATION COEFFICIENT = 0.604
STANDARD ERROR OF ESTIMATE = 14.858
========================================================================
```

Table 3.13: Regression results for outhaul time predicting equation for landing 1.

```
=========================================================================
=========================================================================
VARIABLE                 COEFFICIENT     STND. ERROR    T-VALUE   PROB(>T)
========                 ===========     ===========    =======   ========
Constant                       4.452        0.593          7.49    1.09E-7
Outhaul Distance               0.052        2.03E-3       25.57      0.000

                                    ANALYSIS OF VARIANCE
                                    ====================
SOURCE          SUM OF SQUARES    DF     MEAN SQUARE     F-RATIO   PROB(>F)
======          ==============    ==     ===========     =======   ========
Model                1337.61       1         1337.61      654.11      0.000
Error                 186.09      91            2.04

Total                1523.70      92
=========================================================================
CORRELATION COEFFICENT = 0.937
STANDARD ERROR OF ESTIMATE = 1.430
=========================================================================
```

Table 3.14: Regression results for outhaul time predicting equation for landing 2.

```
=======================================================================
=======================================================================
VARIABLE               COEFFICIENT    STND. ERROR    T-VALUE   PROB(>T)
========               ===========    ===========    =======   ========
Constant                     6.337          0.875       7.24   5.15E-10
Outhaul Distance             0.034          0.004       7.22   5.71E-10

                            ANALYSIS OF VARIANCE
                            ====================
SOURCE        SUM OF SQUARES     DF   MEAN SQUARE    F-RATIO   PROB(>F)
======        ==============     ==   ===========    =======   ========
Model               778.58        1        778.58     52.116      0.000
Error              1015.89       68         14.94

