



Monte Carlo simulation of some logging operations
by Frank Joseph Cesario

A thesis Submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in Industrial Engineering
Montana State University
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Abstract:

The first subsystem of the logging system, logmaking, was simulated by Monte Carlo methods on an IBM 1620 computer. Data gathered from a multitude of sources were used to construct a preliminary computer simulation "model" of the subsystem, by means of which all of the operations usually performed in the field could be done within the comforts of the office. By the use of this approach, hundreds of acres of timber could be "harvested" in just a few hours. An important advantage of the simulation technique is that the logger can make optimum decisions before he begins logging, rather than making costly remedial ones in the field.

Although the model is by no means complete, the results obtained showed that this approach to logging analysis is very promising. A few of the many different alternatives were evaluated to give potential users an indication of how simulation can be used to advantage in logging analysis. The following is a list of the different simulation runs reported in this thesis: 1. Production rate was varied.

2. Different production policies were tested.
3. The amount of defective material was varied.
4. Various payment schemes were compared.

In these runs, cost, profit, and waste material were used as measures of effectiveness.

No statements were made concerning the reliability of either the model or the results, although some phases of the model did prove to be dependable. It was concluded that more data is needed if significant results are to be obtained. Also, the assumption of additivity of data would have to be investigated. The model given in this thesis can, at best, be used as a guide to the construction of a more elaborate model.

A section on logging processes and the production components of logmaking is given for readers unfamiliar with these operations.

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by

FRANK-JOSEPH-CESARIO, JR.

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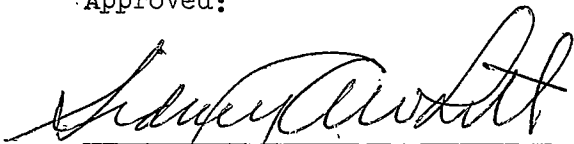
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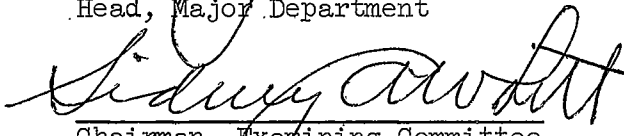
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If this thesis were to be dedicated, the honor would go to Mr. H. Minor Huckeby, (U.S. Forest Service Retired) who instituted the cooperative program and who did so much to guarantee its success. To him goes my deepest gratitude for all the guidance that he provided me, both directly and indirectly, and my sincerest best wishes for many adventure-filled, enjoyable retirement years.

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TABLE OF CONTENTS

1098P

INTRODUCTION

I.1	Historical Development of the Problem	1
I.2	Selection of a Problem Area	2
I.3	Method of Attack	2
I.4	Statement of the Objectives of the Thesis and Restatement of the Problem	5
I.5	Literature Review	5
I.6	Computing Facilities	6
I.7	Thesis Format	7

PART I

CHAPTER 1 THE LOGGING SYSTEM

1.1	Work Systems and Subsystems	9
1.2	The "Blackbox" Logging System	10
1.3	The Logging "Processes"	11
1.4	The "Blackbox" Logging Subsystems	14

CHAPTER 2 THE LOGMAKING SUBSYSTEM

2.1	Logmaking Flow Chart	17
2.2	Irregular Elements	26

CHAPTER 3 MAN, MACHINE, MATERIAL

THE MAN

3.1	One- vs. Two-Man Crews	27
3.2	Efficiency	29

THE MACHINE

3.3	The Chain Saw	36
3.4	Chain Saw Operation	37
3.5	Operator Preference	38
3.6	Future Developments	38

THE MATERIAL

3.7	Logging of Lodgepole Pine	39
3.8	Physical Characteristics	41
3.9	Growth Features	42
3.10	Cull	42
3.11	Rotation	44
3.12	Valuation	45

CHAPTER 4 . PRELIMINARY CONCEPTUAL SIMULATION MODEL .

4.1	Proposed Schema	48
-----	-----------------	----

BLOCK DIAGRAMS AND COMPONENT DESCRIPTIONS

Phase I - Setting up the Forest

4.2	Component Descriptions	51
4.2.1	Sample Data	51
4.2.2	Probability density for dbh	53
4.2.3	Distributions of total heights, crown length and crown/height ratios	55
4.2.4	Volume determinations	63
4.2.5	Cull	65
4.2.6	Merchantable heights	66
4.2.7	Free stem	66
4.2.8	Intermediate output	66

Phase II - Logging the Area in Question

4.3	Component Descriptions	69
4.3.1	Standard log lengths	69
4.3.2	Production rate	70
4.3.3	On-log travel time	71
4.3.4	Limbing time ratios	71
4.3.5	Output from Phase I	72
4.3.6	Distance between trees	72
4.3.7	Registers	73
4.3.8	Felling times	73
4.3.9	Treating cull	73
4.3.10	Optimizing log combinations	74
4.3.11	Limbing and bucking	75
4.3.12	Bucking times	76
4.3.13	Volume determination	76
4.3.14	Travel to the next tree	76
4.3.15	On-ground travel times	77
4.3.16	Revenue	78
4.3.17	Cost	78
4.3.18	Profit (Loss)	78
4.3.19	Output	79

CHAPTER 5 A CASE STUDY

5.1	Basic Assumptions	80
-----	-------------------	----

PHASE I

5.2	The Dbh Distribution	82
5.2.1	Measurements	82
5.2.2	Distribution	82
5.3	The Distribution of Total Heights	84
5.3.1	Measurements	84
5.3.2	Distribution	85
5.4	The Distribution of Crown Lengths	85
5.4.1	Measurements	85
5.4.2	Distribution	86
5.5	Results of Regression and Correlation Analysis on Sample Data	87
5.6	Determination of Sample Values of Dbh, Height, and Live Crown Length	89
5.6.1	Random number generation	90
5.6.2	Crown length	91
5.7	Computing Merchantable Height	91
5.7.1	Merchantable height	91
5.8	Cubic-Foot and Board-Foot Volume Determination	92
5.9	Cull Assignment	93
5.10	Output	95
5.11	Console Operation	96

PHASE II

5.12	Input	97
5.13	Felling	98
5.13.1	Felling times	98
5.13.2	Wait for tree to fall	106
5.14	Cull	106
5.15	Optimizing Number and Sizes of Logs	109
5.15.1	Theory	109
5.15.2	Optimizing log combinations in the program	110
5.16	Limbing and Bucking	112
5.16.1	Limbing and bucking equation	112
5.16.2	Component times	113
5.16.3	Limbing time ratio estimates	113

5.16.4	On-log travel time	116
5.16.5	Bucking times	117
5.17	Travel Time	121
5.17.1	Random normal deviates	122
5.17.2	On-ground travel time	124
5.18	Volume Determinations	124
5.18.1	Cubic-foot volumes	124
5.18.2	Board-foot volumes	125
5.18.3	Stump diameters	127
5.18.4	Bark thickness	128
5.19	Refueling Times	129
5.20	Sharpening the Saw	130
5.21	Cost of Operation	131
5.22	Revenue	131
5.23	Profit (Loss)	131
5.24	Output	131
5.25	Console Operation	133

PART III

CHAPTER 6 RESULTS OF SIMULATION RUNS

6.1	Checks	135
6.2	Simulation Runs	136
6.3	Run 1 - Vary Production Rate	137
6.3.1	Design	137
6.3.2	Results	137
6.4	Run 2 - Vary Acceptable Log Lengths	142
6.4.1	Design	142
6.4.2	Results	142
6.5	Run 3 - Vary Cull	147
6.5.1	Design	147
6.5.2	Results	148
6.6	Run 4 - Vary Board-Foot Estimation Methods	151
6.6.1	Design	151
6.6.2	Results	151
6.7	Summary	152

CHAPTER 7	REFINEMENTS, LIMITATIONS, PITFALLS AND RECOMMENDATIONS FOR FURTHER STUDY	
	REFINEMENTS	
7.1	Slope	154
7.2	Accidents and Breakdowns	154
7.3	Variable Costs	155
7.4	Felling and Bucking Times	155
7.5	Stand Data	155
	LIMITATIONS	
7.6	Expense	156
7.7	Delays	156
	PITFALLS	
7.8	Misinterpretation	157
7.9	Additivity of Data	157
7.10	Interdisciplinary Approach	158
7.11	Teams	158
7.12	Reliability	158
	RECOMMENDATIONS FOR FURTHER STUDY	
7.13	Testing of This Simulation Model With the "Real-World"	160
7.14	Increasing Model Reliability	160
7.15	Devising a New Pay Scheme	160
7.16	The Effect of Slope	160
7.17	Evaluation of Chain Saws	161
7.18	Simulation of Other Subsystems	162
CHAPTER 8	CONCLUSIONS	163
	APPENDIXES	
APPENDIX A	Review of Statistical Theory	168
APPENDIX B	Fortran II Programs	192
APPENDIX C	Data Lists	207
APPENDIX D	Chain Saw Specifications	211
APPENDIX E	Chain Saw Cost Analysis	214
APPENDIX F	Felling Frequency Distributions	215
APPENDIX G	Bucking Frequency Distributions	216
REFERENCES		217

LIST OF TABLES

TABLE	TITLE	PAGE
Table 3-I	Actual vs. Allowable Cut, Gallatin National Forest, 1957-1964	40
Table 3-II	Physical Properties of Lodgepole Pine	41
Table 4-I	A Portion of the Scribner Board-Foot Volume Table for 16-Foot Logs	60
Table 4-II	Comparison of International and Scribner Volumes for 16-Foot Logs	62
Table 4-III	Common Acceptable Log Lengths, $(x_1, \dots, x_n)$	70
Table 5-I	Probability Table for Dbh	84
Table 5-II	Results of Regression and Correlation Analysis-Dbh, Total Heights, and Crown Length	87
Table 5-III	Results of Regression and Correlation Analysis of Dbh, Total Heights, and Crown/Height Ratios	88
Table 5-IV	Conditional Probabilities of Height and Crown/Height on Dbh	89
Table 5-V	Regression Analysis of Taper Tables	92
Table 5-VI	Vital Statistics of Felling Time Study, Gallatin National Forest, 1964	100
Table 5-VII	Average Felling Times for Each Man/Machine-Dbh Combination, and Number of Observations	101
Table 5-VIII	Conditional Probability Distributions for Felling Times	103
Table 5-IX	Results of Analysis of Variance on Felling Time	104
Table 5-X	H-tests of Felling Data	105
Table 5-XI	Conditional Frequency Distributions for Limbing Times	116

Table 5-XII	On-Log Travel Time Ratios	116
Table 5-XIII	Vital Statistics for Bucking Time Study, Gallatin National Forest, 1964	118
Table 5-XIV	Average Bucking Times for Each Man/Machine- Diameter Combination and Number of Observations	118
Table 5-XV	T-tests of Bucking Data	120
Table 5-XVI	Butt Taper of Lodgepole Pine, 1' Stump Height	127
Table 5-XVII	Bark Thickness of Lodgepole Pine	128
Table 6-I	Comparison of Expected and Simulated Log Volumes	135
Table 6-II	Simulation Runs	136
Table 6-III	Operational Time Matrix	139
Table 6-IV	Logmaking Components	140
Table 6-V	Frequency of Log Lengths	143
Table 6-VI	Comparison of Costs with Various Sets of Log Lengths	144

LIST OF FIGURES

FIGURE	TITLE	PAGE
Fig. 1-1	The Monte Carlo Process	4
Fig. 1-1	A Work System	9
Fig. 1-2	The "Blackbox" Logging System	11
Fig. 1-3	Flow Chart of Logging Operations	12
Fig. 1-4	Logmaking Subsystem	15
Fig. 1-5	The "Blackbox" Logging Subsystems	16
Fig. 2-1	Logmaking Input-Output Relationship	17
Fig. 2-2	Logmaking Flow Chart	17
Fig. 2-3	Flow Diagram of Logmaking Alternatives	18
Fig. 2-4	Conventional Undercut	20
Fig. 2-5	A Tree After Undercut and Back Cut Have Been Made	22
Fig. 4-1	The Two-Part Simulation Model	50
Fig. 4-2	Block Diagram of Proposed Phase I	52
Fig. 4-3	Dbh Probability Function	53
Fig. 4-4	Dbh Distribution Function	54
Fig. 4-5	Geometric Forms Assumed by Portions of a Tree Stem	56
Fig. 4-6	Diagram of Scribner Rule Derivation	59
Fig. 4-7	Overrun with the Scribner Log Rule	61
Fig. 4-8	Cull vs. Decreasing Profits	65
Fig. 4-9	Block Diagram of Proposed Phase II	
Fig. 5-1	Dbh Frequency Distribution of Experimental Plot	83
Fig. 5-2	Probability Distribution of Dbh in Experimental Plot	83

Fig. 5-3	Total Height Frequency Distribution in Experimental Plot	85
Fig. 5-4	Frequency Distribution of Crown Lengths in Experimental Plot	86
Fig. 5-5	Frequency Distribution of Crown/Height Ratios in Experimental Plot	86
Fig. 5-6	Average Cutting Times for 5 Different Fellers	101
Fig. 5-7	Theoretical vs. Actual Felling Curve	102
Fig. 5-8	Assumed Form of Cull Type II	107
Fig. 5-9	Cull Type II Shape in Terms of Program Variables	108
Fig. 5-10	Bucking Objective in Graphic Form	109
Fig. 5-11	Average Limbing Time Per Foot vs. Dbh	115
Fig. 5-12	Average Bucking Times for Two Different Buckers	119
Fig. 5-13	Theoretical vs. Empirical Bucking Curve	120
Fig. 5-14	Travel-Time-on-Ground Ratios	124
Fig. 5-15	Bark Thickness of Lodgepole Pine	128
Fig. 6-1	Effectiveness vs. Production Rate	137
Fig. 6-2	Profit vs. Production Rate	138
Fig. 6-3	Cost Per MBF vs. Production Rate	141
Fig. 6-4	Distance Traveled Per Hour vs. Production Rate	141
Fig. 6-5	Wasted Board Feet Under Each Bucking Policy	146
Fig. 6-6	Effectiveness Under Each Bucking Policy	147
Fig. 6-7	Daily Profit vs. Cull	148
Fig. 6-8	Total Profit vs. Cull	148

Fig. 6-9	Excess Bucking Time vs. Cull Type II	149
Fig. 6-10	Wasted Volume vs. Individual Cull Types	150
Fig. 6-11	Wasted Volume vs. Cull Types in Combination	150
Fig. 6-12	The Effect of Various Board-Foot Rules on Profit	151

SYMBOLS USED AND THEIR MEANINGS

Two different symbolisms are encountered in this thesis. The first, algebraic symbols, are used in explaining some basic theoretical statistical notions. The second type of symbolism is the collection of FORTRAN II variable names used in the computer programs. Each symbolism is presented separately.

A. Algebraic Symbols.

Greek letters and English letters are listed separately according to their respective alphabets. Operation symbols are also listed separately.

a	(1) Constant term in a regression equation; (2) A positive parameter; (3) Distance in inches between bark and rotten core of a tree.
a_i	(1) Polynomial coefficient; (2) Number of logs of size i .
A	A random variable.
b	Diameter of rotten core.
b_i	(1) Regression coefficient for the " i .th" group; (2) Time to buck log i .
B_i	(1) Cross-sectional area of a log at point i ; (2) Bucker number.
c	(1) A random variable; (2) A curve.
C_i	(1) Number of observations on feller i ; (2) Length of log i containing limbs.
$C_{n,k}$	The number of combinations of n things taken k at a time.
d	(1) Diameter at a point; (2) Limbing time per foot; (3) Distance to next tree; (4) Diameter at small end of a log.
d_i	(1) Difference between an observed value and a value as estimated by a regression equation; (2) Polynomial coefficient.
D	(1) Stump diameter; (2) Dbh; (3) Diameter at big end of a log.
dbh	Diameter breast-high.
d	Degrees of freedom.
e	$\lim_{t \rightarrow \infty} (1 + \frac{1}{e})^t$, approximately equal to 2.7183.

