

A Simulation-based Approach for Evaluating Logging Residue Handling Systems

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Abstract

Describes a computer simulation model for evaluating logging residue handling systems. The flow of resources is traced through a prespecified combination of operations including: yarding, chipping, sorting, loading, transporting, and unloading. The model was used to evaluate the feasibility of converting logging residues to chips that could be used, for example, to generate electrical power. Empirical results obtained for two processing schemes are reported.

KEYWORDS: Computer programs, forest residues, logging operations **work** sequence.

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Contents

	Page
INTRODUCTION	1
GENERAL DESCRIPTION OF THE MODEL	2
OPERATIONAL CHARACTERISTICS OF REPO	10
PROGRAMING LANGUAGE	13
ILLUSTRATIVE CASE STUDY	13
Sample model configurations	15
Results of the simulation	18
Model I	21
Model II	23
SUMMARY	26
LITERATURE CITED	26
APPENDIX	29

Introduction

Many segments of society are concerned over the large quantities of wood residues generated by logging operations in the Pacific Coast States and across the Nation. Forest management and logging operations are conservatively estimated to produce 9.6 billion cubic feet of residues annually (USDA Forest Service 1972),^{1/} In Washington, Oregon, and California, logging residues over 4 inches in diameter and over 4 feet long resulting from timber harvesting are estimated to exceed 1.1 billion cubic feet annually (Howard 1973).

Forest residues encompass a wide range of materials remaining after logging operations or road construction. Tops, limbs, splintered and rotten logs, bark, and stump-root systems predominate. The quantity of residue in any one of these forms is changing rapidly and likely will continue to do so. Two major factors are responsible: (1) rapidly changing utilization standards and (2) harvesting of younger stands. Due to the size of capital investments, steps taken today to increase the level of residue utilization must be designed in such a way as to be compatible with the character of residues available in the future. Biomass information on forest stands, coupled with predictions of changing utilization standards, gives some indication of the quantities and types of residues that will be produced in the future.

Irrespective of the type of material marketed, the central problem is one of devising processing schemes which minimize production costs. The term "processing," as used herein, includes all steps that must be taken to convert residues to a basic forest product; i.e., all **forms** of manufacturing, handling, transporting, and storing. With few exceptions, the basic products which can be produced from residues have low market value. Consequently, a careful examination of all possible processing schemes for minimizing the cost of production must be undertaken. Minimization of production costs, in turn, depends on full use of labor and machines. Because of the critical nature of this aspect of the problem, the approach reported herein should have wide applicability **for** other wood conversion problems. It must be remembered, however, that production costs are only a portion of the total cost structure. Although not dealt with here, environmental costs should be considered.

The work reported in this paper was conducted in cooperation with the Forest Residues Program (FRP) of the Pacific Northwest Forest and Range Experiment Station. The research objective of the FRP is to develop, test, and evaluate ways to reduce accumulations of forest residues to maintain the productivity and quality of the forest environment. **Our** study relates to the FRP goal of promoting increased utilization of wood fiber and the energy contained in forest residues. The focus for the study was the Estacada and Clackamas Ranger Districts of the Mount Hood National Forest in Oregon. Many of the data used in the study were obtained from these two districts.

^{1/} **U.S.** units are used in this report; see appendix for conversion factors.

The study, designated "Residues for Power" (REPO), was initiated to obtain results which could be used as an aid in determining the feasibility of utilizing forest residues to generate electrical power (Grantham et al. 1974). Our primary objective was to develop a computer simulation model for describing the flow of residues from the forest to a hypothetical power generation facility. The model traces the flow of forest residues through a prespecified combination of operations including: yarding or skidding, loading, transporting, unloading, sorting, and chipping. All operations can be linked together in numerous combinations. Rate functions associated with each of the operations govern the flow of residues. The model terminates with the delivery of chips to the hypothetical power generation site.

Since the simulation model was designed for the overall function of materials handling, it can be used to analyze a wide variety of wood utilization problems. As an example, the model could be modified for use as a timber harvesting and transportation simulator. This particular application has been studied by the Canadian Department of the Environment using a similar but different materials handling system (Newnham 1972a, 1972b). Other publications on harvesting simulation models are noted in the Literature Cited section of this paper (Biller and Johnson 1973, Corcoran 1973, Johnson and Biller 1974, Johnson et al. 1972, Martin 1975, Sammis and Corcoran 1974, Sarna and Corcoran 1973, Schmidt 1970, Seppala 1971, Sinner 1973, Webster 1975).

To permit analysis of the many possible equipment configurations, maximum flexibility was an important design criterion. When one recognizes the many forms in which residues exist, the extensive area over which they are distributed, and the number of methods available for handling, converting, and transporting them, one sees that many configurations are possible. Only two materials handling configurations are illustrated in this paper. However, the potential for using the model for other applications should be readily apparent.

General Description of the Model

The model consists of three components: (1) operations, (2) stores, and (3) decisions, which are arranged serially to permit the processing of residues from a logging site to a point of utilization. Stores, which appear between operations, reflect the level of wood residues in inventory. The level of a store indicates the backlog of residues developing between two operations. Different equipment configurations directly influence the rate functions for an operation and, hence, the level of wood residue in a store at any time,

In contrast to stores, each operation is characterized by a rate function which determines the rate at which residues are moved from one store to another. In the models devised for residue processing, yarding, chipping, sorting, loading, transporting, and unloading are designated as operations. Each of these operations will frequently be made up of a set of characteristic activities. The activities, in turn, are modeled by a combination of several probability distribution functions. Consequently, the model can best be described as a compartment model made up of stochastic rate functions.

REPO is designed to simulate any of the sequences of operations depicted in figure 1. In this figure, the three components are represented symbolically as:

- (1) operations - 
- (2) stores or compartments - 
- (3) decisions - 

Closer inspection of figure 1 indicates that REPO encompasses six basic operations: yarding, chipping, sorting, loading, transporting, and unloading. Only one of these, chipping, involves the conversion of wood from one form to another.

Either of two types of yarding, cable **or** tractor skidding, can be included in the model. In our model, both cable and tractor logging are made up of the usual set of characteristic activities: outhaul, choking, inhaul, and unhooking. Consequently, several types of cable logging (*i.e.*, high-lead and skyline) and tractor logging with either crawler **or** four-wheel skidders can be represented.

Chipping converts raw residue to chipped form. Because of the rapidity and integrated character of this operation, designation of any of its component activities was considered unnecessary,

Sorting of residues can be accomplished at any one of several locations, including the landing, sorting yard, or the point of utilization. Sorting can be accomplished with several machines including the common log loader, as well **as** a vehicle equipped with a front-end lift. Depending on the number of sortings undertaken at a particular location, sorting can be made up of a few to many separate activities.

Sometimes the three remaining operations--loading, transporting, and unloading--are lumped together; because of real and anticipated equipment interactions in other operations, they are recognized separately in **REPO**.

Loading is normally accomplished with a hydraulic log loader equipped with a grapple **or** an older cable-operated loader equipped with tongs. Because the loading operation is cyclic and rapid, knowledge of its component activities is usually unnecessary.

In the transporting operation, the model will accommodate the movement of residue in raw material form as well as in chipped **form**. Transporting is accomplished with any one of three types of trucks: (1) log trucks, (2) open gondola trucks, and (3) chip vans. Normally, transporting requires the introduction of several component activities. At a minimum, the different rates of truck movement over the various types of roads encountered in a given geographic area are needed.

Unloading is normally accomplished with a single item **of** equipment. Irrespective of the type of equipment, the total operation is usually of such a continuous nature that knowledge of component activities is unnecessary. Several types of unloading systems, each with its peculiar

Figure 1.--Flow **chart** of **REPO**, flow diagram branches **A**, **B**, and **C**.

○ - operations; □ - **stores or** compartments; △ - decisions.