Total              1794.46       69
=======================================================================
CORRELATION COEFFICIENT = 0.658
STANDARD ERROR OF ESTIMATE = 3.86
=======================================================================
```

Table 3.15: Probability and duration (in seconds) of four delays.

DELAY TYPE	PROBABILITY	DURATION
CLEAR LANDING	0.142	45.00
CHANGE CORRIDORS	*	5400.00
CHANGE LANDINGS	*	14400.00
INHAUL		
landing 1	0.018	94.16
landing 2	0.075	100.63

*deterministic

considered to be state-of-the-art in current simulation language technology (Kleindorfer 1986). To date no harvest simulators exist that utilize this simulation language. Discussion here will be limited to the discrete modeling capabilities of SIMAN.

Structure

SIMAN is designed around a logical modeling framework in which the simulation program is decomposed into a model frame and an experimental frame. External to this, SIMAN has an OUTPUT processor which collects and analyzes simulation results. Debugging the model code is aided by a system trace and interactive debugger.

Model Frame. The model frame defines the static and dynamic characteristics of the system. Within the model frame, either an event or process orientation can be used to describe the model. The primary modeling orientation for discrete change systems is the process orientation, in which the model is constructed by depicting the functional operations of the system as block diagrams. The block diagram is a linear top-down sequence of blocks which represents specific process functions such as time delays and queues. This orientation was used in the development of the cable logging model.

A second modeling orientation is the event orientation which may be used to augment or replace the block diagram component of the model frame. The event component consists of a set of user written FORTRAN subroutines which contain the mathematical and logical expressions that define instantaneous state transitions within the system.

In future model refinement the event orientation will be used to augment the model that has been developed. Block functions (such as delay for hooking) will be replaced perhaps by a very complex subroutine, thus increasing the level of detail modeled.

In a sense, each block which explains a delay element of the logging cycle may be thought of as a module in the model. Each module may be refined individually by simply replacing a specific block with a FORTRAN subroutine and plugging it back into the model.

Experimental Frame. The SIMAN experimental frame defines the experimental conditions under which the model is to be run in order to generate specific output data. This includes such elements as the initial conditions for the run, machine capacities, the type of statistics to be recorded, and the various parameters and coefficients of the theoretical distributions and regression equations that have been developed. Since these elements are specified external to the model description, they may be easily changed without affecting the basic model definition. Many different scenarios may be modeled by modifying the experimental frame.

Output Processor. Based on the model and experiment, the SIMAN simulation program generates output files which record the model state transitions as they occur in simulated time. The data in the output files can then be subjected to various data analysis within the SIMAN output processor or exported to a statistical package for analysis. Within the SIMAN framework, the data analysis follow the development and running of the simulation program and are completely distinct from it.

System Debugging. Debugging or model verification is the process of isolating and correcting the logic errors that produce invalid results. The SIMAN system trace is used within a discrete model to generate a detailed trace report of the processing of entities. In the event mode, the trace report summarizes the occurrence of each event and details all operations executed within the event. When a logic error is detected, the SIMAN interactive debugger may be used. It allows the user to interactively monitor and control the execution of a simulation. Errors can be isolated and corrected during execution without the need to recompile, relink and rerun the simulation.

Model Validation

The topic of validating simulation models has been discussed in the validation section of Chapter II and so shall not be repeated here. It is the intent of this discussion to describe two methods used in the validation of this model.

It was discussed earlier that a model should be developed with respect to a specific purpose and validated for that purpose. From prior discussion in this chapter, it should be apparent that the purpose of this model was to construct a working model that will pave the way for the development of a more detailed model in the future; to be used as a guide to aid further simulation studies. The model was validated with respect to that purpose.

First, the model was examined to determine if it had a high degree of face validity. The model flowcharts (Figure 3.3 and Figure 3.4) were examined to determine if the model logic "mirrors" the logic of the system under study. Any simulation study embraces a series of compromises as to the level of detail that should be modeled. The model developed, contains all of the major functional elements of the system studied and the static and dynamic relationships seem to make sense. Therefore, the model arguably contains a high degree of face validity.

The following procedure was used to validate the model empirically. Each of the theoretical input distributions were examined for goodness-of-fit. The Chi-square and Kolmogorov Smirnov goodness-of-fit tests were used. Regression equations were examined and detailed residual analysis was performed. Empirical distributions and median values are simply representative of the data points sampled. A detailed discussion of these statistical results were provided in the statistical analysis section of this chapter and will not be repeated here.

Chapter IV

SUMMARY AND CONCLUSIONS

Summary

This project has resulted in the development of a timber harvest simulator that models the actions of a cable yarder operating in the Allegheny Region of Pennsylvania. Elemental yarding time predicting equations were developed from field data collected from that region.

In the model presented in this study, the level of detail is the function itself (e.g. hooking service time, unhooking service time, etc.). Indirectly, many different "what-if" questions may be answered, but it requires the user to estimate the change in the maximum likelihood estimates of the parameters affected by the change proposed. This is illustrated in Appendix B where the model is used to examine two harvest unit configurations in order to choose the best alternative with minimization of make-span as the performance criteria.

The simulation model has been designed around the central premise that a simulation model will go through many stages of development during its lifecycle. At each stage, the model will be refined as more data are collected; perhaps by someone that has not been involved in the study to date.

For this reason the model has been fully documented. Each line of SIMAN code has been commented so that the model logic may easily be understood. The methodology, and data used in the development of input distributions have been included and the results illustrated.

As previously pointed out, the model is modular in design. Specific functions of the model may be developed independently of others. Predicting equations developed from the time study conducted may be used for functions where further data are not available. As further data is collected on other functions, these functions may be developed in greater detail, independently of the others.

Areas For Further Study

As previously mentioned, at the heart of any simulation study is the question of the level of detail to be modeled. Very complex models take more time and resources to develop and are more expensive to use. Less complex models on the other hand, may not be detailed enough to answer specific questions of interest.

The approach that has been taken in the model developed in this study was to model the elemental yarding cycle function as the lowest level of detail. Additional data are needed if a higher degree of detail is to be modeled. These data could be incorporated into a new model that would consider specific elements within each function that has been currently modeled. Several suggestions follow.

What affect does the number of logs yarded per cycle have on productivity? As the number of logs yarded per cycle increases, hooking time, lateral inhaul time, and inhaul time would be expected to increase. The total number of cycles needed to complete the operation however, would decrease. How many logs should be yarded per turn?

What effect does the type of cable logging machine used have on the total cost of the operation? For example, a very powerful machine would be expected to shorten inhaul and lateral inhaul time. Perhaps more logs could be yarded per turn. However, the hourly machine cost would be expected to increase as the machine capacity increases. Would the total harvesting time for the entire operation decrease enough to warrant the use of this larger machine?

In addition to modeling these machine specific variables, a subroutine to calculate the cost of the operation is needed. In general, the least expensive system alternative will be chosen.

The size of the labor force should be considered when predicting independent service times. What is the effect of having a larger labor force? Does the total cost of the operation decrease?

Site specific variables such as slope, brushiness, and stand structure should be considered. In general, a site that is very brushy would take longer to harvest than one that is not. The relationship between slope and productivity may not be as easy to quantify. Productivity may decrease for very steep and very flat sites. This issue must be addressed in future models.

A subroutine to build a stand of trees to be harvested is needed. Cartesian coordinates, a diameter, height, and weight for each tree could be estimated from cruise data. A decision rule, specified by the user, would then be employed to determine which tree or trees should be yarded on a given turn. This would add to the realistic aspect of the operation and many additional "what-if" questions could be addressed.

For example, many different logging configurations could be considered. Several feasible log landing locations could be examined and the best one chosen. The question of how closely the corridors should be spaced as opposed to increasing lateral outhaul distances could be examined in greater detail than addressed in Appendix B.

With some of these suggestions for further research implemented, the simulation model has the potential to become a valuable tool for planning cable logging operations in the Allegheny Region.

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APPENDIX A

REVIEW OF FIVE TIMBER HARVEST SIMULATION MODELS

Forest Harvest Simulation Model

The Forest Harvesting Simulation Model (FHSM) is a FORTRAN / GASP II (Pritsker and Kaviat 1964), event-oriented model that can be used to simulate a wide variety of saw log and pulpwood harvesting operations in the South (Killham 1975). Webster (1975) reported that the requirements in developing this model were that it (a) be flexible enough to duplicate the major systems used in timber harvesting in the South, (b) be detailed enough allow for analysis of individual harvesting functions, and (3) possess a high "degree of believability" in the way it duplicates a system's operations.

Webster further describes the model. To satisfy the first objective, the model simulates the functional elements such as felling, limbing, bucking, skidding, etc. in various configurations. While the configurations do not cover all types of harvesting systems in the South, they do cover a wide range of them.

Each function has been built as a separate component in the model. Development of a model formulation for a specific system involves assembling the various components that comprise that system.

To satisfy the second objective, components of the model (the harvesting functions) are defined so as to allow different pieces of equipment to perform the same function, but also differentiates the equipment characteristics and work capabilities. For example, two different types of skidders may be used in the skidding function.

To satisfy the third objective, the model is detailed enough to allow for the user to follow the flow of wood through the model. In order to achieve this, a tree is felled and it provides the basis for wood input to the rest of the model.

Model input can be divided up into general and operational categories. General input influences the performance of all of the harvesting functions (e.g. tree stand mix, tree size, merchantable height, etc.). Operational input is that which influences one harvesting function (e.g. skidder capacity, travel rate of skidder, etc.).