- f_i (1) Observed frequency in sample i ; (2) Length of free stem of log i .
- $f(x)$ Probability density function of x .
- $f(X_1, X_2)$ Joint probability for X_1 and X_2 .
- $f(X_1/X_2)$ Conditional probability for X_1 given X_2 .
- F Ratio of two mean squares.
- F_i (1) Expected frequency in sample i ; (2) Feller number.
- $F(x)$ Probability distribution function of X .
- g On-ground-travel-time ratio.
- h_{off} Time to disembark from the stem.
- h_{on} Time to mount the stem.
- h Distance up the vertical at which the diameter of rotten core equals half the diameter of the stem.
- h' Distance along the stem at which the diameter of rotten core equals half the diameter of the stem.
- H (1) Test statistic for comparing samples by means of the sum of ranks; (2) Total height.
- H_o Null hypothesis.
- i Variable subscript.
- j Variable subscript.
- k (1) Value of a random variable; (2) Number of units in a sample.
- K A constant.
- K_i Number of observations in group i .
- l Limbing and bucking time.
- L (1) A least-squares curve; (2) Length of a log; (3) Distance up the stem at which the rot tapers to a point.
- L' Distance up the vertical at which rot tapers to a point.
- m (1) Number of logs in the optimal set; (2) Time to make reference cut; (3) Length of butt log.

m_{γ}	Sum of γ uniform variables.
M	Population mean.
M_i	A variance factor.
MBF	Thousand board feet.
n	(1) Number of units in a sample; (2) Number of logs in a tree.
N	Number of units in a population.
P_i	Length of log i .
P	Production rate.
ψ	Pounds per square inch.
$P(A)$	Probability of A .
$P(AC)$	Joint probability of A and C .
$P(A/C)$	Conditional probability for A given C .
r	(1) Correlation coefficient; (2) Time to retract tape; (3) equivalent to $(\sum -6)/4$.
r^2	Percentage of variation attributable to regression.
R	Uniform random variable.
R_i	Sum of ranks for group i .
S	Time to hook tape measure.
$s(x)$	Standard deviation of a sample.
$\bar{s}(x)$	Pooled standard deviation of two samples.
$s^2(x)$	Variance of a sample.
t	(1) Ratio of a variable with unit normal distribution to the sample estimate of the standard error of that variable; (2) Number of observations in a tied set.
T	(1) $(t)(t+1)(t-1)$, where t is defined as in (2) above; (2) A Chebychev Polynomial.
u	Travel time.
V	Volume of a log.
V_h	Cubic-foot volume, Huber.
V_s	Cubic-foot volume, Smalian.

w	On-log walk time ratio.
w_i	An individual random variable.
x_i	(1) An individual sample measurement; (2) Length of log i; (3) Variable in a regression equation.
X	(1) Set of x's, $(x_1, \dots, x_n)$; (2) Abcissa.
$\bar{X}$	Sample mean of variable x.
(X_i, Y_j)	An ordered pair.
X_i	The "i th" sample of X.
X_{ij}	The x value in the "i th" row and "j th" column.
y	Ordinate of a probability distribution.
y_i	The "i th" sample value of y.
$\bar{y}$	Sample mean of variable y.
Y	(1) Set of y's, $(y_1, \dots, y_n)$; (2) Ordinate; (3) Random normal deviate.
Z	(1) A variable with unit normal distribution; (2) Abcissa of normal probability curve; (3) Sum of random numbers.
α	Level of significance.
χ^2	The Chi-squared test statistic.
Δ	An incremental length.
λ	Population parameter.
Θ	Angle between vertical and tree stem.
π	Ratio of the circumference of a circle to its diameter, approximately equal to 3.1416.
δ	An integer.
σ	Population standard deviation.
σ^2	Population variance.
Σ	The sum of.
μ	Population mean.
∞	Infinity.

B. Fortran II Variables

The variables in the following list include all input and output variables, and a selected few defined within the program itself. Variables defined within the program strictly for computational advantage (e.g. transformation of a fixed-point variable to floating-point for use in a calculation) or for storage space conservation (e.g. subscript transformation or alteration of an integer set for use in a computed GO TO) are not given. Therefore, if a variable is not defined in the following list, its meaning is self-evident in the computer source program which appears in Appendix A.

A(I)	The number of logs of size X(I) that can be cut from the merchantable stem, where I = 1, JBUCK.
ABFV	The Scribner board-foot volume of a 16-foot log.
ACRES	The number of acres in the timber stand to be cut.
ADBH	Average dbh in the timber stand, in inches.
ADJ	The length of a log, in relation to a 16-foot log, in percent.
ATHT	Average total height in the timber stand, in feet.
AVE	Average distance between trees, in feet.
B(K)	The number of logs of size X(K) that can be cut from the difference between merchantable height and A(I) * X(I).
BAN	The number of times the tape is hooked and retracted during the limbing of one tree.
BBFV	The Scribner board-foot volume of the difference between volume of an actual log and the volume of a 16-foot log.
BBG	Dummy variable.
BFV	Actual simulated board-foot volume of a tree, Scribner rule.
BFVS1	Scribner board-foot volume of a log, no allowance for taper.
BFVS2	Scribner board-foot volume of a log, allowance for taper.
BFVWT	Board-foot volume of a log, estimated by weight.
BNO(J)	Length of log number J, in feet, where J = 1, MAX.

BSDBH	The summation of dbh in the stand, in inches.
BUCKT	An individual bucking time, in decimal minutes.
BUT	The total number of logs cut in one day.
C(L)	The number of logs of size $X(L)$ that can be cut from the difference between merchantable height and the sum of $A(I) \cdot X(I)$ and $B(K) \cdot X(K)$.
CAN	The number of 4-foot lengths in a log, floating point.
CFV	Actual simulated cubic-foot volume of a tree.
CFVL	Cubic-foot volume of a log.
CHOP	Time involved in making reference marks in limbing a tree, in decimal minutes.
COMBO	The portion of a log that contains live limbs, in feet.
COS	The cosine of the angle between the vertical and the tree stem.
CROWN	The portion of a tree containing live limbs, in feet.
CTIME	The time spent in making excess bucking cuts as a result of rot, in decimal hours.
CTREES	The number of merchantable trees per acre.
CUT	The number of trees cut per day, floating point.
D(M)	The number of logs of size $X(M)$ that can be cut from the difference between merchantable height and the sum of $A(I) \cdot X(I)$, $B(K) \cdot X(K)$, and $C(L) \cdot X(L)$.
DIAM(J)	Diameter of the tree at bucking point J, in inches, where $J = 1, \text{MAX}$.
DIAMM	The diameter at some point between the ends of a log, in inches.
DBH(I)	The number of diameters in diameter class I, where $I = 7, 15$.
DBHS	The number of merchantable trees in the stand remaining to be cut.
DBHSY	The total number of merchantable trees originally in the stand.

DBHX An individual dbh, in inches.

DEAD Proportion of dead trees in a stand of timber.

DEV Random normal deviate.

DIFF1 The difference between merchantable height and $A(I) \cdot X(I)$, in feet.

DIFF2 The difference between merchantable height and the sum of $A(I) \cdot X(I)$ and $B(K) \cdot X(K)$, in feet.

DIFF3 The difference between merchantable height and the sum of $A(I) \cdot X(I)$, $B(K) \cdot X(K)$, and $C(L) \cdot X(L)$, in feet.

DIFF4 The difference between merchantable height and $A(I) \cdot X(I)$, $B(K) \cdot X(K)$, $C(L) \cdot X(L)$, and $D(M) \cdot X(M)$, in feet.

DIFFA Difference between expected and actual cubic-foot volume.

DIFFB Difference between expected and actual Scribner board-foot volume.

DIGIT An 8- digit odd random number, not divisible by 5.

DIST A sample value of distance between trees, in feet.

DISTT The length of the butt log of a tree plus DIST, in feet.

DS The portion of a tree stem containing rot, in feet.

DSTY The number of tree stems per acre.

EBFV Estimated Scribner board-foot volume of a tree.

ECFV Estimated cubic-foot volume of a tree.

ETC The portion of a tree that was cut into logs, in feet.

EXTRA The difference between merchantable height and a given combination of logs, in feet.

FACTOR Cull factor, in percent.

FCOST Fixed cost, in dollars.

FELLT An individual felling time, in decimal minutes.

FREE The portion of a tree containing no live limbs, in feet.

H The distance up the vertical at which the radius of the rotten core exactly equals the radius of the bole, in feet.

HHT	Transformed total height, in feet.
HONOF	The combined time to mount and disembark a tree stem, in decimal minutes.
HP	The distance up the stem at which the radius of the rotten core exactly equals the radius of the bole, in feet.
HTS(II)	The number of heights in each dbh class II, where II = 7,15.
HTT(II,JZ)	The number of height observations in each height subclass JZ contained in diameter Class II, where JZ = JBEG(II), JEND(II).
HTU(II,JZ,K)	The number of height observations in each height subclass K, where K = 1,10.
IBEG	The minimum diameter in the stand, in inches.
IEND	The maximum diameter in the stand, in inches.
JBEG(II)	The minimum height value in diameter class II, rounded to the nearest 10 feet, where II = 7,15.
JBUCK	The number of acceptable log lengths.
JEND(II)	The maximum height value in diameter class II, rounded to the nearest 10 feet, where II = 7,15.
JOP(M)	Equivalent to D(M), in fixed point.
KBEG(JJ)	The minimum crown/height ratio in each diameter class JJ rounded to the nearest 10 feet, where JJ = 7,15.
KEND(JJ)	The maximum crown/height ratio in each diameter class JJ, rounded to the nearest 10 feet, where JJ = 7,15.
KLOGS	The number of logs in any given log combination.
KOKE	The number of days to be simulated.
KOP(L)	Equivalent to C(L), in fixed point.
LBEG(KK)	The minimum on-log travel time ratio estimate in diameter class KK, in decimal hours, where KK = 7,15.
LBBJ	The number of trees cut in any simulated hour.
LBJ	The number of trees cut in any simulated day.

LDECC1	Scribner Decimal C volume of a log, no allowance for taper.
LEND(KK)	The maximum ratio of on-log travel time in diameter class KK, in decimal minutes where $KK = 7,15$.
LHR	The hour of the day.
LOGS1	The number of logs of largest size that can be cut from a tree.
LOGS2	The number of logs of next-to-largest size that can be cut from a tree.
LOGS3	The number of logs of the second lowest size that can be cut from a tree.
LOGS4	The number of logs of smallest size that can be cut from a tree.
LOP(K)	Equal to B(K), in fixed point.
MAN	Equal to BAN, in fixed point.
MAX	The number of logs contained in the optimum log combination.
MBEG(LL)	The minimum limbing time ratio estimate in diameter class LL, in decimal hours multiplied by 100, where $LL = 7,15$.
MEND(LL)	The maximum limbing time ratio estimate in diameter class LL, in decimal hours multiplied by 100, where $LL = 7,15$.
MIN	Equal to CAN, in fixed point.
MOP(I)	Equal to A(I), in fixed point.
N	The number of a tree in the cutting order.
NCULL	Cull type.
NCUT	Same as CUT, in fixed point.
NDBHS	Same as DBHS, in fixed point.
NDECC1	Scribner Decimal C volume of a tree, in fixed point.
NHRS	Number of working hours in a simulated day.
NPR	Production rate, in trees per hour.
NTRIAL	Number of the simulated day.

0I4	International $\frac{1}{4}$ " volume of a fraction of a 4-foot section.
0IA(JJ,JZ)	The number of crown/height ratios in each crown/height class JZ contained in diameter class JJ, where JZ = KBEG(JJ), KEND(JJ).
0IB(JJ,JZ,K)	The number of crown/height ratios in each crown/height subclass K, where K = 1,10.
0IO(JJ)	The number of crown/height ratios in each diameter class JJ, where JJ = 7,15.
0IOX	A sample value of the crown/height ratio of a tree, in percent.
ONTOP(KK)	The number of on-log travel ratios in each diameter class KK, where KK = 7,15.
ONTOPT	A sample value of an on-log travel time ratio, in decimal minutes.
ONTP(KK,JZ)	The number of on-log ratios contained in each ratio class JZ contained in each diameter class KK, where JZ = LBEG(KK), LEND(KK).
OTHER	Proportion of trees containing dockage.
PCT	Percentage of a tree, in terms of length, infected by cull.
PLEFT	Board-foot volume (Scribner) left in the woods.
PLIMB(LL)	The number of limbing time ratio estimates contained in each diameter class LL, where LL = 7,15.
PLMB(LL,JZ)	The number of limbing time ratio estimates in each ratio class JZ contained in each diameter class LL, where JZ = MBEG(LL), MEND(LL).
PRE	The portion of a tree from its base to a particular bucking point, in feet.
PROB	Probability that a tree contains cull.
PROD	Productive time, in hours.
PROFIT	Amount of profit, in dollars.
Q	The portion of a tree, in feet, containing rot.
QP	The distance up the vertical, in feet, to the uppermost penetration of rot.

QUAN	Equivalent to $DBH^2 \cdot HHT$.
R	Equivalent to $(SUMJ - 6) / 4$.
RAN	A random number between 0 and 1.
RDIAM(J)	Small diameter of a log, in inches.
RDECC1	Scribner Decimal C volume of a tree, in floating point.
REFUEL	Refueling time, in hours.
REV	Total revenue in a day, in dollars, based on the Scribner rule.
REV1	Revenue based on volume by weight.
REV2	Revenue based on Scribner volume, no allowance for taper.
REV3	Revenue based on Scribner volume, allowance for taper.
REV4	Revenue based on Scribner Decimal C, no allowance for taper.
REV5	Revenue based on International $\frac{1}{4}$ " log volumes.
RND	A random number between 0 and 1.
ROT	Proportion of rotted trees in the stand.
RUN	Equivalent to MIN, in floating point.
RVI4	Total International $\frac{1}{4}$ " board-foot volume of a log.
SHARP	Time involved in sharpening the chain, in hours.
SMAX	Equivalent to MAX, in floating point.
STD	Standard deviation of distribution of distance-between-trees.
STHT	Summation of total heights in the stand.
STMP	Diameter of the stump (o.b.), in inches.
STUMP	Diameter of the stump (i.b.), in inches.
TBUCK	Total bucking time, in hours.
TCOST	Total cost, fixed plus variable in any given hour, in dollars.
TDIST	Total distance traveled, in feet.

TFELL	Total felling time, in hours.
THETA	The angle between the vertical and the tree stem, in radians.
THRS	The total number of working hours in a simulated day.
THT	Total height of a tree, in feet.
TLAB	Total limbing and bucking time, in hours.
TLIMB(J)	Limbing time of log J, in decimal minutes.
TLMB	Total limbing time, in hours.
TMHT	Merchantable height from base of a tree to a point on the stem 5.6" in diameter.
TOTAL	Total distance up the stem from base to bucking point, in feet.
TPFT	Sample value of travel time per foot.
TRAVT	Travel time between two trees.
TRE	Portion of a tree cut off by excess bucking cuts caused by rot, in feet.
TREES	Number of merchantable trees in the stand.
TTCOST	Total cost in a simulated day, in dollars.
TTRAV	Total travel time, in hours.
TUMP	Diameter of first log (o.b.), in inches.
TV	Travel time between excess bucking cuts caused by cull type II, in hours.
TVI4	Total International $\frac{1}{4}$ " board-foot volume of a tree.
TVSCB	Total Scribner board-foot volume in a simulated day.
UNPROD	Total unproductive time in a simulated day, in hours.
VBF	Total estimated board-foot volume (Scribner) in the stand.
VCOST	Variable cost, in dollars.
VDIAM(J)	Small diameter of a 4-foot section, in inches.
VI4	International $\frac{1}{4}$ " volume of a 4-foot section.

VOLWT	Board-foot volume of a tree estimated by weight.
VSCB1	Scribner board-foot volume of a tree, no allowance for taper.
VSCB2	Scribner board-foot volume of a tree, allowing for taper.
WAIT	Total time taken up by waiting for trees to fall, in hours.
WALK(J)	Time to traverse a free stem, in decimal minutes.
WORK	Total time taken up by felling, limbing, and bucking, in hours.
X(I)	The set of log lengths, $I = 1, JBUCK$, in feet.
XLIMBT	Sample ratio estimate of limbing time.
XM	Random normal deviate.
XMHT	An individual merchantable height, in feet.
XNO(II)	Length of log II, in feet, where $II = 1, MAX$.
Y(J)	The sum of J uniform random numbers, where $J = 1, 12$.

ABSTRACT

The first subsystem of the logging system, logmaking, was simulated by Monte Carlo methods on an IBM 1620 computer. Data gathered from a multitude of sources were used to construct a preliminary computer simulation "model" of the subsystem, by means of which all of the operations usually performed in the field could be done within the comforts of the office. By the use of this approach, hundreds of acres of timber could be "harvested" in just a few hours. An important advantage of the simulation technique is that the logger can make optimum decisions before he begins logging, rather than making costly remedial ones in the field.

Although the model is by no means complete, the results obtained showed that this approach to logging analysis is very promising. A few of the many different alternatives were evaluated to give potential users an indication of how simulation can be used to advantage in logging analysis. The following is a list of the different simulation runs reported in this thesis:

1. Production rate was varied.
2. Different production policies were tested.
3. The amount of defective material was varied.
4. Various payment schemes were compared.

In these runs, cost, profit, and waste material were used as measures of effectiveness.

No statements were made concerning the reliability of either the model or the results, although some phases of the model did prove to be dependable. It was concluded that more data is needed if significant results are to be obtained. Also, the assumption of additivity of data would have to be investigated. The model given in this thesis can, at best, be used as a guide to the construction of a more elaborate model.

A section on logging processes and the production components of logmaking is given for readers unfamiliar with these operations.