Stations

- 0 = cutting unit
- 1 = landing
- 2 = residue processing site on forest
- 3 = power generation site on forest
- 4 = residue processing and power generation site off forest

Symbol definitions

R = residue	LCH = load chipper
SR = sorted residue	U... = unload... (where... is some product)
CH = chip	RTS = yard with rubber-tired skidder
S = sort	CT = yard with crawler tractor
T = transport	HL = yard with high-lead
LT = load for transport	Y = yard

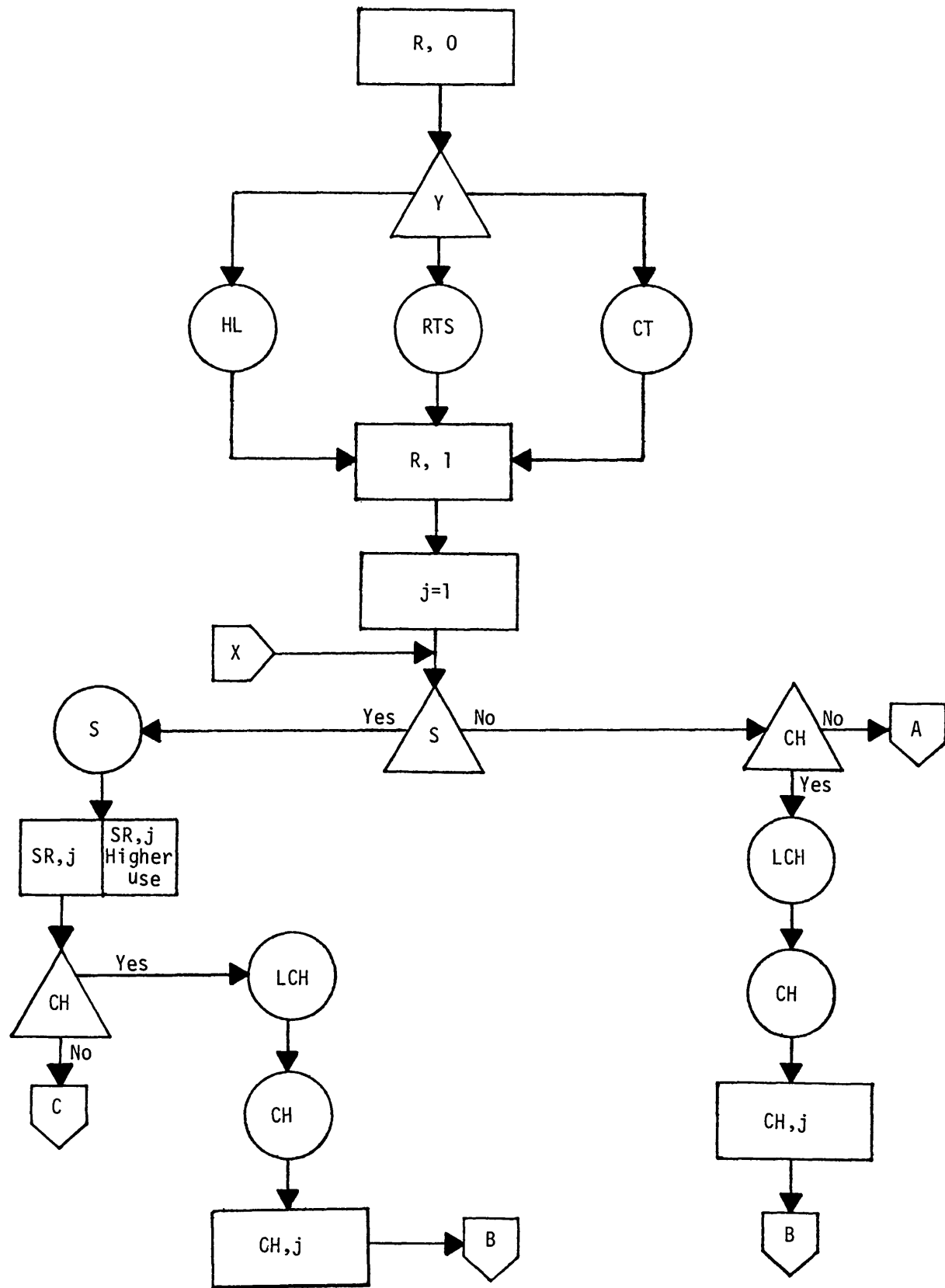


Figure 1. --Continued.

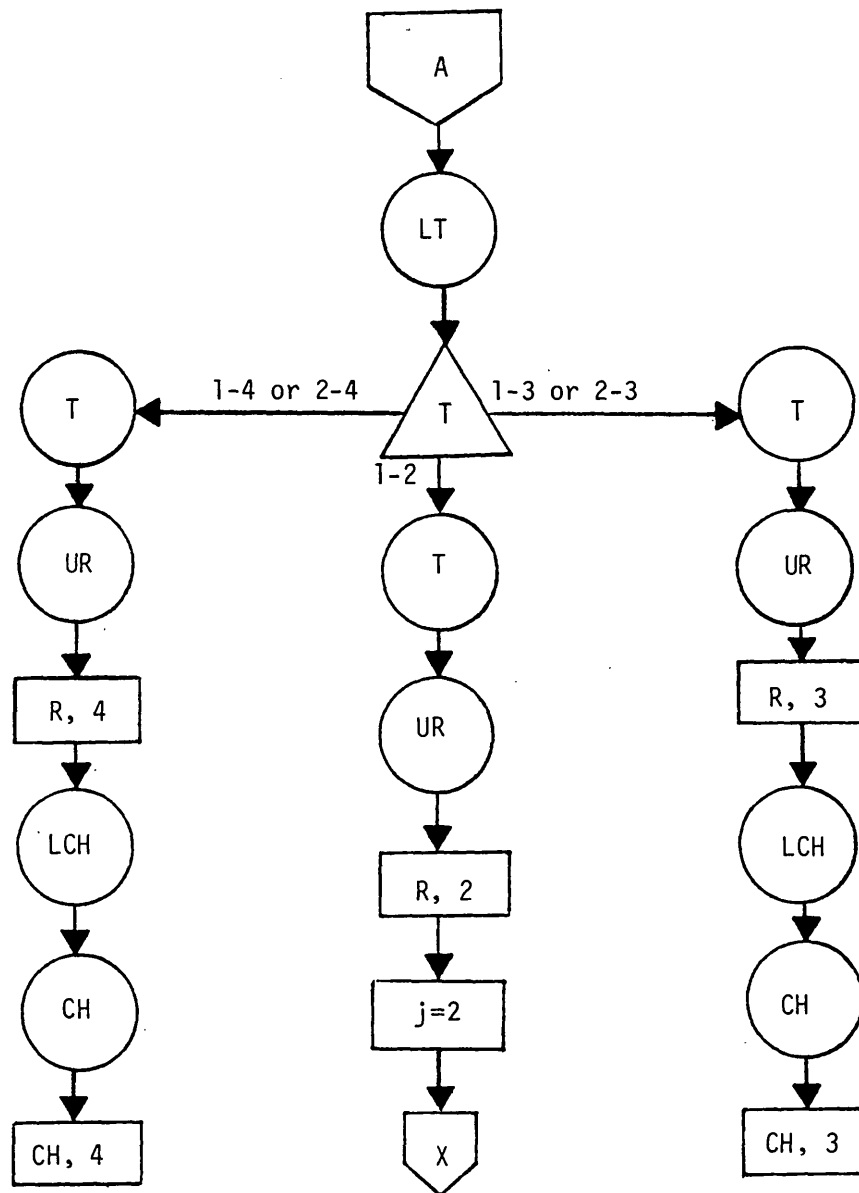


Figure 1.-- Continued.