In general, the model output consists of production data in board feet, cubic feet, and weight for each harvesting component over the time horizon simulated. Additionally, for each harvesting function, production statistics, productive time, and idle time are kept on each piece of equipment or crew member.

Full-Tree Field Chipping and Transport Simulator

The Full-Tree Field Chipping and Transport Simulator (FTFC) is composed of two GPSS (Schriber 1974) simulation models, one for chipping (Bradley et al. 1976) and one for transport (Bradley and Winsauer 1976), and was designed to duplicate the features of a full-tree field chipping operation including a stand of trees, feller-bunchers, skidders, a chipper with loader, trucks and vans, one or two optional setout trucks, a millyard scale and a chip dumper.

Bradley et al. (1976) provide a model description. The model attempts to mirror the harvesting operation down to elemental time within each function in order to give the model a high degree of integrity. It is machine independent in that machine speeds and capacities may be altered to account for different equipment brands and sizes.

FTFC does not consider delays caused by machine breakdown but has instead concentrated on delays caused by machine interaction. For example, the skidder may "look ahead" to see if another skidder is unloading at the chipper. If not, it will take its load to the chipper. If another skidder is unloading, however, it will deposit its load at a stockpile and bring it to the chipper later, thus representing a system delay.

Wood flows through FTFC in a manner identical to FHSM with one exception. Instead of actually passing wood from one function to the other, parallel random number streams are generated at each function. Wood flow is identical to that of FHSM when wood passes through each function in the same sequence. However, when the orders of two bunches have been inverted from felling to skidding, the trees in the bunches have been effectively rearranged, and hence, skid turn statistics will vary from model to model.

Model input requirements include tree locations (in x,y coordinates), tree volumes, and felling order of each tree in the stand. Elemental machine productivity and capacity data are also required.

The model's report generator provides detailed production and cost statistics by operation, system energy consumption, and net energy produced, the latter two in the form of BTU's (Goulet et al. 1979).

Harvest System Simulator

The Harvest System Simulator (HSS) is a FORTRAN-based time and event oriented simulation program and is part of a larger package known as the Harvesting Analysis Technique (HAT) (American Pulpwood Association 1972). The model was designed to simulate the productive and non-productive (downtime, breaks, etc.) activities of a harvesting system by simulating the interaction between harvesting equipment and the stand being harvested.

HSS is different from FTFC and FHSM in that it focuses on the larger systems aspect of the harvesting operation, i.e., function to function interaction and not the detail of any one function (Goulet et al. 1980).

O'Hearn (1977) described HSS. A maximum of 14 machines, working in any combination, and a maximum of six aggregations of like machines (phase) can be simulated. The harvested tract can be divided into a maximum of 14 harvesting areas that can differ in stand type, volume per acre, species, composition, and skidding distance to the primary landing. Individual harvesting areas have no acreage or volume limits. Unique production rates may be specified for each harvesting area-machine combination. The user controls the order in which harvesting areas are processed. Terrain and stand limitations are modeled through move or travel rate modifiers and deck locations. Wood flows from phase to phase in aggregated volumes.

Nonproductive activities, such as machine failures, breakdowns, delays, and servicing, can be imposed logically or stochastically. Repairs can be made at the stump, the deck, or the shop. Repairs at the stump hold the machine in place, while repairs at the deck or shop require the machine to move to the primary deck. Delays are divided into two types: major and minor. Major delays bring the machine back to the deck, while minor delays leave it in place. A distribution between productive and nonproductive time can be provided.

Program output is provided by two report generators that can be called on separately or jointly. They provide time, production, cost, and revenue statistics. Also, discounted cash flow and return on investment analysis can be made. All output reports and detailed and complete.

Simulation Applied To Logging Sytems

Simulation Applied to Logging Systems (SAPLOS) (Johnson 1976) is a discrete event, FORTRAN / GASP IV (Pritsker 1974), general harvest simulation model that is adaptable to a number of harvesting systems.

Johnson et al. (1972) reported, the development of the timber-harvesting model progressed through three phases of analysis: (1) Identify and classify the most common logging systems in Appalachia in terms of the general operations (subsystems themselves) involved and their points of interaction. (2) Within each subsystem identify the activities particular to that subsystem adn determine the sequence of these activities. Activities are the various operations of a subsystem such as movement of a skidder to the landing or the hook-up of logs by the skidder. (3) Combine the particular activities of the subsystems into the general events and activities involved in the actual computer model. Events signal the beginning and ending of activities.

Johnson further describes the model. In the first phase of development, six subsystems were identified and represents the standard operations of this model. They are felling, bucking, prebunching, skidding, loading, and hauling.

In the model, the operation of a particular subsystem is represented by the activities that make up that operation and the events that signal activity changes. The second phase of the model development was accomplished through the indentification of these activities. For example, the arrival of a transporting vehicle at either the stump or skidroad signals the first skidding activity--winching or hooking the log to the skidder. The stump depicts the area where the tree was cut. An end-of-hooking event marks the end of the winching activity and the beginning of a move to either another tree or the landing, depending on whether or not the load is full.

The third phase of development was accomplished through the identification of five "critical locations" where the six logging operations overlap. A "critical location" on the ground forms a control point in the simulation model. They are (1) the stump or tree location in the woods, (2) the skidroad (when prebunchers are used), (3) the landing, (4) the prehaul dock (when shuttle trucks and prehaul trailers are used and, (5) the processing point such as a mill yard).

Two stages of input are required in the computer model. The two stages consist of objective information and subjective information. Objective information consists of the distributions used in the production equations and are used to obtain travel distances and load sizes. Subjective information is used in equations to calculate production times. The subjective information describes the logging system being simulated in terms of the variables unique to that system, e.g., a description of the terrain in terms of slope and soil.

Model output consists of production from the operation in cubic feet of timber, the time required to achieve this production, and the total cost involved in producing the timber.

Timber Harvest and Transport Simulator

The Timber Harvest and Transport Simulator (THATS) (Martin 1975) is a FORTRAN based time and event oriented simulation program which models the major harvesting systems of the Appalachian Region. Martin (1975) describes the structures, methodology, and main components of THATS. THATS is built around a main program composed of eight components (felling, bunching, skidding, bucking, loading, hauling, roadbuilding, and cost accounting) and a "clock." The model is a time oriented simulation in which simulated time on the clock is advanced one minute, then checks are made for active events.

Simulated event times are generated either from given averages and standard deviations, or from event times produced by a regression equation developed from collected data. All random variable event times have either a normal or a lognormal distribution. If any skewing is present in the time study data, the lognormal distribution is used. Regression equations from data collected for Appalachian logging operations are contained in the report.

The system simulates one day at a time and shuts down at the end of the working day in a staggered manner, with each crew finishing the day close to quitting time, though depending on the task at hand, some may be a little early, and some may be a little late.

Wood flows through the model in a volumetric manner.

and the output from the operation is a volume. The next operation draws trees or pieces from the deposited output volume, but these new trees or pieces have no relation to the input trees of the first operation except that their total volume equals the doposited output volume. For example, a tree is generated for the felling operation, felling statistics are collected on that tree, and the volume of that tree is deposited for the bunching operation. The bunching operation will now generate new trees up to the volume of the felled trees deposited.

Input for THATS includes time and motion data appropriate to teh system being studied. For those functions in which operating or delay time has not been related quantitatively to system or stand parameters, the input consist of expected values (and their standard deviations).

Output from THATS include system status information, time summaries, production summaries, and cost summaries Martin (1975).

APPENDIX B

THE SIMAN MODEL

Comparison of Two Harvest Unit Configurations

The simulation model was used to compare two harvest unit configurations. The utility of the model is highlighted and the procedure for modifying the experimental frame is illustrated.

In the first scenario, the unit was harvested from four corridors at landing 1 and two corridors at landing 2; in the second scenario there were two corridors at each landing. Minimization of make-span (total time to complete the operation) was used as the performance criteria.

The crux of the analysies was determining whether it takes more time to harvest the unit from more corridors but with relatively short lateral hauls versus harvesting from fewer corridors but with relatively long lateral hauls.

The first scenario was modeled using equations developed from the time and motion study that was carried out. Modifications were then made to three of these equations in order to reflect the changes that were made for the second scenario.

First, the times (number of cycles to complete at a given outhaul distance) empirical distribution was modified to reflect the increased liklihood of having more yarding cycles at a given distance than in the first scenario. The lateral inhaul and lateral outhaul equations were then modified to reflect the increased liklihood of having relatively longer lateral hauls. These changes are illustrated by comparing the two SIMAN experimental frame listings. The listing for scenario 1 (pp. 73-74) is presented in its entirety. The listing for scenario 2 (p. 75) only includes the changes that were made. All other code is identical to that of the first listing. The SIMAN model frame listing (identical for both scenarios) is presented (pp. 76-79). Directions for the modification of the experimental frame are presented below.

Interpretation of Model Output

When input to a simulation model are random (as is the case here) the output statistics will vary from run to run. It is thus necessary to perform several replications of each scenario and perform statistical analyses on the data of interest. The procedure is straightforward and will not be presented here. The output from two simulation runs (one from each scenario) are presented in Table B.1 and B.2 and are sufficient to highlight the utility of the model. From these tables it can be seen that make-span for scenario one was 144,400 seconds (40.1 hours) and for scenario two 127,000 seconds (35.3 hours). Therefore, scenario two would be chosen.

Directions For Modification of Experimental Frame

The current model is set up to model a harvesting configuration with two landings. Modification of the SIMAN model frame would be necessary to consider additional landings. This discussion will thus only provide instructions for the modification of the number of corridors harvested and of parameters associated with those

Table B.1: SIMAN summary statistics for scenario 1.