INTRODUCTION

I.1 Historical Development of the Problem. Logging has and will always be a major American industrial activity. Wood is used to build our homes, to make our furniture, and to construct hundreds of other things that we use in our everyday lives. This wood must all be extracted from the forest, transported to the conversion center, and processed before it can be delivered to the consumer. The extraction and transportation phases of the above cycle constitute the logging industry.

Like any other manufactured product, the market price of wood reflects the costs incurred in transforming it from raw-material to final form. In general, the higher the purchase price of a product, the higher the costs incurred in producing it, and vice-versa. Also, the higher the market price of a product the more selective people become in its use. The cost of logging is so high in the lodgepole pine country of Montana (anywhere from 35% to 60% of the cost of finished product) that many consumers are discouraged by the resultant high cost of finished product. Often, when available, other less expensive, equally-useful materials are bought as a substitute. The high cost of logging lodgepole pine can, for the most part, be attributed to the nature of the timber itself-lodgepole pine is a small-stemmed species predominating on steep slopes. Current logging methods are not designed to efficiently cope with these two adversities. A barrier to remedying this condition has been the loggers' failure to support the efforts of the few who have endeavored to develop new cost-cutting logging methods. Many times these complacent loggers, suffering the effects of the "profit-squeeze," are forced out of business soon after a short run.

To help the logger in his plight, it has been proposed by the U.S. Forest Service that a long-range program of systematic engineering analysis geared to the development of new logging methods and/or the improvement of existing methods might yield significant results. The findings of such a program might be beneficial to both the logger (who seeks more profit) and the consumer (who yearns for lower market prices). Little work of this nature has been done in the past. This thesis presents one possible way to approach this undertaking.

I.2 Selection of a Problem Area. Out of many possible problem areas, the logmaking operations (i.e. felling, limbing, and bucking) were selected for study. Among the reasons for this choice are:

- (1) Logmaking is the first subsystem in the logging system. It is always a good idea to start in at the beginning. By doing this, the entire logging system can be studied in progressive stages.
- (2) Logmaking represents from 20-35 percent of the total cost of logging lodgepole pine. A cost reduction in this phase will result in a sizable reduction in total cost.
- (3) Logmaking is amenable to the "tools" of industrial engineering. By the nature and simplicity of these operations, one is able to pursue either the "classical" or the more recent "systems" approach.

After a problem area had been chosen, a suitable plan of attack had to be selected.

I.3 Method of Attack. In the field of industrial engineering, the emphasis in recent years has been toward the use of operations research techniques for analyzing man-machine work systems. Operations researchers, in effect, attempt to describe real-world physical situations in terms of

mathematical models. The independent variables in the model can be manipulated to coincide with changes in the real world for purposes of noting the effect this alteration has on certain other variables, called the dependent variables, of practical interest in the problem.

More often than not, a wide gap exists between many of the mathematical models of operations research and the real systems whose characteristics they are intended to portray. First, a basic model is constructed by formulating a simple abstraction of the real world and expressing this abstraction mathematically. Then, by introducing a certain amount of complexity into the model in progressive stages, the simple model is modified toward realism. However, the mathematical complexities usually tend to increase at a faster rate than that at which the model approaches reality. In many instances, the mathematical model becomes unsolvable, or must be restricted by such stringent simplifying assumptions as to render the results useless. It is here that sometimes the right answers are found to the wrong problems. The mathematical abstraction may be helpful in providing insight into the functional relationship between the properties of a system and the related variables, but some other analytical means are usually needed to bridge the gap between theory and useful design procedures.

In many cases simulation can be used to advantage. Simulation takes the real system and in some sense duplicates it. In other words, simulation is the inter-connection of system components in such a way that the inter-connected system simulates, or behaves, in the same manner as the system under study.

Simulation might be considered the last step before complete

mathematical analysis. This approach to work analysis is one source of obtaining the data necessary to quantify significant system variables. A computer is usually essential.

When a simulation includes inherent system variability by making use of a random number generator, it is called by the colorful name, "Monte Carlo". A schematic diagram of the Monte Carlo process might be shown as in Fig. I-1. (4)

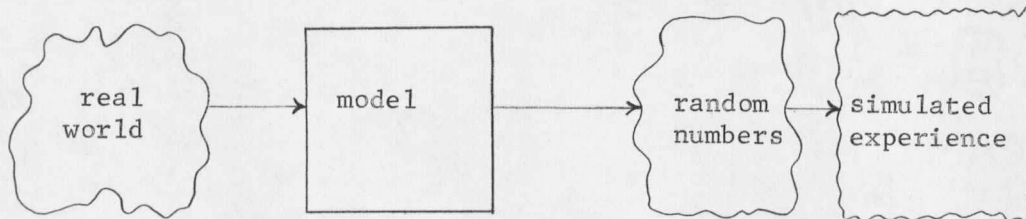


Fig. I-1. The Monte Carlo Process

The jagged, roughly rectangular figure represents the collection of facts as observed in the real-world. From this set of facts, an idealized model, represented by the normal rectangle, is derived. This "model," driven by random number generator, produces an artificially jagged figure representing the simulated experience.

Since the construction of an analytical, "a priori" model of log-making would not be feasible in this thesis, the simulation approach was chosen.

I.4 Statement of the Objectives of the Thesis and Restatement

of the Problem. Every study must have objectives. Some of the objectives of this study are:

- (a) showing how the engineering analysis of part of the logging system might be approached,
- (b) gaining insight into relationships between log-making variables,
- (c) evaluating alternative methods of production,
- (d) identifying major cost factors,
- (e) suboptimizing within the environment of certain given sets of external conditions.

It is hoped that the model obtained can be used to decrease costs and increase production efficiency of this subsystem.

I.5 Literature Review. Before the model was constructed a search of relevant literature was made in an effort to find out what had been done before. Publications on applications of simulation were plentiful; however, only one article--by J.P. Lussier-- was directly concerned with logging (29). In this paper, Lussier emphasizes the systems approach to logging analysis, and illustrates with an example using simulation to analyze the felling and skidding operations on a hypothetical tree-length logging chance. Lussier has written many other papers on the application of operations research to logging (30,31). This thesis might be considered as a direct application of some of his ideas.

Some useful insights into the factors affecting log production were gained from an unpublished report by Herrick, Neebe, and Merz (34). Their study was conducted in order to learn more about the effects of tree size, species, cut per acre, topography, crew size, and saw type upon the cost of felling and bucking Central States hardwoods. An

example is provided to show how a logger, by using their data, could estimate impending felling and bucking costs in a particular timber stand. Although the study was based on sound and thorough research methods, their data and results were deterministic and did not take the variable nature of the process into account.

The paper by Smith and Harrell (44) applying linear programming to log production was extremely helpful and is very similar to this thesis in objective. In their paper, a stand of timber is selected and the proper log combinations to maximize profit are determined by linear programming. Two restrictions--(1) acceptable log lengths, and (2) log grade-- are imposed. Eighteen different logmaking systems are analyzed.

One of the greatest contributions to the model formulation in this thesis came from a paper by Conway, Johnson, and Maxwell (9) in which they discuss some of the problems encountered in digital systems simulation. In particular, their discussion of the problems of "synchronization" and "measurement" were found to be of special interest.

All of these papers contributed in some way to formulating the objectives and planning the data-collection program for this study, but many other publications were used that are not mentioned here. Much of the information gleaned from these studies was used "within" this study, and, in fact, is incorporated in the model in some cases. Rather than mention all of these papers here, they will be discussed as they happen to contribute to the model.

I.6 Computing Facilities. The simulation model was run on the IBM 1620 Model II electronic computing machine located in the Computing

Center, Ryon Laboratory, on the campus of Montana State University. The 60 K core capacity 1620 is linked with a 1622 Model I card reader-punch and the usual unit record equipment. In addition, two 1311 disc-drives having a combined capacity of 4 million digits are available.

I.7 Thesis Format. This thesis is written in three parts. Part I is devoted to defining the production medium-the logging system- in terms of its subsystems. This first section is also concerned with identifying the production components of the logmaking operations which are to be simulated. Part II deals with the planning, design, and construction of the simulation model. Part III presents the results, discussion, and conclusions reached concerning the original objectives of this study. Thus, those familiar with logging processes can bypass Part I; those concerned only with the development of the model need only read Part II; finally, those interested only in results and conclusions can turn directly to Part III. It might be well for the typical industrial engineer, who probably knows little or nothing about logging, to read the entire text.

PART I

The first three chapters are devoted to defining the logging system, first, as a whole, and, secondly, as composed of interrelated components, or subsystems. The logmaking subsystem is then singled out for further discussion. Finally, each production component of logmaking is discussed in detail.

Part I is composed of three chapters:

- Chapter I The Logging System
- Chapter II The Logmaking Subsystem
- Chapter III Man, Machine, Material

This part may be omitted by those already familiar with logging.

CHAPTER 1

THE LOGGING SYSTEM

The word "system" implies an interconnected complex of functionally related components. The effectiveness of each component depends on how it fits into the whole and the effectiveness of the whole depends on the way each unit functions. In the "systems approach" to work design, emphasis is on the interrelationships among the parts of the system and the significance of these interrelationships in solving the engineering problem. It is this "interaction" which, when overlooked, can be the cause of serious discrepancies between calculated, or expected, system performance and actual performance.

1.1 Work Systems and Subsystems. In general terms, a "work system" has five distinct properties - (1) input, (2) output, (3) processes, (4) requirements, and (5) feedback (Fig. 1-1).

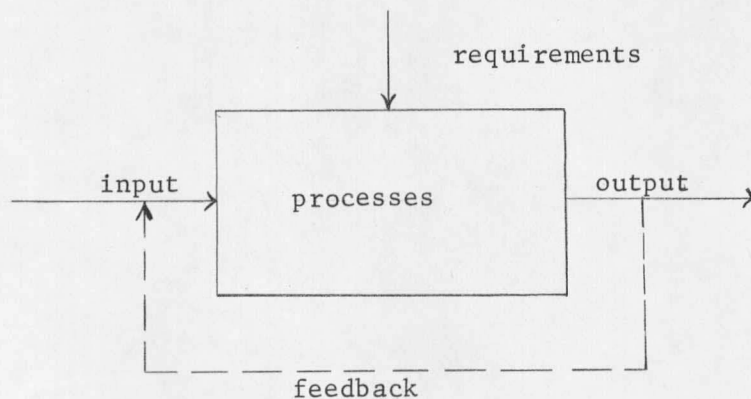


Fig. 1-1. A Work System.

The "work system" commonly receives an input (raw material) which it transforms into an output (finished product) by means of certain

processes (operations involving men and machines), subject to certain requirements (specifications). In addition, in automated systems or systems under control, a self-correcting mechanism called "feedback" exists. Feedback, similar to the thermostatic control of heat in theory, controls the system to keep its processes and operations functioning within certain predetermined operational limits.

A subsystem is defined as a natural, homogenous subdivision of the total system, also having the five system characteristics; it can function independently of the system, but is interrelated with the other system components. Therefore, suboptimization can be exercised.

1.2 The "Blackbox" Logging System. The logging system is an integrated assembly of interacting elements, designed to carry out cooperatively the predetermined function of getting the logs from the "stump" in the woods to the processing plant. Or, to be consistent with the definition of a "work system," the logging system is characterized by the transformation of raw material (trees) to finished product (logs at processing plant) by engaging it in a number of processes (logging operations) subject to certain requirements (land management specifications) and regulated to a certain extent by feedback (corrective information) as shown in Fig. 1-2.

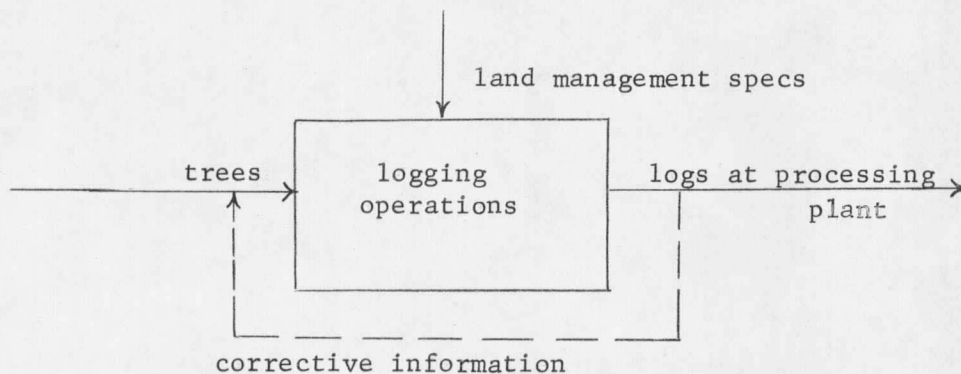


Fig. 1-2. The "Blackbox" Logging System

Here the production media is viewed as a "black box" possessing the five system properties. Since the engineer is responsible for the basic design of the "plant" and of the systems necessary to operate it successfully, his job, then, is to determine the "contents" of the box.

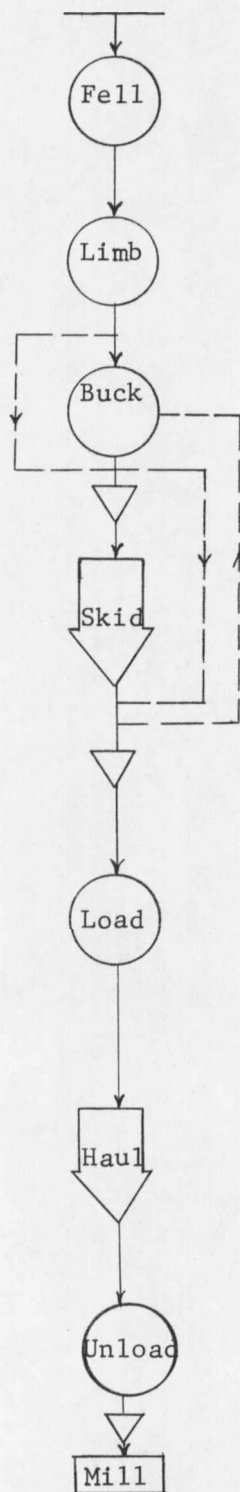
1.3 The Logging "Processes". The logging system can be separated into seven basic well-defined, sequential, interrelated operations, or "processes" - felling, limbing, bucking, skidding, loading, hauling, and unloading (Fig. 1-3). A brief description of each operation is given below:

Felling

Felling consists of cutting or sawing down standing trees, usually with an axe or power chain saw.

Limbing

Limbing refers to the removal of limbs and large knots from the stem. In most logging areas this operation is performed with the same implement used in felling, the power saw; in fact, this operation almost



Symbols	
○	Operation
↓	Transportation
□	Inspection
▽	Storage & Delay

Summary	
Symbol	Number
○	5
↓	2
□	0
▽	3

Fig. 1-3. Flow Chart of Logging Operations

always immediately follows the felling operation.

Bucking

Bucking refers to the sawing of the felled tree into shorter cuts, sections, or logs. This operation is likewise usually performed with the power saw. Bucking may be performed immediately after limbing, may be deferred until after the "skid," or may not even be done at all (e.g. in tree-length logging).

Skidding

Skidding, or yarding, refers to transporting logs from the felled position, or "stump", to a central assembly area called a landing, or deck, preparatory to loading for final delivery. This may be done by animal, tractor, or cable. In recent years animal skidding has largely given way to the latter two skidding methods.

Loading

Loading refers to that operational phase in which logs are transferred from the "woods-landing", or temporary storage, to vehicles for final transportation to the mill. Logs are generally loaded onto the vehicles by means of cranes, tractors, front-end loaders, or other such machines.

Hauling

Hauling is the second, final, and major transportation in the logging process. The term hauling refers to transporting the logs from the "landing" to a processing plant. In this operation, railroads, once the most important log transportation medium in the United States, have given

way to less-costly , more flexible trucks.

Unloading

Unloading, obviously, refers to the removal of the logs from the truck at the processing plant.. This can be done by any of the loading machines, or by other specially designed methods.

1.4 The "Blackbox" Logging Subsystems: The above operations are contained within the "blackbox" system and each has its own input-output relationship, processes, requirements, and feedback. In addition, each has a share in the characteristics of the larger system of which it is a part, and is interrelated with the other operations. Thus, each of these basic logging operations fits the definition of a subsystem.

The input (standing trees) to the first operation, felling, is the input to the system. Output from felling serves as input to the second operation, limbing. The output from limbing in turn provides the input for bucking,....., and the output from the loading operation is the system output.

Since in practice felling, limbing, and bucking are usually performed by the same individual or crew using one machine only - the power saw - these three operations can be grouped together and called "logmaking" (Fig. 1-4).