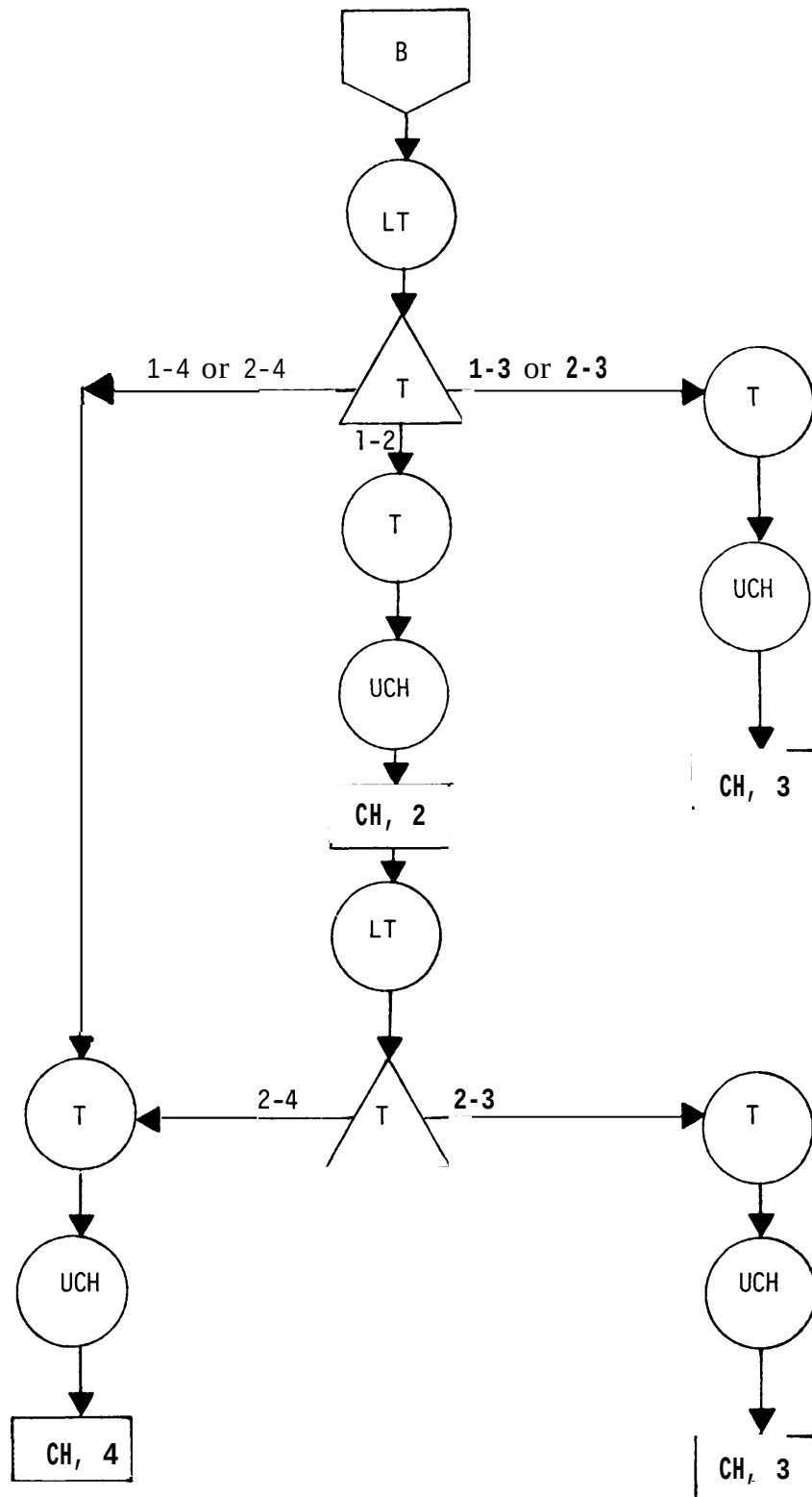
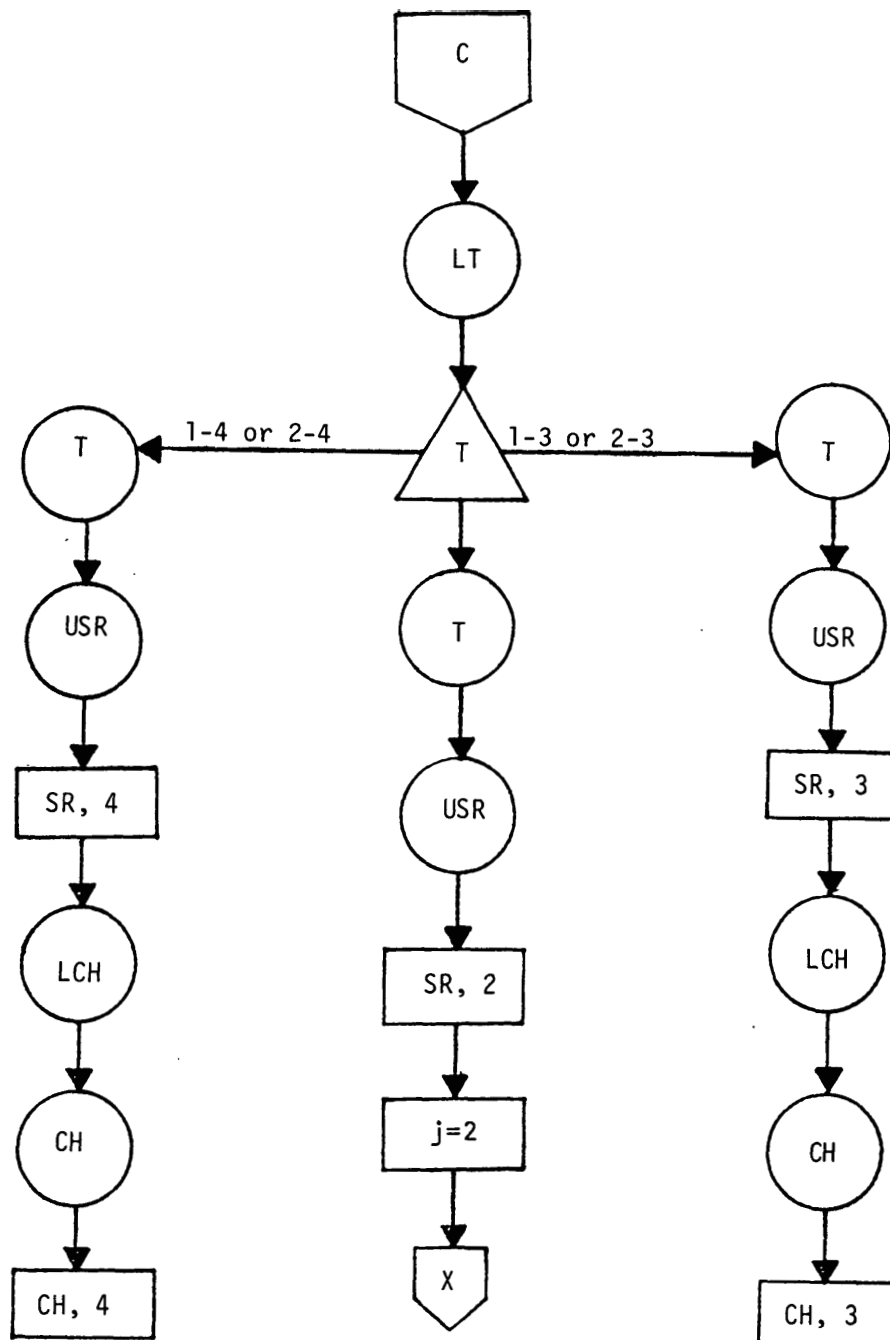


Figure 1.--Continued.



characteristics, may be required to accommodate the various types of trucks incorporated in a complex model.

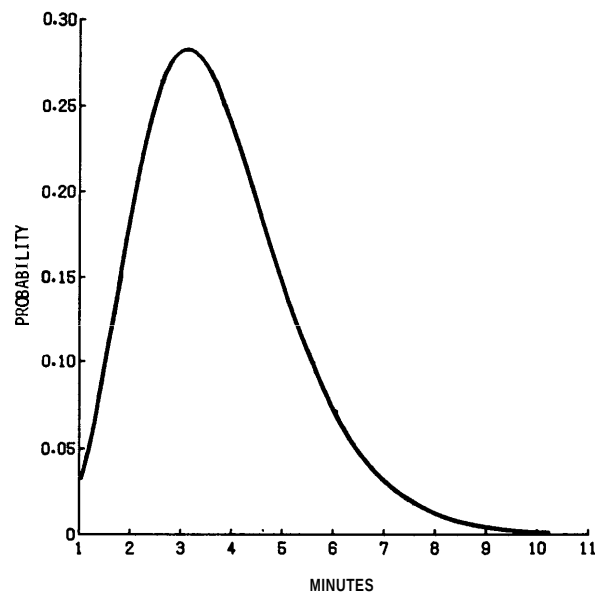
Simulation models, such as REPO, which consist of a series of operations through which material is processed, require two basic types of accounting for their operation. One accounting system encompasses the total elapsed time of a normal workday--say 8 or 9 hours. A second accounting system is required to monitor the quantity of material processed through each operation. Combination of the two establishes the rate of production of each operation. Both accounting systems are fundamental to the functioning of **such** simulation models.

Many subdivisions of a workday are normally required to account for elapsed time. ~~We~~ prefer to adopt two all-inclusive categories: (1) productive and (2) unproductive **or** lost time. Productive time is time during which material is actively processed. It is made up entirely of the cycle times of the operations included in the model. Unproductive **or** lost time is time during which material is not actively being processed. Subdivisions of unproductive time, outlined below, are highly desirable in most simulation models.

Each operation is characterized by a basic cycle time required **for** its completion. The cycle is repeated many times during a normal workday and is interrupted only by actions resulting in lost time. **As** indicated earlier, subdividing the cycle time into two **or** more parts which we have defined as activities is sometimes advantageous. This type of subdivision is particularly appropriate if the activity can be clearly identified and is of sufficient duration to justify a separate designation. Subdivision of the yarding cycle into outhaul, choking, inhaul, and unhooking is commonly used and can be highly desirable in some models. However, a breakdown of some operations into component activities may introduce additional and unneeded complexity.