```
==============================================================================
Project:  CABLE YARDER
Analyst:  PETER HODES
Date   :   2/12/1987

Run ended at time :    .1444E+06


                                 Tally Variables
                                 ---------------

Number Identifier         Average     Standard  Minimum    Maximum    Number
                                      Deviation Value      Value      of Obs.
------------------------------------------------------------------------------

   1   OUTHAUL DISTANCE  144.05520   89.66764   20.00000  295.00000        344
   2   OUTHAUL TIME       11.64366    4.30409    5.50080   19.81180        344
   3   LAT. OUTHL. TIME   36.74237   16.48409     .57633   98.39664        344
   4   HOOK TIME          48.12401   26.84380    1.08319  133.12140        344
   5   LAT. INHL. TIME    69.61497   86.83110    4.00000  385.62970        344
   6   INHAUL TIME        42.64314   21.17064   10.46340   83.66015        344
   7   INHL. DLY. TIME     7.73942   26.04588     .00000  100.63000        344
   8   UNHOOKING TIME     19.55455    7.49970    7.34759   63.21509        344
   9   CLR. LAND TIME      5.75581   15.05127     .00000   45.00000        344
```

Table B.2: SIMAN summary statistics for scenario 2.

```
-----------------------------------------------------------------------------------
Project:  CABLE YARDER
Analyst:  PETER HODES
Date   :   2/12/1987

Run ended at time :    .1270E+06


                                   Tally Variables
                                   ---------------

Number Identifier          Average     Standard    Minimum      Maximum     Number
                                       Deviation   Value        Value       of Obs.
-----------------------------------------------------------------------------------

   1  OUTHAUL DISTANCE   180.12460     86.77548    20.00000    295.00000       321
   2  OUTHAUL TIME        12.87007      3.94855     5.50080     19.81180       321
   3  LAT. OUTHL. TIME    50.02949     18.54502     5.62850    103.12450       321
   4  HOOK TIME           44.70713     23.99140     1.03241    133.12140       321
   5  LAT. INHL. TIME     49.42349     50.18793     4.00000    384.07670       321
   6  INHAUL TIME         48.23970     19.05892    10.46340     83.66015       321
   7  INHL. DLY. TIME      9.66885     29.11992      .00000    100.63000       321
   8  UNHOOKING TIME      19.06803      8.06997     4.93522     85.71700       321
   9  CLR. LAND TIME       4.76636     13.86965      .00000     45.00000       321
```

corridors (corridor length, starting distance, and incremental corridor increase). In general, n corridors may be considered as follows:

1) In the COUNTERS element change the last number to n+1;
2) In the PARAMETERS element 2, change the second number to n;
3) In PARAMETERS element 5, specify the incremental corridor increase desired;
4) In PARAMETERS element 6 and 11, specify the last corridor number at landing 1 and n respectively;
5) In PARAMETERS element 27 through 27+n, specify the corridor lengths;
6) In PARAMETERS element 28+n through 28+2n, specify the starting distance for harvesting at each corridor.

SIMAN Experimental Frame - Scenario 1

```
BEGIN;
PROJECT,CABLE YARDER,PETER HODES,2/12/1987;
DISCRETE,5,3;
TALLIES:
   1, OUTHAUL DISTANCE,11:
   2, OUTHAUL TIME,12:
   3, LAT. OUTHL. TIME,13:
   4, HOOK TIME,14:
   5, LAT. INHL. TIME,15:
   6, INHAUL TIME,16:
   7, INHL. DLY. TIME,17:
   8, UNHOOKING TIME,18:
   9, CLR. LAND TIME,19;
COUNTERS:1,END OF RUN,7;
REPLICATE,1;
PARAMETERS:
   1,2.0:                    ! TOTAL NUMBER OF LANDINGS
   2,6.0:                    ! TOTAL NUMBER OF CORRIDORS
   3,14400.0:                ! LANDING SETUP TIME (SECONDS)
   4,5400.0:                 ! CORRIDOR SETUP TIME (SECONDS)
   5,25:                     ! INCREMENTAL CORRIDOR INCREASE
   6,4.0:                    ! LAST CORRIDOR NUMBER AT LANDING NUMBER 1
   7,4.46:                   ! BETA0 FOR LANDING NUMBER 1
   8,0.05204:                ! BETA1 FOR LANDING NUMBER 1
   9,5.14:                   ! BET00 FOR LANDING NUMBER 1
   10,0.26617:               ! BET11 FOR LANDING NUMBER 1
   11,6.0:                   ! LAST CORRIDOR NUMBER AT LANDING NUMBER 2
   12,.925:                  ! PROB. OF NO INHAUL DELAY AT LANDING NUMBER 2
   13,100.63:                ! DURATION OF INHAUL DELAY AT LANDING NUMBER 2
   14,56.59:                 ! LATERAL OUTIME BETA PARAM  (1) FOR LANDING 2
   15,2.98:                  ! LATERAL OUTIME ALPHA PARAM (2) FOR LANDING 2
   16,6.34:                  ! BETA0 FOR LANDING NUMBER 2
   17,0.03038:               ! BETA1 FOR LANDING NUMBER 2
   18,24.68:                 ! BET00 FOR LANDING NUMBER 2
   19,0.10185:               ! BET11 FOR LANDING NUMBER 2
   20,.24,1,.34,2,.48,3,.55,4,.58,6,.69,7,.72,8,.76,9,.79,10,.82,11,
      .86,12,1,20:           !TIMES DISTRIBUTION
   21,35.50,2.56:            ! LATERAL OUTHAUL TIME DISTRIBUTION INFORMATION
   22,53.81,1.9015:          ! HOOKING TIME DISTRIBUTION INFORMATION
   23,.01,4,.1,11,.2,14,.3,17,.4,22,.5,30,.6,40,.7,68,
      .8,92,.9,136,1.,387:   ! LATERAL INHAUL TIME DISTRIBUTION INFO.
   24,.892,0.0,1.0,94.16:    ! INHAUL DELAY TIME INFORMATION
   25,18.98,7.73:            ! UNHOOKING TIME DISTRIBUTION INFORMATION
   26,.858,0.0,1.0,45.0:     ! CLEAR OF LANDING TIME INFORMATION
   27,300.0:                 ! LENGTH OF CORRIDOR NUMBER 1
   28,300.00:                ! LENGTH OF CORRIDOR NUMBER 2
   29,300.00:                ! LENGTH OF CORRIDOR NUMBER 3
   30,300.00:                ! LENGTH OF CORRIDOR NUMBER 4
```

```
   31,300.00:              ! LENGTH OF CORRIDOR NUMBER 5
   32,300.00:              ! LENGTH OF CORRIDOR NUMBER 6
   33,20.00:               ! STARTDISTANCE AT CORRIDOR NUMBER 1
   34,20.00:               ! STARTDISTANCE AT CORRIDOR NUMBER 2
   35,20.00:               ! STARTDISTANCE AT CORRIDOR NUMBER 3
   36,20.00:               ! STARTDISTANCE AT CORRIDOR NUMBER 4
   37,20.00:               ! STARTDISTANCE AT CORRIDOR NUMBER 5
   38,20.00;               ! STARTDISTANCE AT CORRIDOR NUMBER 6
END;
```