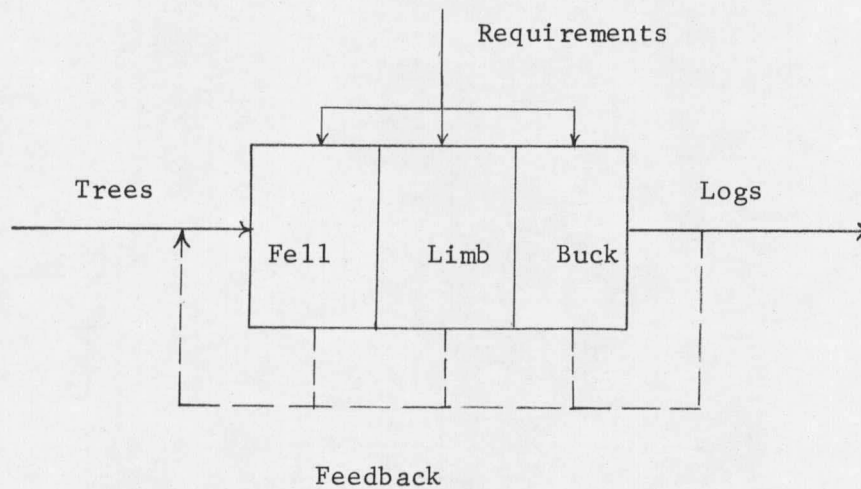


Fig. 1-4. Logmaking Subsystem

Since these three operations sometimes will not all be performed on the same logging chance, it is possible to have all three operations considered logmaking, any combination of two that contains felling, or just felling alone for that matter. Logmaking, then, can be considered to constitute one subsystem, subject to the above interpretation.

Fig. 1-5 shows the logging subsystems schematically in a block diagram.

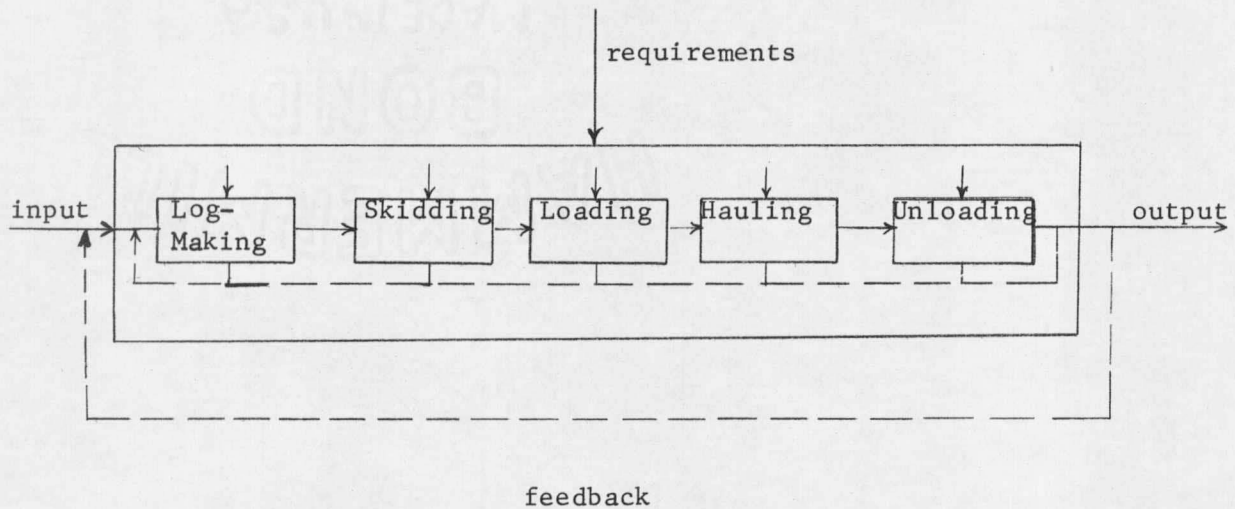


Fig. 1-5. The "Blackbox" Logging Subsystems

Each of these subsystems can be broken down into its elements, or "processes" remembering that each such element is but one component of the subsystem which is in turn only one component of the total logging system.

The logging system, then, is composed of the subsystems logmaking, skidding, loading, hauling, and unloading. This study focuses attention on logmaking.

CHAPTER 2

THE LOGMAKING SUBSYSTEM

The basic objective of logmaking is to convert standing trees to merchantable logs (Fig. 2-1). Logmaking, from before, consists of the operations felling, limbing, and bucking. The logmaking cycle begins when

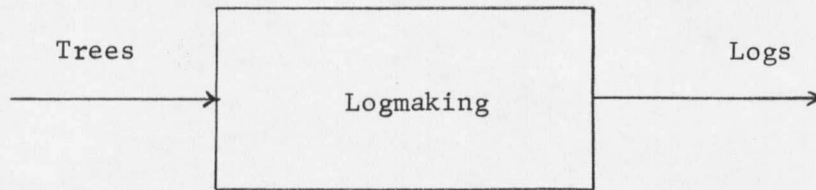


Fig. 2-1. Logmaking Input-Output Relationship

a tree is selected to be cut and ends after the operator has traveled to the next tree.

2.1 Logmaking Flow Chart. The sequence of activities involved in logmaking can readily be shown in flow chart form (Fig. 2-2).

Step	Element	Symbol
1	Select Tree	□
2	Clear Underbrush	⊖
3	Start Saw	○
4	Make Undercut	○
5	Make Backcut	○
6	Wait for Tree to Fall	▽
7	Determine Optimum Log Combination	□
8	Hook Tape	○
9	Walk and Limb	⊗
10	Measure Log	□
11	Reel in Tape	⊖
12	Make Back Cut	○
13	Travel to Next Tree	➡

Fig. 2-2. Logmaking Flow Chart

The sequence shown in Fig. 2-2, although enumerating every possible step, is rarely exactly encountered in practice. There are many variations from this typical sequence which may be chosen by the logger to meet his particular needs. For instance, in many lodgepole logging areas the trees are not bucked into logs at the "stump"---they are skidded "tree-length" to the landing. Then, at the landing, the trees can either be bucked and then loaded, or full-length trees can be loaded "as is" onto outgoing hauling vehicles. Also, the logger does not usually limb and buck each tree as it is felled. He will often fell five or six trees in succession, and then convert them all to logs before felling another cluster of trees. Another variation of Fig. 2-2 is that the saw is not usually shut off after each tree has been worked on; it is carried around at idle speed when not in use.

The different "modus operandi" represent different alternatives open to a logger in any particular area, and, for that matter, for any particular tree. Fig. 2-3, a modification of Fig. 2-2, shows these alternatives in dotted lines.

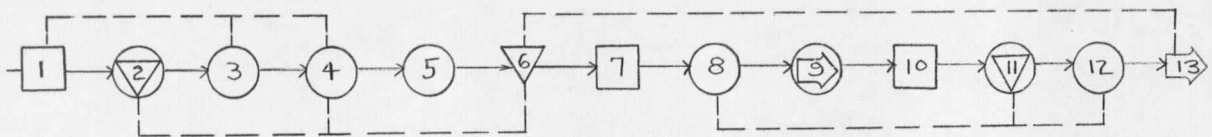


Fig. 2-3. Flow Diagram of Logmaking Alternatives

Each step in Figs. 2-2 and 2-3 is defined below.

1. Tree Selection

Lodgepole pine forests are generally harvested by the "clear cutting" method, which dictates that all merchantable trees in a prescribed area are to be cut down. Trees that are dead or undersized need not be removed. It has been found that this procedure satisfies the silvical requirements of lodgepole pine more than any other tested method of removal. The specific trees to be cut are selected according to three criteria - (1) dbh (diameter breast-high), (2) merchantable height, and (3) degree of soundness. Dbh is the diameter of a tree 4.5 feet above average ground level. Merchantable height is measured from average ground level to the top end of the last merchantable log. A sound tree is one that is free of flaw, defect, or decay. Minimum specifications for these three variables are set by the processing plant. These specifications, of course, will vary from area to area depending on the type, size, and capacity of sawmill machinery and current market demands.

2. Clear Obstacles

Many times the cutter is faced with the prospect of removing obstructions such as underbrush, fallen limbs from other trees, young growth, and rocks that lie near the tree. Obstacles are not present near every tree, but when they are, their removal represents an "unavoidable delay." If the obstruction is a small tree, or part of a larger one, the feller may have to use his saw to cut them away.

In lodgepole stands underbrush is usually not prevalent and this "unavoidable delay" time is kept at a minimum. Clearing obstructions

is thus not usually a major cost factor in lodgepole pine logging.

3. Start Saw

After the first tree to be cut has been selected, the cutter starts his saw. The saw is usually not shut down again until a rest break. In the interim, it is carried around at "idle" speed when not actually in use.

4. Make Undercut

The undercut is the first cut and is made on the side toward which the tree will fall. It is a wedge-shape cut commonly extending in about one-fourth of the tree diameter to remove support for the tree at that point. Fig. 2-4 shows the conventional undercut for small trees such as lodgepole pine.

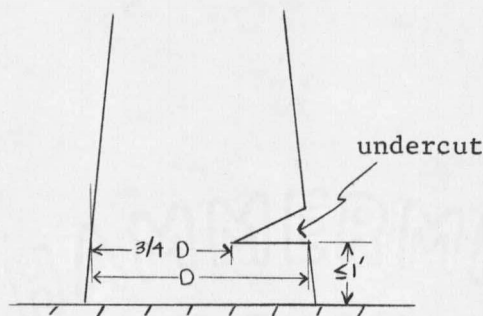


Fig. 2-4. Conventional Undercut

The undercut consists of two intersecting cutting planes.

The size of the undercut varies with several factors, the most important of which are:

- (1) Wind
- (2) Degree of lean of the tree
- (3) Limbiness of the tree
- (4) Size of tree butt

For instance, if the wind is blowing hard in the direction of the fall,

only a small undercut may need to be made. Conversely, if the wind is blowing heavily in the opposite direction, a larger wedge might have to be removed. Then, if the tree leans far enough in the falling direction a wedge-shaped cut may not be necessary - a "straight cut" might suffice. Also, limbs are usually concentrated on one side of a tree rather than being uniformly distributed around the bole. If they are concentrated on the side of the direction of fall, only a small undercut is necessary, and vice-versa. Finally, the absolute size of the undercut varies directly with the diameter at the cutting level.

From elementary geometry, the intersection of two planes forms a straight line. This is essentially what is formed when the undercut is made. The undercut pinpoints the stress concentration at this "line of convergence" of the two intersecting cutting planes.

The undercut is almost always made at a level which is lower than one foot above average ground level. Two considerations are involved here. One is that the bulk of the value of a tree lies in the butt log. It seems reasonable, then, to set a limit on the amount of butt that can be left in the woods. Secondly, high stumps are hazardous. A high stump not only obstructs the path of equipment but is also hazardous when the cutter must move about deftly in case of danger. Taking these two factors into consideration, the Forest Service, for example, has concluded that 12 inches is a "reasonable" maximum stump height.

5. Make Back Cut

The tree is severed by the "back cut" made on the opposite side of the trunk from which the under cut was made. This cut provides the "finishing touch" needed to fell the tree. Fig. 2-5 shows a tree

immediately after the undercut and back cut have been made. The arrows denote stress concentration.

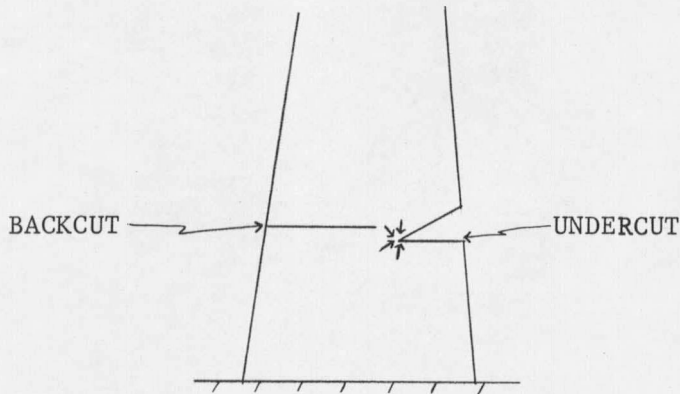


Fig. 2-5. A Tree After Undercut and Back Cut Have Been Made

The conventional back cut is usually made at a level slightly higher than the line of convergence of the undercut. When the backcut is made, the moment of the stem causes the tree to topple, with the "line of convergence" of the undercut acting as a hinge. If the tree does not fall after these cuts are made, it may be necessary for the cutter to either insert a "wedge" in the back cut or push the tree over by hand. A "clean" break is desired.

6. Wait for Tree to Fall

The cutter should remain unproductive, or idle, in the period between when the tree starts to fall and when it finally comes to rest on the ground. This is perhaps the most dangerous period of the logmaking cycle. The feller must keep his attention focused on the falling tree and watch for unseen "widow-makers" and "snags" - the most sinister enemies of the logger - at the same time.

A "widow-maker" is a dead or live limb hanging loose in a tree, high overhead. "Widow-makers," when falling, make little or no noise

on their way down. Delayed action "leaners" or "snags" - which when meshed together are called "tepees" - are another woods hazard. These are live or dead trees that hang up on one another, due to bad wood, bad wind, or bad aiming by the fellers. These trees keep leaning until something or someone sends them tumbling down. The importance of keeping aware of these lurking dangers cannot be overemphasized.

The danger of falling "widow-makers" and "snags" is particularly high in overmature or diseased forests. When a feller is proficient enough to avoid building "tepees" out of felled trees these dangers are minimized; however, even in the "cleanest" forests a danger factor, however small, is always present.

7. Determine Optimum Number of Logs

The proper combination of logs that can be cut from the merchantable portion of the tree stem must be determined. The feller seeks that combination which will yield him the most profit. Profit can vary considerably depending on the way the tree is apportioned into logs. Log length restrictions, discussed at length in Chapters 5 and 6, act as constraints.

8. Hook Tape in Butt

All efficient fellers carry a 50-foot "logger's tape," calibrated in inches, as standard equipment. The logger's tape, hooked on the end, is similar to the familiar retractable metal tape measure in appearance. It can be fastened to the logger's belt for easy handling. The feller fastens the hooked end of the tape onto the butt end of the logs to facilitate his log-measuring phase. After use, the tape retracts into the case automatically.

9. Walk and Limb

When the tape measure has been hooked in place, the feller begins his limbing and bucking duties. He mounts and walks on top of the log from the butt end toward the top of the tree, letting tape out as he goes. Live limbs encountered before the first log can be completely measured off must be removed. Only those limbs that are not likely to fall off during skidding are removed.

10. Measure Log

Assuming that the logger has previously determined the optimum combination of logs to be extracted from the stem, he must now ascertain, by use of his tape measure, where the buck cuts should be made. At these points on the stem, he makes a "reference" cut, a slight gash, into the bark.

11. Reel in Tape

The tape may or may not be retracted at each bucking point. Some loggers reel in their tape measure after each log is measured. Others do not retract the tape until it is let out completely. Still others will retract if the length of the next log to be measured exceeds the length of the remaining portion of the tape. Let us call these Case I, Case II, and Case III.

Case I. This is the simplest case. After determining the length of the first log, the tape is retracted. If another log is to be obtained, the tape must be hooked in at this point, the next log measured, and so on.

Case II. In this case, the logger will not retract unless the tape is or is close to being used all up. This may be in the middle of the

second log, somewhere along the third log, or anywhere else it happens to occur. This is the next simplest case.

Case III. This is the most complex case. Assume three logs are cut from a tree. Call the length in feet of the three logs L_1, L_2, L_3 . Now, for the tape to be retracted after measuring the first log, the length of the second log would have to exceed the length of the remaining portion of the tape (i.e. $L_2 > 50 - L_1$). In this case, the tape would have to be hooked to the butt of the second log and be retracted after measuring the second log only if the length of the third, as before, was greater than what remained after measuring the second log. (i.e. $L_3 > 50 - L_2$).

Now, assume that the tape had not been retracted after the first log (i.e. $L_2 \leq 50 - L_1$). Now the tape would be retracted after the second log was measured only if the length of the third log exceeded the remaining portion of tape (i.e. $L_3 > 50 - (L_1 + L_2)$). If not, then the tape could be used to measure all three logs.

12. Make the Buck Cuts

After all logs have been measured, the logger disembarks to make the necessary buck cuts. In the great majority of cases, each buck cut is made with a single pass of the blade. At other times a cut is made from the top down to about one-fifth of the way from the bottom side of the bole, after which the saw is removed and the cut is finished from the bottom up. The method used depends on the position and size of the felled tree. Congested trees and large diameters require two cuts and readily accessible trees and small boles only one.

If only one log can be obtained from the tree, the initial buck cut marks the end of the logmaking operation for that tree. If more than one log is obtainable, the logger travels to the successive bucking points (on the ground this time) to make his cuts. The travel time between cuts is obviously a part of total limbing and bucking time.

13. Travel to the Next Tree.

After the tree has been felled, limbed, and bucked, the feller travels to the next tree to be cut.

2.2. Irregular Elements: In addition to the above list of operations, there are several irregular, or periodic, elements that are a part of the total logmaking operation. The most important of these are refueling and sharpening the saw chain. These irregular elements are described in Chapter 3.

CHAPTER 3

MAN, MACHINE, MATERIAL

This chapter will be devoted to a discussion of the production components of logmaking and selected problem areas that could be investigated by simulation. The comments made in this chapter will apply strictly to Western lodgepole pine logging. Some of the statements may not be true of the logging of other species in other areas.