Irrespective of the particular operation, repeated measurements of a basic cycle are necessary to obtain a measure of its mean value and of the dispersion about the mean value. A theoretical distribution for the cycle time of a high-lead yarder is shown in figure 2. Note that, in

Figure 2.--Theoretical probability distribution of cycle time for a typical high-lead relogging operation for distances ranging from 101 to 200 feet.



this particular example, the yarding cycle time is described by a gamma probability distribution. The mean yarding cycle time is 3.73 minutes, and the standard deviation is 1.52 minutes. This particular type of distribution, typical of many high-lead operations, encompasses yarding distances ranging from 101 to 200 feet.

The productive cycles of each operation are interrupted by unproductive or lost time; and our experience suggests five broad categories: (1) machine warmup time, (2) crew rest time, (3) operational delays, (4) equipment relocation, and (5) lost time due to equipment breakdown (downtime). Our grouping of unproductive time is reasonably consistent with that of others reported in the literature. Clearly, each category can be further divided just as cycle time can be subdivided into various activities.

Operational delays are particularly important examples of unproductive time for which subdivisions may be important. For example, several kinds of delays occur during yarding; certain ones may be associated with outhaul, choking, inhaul, or unhooking activities. Finally, just as cycle time is represented by a distribution of times, any one of the categories and subcategories of unproductive time is also characterized by a mean value and a distribution. The shapes of these distributions are strongly influenced by the frequency with which a particular category of unproductive time occurs in a given operation.

In addition to an accounting system for the elapsed time of a workday, an accounting must be kept of the quantity of material processed. For most operations, a quantity will be associated with each of the repeated basic operating cycles. For example, during yarding, a certain number of logs of a range of sizes is transferred to the landing on completion of the cycle. Because both size and number of logs to be choked vary from cycle to cycle, the quantity of material processed during a cycle is variable and is represented by a distribution.

In summary, simulations of the type represented by REPO require an accounting of both productive (cycle) and unproductive (lost) time and the quantity of material processed during the productive time. Both accounting systems require the use of a number of distribution functions to realistically account for inherent variability. Precision is incorporated into models of this type by allowance for as many sources of variation as possible

Operational Characteristics of REPO

REPO was designed to permit an analyst to alter the sequence, type, and number of operations to be evaluated in any one simulation run. In its present form, REPO permits the evaluation of any combination of operations displayed in figure 1. The sequence and type of operations to be evaluated must be specified as well as the relationships between operations. Lastly, the activities into which each operation is to be divided must be identified. Obviously, the exact number of activities identified for a particular operation will vary greatly between users. This flexible model structure was implemented on the computer with the SIMCOMP preprocessor, a brief discussion of which follows this section.

REPO operates as a fixed time increment simulator, with each 9-hour workday corresponding to one time increment. During each day of simulated activity, **REPO** serially calculates the rate at which residues will be processed from one compartment (store) to another. Both the fixed time increment and serial character of **REPO** have important ramifications. For example, the fixed time character does not permit **REPO** to track the occurrence of a machine breakdown within a given time period. Because of this characteristic, **REPO** does not account for interactions between dependent operations within a time period. However, the model does account for interactions between time periods. Further, because of the serial character of **REPO**, during any time period, the last operation in a given processing sequence is not simulated until all preceding operations have been simulated. Thus, if the last operation in a processing sequence suffers a machine breakdown, it will have no effect on previous operations during the same time increment. Maximum limits can be set for each store to partially circumvent the impact of this characteristic. These limits would have to be carefully determined so as not to overconstrain any operation.

A snapshot of the system at any time reveals the amount of residue in various stores in the system. At the conclusion of a computer run of 130 simulated workdays (i.e., 6 months), tabular and graphical output reveals the total amount of residue processed, the amount of residue remaining in the system in various stores, and an evaluation of equipment efficiency.

To understand how **REPO** determines the amount of forest residue to be processed during each simulated day, consider this example involving the loading operation: First, each workday (one time unit) of 540 minutes is reduced by subtracting the unproductive time expected that day. In general, this is accomplished by sampling from distributions representing the various categories of unproductive time such as machine warmup, crew rest, operational delays, and equipment breakdowns. In the current version of **REPO**, construction of separate distributions for each of the above categories is not possible because of a lack of data. Instead, each workday is reduced by a constant 15 percent to account for machine warmup, crew rest, and operational delays. The amount of unproductive time due to equipment downtime is then subtracted; this unproductive time is estimated from a distribution representing the number of machine breakdowns expected that day. If none are expected, the machine begins to load residue. If, however, a breakdown is indicated, a sample is drawn from the distribution function representing the length of downtime for loaders. This downtime further reduces the productivity of the loader on that day.

After unproductive time is determined, the simulator samples from the distribution function representing the cycle time for loaders. Next, another distribution function is sampled to determine the number of pieces to be loaded during the cycle. A check is made during each cycle to determine if the productive time available for loading has elapsed or if another cycle can be completed. Similarly, a check is made during each cycle to determine if any residue is available for loading or if the loader should be moved to the next landing. If no residue exists, the machine either is idle or is moved to another landing. In the latter case, additional unproductive time occurs during the machine relocation process.

REPO simulates the relogging of forest residues in a given region by sequencing through a list of available cutting units. Each cutting unit is further divided into a number of settings. An assumed road network consisting of spur, main line, and State highways interconnects the various cutting units.

A series of attributes describing each cutting unit is generated from distribution functions empirically constructed to represent data from a particular area or region. These attributes are:

1. Average slope yarding or skidding distance per setting
2. Area of a setting
3. Number of settings per cutting unit
4. Average slope per setting
5. Area of a cutting unit.

Three additional distribution functions are used to assign road characteristics for each cutting unit. Distribution functions are used to generate the mileage for:

1. Spur roads
2. Main line haul roads
3. State highways.

These mileages permit the model to account for travel time to and from each cutting unit at varying rates of speed. However, they do not permit the spatial location of cutting units on a Cartesian coordinate system.

The residue on each cutting unit is characterized by the gross and net cubic-foot volumes and the number of pieces of residue per acre by diameter and length classes. The total volume to be relogged is determined from the minimum and maximum diameter and length classes of pieces to be relogged, the average volume per piece, and the total number of pieces per acre.

All volume production figures in REPO are given in cubic feet of solid wood. These relationships can be used for other units of measure: 1 unit of chips $\approx$ 200 cubic feet of wood chips $\approx$ 80 cubic feet of solid wood $\approx$ 1 cord $\approx$ 2 green tons or 1 air-dry ton,

Although REPO was designed to be as flexible as possible, certain limiting assumptions were necessary. For example, REPO permits, at most, two transport operations between the logging site and the point of final utilization. Second, only one yarder is permitted per setting and only one setting can be actively relogged at a time. Third, except for the first day of simulated activity, all trucks are assumed to originate and terminate their daily activities at a source of residue awaiting transport. Essentially, this implies that trucks are not dispatched unless a round trip can be completed between the origin and the destination before the end of a workday. Fourth, cutting units are assumed to be clustered in groups of six so that the movement of equipment over State highways is only required every sixth unit. Lastly, REPO was designed to permit the evaluation of on-forest as well as off-forest locations of residue processing and power generation sites. As shown in figure 1, two on-forest

sites (stations 2 and 3) or one off-forest location (station 4) is permitted. Further, any one of six possible locations is allowed for stations 2 or 3, but only one location for the off-forest site is permitted.

Programing Language

The SIMCOMP programing language was used to translate the symbolic representation of REPO into the computerized version. SIMCOMP is a machine-dependent simulation language written at Colorado State University for the CDC 6400 computer (Gustafson and Innis 1972). The language is designed for compartment-oriented simulation models. Programing in SIMCOMP requires an understanding of the FORTRAN IV language, since the SIMCOMP compiler creates a FORTRAN program which is compiled by the CDC Extended FORTRAN compiler.

SIMCOMP programs are divided into two sections--source program and data. The source program contains SIMCOMP directives and FORTRAN statements and subprograms. The data section contains initial values for all parameters and compartments. Varying the sequence of the various subprograms, each representing an operation, makes possible design of unique residue handling systems. The subprograms are invariant with respect to these different configurations.

SIMCOMP was selected as the programing language because of the automatic and flexible handling of the timing mechanism, the ease of obtaining graphical and tabular output, and the capability of examining other materials handling systems. However, computing costs with SIMCOMP are quite high. Furthermore, the language is machine dependent and has received limited distribution to date.

Illustrative Case Study

The following example illustrates the potential utility of REPO for evaluating two sequences of operations for disposing of forest residues. The physical setting for this problem is the Estacada and Clackamas Ranger Districts of the Mount Hood National Forest. These two Districts, located southeast of the city of Portland, have a common boundary--the Clackamas River. The various operations included in the alternatives presented below are designed to occur on either of the Districts or at some point along the State highway which roughly parallels the Clackamas River. Further, all residue is assumed to be transported over this State highway to the town of Estacada. From there, it is transported to Portland--a distance of 30 miles.