```
                    **SIMAN Experimental Frame - Scenario 2**
BEGIN;
   .
   .
   .
COUNTERS:1,END OF RUN,5;
   .
PARAMETERS:
   .
  2,4.0:                    ! TOTAL NUMBER OF CORRIDORS
   .
   .
  6,2.0:                    ! LAST CORRIDOR NUMBER AT LANDING NUMBER 1
   .
   .
   .
   .
  11,4.0:                   ! LAST CORRIDOR NUMBER AT LANDING NUMBER 2
   .
   .
  20,.21,1,.28,2,.39,3,.42,4,.48,6,.62,7,.68,8,.74,9,.77,80,.80,11,
     .86,12,1,20:           !TIMES DISTRIBUTION
  21,50.00,2.56:            ! LATERAL OUTHAUL TIME DISTRIBUTION INFORMATION
   .
   .
  23,.01,4,.07,11,.14,14,.21,17,.35,22,.49,30,.63,40,.77,68,
     .92,92,.97,136,1.,387:  ! LATERAL INHAUL TIME DISTRIBUTION INFO.
   .
   .
  27,300.0:                 ! LENGTH OF CORRIDOR NUMBER 1
  28,300.00:                ! LENGTH OF CORRIDOR NUMBER 2
  29,300.00:                ! LENGTH OF CORRIDOR NUMBER 3
  30,300.00:                ! LENGTH OF CORRIDOR NUMBER 4
  31,20.00:                 ! STARTDISTANCE AT CORRIDOR NUMBER 1
  32,20.00:                 ! STARTDISTANCE AT CORRIDOR NUMBER 2
  33,20.00:                 ! STARTDISTANCE AT CORRIDOR NUMBER 3
  34,20.00;                   STARTDISTANCE AT CORRIDOR NUMBER 4
END;
```

SIMAN Model Frame

```
BEGIN;
SYNONYMS:
  TIMES = X(1):      ! NUMBER OF CYCLES AT A SPECIFIED OUTHAUL DISTANCE
  CTIME = X(2):      ! NUMBER OF CYCLES COMPLETED AT CURRENT OUTHAUL DISTANCE
  INCRE = X(3):      ! INCREMENTAL CORRIDOR DISTANCE INCREASE
  BETA0 = X(4):      ! Y-INTERCEPT IN EQUATION TO PREDICT OUTHAUL TIME
  BETA1 = X(5):      ! COEFF. OF ODIST IN EQUATION TO PREDICT OUTHAUL TIME
  BET00 = X(6):      ! Y-INTERCEPT IN EQUATION TO PREDICT INHAUL TIME
  BET11 = X(7):      ! COEFF. OF ODIST IN EQUATION TO PREDICT INHAUL TIME
  LNUMB = X(8):      ! CURRENT LANDING NUMBER
  CNUMB = NC(1):     ! CURRENT CORRIDOR NUMBER
  NUMBL = X(9):      ! TOTAL NUMBER OF LANDINGS
  NUMBC = X(10):     ! TOTAL NUMBER OF CORRIDORS
  LTIME = X(11):     ! ELAPSED TIME SINCE CORRIDOR BEGAN
  CLENG = X(12):     ! LENGTH OF CURRENT CORRIDOR
  SDIST = X(13):     ! DISTANCE WHERE HARVESTING BEGAN AT CURRENT CORRIDOR
  TTIME = A(1):      ! MARKS SIMULATED TIME AT BEGINNING OF A TURN
  ODIST = X(14):     ! CURRENT OUTHAUL DISTANCE
  TCLEA = X(15):     ! TIME TO CLEAR CURRENT LANDING OF LOGS
  OTIME = X(16):     ! OUTHAUL TIME
  LOTIM = X(17):     ! LATERAL OUTHAUL TIME
  LITIM = X(18):     ! LATERAL INHAUL TIME
  ITIME = X(19):     ! INHAUL TIME
  HOTIM = X(20):     ! HOOKING TIME
  UHTIM = X(21):     ! UNHOOKING TIME
  IDTIM = X(22):     ! INHAUL DELAY TIME
  LCORR = X(23):     ! NUMBER OF LAST CORRIDOR AT THE CURRENT LANDING
  LSUTI = X(24):     ! LANDING SETUP TIME
  CSUTI = X(25);       CORRIDOR SETUP TIME
;
START    CREATE,1;
         ASSIGN: 'NUMBL' = CO(1);        ASSIGN NUMBL
         ASSIGN: 'NUMBC' = CO(2);        ASSIGN NUMBC
         ASSIGN: 'LSUTI' = CO(3);        ASSIGN LSUTI
         ASSIGN: 'CSUTI' = CO(4);        ASSIGN CSUTI
         ASSIGN: 'INCRE' = CO(5);        ASSIGN INCRE
;
;***********************************************************************
;*                 INITIALIZE VALUES FOR LANDING NUMBER ONE           *
;***********************************************************************
;
LAND1    ASSIGN: 'LNUMB' = 1;            ASSIGN LNUMB
         ASSIGN: 'LCORR' = CO(6);        ASSIGN LCORR
         ASSIGN: 'BETA0' = CO(7);        ASSIGN BETA0
         ASSIGN: 'BETA1' = CO(8);        ASSIGN BETA1
         ASSIGN: 'BET00' = CO(9);        ASSIGN BET00
```

```
         ASSIGN: 'BET11' = CO(10);         ASSIGN BET11
         DELAY:  'LSUTI': NEXT(NEWCORR);   DELAY BY LSUTI THEN PROCEDE TO
;                                           BLOCK NEWCORR
;
;*********************************************************************
;*                 INITIALIZE VALUES FOR LANDING NUMBER TWO          *
;*********************************************************************
;
LAND2    ASSIGN: 'LCORR' = CO(11);         ASSIGN LCORR
         ASSIGN: P(24,1) = CO(12);         ASSIGN PROB. OF AN INHAUL DELAY
         ASSIGN: P(24,4) = CO(13);         ASSIGN DURATION OF AN INHAUL
;                                                 DELAY
;                                          ASSIGN LATERAL OUTHAUL DISTRIBUTION:
         ASSIGN: P(21,1) = CO(14);          1. BETA PARAMETER
         ASSIGN: P(21,2) = CO(15);          2. ALPHA PARAMETER
         ASSIGN: 'BETA0' = CO(16);         ASSIGN BETA0
         ASSIGN: 'BETA1' = CO(17);         ASSIGN BETA1
         ASSIGN: 'BET00' = CO(18);         ASSIGN BET00
         ASSIGN: 'BET11' = CO(19);         ASSIGN BET11
         DELAY:  'LSUTI': NEXT(CONTINU1);  DELAY BY LSUTI THEN PROCEDE TO
;                                           BLOCK CONTINU1
;
;*********************************************************************
;*                 INITIALIZES VALUES WHEN CHANGING CORRIDORS        *
;*********************************************************************
;
NEWCORR  COUNT: 1,1;                                INCREMENTS CNUMB
          BRANCH, 1:
           IF, 'CNUMB' .EQ. 'LCORR' + 1, NEWLAND:
           ELSE, CONTINU1;                         IS LANDING COMPLETED
;
CONTINU1 DELAY:  'CSUTI';                          DELAY CSUTI
         ASSIGN: A(2)  = 'CNUMB'+26;               INCREMENTS A(2)
         ASSIGN: A(3)  = 'CNUMB'+26+'NUMBC';       INCREMENTS A(3)
         ASSIGN: 'LTIME' = 0;                      ASSIGN LTIME
         ASSIGN: A(1)=TNOW;                        ASSIGN TTIME
         ASSIGN: 'CLENG' = CO(A(2));               ASSIGN CLENG
         ASSIGN: 'SDIST' = CO(A(3));               ASSIGN SDIST
         ASSIGN: 'ODIST' = 'SDIST';                ASSIGN ODIST
         ASSIGN: 'TIMES' = DP(20,1);               ASSIGN TIMES
         ASSIGN: 'CTIME' = 1: NEXT(CORRIDOR);      ASSIGN CTIME THEN GO
;                                                   TO BLOCK CORRIDOR
;*********************************************************************
;*        INITIALIZES VALUES WHEN STARTING AT A NEW OUTHAUL DISTANCE   *
;*********************************************************************
NEWDIST  ASSIGN: 'LTIME' = TNOW - 'TTIME';         ASSIGN LTIME
         ASSIGN: 'ODIST' = 'ODIST' + 'INCRE';      ASSIGN ODIST
         ASSIGN: 'TIMES' = DP(20,1);               ASSIGN TIMES
         BRANCH, 1:
```