The three m's of production (man, machine, material) can be easily identified in the logmaking subsystem. These are: the feller (man), the power chain saw (machine), and the trees (material). Discussion of these components will be presented in three parts:

- (1) discussion of the man.
- (2) discussion of the machine.
- (3) discussion of the material.

The problem analysis is incorporated into these discussions.

THE MAN

By and large, logmaking is carried out by one man working alone. For safety's sake, though, it is a good idea to have at least one more worker in the same general area.

In western Montana a good lodgepole feller can average about 6,000 board feet per day. Of course, daily production varies with the size and quality of the timber and the worker's overall efficiency.

3.1 One- vs. Two-Man Crews. It has been proven conclusively (20,34) that one-man crews are superior to two-man crews. In particular, the study conducted by Merz, Neebe, and Herrick (34) in the Kaskasia Experimental Forest in southern Illinois showed that production per man-hour:

- was greater for one-man crews than for two-man crews, regardless of type of saw used, size of trees cut, volume cut per acre, or the topography of the area.

- increased with the size of trees cut.

- increased with the volume cut per acre.

- was not significantly affected by topography, the type of saw used, or the species of tree cut.

In their study, production per man-hour with one-man crews exceeded that of two-man crews by 60 to 65 percent.

Nothing would be gained by restudying the comparative effectiveness of one- and two-man crews, since this problem has already been explored and resolved. Besides, no two-man crews were observed during the course of the present study. One might argue that since the previous studies were conducted on relatively moderate slopes (the maximum slope studied by Merz, et al. was slightly in excess of 30 percent) there is no way of knowing whether the same relationships hold on steeper slopes. There may be some justification for this argument; however, the author believes that two-man crews on steep slopes would be far more ineffective in comparison to one-man crews than they would be on moderate slopes. One reason for this is that the footing on steep slopes would be too perilous for a second man to follow behind the cutter safely, unless he remained a good distance away. This would undoubtedly reduce the crew's effectiveness. The other factors--tree size, volume cut, topography, and saw type can be examined as they affect production. Methods of doing this are brought out in other sections of this thesis. The final factor, the effect of tree species on production, is not significant since this study focuses attention on one tree species only --lodgepole pine.

3.2 Efficiency, Perhaps the biggest single problem associated with the man is the effect of changes in his overall working efficiency on production. There are many factors having a bearing on worker efficiency. Among these:

- (1) skill
- (2) experience
- (3) motivation
- (4) physical characteristics

Their importance is not necessarily in the order listed. Other exogenous factors such as forest conditions and weather, granted, will also have some effect on the worker's day-to-day performance. The four factors listed above are those that have a constant effect on performance and are independent of external conditions. They relate to the man himself.

(1) Skill

Worker skill, or technical proficiency, is undoubtedly one of the most important single factors affecting production. The worker's skill, of course, is somewhat dependent on the other factors mentioned above, but can be considered independently for all practical purposes.

Skill varies among workmen. Studying workers with varying amounts of skill can lead to erroneous performance standards if the analyst does not compensate for it. A worker's skill can be subjectively "rated" relative to what is considered average proficiency. When a worker is "rated," his production figures can be adjusted to average expected output. For instance, say Worker A is rated at 110%, or 10% above average. Worker B is judged to be a 95% man. It takes Worker A 75 seconds to perform an

element of a production operation; it takes B 87 seconds to perform that same element. These figures must both be adjusted to normal expected operational time. Multiplying 75 by 110%, we get an expected normal work time of 82.5 seconds for Worker A. Multiplying 87 by 95%, we get about 82.5 seconds for Worker B also. This is the time in which we would expect an average worker, working at an average pace, under average conditions to do the job. For example, if a Worker C was rated at 100%, he should have taken about 82.5 seconds to do the job.

In this hypothetical example, the ratings for A and B were fairly equipollent. This is not always the case, due to the subjective nature of the rating procedure. The accuracy of rating depends to a large extent on the analyst's knowledge of the job and his experience.

(2) Experience

Unfortunately, the majority of fellers in this area today have had less than one year of logging experience. Also, fellers tend to be a migratory group. Out of all the fellers observed in the field, not one was a native Montanan. The large majority of cutters migrate into Montana from either the Lake States or the West Coast.

Although the formal education requirement is far from prohibitive, "young blood" is not being attracted to the woods. Even when it is, it does not seem to remain long. One reason for this is that there are other, more desirable jobs in the population centers where the working day is not as long, the work is a little easier, and the pay is a little higher. Another prohibiting factor is the fact that logging is a seasonal occupation, often not lasting more than nine months of the year, and often conducted under adverse conditions. In addition, the "fringe

benefits" are not good. Finally, one of the biggest reasons why felling is not attractive is the inherent danger involved. Cutting timber is one of the most dangerous jobs known to man. Some of the specific hazards were discussed in Chapter 2.

The experience, or lack of it, of a worker is most significant on this last factor--safety. Months and even years of practice are required before a cutter can become proficient in felling a tree. Out of 668 disabling injuries in the West in 1955, 185, or roughly 38 percent of them were incurred by workers primarily involved in felling, limbing and bucking (50). Loggers are hence difficult and expensive to insure. The insurance rate for Montana, for example, is roughly \$21 per \$100 of payroll, the highest in the country. The problem is not so much the fault of the man as it is with the system. Upon being hired, most of the men do not receive any instructions or guidance on how to perform their job. As it is, there are no stipulations on the amount of experience or necessary supervision in the hiring policies around the state of Montana. It is probable that if there were such a stipulation, there might not be any fellers at all. Perhaps vocational school training, which is nonexistent in Montana, would be one solution to this pressing problem.

(3) Motivation

In general, the feller is an unmotivated individual. Motivation is a factor that is difficult, or even impossible, to measure since it is affected by many factors which have both psychological and sociological roots. Some of these factors are (27):

- (a) personal bond between the worker and his work,

- (b) the meaning of work to the individual,
- (c) the individual's recognition of his own goals and objectives and those of the company,
- (d) the relationship of supervision with the individual.

Each of these factors will be discussed briefly.

(a) Personal bond between the worker and his work.

It is difficult to say whether the typical logger has a personal bond with his job, or whether he feels that there is any point in doing so. This much can be said--every feller likes to think of himself as the hardest worker and fastest cutter in the woods, although this is probably true of almost any worker that relies upon his brawn more than his brains.

(b) The meaning of work to the individual.

The concept of dignity is quite basic to human nature. Work must not be degrading if work is to be satisfying.

Granted, felling timber is not a glamorous job. Although many loggers view work as it really is, a necessary and dignified activity, the great majority seem to look at work in a negative sort of way. "What's in it for me?" seems to be the basic motivating factor.

Truly, the opportunity to be creative and individualistic is limited. Perhaps this is one reason for the lack of motivation.

(c) The individual's recognition of his own goals and objectives and those of the company.

Individual goal accomplishment is directly related to the organization's goal accomplishment. Each and every individual in an organization should understand the objectives of his organization and

his own personal objectives. Furthermore, everyone should clearly know how these objectives are similar and can be achieved in a compatible manner.

Usually, the feller's objective is simple--to make money. Although the dollar is the prime mover in a feller's activities, he will comply with the owner's wishes if given a "square deal." If he thinks he has been wronged, however, the logger may forget about any company objectives that he may have been aware of.

Since most of the fellers are subcontracted by "gypos" who are, in turn, under contract with the processing plant, they usually pledge allegiance to the "gypo." The company is in fact apt to be looked upon as "Big Brother", who hands down ultimatums with an iron hand--the ultimate of dictatorship. This is not always the case, obviously.

The author feels that this prevailing attitude is a result of an extremely hostile, impersonal, outdated communication system within the overall organization. Rarely, if ever, does a feller receive any communiques from the company. When changes in policies are made, the logger is the last to hear, and even then he finds out by indirect means. When he feels he has been wronged, the logger has no outlet through which he can air grievances since he does not belong to a trade union. Communication is the essence of good organization. Worker motivation is certainly not enhanced by the present system. Perhaps one answer is to set up a union affiliation through which grievances could be worked out.

(d) The relationship of supervision with the individual.

The supervisor is a key figure in any organization. He represents

the organization to the men. He should provide guidance and encouragement. He should stimulate and support the self-esteem and emotional security of his employees.

The feller's supervisor is the "gyppo." Close supervision is unheard of. Being an independent lot, this situation is quite satisfactory to the fellers. Many times supervision is restricted to informing the feller of what area is to be cut next. Cutting methods and working hours are at the feller's discretion. If relationships with the "gyppo" are good, the feller, feeling a sense of duty, will usually do his best to produce at a high level. If, on the other hand, relationships are not good, motivation is at its lowest ebb.

All of the above factors are important contributors to motivation; sadly enough, in logging, not many of these contributions are positive.

(4). Physical Characteristics

The physical characteristics of the logger have a profound effect on his efficiency. His job is taxing since his machine, the chain saw, which weighs about 25 pounds (less bar and gas), must be carried everywhere. The conditions under which the saw must be carried are anything but desirable--assorted felled trees, branches, and undergrowth impede free movement. Footing is at times treacherous. It is not unusual for a feller to lose his balance and stumble head-over-heels from an apparently rigid log. Thus, a feller needs a considerable amount of strength (to tote his saw) and stamina (to carry it all day under adverse conditions).

In addition, the feller must be able to react quickly to unforeseen emergencies. This requires a keen and alert mind as well as the ability to make a snap decision. These traits are known to deteriorate with age. A fraction of a second could mean the difference between life and death in the woods. Getting out of the way of "widow makers" is a good example of this.

It has often been said that a man should not be allowed to cut if he is under 21 or over 40 years of age. After observing this operation firsthand, the author is convinced that this "postulate" is true. When a feller has completed a full day's work, he is usually physically and mentally exhausted, especially in steep slope country. A corpulent or otherwise physically unfit man is at a decided disadvantage.

To summarize, in the logging industry, the man is far more independent than are similar employees in other industries, since the nature of logging is such that it is advisable that every man be on his own in the woods. Close supervision is almost impossible. The worker is usually hired on a contract basis. He is given his cutting area and left on his own. The employee works his own hours, at his own pace. A good cutter will average 6,000 board feet per day of lodgepole pine. The option rests with the owner of releasing the man from his employ if he consistently fails to produce at a satisfactory level.

Efficiency has a considerable effect on production, perhaps moreso than any other factor. The efficiency with which the man works

depends on four factors:

- (1) skill
- (2) experience
- (3) motivation
- (4) physical characteristics

All of these factors contribute in some way, either positively or negatively.

THE MACHINE

3.3 The Chain Saw. The felling, limbing, and bucking operations are almost universally accomplished with a power chain saw. Wheel saws and plunge cut bow saws are also used to some extent in Southeast pulpwood stands. Ranging in weight from about 12 to 25 pounds (less gas, bar, and chain) the power saw has been determined to be a useful, efficient tool for cutting timber. In all, there are over 15 different manufacturers of chain saws, each offering from one to six different models. Prices range from \$150 to \$375 depending on size, type of chain, and length of bar. As a result of a common agreement among manufacturers, chain saws are no longer rated in horsepower. Only Homelite and McCulloch brand saws were observed in this area; thus, a good sample of the 15 different kinds was not possible. Specifications for the saws observed in this study are given in Appendix D.

No one brand of chain saw appears to be distinctly superior from an engineering standpoint; however, the most suitable saw and bar lengths for specific forest conditions have never been determined--usage is based largely on tradition and availability of a particular saw. Thus,

since they are the only two companies represented here, this could explain why Homelite and McCulloch saws are so prevalent in the Gallatin Valley.

Power saws are of two types--direct drive and reduction drive. Most saw manufacturers make both types. In the direct drive saw, the chain sprocket is attached directly to the engine crankshaft resulting in a 1 : 1 drive ratio. The reduction saw utilizes a gear-reduction transmission that operates the chain drive at about a 3 : 1 drive ratio. Most fellers seem to prefer the direct drive saw because of its lighter weight, faster chain speed, and lower tendency to pull into the cut. Gear saws can be "lugged down" to cut faster, but it is usually not worthwhile from either an economic or weight standpoint to do so.

Both one-man saws and two-man saws are available. Two-man saws have a longer cutting blade and more power than one-man saws, and are used mostly for felling exceptionally large trees. No two-man saws were observed in this area, probably because of the small-sized timber found here.

3.4 Chain Saw Operation. Most power saws operate on "regular" gasoline, with a 30-weight oil added in a ratio of 1:4. In addition, this same 30-weight oil is used to keep the chain lubricated. Saw manufacturers recommend their own brand of oil, but any common brand will suffice. The capacities of the fuel and oil tanks vary with the type of saw, but the average is somewhere around 42 ounces for fuel

and 15 ounces for chain oil. The frequency with which fuel and oil are added depends mainly on the use to which the saws are put.

Maintenance is a big problem. For best cutting, the chain should be sharpened twice a day. In addition, minor breakdowns frequently occur to invoke unavoidable delay. It is sometimes a good idea to have two saws--one in reserve for use in case the first breaks down. Of course, there would have to be an economic justification for doing this. For instance, as a result of an extended study on saw breakdowns, one big company provides four saws for every three cutters.

3.5 Operator Preference. By and large, in this area, the fellers seem to prefer a one-man, direct drive, gas-powered saw ranging from 19 to 24 pounds in weight with an 18" to 24" draw bar. The worker provides his own chain saw and all of the maintenance, repair, and fuel that is required. The remuneration he receives for his services must not only cover the cost of saw operation, but must also provide him with an adequate profit margin.

3.6 Future Developments. It seems unlikely that many further developments will be made in chain saw technology. The power saw has been constantly improved on over the years so that it is now an extremely well-engineered, versatile, efficient piece of machinery. Of course, some new methods of taking trees down are in the process of being developed. Industry is well on its way to putting some of these developments on the market. New multipurpose machines, such as the Busch combine which fells with a shearing action, are almost "ready to go." Within the next few years, we may witness a new revolution

in small-stem logging. Preliminary indications are that these bulky combines may not be adaptable to steep slopes, however.

THE MATERIAL

In total acreage, lodgepole pine (pinus contorta) is one of the largest timber types in the West, ranking third behind Douglas fir and Ponderosa pine. In all, there are about 14.5 million acres of lodgepole pine in the United States (56). About 11.6 million acres, or about 80 percent to the total acreage of lodgepole pine, is concentrated in the mountain states of Montana, Idaho, Wyoming, and Colorado.

3.7 Logging of Lodgepole Pine. As a lumber species, lodgepole pine is one of the better softwoods. The logging of lodgepole pine was begun in earnest in this area around the year 1953 when some important industrial uses were found for it. Up to then, it was considered a weed tree. There are now eight saw-mills with an annual capacity of about 69,000 MBF and a pulp-mill with a capacity of 25,000 cords per year serving the Gallatin Forest alone(2).

Although the timber harvest has been steadily increasing to keep up with increasing demand, the volume removed per year has not nearly approached the allowable cut; or that volume which could conceivably be removed. In 1955, for instance, only 20 percent of the total allowable cut in the mountain states was removed (56). To illustrate, a comparison between actual and allowable cut for all species in the Gallatin National Forest for the last eight fiscal years is given in Table 3-I.

Table 3-I. Actual vs. Allowable Cut,
Gallatin National Forest, 1957 - 1964

Year	Allowable Cut (MBF)	Actual Cut (MBF)	Percent of Allowable Utilized
1957	72,380	25,637	35.4
1958	72,380	16,725	23.1
1959	72,380	31,990	44.2
1960	72,380	24,782	34.2
1961	72,380	21,230	29.3
1962	72,380	17,796	24.6
1963	72,380	41,458	57.3
1964	72,380	48,506	67.0

Lodgepole pine is the main timber type in the forest comprising about 75 percent of the total wood volume. In a "Fact Sheet" published by the Gallatin Forest, five reasons are given to account for the relatively low volume of timber being cut. These are:

- (1) Steep topography and rock conditions make it uneconomical for industry to log using present methods.
- (2) Industry cannot afford to log low volumes per acre under present market conditions and logging methods.
- (3) Private lands prevent public access to National Forest lands in many areas.
- (4) Timber volumes will not support heavy road construction costs to open up many areas on the forest, and
- (5) Recent timber losses from the spruce woodworm has reduced the volume inventory of Douglas fir.

The first four reasons serve to point out why lodgepole pine logging is such a highly marginal venture. It is apparent that revolutionary logging methods and equipment must be developed.

3.8 Physical Characteristics. Lodgepole pine has good form. It is a smooth, uniform tree with little taper and relatively few limbs. As tree species go, lodgepole pine has a relatively small stem. The sizes that the trees attain will vary with the locality. The average diameter of any given mature lodgepole pine stand in the Gallatin Forest, for example, varies from 9 to 12 inches. The average height of these stands varies from 50 to 80 feet. Compared to the giant sequoias and redwoods of the West Coast, a typical lodgepole might be but a limb.