REPO does not spatially locate cutting units on a Cartesian coordinate system. Instead, probability distributions characterizing the mileages over which residue is transported from each cutting unit to Portland are utilized. These distributions, indicated in table 1, were derived from data provided by Ranger District personnel. Mileage was obtained from these distributions which, when multiplied by the appropriate travel rates, provided the total round trip travel time from each cutting unit to Portland.

With data supplied by Ranger District personnel, distributions were

Table 1--Probability distributions in *residues* for *power (REPO)*

Item	Equipment	Type distribution	Parameters ^{1/}		Mean
Average slope yarding distance (ft)	Cable	Gama	K=10	A=0.02	500.00
Average slope yarding distance (ft)	Tractor	Gama	K=13	A=0.04	325.00
Number of settings per cutting unit	Cable	Gama	K=6	A=2.5	2.40
	Tractor	Uniform	a=0	b=5	2.50
Area of settings (acres)	Cable	Gama	K=4	A=0.29	13.79
	Tractor	Gama	K=2	A=0.29	6.90
Average slope per setting (percent)	--	Gama	K=3	A=0.11	27.27
Spur road distance (mi)	--	Exponential	--	$\lambda=6.67$	.15
Main line haul road distance (mi)	--	Normal	$\bar{X}=12.54$	$s=4.137$	12.54
State highway distance (mi)	--	Normal	$\bar{X}=29.9$	$s=10.1$	29.90
Cable yarding, time per turn (min):					
0-100 feet	Cable	Gama	K=4	A=1.46	2.74
101-200 "		Gama	K=6	A=1.61	3.73
201-300 "		Gama	K=8	A=2.10	3.81
301-400 "		Gama	K=6	A=1.53	3.92
401-500 "		Gama	K=13	A=2.11	6.16
501-600 "		Gama	K=5	A=0.78	6.41
601-700 "		Gama	K=4	A=0.59	6.78
Number of logs per turn	Cable	Normal	$\bar{X}=3$	$s=0.67$	3.00
Number of breakdowns per day	Cable	Gama	K=4	A=1.75	2.29
Length of each breakdown (min)	Cable	Exponential	--	$\lambda=0.03333$	30.00
Tractor yarding:					
Number of breakdowns per day	Tractor	Gama	K=1	A=1	1.0
Length of each breakdown (min)	Tractor	Exponential	--	$\lambda=0.01818$	55.00
Number of logs per turn	Tractor	Gama	K=5	A=1.16	4.31
Loading:					
Cycle time (min)	Grapple loader	Gama	K=3	A=0.05	60.00
Number of logs loaded per cycle	Grapple loader	Gama	K=7	A=5.93	1.18
Number of breakdowns per day	Grapple loader	Gama	K=4	A=3.74	1.07
Length of each breakdown (min)	Grapple loader	Exponential	--	$\lambda=0.01538$	65.00
Transport:					
Number of breakdowns per day	Log truck or chip 'van	Exponential	--	$\lambda=2.0$	.50
Length of each breakdown (min)	Log truck or chip van	Exponential	--	$\lambda=0.02222$	45.00
Unloading and sorting:					
Unloading cycle time (min)	Front-end loader	Normal	$\bar{X}=120$	$s=30$	120.00
Sorting cycle time (min)	Front-end loader	Gama	K=19	A=3.65	5.21
Number of logs per cycle	Front-end loader	Normal	$\bar{X}=7$	$s=2.5$	7.00
Number of breakdowns per day	Front-end loader	Gama	K=1	A=1.0	1.00
Length of each breakdown (min)	Front-end loader	Exponential	--	$\lambda=0.01818$	55.00
Chipping:					
Number of breakdowns per day	Chipper	Gama	K=3	A=0.05	60.00
Length of each breakdown (min)	Chipper	Exponential	--	$\lambda=0.50$	2.00

^{1/} See appendix for a description of these parameters.

generated for average slope yarding (skidding) distance per setting, number of settings per cutting unit, acreage of each setting, and average slope of the cutting unit (table 1).

The per-acre volume of residues on each cutting unit was generated from data supplied by Ranger District personnel. These data were estimated by the line intersect method of measuring forest residues on 12 cutting units of the Clackamas and Estacada Ranger Districts. The units were measured during the summer of 1972. Gross and net volumes by diameter and length classes, gross and net volumes by species composition, and number of pieces per acre by diameter and length classes were determined from the line intersect measurement data.

Distribution functions for each operation incorporated in the two processing schemes had to be developed in addition to distribution functions characterizing the cutting units and the road network. As discussed earlier, distributions were used to represent machine cycle times and rates of productivity as well as the unproductive time due to machine breakdowns. The following discussion reviews the development of all distributions in both models.

SAMPLE MODEL CONFIGURATIONS

Two versions of REPO, Models I and II, were designed to evaluate the two processing schemes. Model I consists of the following operations:

1. Yarding or skidding
2. Loading (chipper)
3. Chipping (at landing)
4. Transporting chips from the landing to Portland
5. Unloading.

The more complex Model II consists of these operations:

1. Yarding or skidding
2. Loading (raw residue)
3. Transporting **raw** residue from the landing to an on-forest residue processing facility
4. Unloading
5. Sorting
6. Transporting (within sorting yard)
7. Loading (chipper)
8. Chipping (at residue processing facility)
9. Transporting chips from the residue processing facility to Portland
10. Unloading.

Figure 1 indicates that these models are just two of many that can be developed within the framework of REPO. There is no assurance that either of these models will lead to the least-cost production of chips. To date, no attempt has been made to use REPO to identify the least-cost processing scheme.

Six locations for the on-forest residue processing and power generation sites were permitted in the general formulation. In the empirical

results reported later for Model II, the on-forest residue processing facility was assumed to be located at Three Lynx, Oregon, one of the six possible locations. The permanent off-forest residue processing and power generation facility was assumed to be in Portland.

Yarding.--The cable yarding operation, relogging with a high-lead, consisted of four activities--outhaul, choking, inhaul, and unhooking. Cycle times for each activity were treated solely as a function of average slope yarding distance. From Adams' (1965) data, seven distributions of yarding time were derived by 100-foot increments of average slope yarding distance. These distributions were characterized by gamma functions, the constants for which are listed in table 1. Mean yarding times of the seven distributions ranged from 2.74 to 6.78 minutes. The distribution function used to represent the number of logs yarded per cycle is also listed in table 1.

Lost time due to equipment breakdown was represented by a combination of a gamma function for the number of breakdowns per day and an exponential function for the length of each breakdown (table 1). Unproductive time due to crew rest, machine warmup, and operational delays was incorporated by reducing each workday of 540 minutes by 10 percent. Only one cable yarding system was allowed per setting.

A fixed time of 17 minutes was allowed for changing cable roads on a setting, and 72 minutes was allowed for changing the setting on a given cutting unit. In general, cutting units on the two Ranger Districts were clustered in groups of six. Consequently, after six cutting units were yarded, the model required moving of the yarder. To simulate typical relocation of equipment, a moving distance equal to twice the length of the main line haul road plus 15 miles of State highway was used in the model. The rate of travel was set at 6 minutes per mile.

The tractor yarding operation also was composed of four activities--outrun, choker setting, skidding, and unhooking. However, because of the characteristics of the available raw data, a distribution of cycle times for tractor yarding could not be constructed. Rather, for tractor logging, the regression equations reported by Adams (1967) had to be adjusted. The equations summarized the best available data at the time the study was undertaken. These equations and the standard errors of estimate incorporated into REPO are listed in the tabulation below. Any number of tractors of either the crawler or four-wheel skidder variety was permitted on a setting.

Unproductive time due to crew rest, operational delays, and warmup for tractors was assumed to be 10 percent of the workday. Downtime characteristics for the tractor were represented by two distribution functions--one for the number of breakdowns per day and a second for length of downtime. The characteristic parameters of these distributions are listed in table 1. The distribution function representing the number of logs per turn also is contained in table 1. The time to move equipment from one setting to another was fixed at 30 minutes. All equipment was moved to a new cutting unit upon completion of yarding of six cutting units. The distance of move was computed with the same assumptions as for the cable yarding system. Travel time was set at 4 minutes per mile.