```
          IF, 'TIMES' .EQ. 0, NEWDIST:
          ELSE, CONTINU2;                          ANY TURNS AT CURRENT
                                                    ODIST
;
CONTINU2 ASSIGN: 'CTIME' = 1;                      ASSIGN CTIME
        BRANCH, 1:
          IF, 'ODIST' .GT. 'CLENG', NEWCORR:
          ELSE, CORRIDOR;                          TESTS IF CORRIDOR IS
;                                                   COMPLETED
;*********************************************************************
;*                INITIALIZES VALUES WHEN STARTING A NEW LANDING     *
;*********************************************************************
;
NEWLAND  ASSIGN: 'LNUMB' = 'LNUMB' + 1;            ASSIGN LNUMB
        BRANCH, 1:
          IF, 'LNUMB'.EQ. 2, LAND2:
          ELSE, FINISHED;                          NEW LANDING OR JOB
;                                                   COMPLETED
;*********************************************************************
;*                COMPLETES A YARDING CYCLE                          *
;*********************************************************************
CORRIDOR ASSIGN: 'OTIME' = 'BETA0' + 'BETA1'*'ODIST';  ASSIGN OTIME
        DELAY:    'OTIME';                            DELAY OTIME
        TALLY: 1, 'ODIST';                            RECORD ODIST
        TALLY: 2, 'OTIME';                            RECORD OTIME
;
        ASSIGN:   'LOTIM' = WE(21,1);                 ASSIGN LOTIM
        DELAY:    'LOTIM';                            DELAY LOTIM
        TALLY: 3, 'LOTIM';                            RECORD LOTIM
;
        ASSIGN:   'HOTIM' = WE(22,1);                 ASSIGN HOTIM
        DELAY:    'HOTIM';                            DELAY HOTIM
        TALLY: 4, 'HOTIM';                            RECORD HOTIM
;
        ASSIGN:   'LITIM' = OP(23,1);                 ASSIGN LITIM
        DELAY:    'LITIM';                            DELAY LITIM
        TALLY: 5, 'LITIM';                            RECORD LITIM
;
        ASSIGN: 'ITIME' = 'BET00' + 'BET11'*'ODIST';  ASSIGN ITIME
        DELAY:    'ITIME';                            DELAY ITIME
        ASSIGN:   'IDTIM' = DP(24,1);                 ASSIGN IDTIM
        DELAY:    'IDTIM';                            DELAY IDTIM
        TALLY: 6, 'ITIME';                            RECORD ITIME
        TALLY: 7, 'IDTIM';                            RECORD IDTIM
;
        ASSIGN: 'UHTIM' = RL(25,1);                   ASSIGN UHTIM
        DELAY:  'UHTIM';                              DELAY UHTIM
        TALLY: 8, 'UHTIM';                            RECORD UHTIM
;
        ASSIGN:   'TCLEA' = DP(26,1);                 ASSIGN TCLEA
```