Table 3-II summarizes the important physical properties of lodgepole pine.

Table 3-II. Physical Properties of Lodgepole Pine^(a)

Property	Value
Specific Gravity	.45
Weight (8% moisture)	28.2 lbs/ft ³
Bending Strength (12% moisture content)	6700 p.s.i.
Crushing Strength	2460 p.s.i.
Shear Strength	712 p.s.i.
Modulus of Elasticity	993
Resistance to Impact ^(b)	16
Hardness (12% moisture content) ^(c)	480 pounds
Shrinkage (6% moisture content)	
Tangential	5.4%
Radial	3.6%

- (a) based on data published in references (32) and (56).
 (b) height in inches at which drop of 50# load causes breakage.
 (c) load required to imbed 0.444-inch ball to $\frac{1}{2}$ its diameter.

3.9 Growth Features. Besides being a small-stem species, lodgepole pine tends to grow at high elevations (between 4500 and 9000 feet) on steep and rugged mountain terrain. Logging has been observed in Montana on slopes of up to 70 percent! Not only are the trees small, but they are also inaccessible.

Lodgepole pine grows in both pure and mixed stands. Pure stands are those in which the percentage of lodgepole contained therein equals or exceeds 90. Mixed stands can contain one or more species besides lodgepole, the total percentage of which exceeds 10.

In addition, lodgepole stands can be either even-aged or uneven-aged. Even-aged stands are those in which all the trees are approximately the same age ($\pm$ 10 years from the mean age). Uneven-aged stands, naturally, contain trees of many different age groups and sizes. The trees in an uneven-aged stand originate more or less continuously, in contrast to the simple reproductive period characterizing an even-aged forest.

3.10 Cull. The amount of profit that a feller can make depends to a large extent on the type, size, and soundness of his material. Since the cutter is paid for the amount of usable product he cuts, the loggers "utopia" is a forest filled with an infinite number of large, straight, mature, sound trees. This "logger's dream" is seldom, if ever, encountered, especially in existing lodgepole stands. The problem plaguing the logging industry today is the overabundance of overmature stands that must be removed before the younger, more desirable ones can be worked on. Overmature stands tend to contain an abundant amount of "cull."

"Cull" is the general term used to denote those trees, or portions of trees that are rendered useless because of defects or decay of some kind. There are many different kinds of defects. Insects such as the mountain pine beetle (Dendroctonus menticolae), the lodgepole pine beetle (Dendroctonus murrayanae), and the lodgepole terminal weevil (Pissodes terminalis) can at times cause great damage to trees. Diseases like the dwarf mistletoe (Arceuthobium americanum) which inhibits growth, and certain fungi, such as the familiar "red rot," which cause decay, are dangerous enemies. In areas where there has been a fire within the last decade or so, standing trees may seem perfectly sound, but when cut down may prove to be dead or decayed in whole or in part. Animals, too, can be destructive. Porcupines and bears have been known to cause severe damage to trees by their sharp claws. And, like all living things, just plain old age gives way to decay and ultimately, death. Even a crooked or slightly bowed log is considered defective since the lumber recovery will be less than what could be cut from a straight log of the same dimensions.

The logger is usually paid according to an estimate of the ultimate usable product which might be recovered at the mill. The total volume of sound logs in board feet is deducted by the amount of estimated cull in arriving at the volume for which the logger will be paid. Thus, the cull factor, the percentage of nonusable wood in a stand, is of extreme importance to the logger. When a dead or deformed tree is cut down unknowingly, it is obviously a sunk cost. One of the things that this study should show is the effect of cull on earning.

The fact that the amount of cull is pronounced in old stands does

not mean that young stands are devoid of it. The implication here is that the probability that a young stand has less cull than this same stand would have if it were allowed to grow old is almost unity. To be sure, insects can attack young or old trees; fungi can creep in on young trees as well as old, etc. The point is that the effect of these injurious agencies, once they have set in, increases with time.

3.11 Rotation. There is an "optimum" age, called the "rotation age," at which a tree should be cut. The rotation age of a crop is affected by two basic groups of factors, (1) market factors, and (2) forest factors (3).

(1) Market Factors. The size and quality of timber that can be advantageously marketed exerts a powerful influence on the length of rotation. Since the purpose of growing the timber is to utilize it, there is no point in growing timber that cannot ultimately be marketed.

As an example of how this problem can be approached--assume that trees 15 inches in diameter are considered the ideal sawlog size. The rotation in considering the market factor only would be the time necessary to grow trees to about this size for the particular species, site, and kind of management involved. (Of course, at this time in point, all the trees will not be 15 inches in diameter; the diameters would be distributed about 15 inches as the mean).

(2) Forest Factors. The second influential set of forces affecting rotation is concerned with the productivity of the forest. Included in this set are measures of wood volume productivity, and pathological, entomological, and silvicultural considerations that operate as bio-

logical conditioning and limiting factors (10). Pathological and entomological considerations have already been discussed. Physical productivity refers to the physical capacity of the forest to produce wood--at what age is maximum volume achieved? Silvicultural, or regeneration, considerations of course are important also.

Thus, the length of rotation is set by finding the "best" combination of these variables for certain given conditions to maximize yield. In other words, the rotation age is the age at which a forest should be cut to maintain the proper balance among the aforementioned factors, while at the same time maximizing the return in terms of dollars, or usable timber. The optimum rotation age for lodgepole pine is about 100 years.

3.12 Valuation. In terms of dollar yield, lodgepole pine is a low-value crop. The stumpage price of lodgepole pine is somewhere in the neighborhood of \$2 per MBF. On the average, yields of 12,000 to 15,000 board feet are recovered from stands with densities of about 1,000 trees per acre, although the yield has been known to vary from less than 1,000 where trees are extremely small to over 20,000 board feet per acre in mixed old growth. Yields greater than 20,000 board feet per acre are uncommon (48).

Using an average figure of 13,500 board feet per acre, the value of a crop turns out to be about \$27,000 per acre per rotation period. Assuming rotation to be 100 years, this places a value of an acre of lodgepole pine per year of roughly \$270 (excluding interest). In addition, the land itself is not worth very much.

The low value of a crop poses some serious limitations when one

considers the amount of capital investment the typical logger has got to contend with. One large machine alone may cost up to \$75,000. Furthermore, a logging road must be built to gain access to the trees, and this is used only once. The only solution is for the logger to cover as much ground as he possibly can in order to "spread" out his costs. Factor (2) following Table 3-I says precisely this. Unless the timber volume is magnanimous, most loggers probably shouldn't even bid for a sale. If the volume is low, the cost of moving equipment from place to place might be more than the crop is worth. Although this will not be investigated in this work "per se," it is good food for thought.

In summary, lodgepole pine is one of the largest timber types in the West in terms of total area. It is a relatively low-value timber species. Lodgepole pine is smaller in size than most lumber species and grows at high elevations, often on steep slopes which makes the logging of the species difficult and expensive. The rotation age for the species is about 100 years. Like any other tree species, cull has a significant effect on the value of a crop. It must be controlled.

Part II

In this section, the model of the logmaking production subsystem is constructed and several trial simulation runs are made.

Chapter 4 outlines the preliminary conceptual model which was envisioned at the outset of this project. In this discussion, the computer block diagrams that describe the "system" graphically are presented and each phase of the diagrams is discussed. Chapter 5 is devoted to the data analysis and testing of the model under simulated field conditions.

Appendix A presents some of the more important statistical concepts and techniques used in the model construction.

CHAPTER 4

PRELIMINARY CONCEPTUAL SIMULATION MODEL

4.1 Proposed Schema. At the outset of this study, it was believed that a "generalized" model of logmaking could be constructed. That is, it was hoped that the model could be used for evaluating any given logmaking operation on any given area. By varying input data and basic parameter values, the model could be manipulated at will and the results of each trial observed, tabulated, and compared.

However, at the present stage of development this approach would not be feasible. Perhaps the greatest limiting factor was the author's ignorance of certain important aspects of forest technology. As pointed out before, silvicultural, biological, and pathological considerations all have an effect on the productivity of both the logger and the forest. Relationships between site and stand factors such as growth rate, ultimate diameter and height attained in a particular stand, spacing between trees, etc. would need to be known. However, research on lodgepole pine is relatively new. As it stands now, few general statements can be made on the stand characteristics one would expect to find in any given lodgepole pine stand.

For this and other reasons, it was decided that the problem should be approached along the lines of a "case study." The results of the "case study" model would be meaningful in any given area, provided that complete stand information was available for that area. The recording of certain necessary field data to ultimately serve as input to the model would be required.

Part of the original plan was to follow every movement that the

worker would be expected to make. The smallest time element in this case would be seconds, or fractions of seconds. This approach assumes that the worker's movements at any given time and certain unforeseen "unavoidable delays" are predictable. After experimenting with this approach, it was seen to be too detailed an analysis to undertake with the knowledge that is currently available or could be obtained within the time limit imposed. Besides, the practicality of such an approach is questionable. Time involved in making a decision, stumbling, freeing a pinched saw, and other similar delays could not possibly be anticipated, and the attempt to do so would probably belie the results obtained considerably. As Conway, Johnson and Maxwell pointed out (9) the tendency to become too detailed in model-building often leads to erroneous conclusions.

The basic time unit with which to experiment was then set at one hour. However, during this hour time unit, activity involving only minutes and seconds could be "observed" and transformed to hour time units for analysis purposes.

Using this approach, a certain amount of time within hours would be unaccounted for, from which certain inferences on delay time could be made. This "lost time" could be taken to represent such things as:

- (1) making a decision
- (2) freeing a pinched saw
- (3) freeing "hangers"
- (4) removing obstacles
- (5) stumbling
- (6) minor breakdowns
- (7) travel to and from gas cans
- (8) idleness

This list is intended to point out the wide variety of delays that can be encountered and is certainly not all-inclusive.

Thus, the visualized model can (1) account for productive time, in total and by constituent, and (2) estimate total unproductive time. If total unproductive time were found to be sizeable enough to warrant special investigation, recommendations would be made along these lines.

BLOCK DIAGRAMS AND COMPONENT DESCRIPTIONS

Block diagrams depicting the "logic" to be involved in the model were constructed. The program was to be eventually written in two phases. Block diagrams for both phases will be presented and discussed separately.

In the first part (Phase I) basic forest data from which the area to be logged is "set up" is read in. The second phase (Phase II) receives the intermediate output from Phase I as input and "performs" the log-making operations on the forest (Fig.4-1).

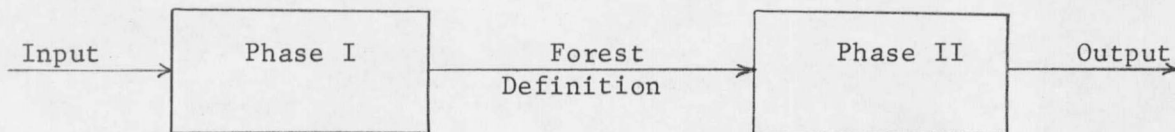


Fig. 4-1. The Two-Part Simulation Model

A discussion of each phase follows.

Phase I - Setting Up the Forest

This phase is relatively straight forward (Fig.4-2). Probability distributions of dbh, total height, and limbage* serve as input. A tree is "defined" by sampling from each of these distributions. Merchantable height of each tree is computed. The length of stem that is free of limbs is determined. If the tree contains cull, cull type (s) and the percentage of the tree affected is ascertained. This information is punched, one card for each tree, and is received as output in a probable cutting order.

4.2 Component Descriptions.

4.2.1 Sample data: Before any "logging" can be done, the forest must be defined. This requires reading in the distributions of diameters, heights and limbage for the given area.** Field measurements of the following tree characteristics in the area to be logged must be sampled:

- (1) diameter at breast high (dbh)
- (2) total height
- (3) length of stem that contains live limbs.

One need only measure those trees that are, by size, considered merchantable, but the number of nonmerchantable trees in the sample

* Length of live crown, or crown/height ratio

** Subject to certain restrictions discussed later.

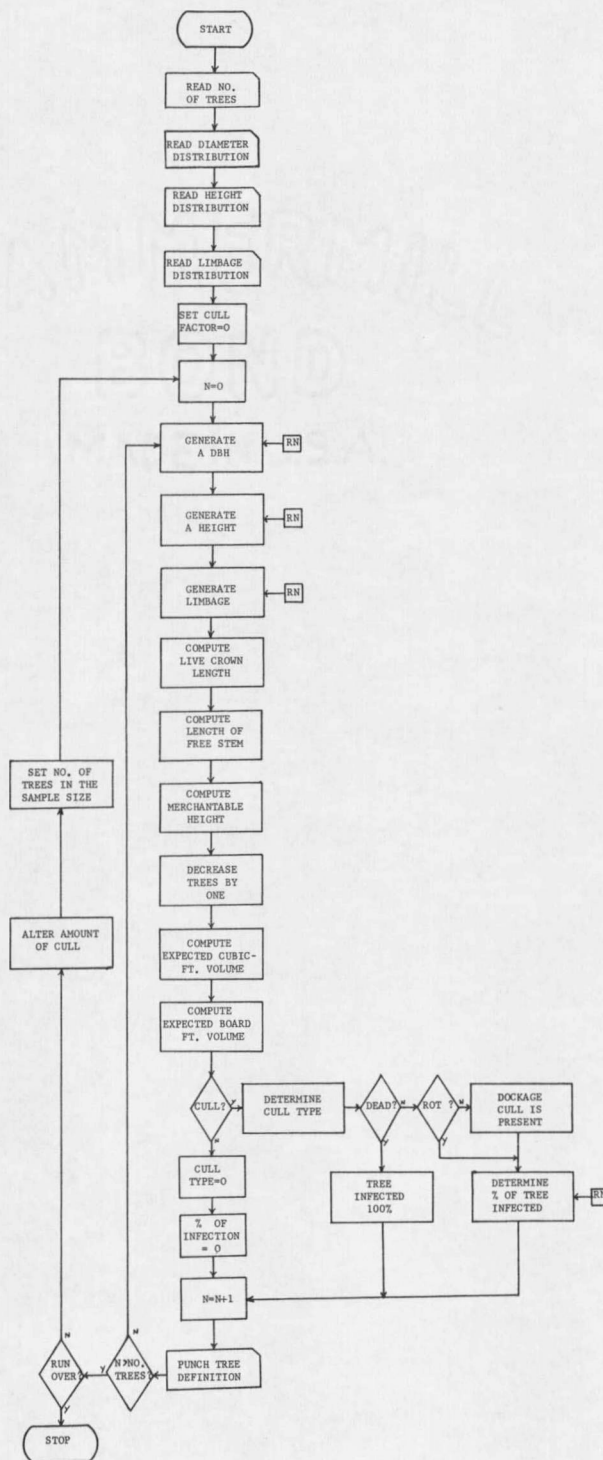


Fig. 4-2. Block Diagram of Proposed Phase I

should also be tallied for reference. Total heights are measured to the uppermost point of the tree. Since "dry" limbs are expected to fall off during skidding, only live limbs are included in measurement number (3).

Age would seem to be interrelated with these tree characteristics. However, age is difficult and expensive to measure. Unless the further refinements created as a result of its inclusion are sufficient, the author does not recommend that age data be gathered. Also, the amount of cull need not be estimated. Reasons for this are brought out later.

From the above data, (4) crown/height ratios and (5) density, in trees per acre, can be computed. Probability functions for variables (1), (2), (3), and (4) can then be constructed.

4.2.2 Probability function for dbh. The empirical probability function for dbh might look something like Fig. 4-3.

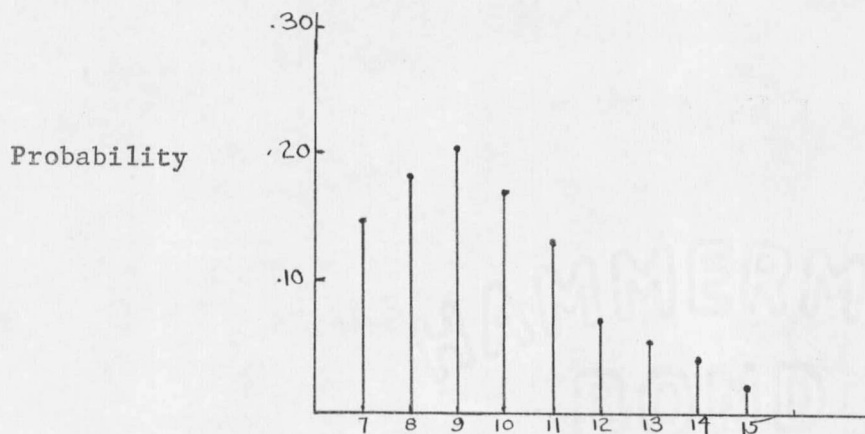


Fig. 4-3. Dbh Probability Function

The shape of the function may be regular or irregular. Bruce and Schumaker (6) state that in even-age stands, the diameter distribution

is approximately normal, and in uneven-aged stands, somewhat exponential. Most stands are somewhere in between these two extremes (11). For this reason, it is suggested that empirical distributions be used in the simulation, although where it can be proven with a reasonable degree of confidence that the empirical distribution conforms to a well-known mathematical distribution, the mathematical distribution should be used.