The regression equations used for simulation of tractor yarding are:

<u>Activity</u>	<u>Regression equation</u>
1. Outrun time (min)	
a. Crawler	$1.341+0.004136 (AVYD)$
b. Four-wheel skidder	$0.8534+0.002951 (AVYD)$
2. Choker-set time (min)	
a. Crawler	$-1.084+2.65 (NOLOGS)-0.004776 (NOLOGS) (NOPS/AC)+0.00004951 (NOPS/AC)^2$
b. Four-wheel skidder	$1.23+0.6952 (NOLOGS)+0.002431 (NOLOGS) (NOPS/AC)$
3. Skid time (min)	
a. Crawler	$1.22+0.005771 (AVYD)$
b. Four-wheel skidder	$-0.08486+0.003425 (AVYD)-0.000001057 (AVYD)^2+0.009834 (AVOL/LOG) (NOLOGS)$
4. Unhooking (min)	
a. Crawler	$0.5228+0.009761 (NOLOGS) (AVOL/LOG)$
b. Four-wheel skidder	$1.054+0.2627 (NOLOGS)$

where :

AVYD = Average slope yarding distance in feet

NOLOGS = Number of logs per cycle

NOPS/AC = Number of pieces of residue per acre to be skidded

AVOL/LOG = Average cubic-foot volume per piece

<u>Activity</u>	<u>Standard error of estimate (min)</u>	
	<u>Crawler</u>	<u>Four-wheel skidder</u>
Outrun time	1.39203	1.2863
Choker-set time	4.1397	2.6771
Skid time	1.96476	1.1729
Unhook and deck time	1.6652	.8794

Log hauling.--Log hauling consists of three basic operations--loading, transport, and unloading. Loading in the model is accomplished with a hydraulic grapple loader. Two distribution functions were required to characterize the rate of loading--one for cycle time and a second for the number of pieces loaded per cycle. As with the yarding operation, two distribution functions were required to represent equipment downtimes. Each workday was reduced by a constant 15 percent for equipment warmup, crew rest, and operational delays. All the distributions used for loading are listed in table 1. At least two grapple loaders are required at station 1, 2, or 3 if both sorting and chipping or sorting and loading for transport are performed.

A time of 30 minutes was allowed for moving the loader between landings. The distance between clusters of cutting units was computed in the same manner as for cable yarding equipment. Travel time was computed at 4 minutes per mile.

Unloading of log trucks was accomplished with a four-wheeled front-end loader having a capacity of about 50 tons. The characteristic constants of the distributions used to represent the cycle time, number of logs per cycle, and equipment breakdown are listed in table 1. Each workday was reduced 10 percent for machine warmup, crew rest, and operational delays. The time required to unload a chip van by hydraulic lift was assumed to be a constant 17 minutes. In Model 11, the front-end loader located at station 2 unloads trucks and transports residue in the sorting yard. First priority is given to the unloading operation.

Sorting.--In Model 11, sorting of the residues takes place at station 2. This operation, of course, requires a sorting yard large enough to handle the volume of material being processed. Sorting is accomplished with a hydraulic grapple loader for segregating the material into two or more grades and a front-end loader for transporting the material across the sorting yard. The characteristics of the grapple loader used for sorting are identical to those described earlier. The front-end loader used for transporting material across the yard is identical to that used for unloading logs. The distribution functions for sorting cycle time and the number of logs unloaded per cycle are shown in table 1.

Chipping.--A portable chipper with a nominal production rate of 1,200 cubic feet of solid wood per hour was used in both models. Downtime characteristics were represented by the two distribution functions listed in table 1. Each workday was reduced by 15 percent for equipment warmup, crew rest, and operational delays. If chipping was completed at the landing, 45 minutes were allowed for moving the chipper between settings. Distances were computed in the same manner as for cable yarding equipment. A rate of 6 minutes per mile was allowed for computing total travel time. No lost time for moving was recorded for a chipper stationed at a sorting station as in Model 11.

RESULTS OF THE SIMULATION

The distribution functions contained in table 1 were incorporated into the computer version of REPO where they were used to simulate 6 months of yarding and processing residues. In addition to the information presented above, it was also necessary to indicate:

1. Number of pieces of equipment to be evaluated on any given run of the simulator
2. Cost of operating equipment
3. Labor costs
4. Minimum and maximum diameter and length classes of pieces to be processed
5. Maximum allowable spur and main line haul road distances
6. Maximum slope on which tractors could safely operate
7. Type of skidders (i.e., four-wheel or crawler) and trucks (i.e., log or chip van) to be evaluated.

The equipment configurations evaluated in Models I and II are:

	<u>Model I</u>	<u>Model II</u>		<u>Model I</u>	<u>Model II</u>
Yarder	1	1	Chippers	1	1
Four-wheel skidder	2	2	Chip vans	2	2
Grapple loaders	1	4	Log trucks	0	2
Front-end loaders	0	2			

Table 2 indicates the machine and labor costs associated with each model. All costs were taken from BLM schedule 18 (Bureau of Land Management 1973) except those reported for log trucks, chip vans, and chippers. These latter costs were derived from personal communication with various logging superintendents.

Table 2--Equipment and labor costs in residues for *pmer* (REPO), Models I and II

Ooperation	Model Number	Per hour costs		
		Equipment	Labor	Total
- - - - Dollars - - - -				
Yarding ^{1/}	I and II	17.62	33.59	51.21
Skidding ^{2/}	I and II	11.46	22.62	34.08
Grapple loader	I	4.17	9.32	13.49
Grapple loader	II	16.68	37.28	53.96
Chipper ^{3/}	I and II	15.41	--	15.41
Front-end loader ^{4/}	II	11.46	15.80	27.26
Log truck ^{5/}	II	16.40	13.24	29.64
Chip van ^{5/}	I and II	16.40	13.24	29.64

^{1/} Yarding equipment consisted of a high-lead mobile yarder operated by a crew of 4.

^{2/} Skidding was performed by a 4-wheeled rubber-tired skidder (\$5.73/h) operated by a tractor operator (\$7.90/h) plus 1 laborer (\$6.82/h).

^{3/} Chipping equipment consisted of a portable chipper operated by loader operator.

^{4/} Front-end loader equipment rate was same as that for rubber-tired skidder (\$5.73/h). Operator rate was \$7.90/h.

^{5/} Equipment rates for both log trucks and chip vans were assumed equal (\$8.20/h) with labor rates of \$6.62/h.

In both Models I and II, cutting units with slopes of less than or equal to 15 percent were yarded by four-wheel skidder. Also, pieces with diameters of 0 to 36+ inches and lengths of 4 to 20+ feet were assumed to be yarded to the landing. Spur roads over one-half mile and main line haul roads over 20 miles long were not permitted in the model.

For an evaluation of the performance and sensitivity of REPO, both Models I and II were replicated five times. These replications were necessary because of the probabilistic nature of REPO and were performed by reinitializing the pseudorandom number generator before each simulation run. However, no attempt was made to determine whether five replications represented an adequate sample size. The results of one of these replications for Model I are illustrated in figure 3.

Figure 3A shows the level of residues remaining on each cutting unit as it is yarded. As illustrated in figure 3A, three cutting units were relogged over the 6-month period, with the third unit still being treated at the end of the 6th month of simulated time.