```
        DELAY:    'TCLEA';                                DELAY TCLEA
        TALLY: 9, 'TCLEA';                                RECORD TCLEA
;
        ASSIGN: 'CTIME' = 'CTIME' + 1;                    ASSIGN CTIME
        BRANCH, 1:
         IF, 'CTIME' .LT. 'TIMES', CORRIDOR:
         ELSE, NEWDIST;                                   TESTS IF ALL TURNS
;                                                          COMPLETED AT CDIST
;
FINISHED COUNT:1,1:DISPOSE;                               ENDS THE SIMULATION
END;
```

APPENDIX C

STATISTICS COLLECTED

COLUMN 1 = CYCLE NUMBER
COLUMN 2 = OUTHAUL TIME (SECONDS)
COLUMN 3 = OUTHAUL DISTANCE (FEET)
COLUMN 4 = LATERAL OUTHAUL TIME (SECONDS)
COLUMN 5 = LATERAL OUTHAUL TIME (FEET)
COLUMN 6 = HOOKING TIME (SECONDS)
COLUMN 7 = LATERAL INHAUL TIME (SECONDS)
COLUMN 8 = INHAUL TIME (SECONDS)
COLUMN 9 = UNHOOKING TIME (SECONDS)
COLUMN 10 = NUMBER OF STEMS LANDED
COLUMN 11 = TOTAL CYCLE TIME (SECONDS)
COLUMN 12 = COLUMN WHERE DELAY OCCURRED

3	23.00	100	39.80	30	9.74	6.20	34.40	16.09	1	129.23	
4	6.00	100	57.80	40	14.85	240.35	34.18	11.59	1	364.77	4
5	6.00	100	39.00	45	14.28	4.18	32.75	34.83	1	131.04	
6	10.00	120	27.40	50	21.05	45.17	31.78	15.29	1	150.69	
8	10.00	120	27.70	50	32.82	12.32	32.63	18.49	1	133.96	
9	11.00	120	43.30	75	13.67	16.39	32.42	17.12	1	133.90	
10	10.00	120	29.20	86	24.99	21.00	32.78	35.28	3	153.25	
11	11.00	120	47.10	100	26.02	19.67	32.27	27.74	2	163.80	
12	11.00	120	72.50	100	35.64	44.75	28.80	16.79	1	209.48	
13	11.00	120	26.50	60	26.14	19.16	32.55	124.60	1	239.95	6
14	12.00	150	49.40	20	42.98	16.08	41.71	116.76	1	278.93	6
15	12.00	150	35.40	30	81.72	16.21	43.42	158.00	2	346.75	6
16	16.00	220	16.92	25	48.99	28.58	163.00	20.55	1	294.04	5
17	18.00	220	29.00	35	34.11	15.17	63.53	22.41	1	182.22	
18	16.00	220	27.90	35	54.01	165.60	57.68	14.78	1	335.97	5
19	18.00	220	29.00	40	24.44	14.00	54.20	25.09	1	164.73	
20	18.00	220	34.80	10	31.62	19.06	60.32	13.40	2	177.20	
21	16.00	220	28.50	25	82.07	24.00	61.46	19.53	2	231.56	
22	17.00	220	26.40	30	65.07	27.50	61.19	233.37	1	430.53	56
23	17.00	250	17.80	15	40.03	15.08	78.42	20.78	1	189.11	
24	21.00	250	18.50	20	65.71	15.85	74.70	38.42	2	234.18	
26	18.00	250	29.30	60	100.14	26.18	73.99	178.03	2	425.64	46
27	22.00	325	27.30	20	80.72	10.82	97.92	32.91	1	271.67	3
28	22.00	325	16.40	25	34.14	13.73	96.03	17.15	1	199.45	
29	22.00	325	30.40	30	16.72	13.43	84.16	27.57	1	194.28	
30	20.00	325	16.30	30	25.85	19.95	82.45	21.49	1	186.04	
31	21.00	325	16.80	25	18.30	17.19	85.09	28.81	1	187.19	
32	22.00	325	42.10	30	29.67	14.33	91.77	19.02	2	218.89	
33	22.00	325	30.00	50	59.99	16.63	94.64	173.65	1	396.91	6
34	21.00	325	14.30	60	40.89	16.03	75.17	10.92	1	178.31	
35	21.00	325	36.80	40	20.01	18.17	79.25	123.05	1	298.28	6
36	21.00	325	27.60	35	32.74	20.15	78.66	24.96	2	205.11	
37	20.00	325	32.50	75	48.67	20.00	76.95	32.53	2	230.65	
38	21.00	325	28.00	60	72.78	39.66	80.63	114.81	1	356.88	6
39	20.00	325	30.90	45	31.87	19.67	122.31	19.14	1	243.89	
40	23.00	325	52.60	80	35.06	24.30	89.74	20.58	2	245.28	

41	21.00	325	23.40	50	33.58	16.93	81.08	28.53	2	204.52	
42	21.00	325	38.50	60	34.01	29.45	76.82	26.99	2	226.77	
43	23.00	325	28.30	70	210.64	18.03	83.10	30.10	3	393.17	3
44	21.00	325	41.30	70	10.86	32.38	144.86	41.87	1	292.27	5
45	22.00	375	24.20	15	33.67	9.94	97.10	20.32	1	207.23	
46	23.00	375	15.90	10	54.05	10.67	102.21	34.19	2	240.02	
47	25.00	375	31.00	50	48.14	10.78	89.58	15.15	1	219.65	
48	25.00	375	23.00	45	37.68	12.66	92.31	15.24	1	205.89	
49	25.00	375	17.80	60	48.13	12.38	91.98	18.51	2	213.80	
50	25.00	375	48.80	70	29.35	30.48	95.37	18.15	1	247.15	
52	15.10	230	279.00	10	350.00	5.00	59.51	9.06	1	717.67	
53	18.10	250	11.00	2	32.00	61.00	96.28	14.74	1	233.12	
54	17.30	260	22.00	10	7.00	67.00	96.38	11.93	1	221.61	
55	17.50	290	45.00	1	50.00	68.00	97.85	9.39	1	287.74	4
56	17.60	280	22.00	4	47.00	74.00	72.45	19.49	1	252.54	
58	18.13	275	15.00	20	25.00	40.00	74.03	10.13	1	182.29	
59	19.90	270	13.00	8	28.00	42.00	73.24	12.41	1	188.55	
60	17.60	260	16.00	20	51.00	70.00	79.71	11.64	2	245.95	
61	18.50	260	3.00	25	68.00	176.00	68.98	9.57	1	344.05	
62	17.20	260	33.00	35	115.00	176.00	88.70	23.25	2	453.15	
63	17.60	260	21.00	10	45.00	163.00	178.55	11.10	1	436.25	5
64	20.00	260	35.00	30	51.00	73.00	80.86	6.87	1	266.73	
65	18.98	260	23.00	30	44.00	69.00	76.41	9.14	1	240.53	
66	20.10	260	29.00	35	55.00	80.00	91.51	7.97	1	283.58	
67	18.80	260	45.00	40	83.00	109.00	82.29	14.37	1	352.46	
68	18.50	260	25.00	20	39.00	68.00	74.81	8.87	1	234.18	
69	20.10	260	25.00	25	64.00	83.00	73.00	8.28	1	273.38	
70	18.40	260	33.00	35	69.00	92.00	81.43	11.37	1	305.20	
71	21.70	260	28.00	12	55.00	62.00	78.95	8.63	1	254.28	
72	18.50	265	23.00	20	61.00	77.00	91.17	20.64	1	291.31	
73	20.50	265	46.00	30	128.00	125.00	334.72	16.15	2	670.37	5
74	17.20	265	35.00	10	57.00	76.00	71.03	9.54	2	265.77	
75	22.50	310	39.00	2	44.00	64.00	82.80	11.52	1	263.82	
76	18.27	320	38.00	8	65.00	134.00	107.83	15.27	2	378.37	
77	21.96	320	37.00	20	71.00	95.00	93.52	36.62	1	355.10	
78	22.60	330	5.00	5	24.00	58.00	97.50	9.02	1	216.12	
79	19.50	330	10.00	3	38.00	61.00	96.94	16.28	1	241.72	
80	23.30	330	25.00	20	55.00	82.00	282.12	17.16	2	484.58	
81	22.30	330	24.00	25	63.00	90.00	96.60	9.61	1	305.51	
82	21.90	340	31.00	30	57.00	85.00	98.95	24.69	1	318.54	
83	22.50	340	13.00	5	32.00	52.00	95.26	11.24	1	226.00	
84	22.30	340	27.00	40	53.00	85.00	104.46	10.02	1	301.78	
85	22.20	340	35.00	50	54.00	86.00	110.97	31.16	1	339.33	
86	21.20	340	30.00	50	81.00	110.00	166.03	16.36	2	424.59	
87	23.96	340	38.00	45	68.00	99.00	107.79	15.99	2	352.74	
88	20.10	340	65.00	50	96.00	242.00	92.54	12.78	1	528.42	4
89	20.20	340	42.00	55	120.00	155.00	108.02	16.23	2	461.45	
90	21.10	340	67.00	60	125.00	159.00	105.75	12.15	2	490.00	
91	21.20	345	48.00	65	102.00	347.00	102.62	15.58	2	636.40	4