In order to sample for dbh, it is necessary to construct the distribution function, $F(x)$, shown in Fig. 4-4.

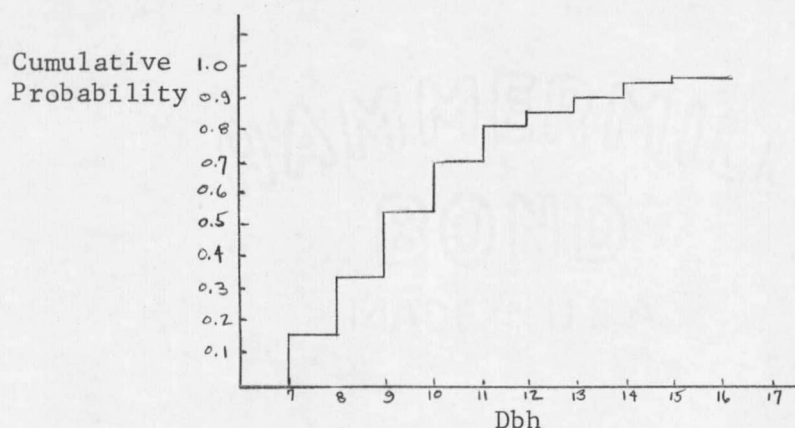


Fig. 4-4. Dbh Distribution Function

From Fig. 4-4, a probability table for dbh can be set up. Then, by generating random numbers within the computer program and entering the table at the appropriate places, sample values of dbh can be obtained. This event will mark the selection of a tree. The order (random) in which they are selected corresponds to one probable order of selection in the field. After each sample value has been obtained, the corresponding ordinate must be decreased by one, since we are dealing with a finite population. Thus, by starting with N values of dbh, and decreasing by one each time a sample value is drawn, the distribution will have vanished

after N sample values have been taken.

4.2.3. Distribution of total height, crown length, and crown/height ratios.

Height and crown data can be similarly analyzed, only now conditional probabilities must be dealt with. This is where one must be extremely careful. In any given area, independence of diameter, height and limbage cannot be assumed. It is desirable to investigate each case separately, since lodgepole pine growth characteristics are unpredictable. Among stands, there seems to be no predictable association between height and diameter, say, although within any given stand, such an association might exist (stand density has proven to be a significant variable here). Immediately after the data is collected, it is a good idea to determine the nature and degree of relationship among the stand variables. If a statistically significant relationship between these factors can be inferred, it must be taken into account in the model. Methods of doing this are brought out in the next chapter.

4.2.4 Volume determinations.

Estimated tree volumes, both cubic-foot and board-foot, will be computed in Phase I. In Phase II actual volumes will be computed for comparison. Cubic foot volume is a measurement of actual solid wood content while board foot volume is an estimate of the yield in terms of usable lumber. It is the latter volumetric measurement that determines the dollar value of the log or tree to the logger.

a. Cubic-foot volume. In most cases, the cubic foot volume of a tree or log (inside bark) can be estimated quite accurately when its shape is assumed to be that of a regular geometric solid. The inherent error in this approach, naturally, depends on the similarity between the form of

the tree section to be measured and the geometric solid upon which the formula is based. Although trees seldom, if ever, exactly fit the dimensions of regular solids, the error accrued by using standard formulas is usually not appreciable (22).

Although the tree as a whole is usually assumed to be in the shape of a paraboloid or cone, when that tree is cut into several logs or sections the individual pieces approach different forms, depending on their position in the tree (Fig. 4-5).

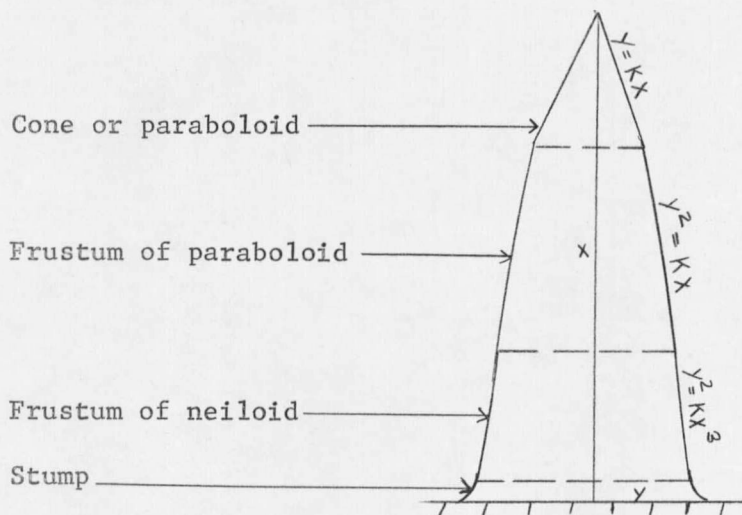


Fig. 4-5. Geometric Forms Assumed by Portions of a Tree Stem

The butt section of the tree is similar to a frustum of neiloid; the central portions approximate frustums of paraboloids; and the top section approaches a paraboloid or a cone, depending on the assumed tree form.

Each of these solids - neiloid, cone, paraboloid - is produced by the revolution about the x - axis of a curve of the form $y^2 = KX^r$. As the exponent r varies, the solids shown in Fig. 4-5 are produced.

For logs approaching frustums of paraboloids (which is usually every log but the first) either Smalian's or Huber's formula is used to compute

cubic foot volumes.

Smalian's formula is of the form

$$V_s = \frac{L}{2} (B_b + B_u) \quad (\text{eq. 4.1})$$

where V_s = cubic foot volume, Smalian
 L = total length of section
 B_b = cross-sectional area of base
 B_u = cross-sectional area of top,

and is the most-used.

Since the cross sectional area at a point halfway between the ends of a frustum of paraboloid is exactly the average of its end areas, cubic foot volume can also be obtained from Huber's formula:

$$V_h = LB_{\frac{1}{2}} \quad (\text{eq. 4.2})$$

where V_h = cubic foot volume, Huber
 L = total length of section
 $B_{\frac{1}{2}}$ = cross-sectional area halfway between ends.

Although Smalian's formula is used more often, Huber's formula is known to give more accurate results if the logs are not exactly paraboloids. However, the difference between values obtained by either of these formulas is usually slight.

Butt log volumes are not so easily obtained. For most tree species neither the Huber nor the Smalian formula usually gives adequate results here since the butt logs have an odd shape due to butt swell. However, since the typical lodgepole pine has very little butt swell, the Smalian or Huber formula has proven to be an adequate measure of cubic foot volume for the butt log.

The volume of the top of the tree can be approximated by using a paraboloid or conic formula. Since in reality the actual form of the

top is somewhere between the two, it usually makes little difference which form is assumed.

The volume of the entire tree can be computed in any one of four ways. The first, adding up the individual section volumes that make it up, is the most accurate. The second way to obtain total tree volume is to assume a geometrical solid and compute the volume using an assumed formula. This is perhaps the most inaccurate method. The third way is to construct a volume table in which the average cubic foot volume is given corresponding to a particular dbh and height. The cubic volumes given in the table are obtained from direct measurement. The last method, which is related to the third, is to derive a regression equation of the form

$$y = a + bx \quad (\text{eq. 4.3})$$

where

y	=	total tree height
a	=	a constant
b	=	a regression coefficient
x	=	(diameter) ² (height),

using the volume table as a basis. This is now the most popular approach.

b. Board-foot volume. Measurement of trees or logs in board feet is an attempt to predict the ultimate amount of usable product that will be obtained from that tree or log after slab, kerf, and edgings are removed.

One "board foot" is a unit 12 inches wide, 1 inch thick, and 12 inches long. At the present time, there are over 40 different log rules in use throughout the United States, each resulting in a different board foot value for logs of the same dimensions (46). No single rule has been adopted as standard by the logging industry; however, the United States

Forest Service has officially accepted the Scribner Decimal C Log Rule (a variation of the Scribner rule) as its guide, despite serious inaccuracies. For logs of the same dimension, variation in the obtainable board feet can be due to any one or more of the following factors (22):

- (1) Amount of defect, such as rot, and the straightness of the log
- (2) Thickness of the saws used in milling
- (3) Amount of waste in slabs and edgings
- (4) Thickness of lumber sawed
- (5) Width of narrowest board sawed
- (6) Skill of sawyer
- (7) Efficiency of sawmill machinery and mill crew
- (8) Amount of log taper

It is at this time inconceivable that a universal log rule could possibly accurately account for all these factors, which tend to vary with the locality. It would probably be impossible to find a sawmill that would meet exactly the conditions on which a particular log rule is based.

A few of the more popular board-foot estimation methods will be discussed below.

The Scribner Log Rule was prepared by marking off boards that might be sawed from a log on a scale diagram which represents the small end of the log (Fig. 4-5).

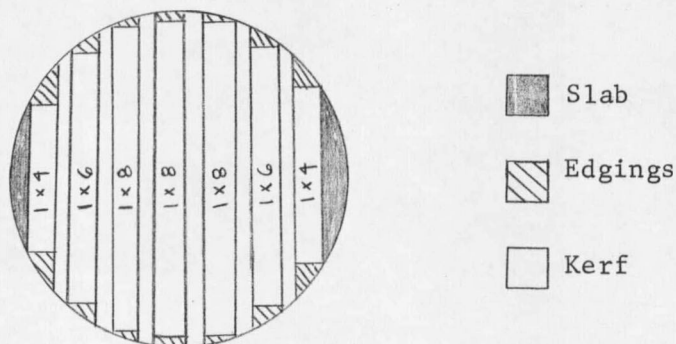


Fig. 4-5. Diagram of Scribner Rule Derivation (6).

The small end is used because this is taken to represent the maximum board width dimension obtainable (a premise which is no longer true because of the development of more modern mill machinery).

Starting from the left, board 1 is the thickness and width of the minimum board which is considered merchantable. By drawing in all of the merchantable boards out of the remaining portion, allowing for saw kerf, edging, and slabs, the board foot volume of that log can be computed by adding up the individual board feet; assuming, of course, that the length of the log is known. The Scribner rule is based on inch boards, assuming a $\frac{1}{4}$ " kerf; and volumes were computed for whole inches, disregarding fractional values.

By repeating the above procedure for a large number of logs, the results may be incorporated into a log rule or volume table. Since the 16.3 foot log, commonly called a 16-foot log, is by far the most common, a table was worked up for the Scribner board-foot-volume of logs of this size (Table 4-I).

Table 4-I. A Portion of the
Scribner Board-Foot Volume Table for 16-Foot Logs.

[illegible]

As no allowance is made in the Scribner rule for taper, the board-foot contents of logs of equal small-end diameter are directly proportional to their length, although taper allowance can be made for logs over 16 feet in length by dividing the log into 16-foot sections, and summing the volume of each section.

The Scribner rule was derived over one hundred years ago (in 1846) and is considered highly inaccurate today. It has been shown (6) that log scale and mill tally agree fairly well for logs up to about 28 inches in diameter, above which the mill can produce more than is indicated by Scribner. This is called overrun and is usually expressed as a percentage of log scale. By way of illustration of the inadequacy of the Scribner rule, Fig. 4-7 shows the percentage of overrun by diameter classes which can be considered to be typical of the Scribner rule.

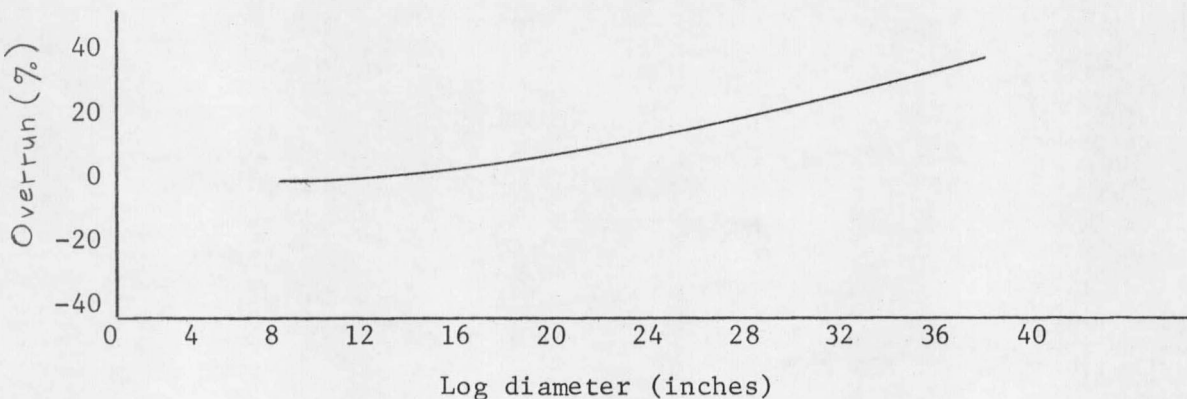


Fig. 4-7. Overrun With the Scribner Log Rule

The Scribner Decimal C Log Rule used by the Forest Service is obtained by rounding off all volumes of the Scribner rule to the nearest ten and dropping the zero.

When computing board-foot volumes with either Scribner or Decimal C the fact that the butt logs approach frustums of neiloid is of no concern, since the small diameter is used. Thus, butt swell, although it can have an effect on cubic-foot volume computations, has no effect on board-foot volume computations.

The International Rule is probably next to the Scribner rule in popularity. It is known as a "formula" rule as opposed to the Scribner rule, which is a "diagram" rule. Formula rules have been derived by working out mathematical formulas to give the volume of a log in terms of its small diameter and length. The International rule was derived by repeatedly refining the formula for the volume of a cylinder by taking into consideration the losses that are incurred in the sawing process.

The International rule provides an allowance for taper. It also has the advantage of being easily modifiable to apply to any thickness of saw kerf. Also, there is usually little overrun when it is used.

A comparison of a few Scribner and International $\frac{1}{4}$ " volumes is provided in Table 4-II.

Table 4-II. Comparison of International and Scribner Volumes
for 16-Foot Logs

Log Rule	Diameter, small end, in inches						
	6	7	8	9	10	11	12
Scribner	12	21	31	42	51	70	86
International	20	30	40	50	65	80	95

International rule volumes are consistently higher than corresponding Scribner volumes. The major reason for this is that no allowance is made in the Scribner rule for log taper.

Volume by Weight is the most recent board-foot estimation method. Many processing plants now compute board-foot volumes of log loads strictly on a weight basis. Prior to being logged, the area to be harvested is sampled for a tree "weight factor" (i.e. pounds per board-foot). At the mill, the loaded truck is driven over a scale, and the gross weight is recorded. The load is removed, the truck is reweighed (minus logs), and the weight difference computed. This figure is then divided by the pre-determined "weight factor" to give an estimate of the number of board feet contained in the load.

Although, in essence, the weight scaling procedure is a different method of board-foot estimation, the derivation of the "weight factor" is obviously dependent on one of the board foot rules. Thus, similar results should be obtained.

Loggers complain about this estimation method on the premise that the weight of wood varies within stands, depending on its moisture content, greenness, and age. They argue that the assignment of a "flat" weight factor is unrealistic.

4.2.5. Cull. Cull would not be recorded on the survey. It is almost impossible to predict the amount of cull accurately enough for our purposes, since one cannot always determine whether some tree defect exists. It seems to be more practical to vary the amount of cull within the model and observe the results of such manipulation.

Assigning a "flat" value of the cull factor (a fixed percentage of total volume) is misleading, since it gives no indication of the nature and effect of different types of cull. Each type of cull has to be treated differently - with varying costs associated with each treatment. For example, a dead tree is not even cut down - no "out-of-pocket" cost is incurred. On the other hand, portions of trees containing red rot are salvageable - with increasing costs caused by the extra necessary cuts. A penalty for log defects is imposed at the mill - in the form of the cost of a certain percentage of total volume. If a log contains a large amount of defective material, the value of usable material may be less than the cost of producing it!

Thus, in this analysis, three different types of cull are distinguished-- (1) dead trees, (2) rot, and (3) defects assessed at the mill. It may be shown that one cull type is more disadvantageous than another, although no cull at all is obviously the most desirable.

If a tree has been found to have cull, in part or in total, the model will assign a specific type of cull to the tree and determine the percentage of the tree infected. The fact that a log contains cull does not always render it completely useless; in fact, the mills in this area will take anything over 50% sound.

What is envisioned is something like the following. As the cull factor increases the amount of profit that a logger can make decreases. Schematically, the situation looks somewhat like Fig. 4-8.