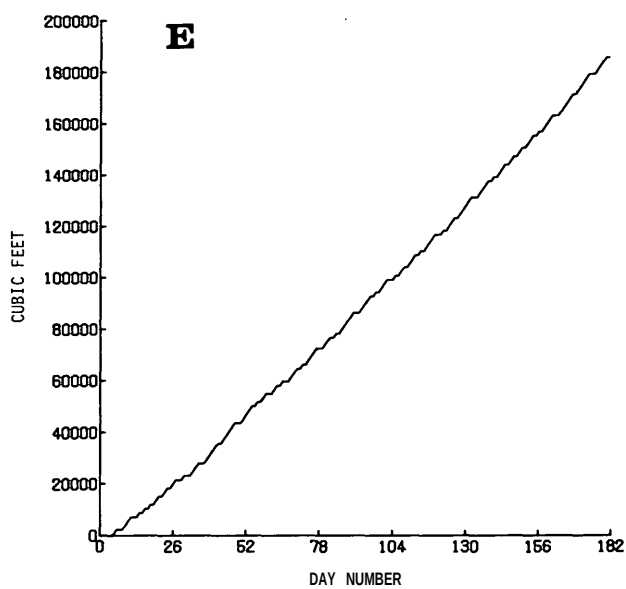
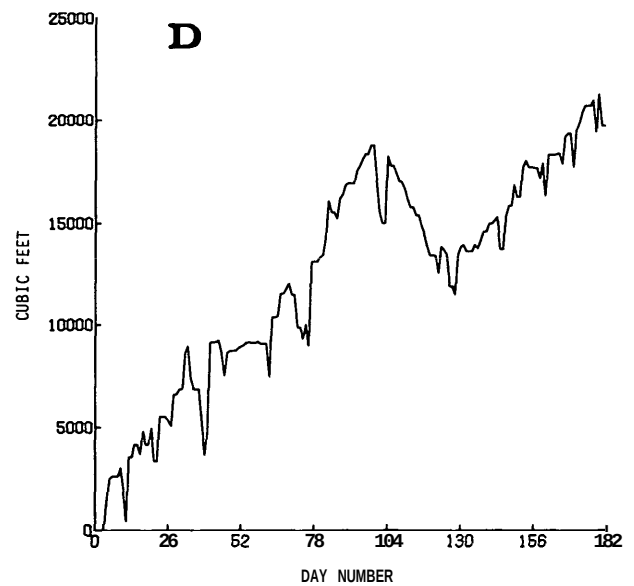
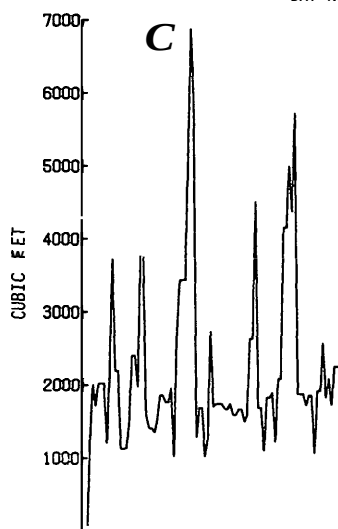
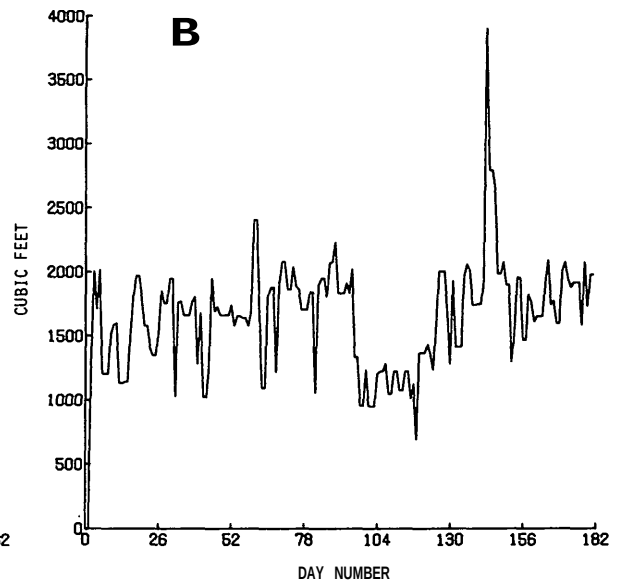
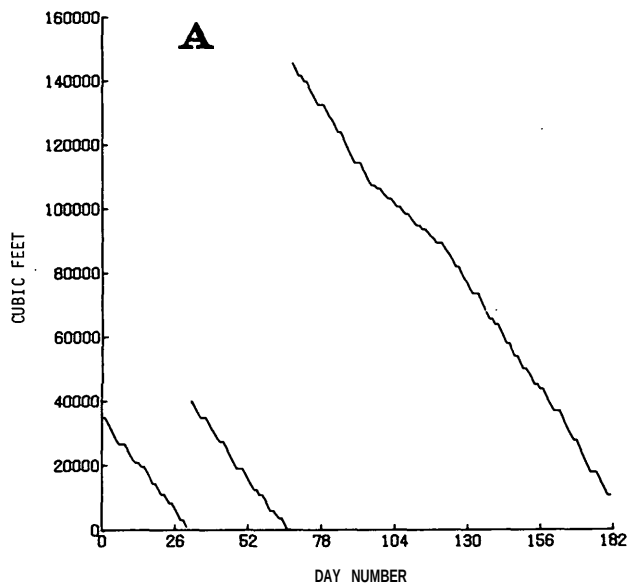


Figure 3.--Volume of residue: A, on three cutting units; B, yarded to landing awaiting loading; C, loaded and awaiting chipping; D, chipped and awaiting transport; E, chipped and delivered.

Figure 3B depicts the volume of logging residue yarded or skidded to the landing, that has not been loaded into the chipper. As an example, during the 145th day of simulated time, the level of residue in this compartment increased to a peak of almost 4,000 cubic feet of solid wood. This occurred because the loader had broken down that day, allowing the residue inventory to build up at that point in the processing sequence. If desired, peak volumes like this can be avoided if a maximum limit is set on store capacities. No limits were set on any of the compartments depicted in Model I or Model 11. Consequently, peak volumes shown in the graphs in figure 3 may be unrealistic. Low points in figure 3B correlate with either a machine breakdown or a reduction in rates of production due to some peculiar characteristic of the cutting unit being relogged. For example, the graph shows a substantial decrease in the volume of yarded residue between days 90 and 105. This was due to the large average slope yarding distance generated for the setting being relogged during this period. In fact, this setting had the largest average slope yarding distance of all settings relogged during the 6-month period.

Figure 3C shows the volume of residue processed by the loader but not chipped. As in figure 3B, there are large fluctuations in the level of residue at this particular point in the processing sequence which could be minimized if maximum limits were set on store capacities. High points correlate with breakdowns of the chipper and low points with breakdowns of the loader.

Figure 3D is a graph of the volume of chipped residue at the landing awaiting transport. This volume could be reduced if either a maximum limit were set on store capacity or additional chip vans were added to the system. Figure 3E depicts the amount of chipped residue delivered to the off-forest residue processing and power generation facility. Similar results were obtained on successive runs of the simulator. These results are discussed below.

Model I

Table 3 contains a summary of the simulation results for the five replications of Model I. Three of the compartments, or points of storage, are defined at the bottom of the table .

The cost of delivering chips to Portland is computed from the statistics summarized in table 4. On the average, 2,103 units of chips with a standard deviation of 336 units are delivered with a mean daily delivery rate of 16.2 units and a standard deviation of 2.6 units. Cost data from table 2 and the mean percent utilization rates for the cable yarder and the two four-wheel skidders as shown in table 5 were used to compute the cost of delivering a unit of chips to Portland. The final costs in table 6 reflect the percent of time the equipment was actually used to yard or skid forest residues. The costs do not

Table 3--*Summary of inventory in residues for pmer (REPO), Model I* (130 workdays)

Replication number						
	1		2		3	
	$\bar{x}^2/$	$s^3/$	$\bar{x}^2/$	$s^3/$	$\bar{x}^2/$	$s^3/$
	----- Cubic feet -----					
1	1,644	507	2,094	1,047	12,465	6,262
2	1,346	439	1,317	689	3,920	2,695
3	1,735	618	1,802	994	28,569	10,720
4	1,274	514	1,437	623	9,058	3,573
5	1,367	862	1,330	752	3,836	6,279

^{1/} Compartment numbers refer to points of storage within the sequence of operations being simulated. For Model I, the compartments contain: 1 = volume of residue yarded to landing waiting to be loaded, 2 = volume of residue loaded into chipper awaiting chipping, 3 = volume of chipped residue awaiting transport.

^{2/} Mean.

^{3/} Standard deviation.

Table 4--*Summary of production in residues for pmer (REPO), Model I*

Replication number	Total production (130 workdays)		Average daily production rates	
	Wood	Units of chips ^{1/}	Wood	Units of chips ^{1/}
	cubic feet		Cubic feet	
1	187,121	2,339	1,439	18.0
2	168,636	2,108	1,297	16.2
3	192,104	2,401	1,478	18.5
4	169,218	2,115	1,302	16.3
5	123,980	1,550	954	11.9
Mean	168,212	2,103	1,294	16.2
Standard deviation	26,861	336	206	2.6

^{1/} 1 unit of chips $\approx$ 80 ft³ of solid wood.

Table 5--*Utilization rates for two 4-wheel skidders and cable yarder in residues for pmer (REPO), Model I*

Replication number	Percent of time equipment utilized	
	4-wheel skidders	Cable yarder
1	17	83
2	28	72
3	4	96
4	34	66
5	19	81
Mean	20	80
Standard deviation	11	11

Table 6--Costs of production in residues for power (REPO), Model I

Equipment	Total hourly cost	Replication number				
		1	2	3	4	5
Total per hour	--	106.83	104.95	109.06	103.93	106.50
Total per day ^{1/}	--	961.47	944.55	981.54	935.37	958.50
Cost per unit of chips	--	53.42	58.31	53.06	57.38	80.55
Average unit cost	60.54					
Standard deviation	11.42					

^{1/} 9 hours.

reflect charges for tasks other than yarding or skidding. This assumption applies to both Models I and 11. As shown in table 6, the five replications of Model I produced an average cost of \$60.54 per unit of chips, with a standard deviation of \$11.42.