92	19.40	345	55.00	70	97.00	143.00	115.17	12.50	2	442.07	
93	20.30	345	47.00	10	87.00	109.00	112.54	10.74	1	386.58	

94	23.79	345	25.00	12	70.00	100.00	98.89	19.55	2	337.23
95	22.31	345	37.00	25	80.00	107.00	103.27	13.73	1	363.31
96	21.89	345	42.00	35	76.00	108.00	105.78	19.07	1	372.74
97	21.64	345	46.00	70	58.00	130.00	119.63	11.70	1	386.97
98	20.37	345	40.00	35	68.00	37.00	98.38	9.44	1	273.19
99	20.78	345	34.00	70	75.00	105.00	103.91	8.15	1	346.84
100	22.80	345	41.00	60	74.00	100.00	90.64	14.68	1	343.12
104	13.00	300	48.00	70	45.00	17.00	40.00	25.00	1	188.00
105	11.00	300	66.00	70	94.00	20.00	88.00	28.00	1	307.00
106	13.00	300	77.00	70	73.00	890.00	159.00	142.00	1	1354.00
107	11.00	300	77.00	70	43.00	42.00	76.00	50.00	1	299.00
108	20.00	300	79.00	60	14.00	13.00	36.00	24.00	1	186.00
109	67.00	300	56.00	70	36.00	95.00	35.00	31.00	1	320.00
110	36.00	300	66.00	70	62.00	32.00	65.00	17.00	1	278.00
111	12.00	300	49.00	50	40.00	387.00	54.00	19.00	1	561.00
112	12.00	300	41.00	40	34.00	518.00	133.00	15.00	1	753.00
113	73.00	300	47.00	50	112.00	84.00	42.00	19.00	1	377.00
114	12.00	300	60.00	50	112.00	361.00	48.00	17.00	1	610.00
115	13.00	300	65.00	50	75.00	38.00	46.00	28.00	3	265.00
116	97.00	300	68.00	70	108.00	371.00	55.00	22.00	3	721.00
117	14.00	300	63.00	20	103.00	21.00	44.00	34.00	3	279.00
118	13.00	300	49.00	20	107.00	10.00	66.00	20.00	1	265.00
119	7.00	300	63.00	40	53.00	31.00	51.00	15.00	1	220.00
120	164.00	300	76.00	40	19.00	31.00	44.00	17.00	1	351.00
121	13.00	300	62.00	50	62.00	31.00	56.00	10.00	2	234.00
123	20.00	320	55.00	30	10.00	46.00	113.00	19.00	1	263.00
124	15.00	350	49.00	50	54.00	25.00	35.00	22.00	1	200.00
125	15.00	350	68.00	50	19.00	31.00	51.00	25.00	1	209.00
126	14.00	350	88.00	50	10.00	25.00	42.00	20.00	1	199.00
127	15.00	350	59.00	40	31.00	40.00	37.00	28.00	1	210.00
128	16.00	350	59.00	40	37.00	38.00	46.00	35.00	2	231.00
129	15.00	350	86.00	65	39.00	26.00	54.00	20.00	1	240.00
130	16.00	350	66.00	50	35.00	129.00	62.00	16.00	1	324.00
131	17.00	350	56.00	60	31.00	16.00	78.00	18.00	1	216.00
132	13.00	75	17.00	10	27.00	5.00	37.00	25.00	1	124.00
133	13.00	75	36.00	50	17.00	33.00	42.00	43.00	1	184.00
134	10.00	160	23.00	20	48.00	10.00	33.00	38.00	1	162.00
135	15.00	160	19.00	10	20.00	15.00	43.00	17.00	1	129.00
136	13.00	160	18.00	20	20.00	184.00	91.00	19.00	1	345.00
137	47.00	160	80.00	30	22.00	23.00	43.00	19.00	1	234.00
138	16.00	160	36.00	40	32.00	45.00	28.00	24.00	1	181.00
139	16.00	160	23.00	50	25.00	53.00	68.00	11.00	1	196.00
140	39.00	160	33.00	20	39.00	30.00	58.00	60.00	2	259.00
141	11.00	210	87.00	20	52.00	86.00	191.00	21.00	1	448.00
142	20.00	210	36.00	10	24.00	18.00	36.00	18.00	1	152.00
143	21.00	210	69.00	40	21.00	25.00	162.00	89.00	2	387.00
144	20.00	210	67.00	40	31.00	33.00	107.00	38.00	1	296.00
145	19.00	210	28.00	30	17.00	25.00	87.00	61.00	1	237.00
146	59.00	210	43.00	20	16.00	29.00	83.00	33.00	2	263.00
147	22.00	210	38.00	20	30.00	39.00	65.00	43.00	1	237.00
148	20.00	210	25.00	30	61.00	12.00	66.00	26.00	1	210.00

149	25.00	210	58.00	30	32.00	34.00	59.00	34.00	2	242.00	
150	101.00	210	76.00	60	84.00	35.00	57.00	58.00	3	411.00	
151	16.00	210	50.00	50	31.00	81.00	62.00	21.00	1	261.00	
152	4.87	50	39.91	20	41.70	10.67	32.47	13.13	1	142.75	
153	2.72	50	30.70	60	33.56	27.96	32.10	15.63	1	142.67	
154	6.09	50	29.66	30	22.74	16.64	24.19	27.89	1	127.21	
155	5.76	50	14.73	5	11.96	8.38	34.11	76.98	1	151.92	6
156	7.53	50	25.64	20	31.29	18.32	17.53	20.48	1	120.79	
157	5.61	50	34.09	25	45.87	9.16	23.69	16.25	1	134.67	
158	6.66	50	8.29	2	13.17	6.73	25.64	18.60	1	79.09	
159	6.29	50	20.86	20	12.46	17.62	24.41	14.07	1	95.71	
160	5.82	50	22.85	45	16.54	161.00	18.43	18.52	1	243.16	
161	5.58	50	45.94	50	36.65	23.27	21.65	16.46	1	149.55	
162	5.38	50	61.60	70	33.67	24.17	16.82	13.51	1	155.15	
163	4.82	50	47.61	30	55.60	160.00	23.33	13.15	2	304.51	
164	6.49	50	55.00	45	56.30	8.00	25.03	18.88	2	169.70	
165	5.66	50	52.75	60	27.26	22.82	25.42	106.86	1	240.77	6
166	5.40	50	48.31	60	82.23	21.76	18.89	14.44	1	191.03	
167	5.88	50	67.00	65	102.02	16.60	18.68	33.68	2	243.86	
168	4.93	50	58.40	35	25.94	11.64	22.33	15.32	1	138.56	
169	4.31	50	56.06	75	35.06	14.83	20.35	15.58	1	146.19	
171	5.93	50	31.28	40	44.80	136.00	24.64	66.44	1	309.09	4
173	5.51	50	57.66	85	69.82	504.70	16.91	178.25	1	832.85	46
174	10.48	125	53.10	10	79.46	12.35	38.62	14.34	1	208.35	
175	11.54	125	40.39	20	80.06	8.60	35.84	20.89	1	197.32	
176	6.88	125	42.60	30	71.61	8.14	58.48	17.99	1	205.70	
177	12.07	125	38.66	25	44.76	7.80	33.86	75.85	1	213.00	6
178	11.79	125	50.66	40	38.12	13.96	40.44	13.72	1	168.69	
179	11.92	125	65.84	35	55.50	13.65	37.85	92.93	2	277.69	6
180	10.81	125	46.14	45	73.41	14.52	36.09	20.57	1	201.54	
181	11.40	125	44.08	50	61.42	15.04	32.85	18.33	1	183.12	
182	11.93	125	74.00	50	139.24	17.50	31.32	160.21	1	434.20	6
183	10.01	125	32.59	25	68.06	191.00	32.65	18.16	1	352.47	4
184	10.85	125	74.00	35	41.21	6.92	40.00	18.10	2	191.08	
185	11.20	125	58.50	85	54.12	118.00	37.54	20.86	1	300.22	

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Goldberg, Matthew S. *Logit Specification Tests Using Grouped Data*, 26 pp., Jan 1985

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[1] CNA Professional Papers with an AD number may be obtained from the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22151. Other papers are available from the Management Information Office, Center for Naval Analyses, 4401 Ford Avenue, Alexandria, Virginia 22302-0268. An index of selected publications is also available on request. The index includes a listing of professional papers, with abstracts, issued from 1969 to December 1983.

[2] Listings for Professional Papers issued prior to PP 407 can be found in *Index of Selected Publications through December 1983*, March 1984.

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