Using the empirical results obtained from the five replications, we can set confidence limits around the mean cost of delivering chips if the above sequence of operations is used. Because it was not possible to generate the entire cost distribution, it is impossible to estimate the probability function for the cost of chips delivered at Portland. However, using Chebyshev's inequality, a distribution-free method, we can determine with 75-percent confidence that the "true" unit cost for Model I will lie between $\$60.54 \pm \$22.84$. With approximately 89-percent confidence, we can say the "true" cost will lie between $\$60.54 \pm \$34.26$. Thus, we are able to provide an interval estimate for the forecasted cost of relogging selected cutting units using the materials-handling configuration represented in Model I.

Model II

The results of the five replications run for Model II are summarized in table 7.

A summary of total chip production, as delivered at Portland, is shown in table 8. On the average, 2,086 units of chips with a standard deviation of 83 units are delivered with a mean daily production of

Table 7--*Summary of inventory in residues for power (REPO), Mode2 II (130 workdays)*

(In cubic feet)

Replication number	Compartment number ^{1/}									
	1		2		3		4		5	
	$\bar{x}^{2/}$	$s^{3/}$	$\bar{x}^{2/}$	$s^{3/}$	$\bar{x}^{2/}$	$s^{3/}$	$\bar{x}^{2/}$	$s^{3/}$	$\bar{x}^{2/}$	$s^{3/}$
1	1,429	560	1,875	746	1,500	766	1,559	664	1,364	684
2	1,576	646	2,159	963	1,360	557	1,567	949	1,380	1,068
3	1,622	894	2,494	1,576	1,320	769	1,569	799	1,680	985
4	1,575	900	1,718	777	1,331	536	1,320	541	1,429	612
5	1,391	435	1,874	705	1,576	680	1,322	536	1,589	835

Replication number	Compartment number ^{1/}									
	6		7		8		9		10	
	$\bar{x}^{2/}$	$s^{3/}$	$\bar{x}^{2/}$	$s^{3/}$	$\bar{x}^{2/}$	$s^{3/}$	$\bar{x}^{2/}$	$s^{3/}$	$\bar{x}^{2/}$	$s^{3/}$
1	1,241	902	4,749	2,881	1,246	706	1,646	1,141	1,651	1,209
2	1,490	881	4,685	3,194	1,393	1,272	2,058	1,163	2,072	2,339
3	1,158	926	4,613	3,034	1,945	2,175	1,001	1,096	2,119	1,250
4	1,425	740	4,656	3,123	1,462	790	1,289	883	1,460	1,144
5	1,168	796	4,341	2,806	1,140	740	1,459	1,095	1,889	1,007

^{1/} 1, volume of residue yarded to landing waiting to be loaded; 2, volume of residue loaded onto trucks at landing and awaiting transport; 3, volume of residue delivered to on-forest residue processing station and awaiting unloading; 4, volume of unloaded residue at on-forest residue processing station; 5, volume of residue loaded and awaiting sorting at on-forest residue processing station; 6, volume of residue waiting to be chipped; 7, volume of unchipped residue at on-forest residue processing station; 8, volume of chippable residue transported across on-forest residue processing station sorting yard awaiting chipping; 9, volume of residue loaded into chipper awaiting chipping; 10, volume of chipped residue awaiting transport.

^{2/} Mean,

^{3/} Standard deviation.

Table 8--*Summary of production in residues for power (REPO), Model 11*

Replication number	Total production (130 workdays)		Average daily production rates	
	Wood	Units of chips ^{1/}	Wood	Units of chips ^{1/}
Mean	166,901	2,086	1,284	16.1
Standard deviation	6,616	83	51	0.6

^{1/} 1 unit of chips $\approx$ 80 ft³ of solid wood.

16.1 units and a standard deviation of 0.6 unit. The per-unit cost of delivering chips to Portland for Model II is shown in table 9. These unit costs are based on the cost data presented in table 2, and the mean percent utilization rates for the four-wheel skidder and cable yarder as shown in table 10. The mean per-unit cost of chips of \$114.09 is considerably greater than the \$60.54 per unit obtained for Model I.

This increased cost is due almost entirely to an increased hourly cost, because more men and equipment were used. One factor omitted from the above analysis is the value of the material sorted for higher use at the on-forest residue processing facility.

Again, using Chebyshev's inequality, we can determine with 75-percent confidence that the "true" unit cost for Model II will lie between

Table 9--Costs of production in residues for power (REPO), Model II

Equipment	Total hourly cost	Replication number				
		1	2	3	4	5
----- Dollars -----						
Cable yarder	51.21	17.41	51.21	40.46	43.53	51.21
Four-wheel skidders	34.08	22.49	0	7.16	5.11	0
Grapple loaders	53.96	53.96	53.96	53.96	53.96	53.96
Log trucks	29.64	29.64	29.64	29.64	29.64	29.64
Chip vans	29.64	29.64	29.64	29.64	29.64	29.64
Front-end loaders	27.26	27.26	27.26	27.26	27.26	27.26
Chipper	15.41	15.41	15.41	15.41	15.41	15.41
Total per hour	--	195.81	207.12	203.53	204.55	207.12
Total per day ^{1/}	--	1,762.29	1,864.08	1,831.77	1,840.95	1,864.08
Cost per unit of chips	--	112.25	109.65	112.38	114.34	121.84
Average unit cost	114.09					
Standard deviation	4.64					

^{1/} 9 hours.

Table 10--Utilisation rates for two 4-wheel skidders and cable yarder in residues for power (REPO), Model II

Replication number	Percent of time equipment utilized	
	4-wheel skidder	Cable yarder
1	66	34
2	0	100
3	21	79
4	15	85
5	0	100
Mean	20	80
Standard deviation	27	27

\$114.09 $\pm$ \$9.28. With approximately 89-percent confidence, we can say the "true" cost will lie between \$114.09 $\pm$ \$13.92.

The results of both Models I and II indicate that the processing of logging residues for the production of chips varies considerably, depending on the sequence of operations.

Summary

This paper has reported the development of a simulation model useful for evaluating a wide variety of raw materials handling systems encountered when timber is harvested or relogged in the Western United States. Model flexibility was demonstrated through two hypothetical configurations for relogging forest residues. Results obtained for five replications of each model also were reported.

We emphasize at this point that caution must be observed when the results reported herein are interpreted. First, the raw data used to construct the probability distributions incorporated in REPO were obtained from a variety of sources. Some data were taken from published and unpublished reports. Other data necessary to construct many of the distributions were not available. Therefore, these distributions were based on assumed values and relationships. Although we used the best data available, much additional information must be collected before REPO can be operationally useful.

Another reason for carefully interpreting these results is that they apply only to two particular combinations of processing operations. These sequences were selected solely to illustrate the structure and flexibility of the model and not because they lead to the least-cost production of chips. Other residue handling systems might produce equivalent volumes of chips at much lower cost. Thus, before a decisionmaker can reach a valid conclusion on a specific problem, he must extensively test each materials handling sequence. It must be remembered, however, that the usefulness of computer results as a decisionmaking aid is directly related to data reliability.

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Appendix

As discussed in the text of the paper, several probability density functions were incorporated into simulation model **REPO**. This appendix will interest those desiring additional information concerning these distributions.

<u>Distribution</u>	<u>Density function</u>	<u>Cumulative function</u>
Uniform	$f(x) = \begin{cases} \frac{1}{b-a} & a < x < b \\ 0 & \text{elsewhere} \end{cases}$	$F(x) = \frac{x-a}{b-a}$
Exponential	$f(x) = \lambda e^{-\lambda x}$ $\lambda > 0$ $x \geq 0$	$F(x) = 1 - e^{-\lambda x}$
Gamma (Erlang)	$f(x) = \frac{A^K x^{(K-1)} e^{-Ax}}{(K-1)!}$ $A > 0$ $K > 0 \text{ (integer)}$ $x \geq 0$	$F(x)$ does not exist in explicit form
Normal	$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$ $-\infty < x < \infty$	$F(x)$ does not exist in explicit form

Conversion Factors - U.S. to Metric

1 inch = 2.54 centimeters

1 foot = 0.3048 meter

1 mile = 1.609344 kilometers

1 ft³ = 0.0283168 m³

1 standard cord (4 by 4 by 8 feet) = 3.6245564 m³

1 short ton (2,000 lb) = 0.9072 metric ton

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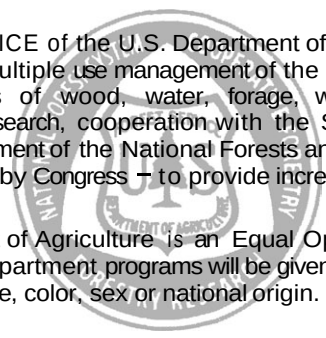
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The FOREST SERVICE of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

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