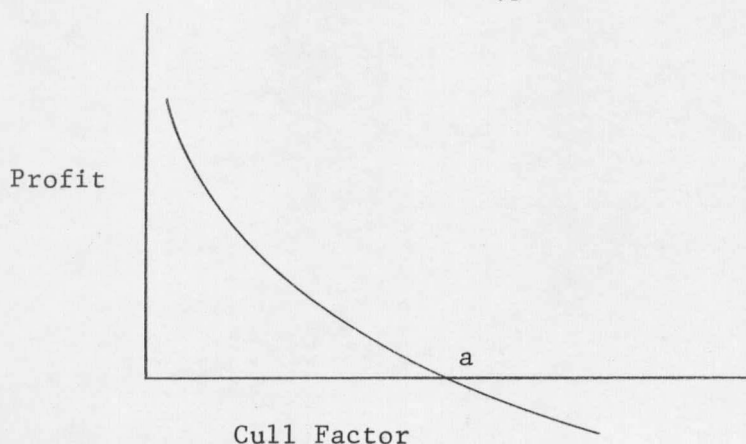


Fig. 4-8. Cull vs. Decreasing Profits

There is some point, denoted by "a", at which income exactly equals cost. Beyond this point, it actually is a losing proposition; it costs more to operate than is received for the product! We will call the point "a" the break-even point (BEP).

In the model a tally will be kept of cull volume and total usable board-foot volume. The stand cull factor is then computed as the quotient of cull volume and the quantity cull volume plus usable volume. Revenue could then be computed to compare with the cost of operation, and the results plotted and analyzed.

4.2.6 Merchantable height. In order to evaluate the dollar-value of the tree and to determine the optimum combination of logs to be obtained, merchantable height must be computed. Merchantable heights can be taken in one of three ways, viz.

1. To a point on the tree where the diameter is a fixed number of inches.
2. To a point on the tree which marks the top of the last merchantable log.
3. To a point on the tree where the diameter is some fixed percentage of the dbh.

The choice (in the model) of one of these methods should be dictated by local policy.

In order to compute merchantable height, the taper of the tree must be known. Taper is the decrease in diameter of an entire tree or section from its base to its tip. By measuring diameters at successive points along the stem, it is possible to develop average taper tables which show expected diameters at certain heights along the stem for trees of a given height and dbh. In other words, the diameter at any point is a function of the dbh, the height, and the height of the point at which the diameter is to be measured. Taper tables for lodgepole pine in Gallatin County can be found in a publication by Mason (32).

4.2.7 Free stem. In addition to the above, one more computation is made. This computation determines the length of stem that is devoid of live limbs. It is useful because when computing limbing time, we would want to know the distance traveled on the log before starting the actual limbing operation. It would be completely erroneous to assign the same limbing time estimate to both the traversing of the "free" stem and to the actual removing of limbs.

4.2.8 Intermediate output. The output desired from Phase I is a card for each tree in the logging chance. The order in which the cards are punched is one possible order in which the trees will be cut (note: it is not the only order). Each output card will contain values for all parameters computed within the program. It should contain:

- (a) tree number
- (b) dbh
- (c) total height

- (d) merchantable height
- (e) crown length
- (f) length of free stem
- (g) estimated cubic foot volume
- (h) estimated board foot volume
- (i) type of cull, if any
- (j) percentage of the tree affected by cull

This information serves as the major input to Phase II.

Phase II - Logging the Area in Question

The second phase of the model "logs" the output from Phase I. From before, the logging can be performed in a variety of ways. The simulation model should have provisions for evaluating each possibility.

In Phase II (see Fig. 4-9), basic deterministic data such as the number of trees to be cut, standard log lengths, and production rate* (assume constant production rate in any one day) are read into the machine. Then, the walk-on-log travel time and limbing-time-per-foot distributions are read in.** The parameters of the distribution of the distance-between-trees, the mean and the standard deviation, are computed. The various accounting registers are set to zero and the simulated logging experience begins. A data card (from Phase I) is read in. A sample cutting time is generated, and the tree is "cut down." The tree is examined for cull and the appropriate action taken depending on (1) whether the tree contains cull; (2) what type of cull is present, if any, and (3) the percentage of the tree infected. Subject to the outcome of the cull investigation, the optimum combination of logs is determined. The tree

* trees cut per hour

** These variables are explained in sections 4.3.3 and 4.3.4.

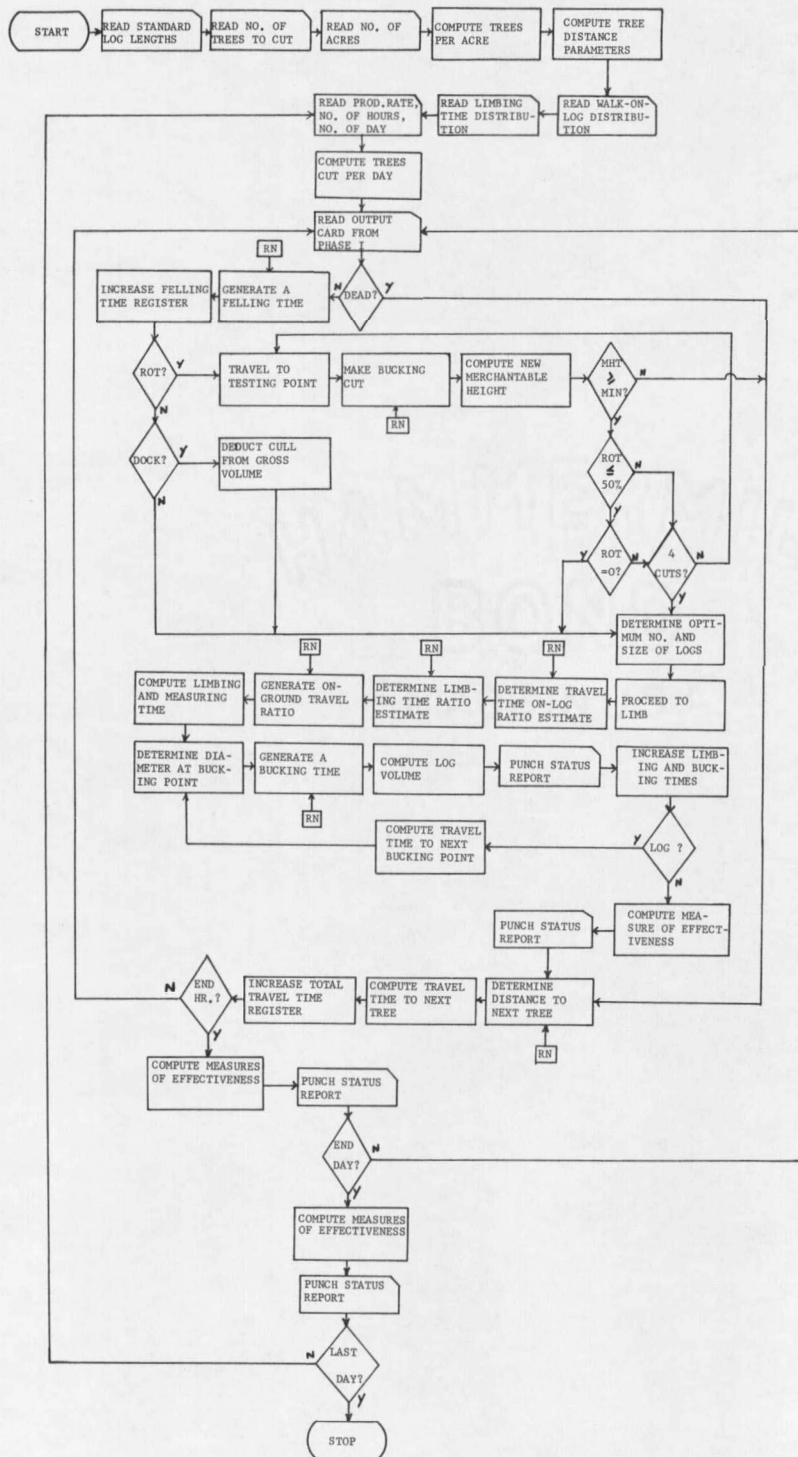


Fig. 4-9. Block Diagram of Proposed Phase II

must next be limbed and bucked. Sample values of on-log travel time and limbing time ratio estimates are generated. Limbing time for the tree is the length of "free" stem multiplied by the sample value of on-log travel time plus the product of the sample limbing time and the length of tree containing live limbs. The diameter at the points of bucking must be determined. With these diameters known, random bucking times can be assigned. Total limbing and bucking time is computed as the sum of limbing time, bucking time, travel time between bucking cuts, and all time taken up by measuring and climbing on and off the stem.

Volume, both cubic-foot and board-foot, is computed for each log. Costs and revenues are computed. Profit (or loss) is determined. Then, the distance to the next tree is determined, a sample value of walk time per foot of distance obtained, and travel time is estimated by multiplying these two quantities. The appropriate accounting registers are increased by the proper amount at each step of the above process. Output consists of a series of "status" reports - one after each log has been produced, another after an entire tree has been worked on, a third at the end of each hour, and, finally, one at the end of each day. These "status reports" give information on production, cost, revenue, and profit. One or all of these reports may be desired.

4.3 Component Descriptions.

4.3.1 Standard log lengths. The acceptable log lengths must be read in and can be varied at will to correspond to reality.

The set of acceptable log lengths handed down by the processing plant is the primary restriction on the bucking operation. The number of acceptable log lengths can vary from 3 to 7 depending on the type of

of mill involved. For example, a mill sawing solely sawlogs will accept logs no shorter than 16 feet; a stud mill will take logs as short as 8 feet; and a pole manufacturer accepts nothing shorter than a 25-foot log. Similar comparisons can be made on the acceptable upper bound. These specifications must be adhered to. If not, the logger is "docked," or penalized, a certain percentage of his pay for cutting short or long logs.

The most common log lengths, in feet, are given in Table 4-III.

Table 4-III. Common Acceptable Log Lengths ($x_1, \dots, x_n$)

Set	Number of Logs	x_1	x_2	x_3	x_4	x_5	x_6	x_7	Primary Mill Product
1	3	33	25	16	-	-	-	-	Lumber
2	4	33	25	16	8	-	-	-	Stud
3	5	45	40	35	30	25	-	-	Pole
4	6	33	31	29	27	25	16	-	Lumber
5	7	33	31	29	27	25	16	8	Stud

Logs are not cut to the even foot as indicated here. For example, a 16-foot log is actually 16.3 feet long; a 33-foot log is actually 32.6 feet long, etc. The extra margin of .3 feet per 16 feet of log length allows for trimming at the mill.

Naturally, any merchantable timber left in the woods is not creditable for payment purposes and is a wasted resource. The amount of timber left behind is really a source of potential income for the logger. Wasted timber is a function of the accepted log lengths and logger proficiency.

4.3.2. Production rate. It is desired to vary production rate and note the effect this alteration has on (1) profit, (2) total cost, (3) productive and unproductive time (effectiveness). Trees cut per hour, working hours

at this production rate, and numbers of the simulated day are to be read in. From this data, the number of trees to be cut per day can be computed.

4.3.3 On-log travel time: On-log travel time is distinguished from on-ground travel time. On-log travel time denotes the time per unit distance required to traverse a clean*felled tree, or log. As mentioned in Chapter 2, when the feller performs the limbing and measuring phase of his operation, he usually walks on top of the stem. The time to traverse a log is suspected to be greater than the time to travel the same distance on land. Therefore, separate travel time ratios should be computed for each.

There are many impediments affecting on-log travel time besides the obvious one of balancing oneself on a round bole. One of these factors is the taper of the tree. Theoretically, the travel time per unit distance on any given log is a function of the diameter of the log at the point of contact. Diameter at any point, of course, varies with form, or taper of the log. Thus, even though the difference may be insignificant, travel time per foot on a 32-foot log with a top diameter of 16-inches that tapers down to a 6-inch diameter would, in all probability, be greater than the travel-time ratio for a 32-foot log with a 16-inch top diameter that tapered down to 10 inches. Again, no one constant value of a travel time ratio would be desirable. By sampling a large number of walk times on trees or logs of a given size, a distribution of ratios from which to sample could be constructed. Even though this approach will be adequate for this study, there are probably more elegant ways of doing it.

4.3.4 Limbing time ratios: The time to limb a tree depends on (1) log

* i.e. a portion of a tree containing no limbs

length, (2) the length of the stem on which there are limbs, (3) the number of limbs, (4) the size of limbs, and (5) the efficiency of the sawyer. In addition, since limbing is performed while walking along the log, and on-log travel time depends on diameter and taper of the log, then limbing time would also depend on these two factors as well.

By securing limbing data on a sufficient number of trees, limbing time per foot for a tree of a given dbh can be conditionally distributed.

4.3.5. Output from Phase I. The major input to Phase II, as mentioned before, is the output from Phase I. The cards are read in exactly as punched in Phase I. Each card represents one tree. Some of the characteristics read in will be used for computing certain quantities of special interest, others will be used strictly for comparison purposes, and still others will be used solely for identification.

4.3.6 Distance between trees. The reason that the path of a feller can never be predicted with any certainty is that the distance from any one tree to the "next" is difficult to define, since the progress of a cutter through the woods can be thought of as a "random walk." One might try to simulate the cutter's experience by picking a starting point A, and advancing to the tree nearest to it; etc., and recording distances between each, until all the trees have been reached. There is no assurance, however, that this will be the path followed.

Actually, only the average distance between trees and the deviation from this average need be known. Distance between trees can also be expressed in a probability distribution, and has been found by experiment to be closely approximated by the normal distribution. This will be discussed in the next chapter.

Average spacing can be found by dividing the area of a stand by the number of trees to cut per acre and taking the square root of this quantity (9). The distance from one tree to the next is usually measured between center lines. When the measurements are taken, follow the procedure mentioned above. Choose a starting point and measure the distance to the nearest merchantable tree. Continue this practice until all the trees have been included. Do this a number of times, starting at a different tree each time, and analyze the results.

4.3.7 Registers. Registers for keeping track of values of all the variables of interest must be set to zero. These registers will be modified as we proceed.

4.3.8 Felling times. Felling times for trees of different diameters could easily be obtained through field work. Naturally, cutting time increases with diameter. Perhaps some empirical formula could be derived that would yield the expected cutting time for a given dbh. Unable to find such a formula, we may be required to work with conditional probability distributions. At any rate, measurement of dbh and time required to fell the tree would seem to be all that was needed. Associated elements such as clearing obstacles and pushing the tree over can be included at the discretion of the analyst.

4.3.9 Treating cull. Each type of cull is treated in a different way. If the selected tree is found to contain no cull, the program advances directly to the next section-"optimizing log combinations." If cull type (1), (2), or (3) in 4.2.5 is present as indicated on the input card, the following is done:

Type 1* Dead trees

-Once a tree has been selected and found to be dead, the cutter proceeds to the next tree (i.e. travel time to the next tree is computed and another sample dbh is generated)

Type 2 Rot

-Portions of a rotten tree, provided it is only partially rotted-out, may be salvageable. If stump rot in excess of 50% of bole diameter is detected after the tree is cut, a maximum of four cuts are made at 4-foot intervals along the stem until

- (a) no rot remains,
- (b) rot remains after 4 cuts, but comprises less than 50% of bole diameter,
- (c) the remaining merchantable height is less than the minimum allowable merchantable height.

If either (a), (b), (c) has occurred, the cutter proceeds to the next tree.

Type 3 Dockage

-This cull type is handled by deducting the percentage of the tree affected by cull from gross volume.

4.3.10 Optimizing log combinations: After the tree has been felled and any cull removed, the proper combination of logs to maximize profit must be determined. The big restriction here is that the logs must all be of an acceptable length. The logger tries to minimize

- (1) amount of merchantable tree left in woods, or
- (2) number of necessary cuts,

in that order.

Essentially, the logger attempts to maximize the volume of wood taken while minimizing his effort. He wishes to determine the log combination that will minimize waste. If only one log combination yields

* Actually, this cull type is detected before the tree is cut down, both in the field and in the model. If the tree is dead, it is not felled.

minimum waste, choose that one. If more than one combination yields minimum waste, choose the one with the least number of logs. If more than one minimal set is composed of an equal number of logs, choose that combination that will allow the cuts to be made at the points on the tree with the smallest diameters. These are the so-called "rules" of the logmaking game.

4.3.11 Limbing and bucking. Limbing and bucking are carried out simultaneously. The logger mounts the butt end of the tree, fastens the end of his tape in the butt and proceeds to measure off the first log, limbing as he goes. If the first log contains no live limbs, the limbing time for that log is simply the on-log ratio estimate multiplied by the length of free stem plus the limbing time ratio estimate multiplied by the difference between log length and free stem. If the log is completely covered by limbs, the limbing time, is, of course, the limbing time ratio estimate multiplied by the length of the log. When a bucking point is reached, the time to make his reference mark would be accounted for, or, if only one log in the tree, time to disembark and reel in the tape would be accumulated and the bucking time determined. If only one log is to be obtained from the tree, this point marks the end of the limbing and bucking operation.

Assuming more than one log is obtainable, once the first bucking time is determined the feller must retrace his path--on the ground this time--to the preceding bucking points. Therefore, the travel time is determined by multiplying the on-ground travel time ratio estimate by the length of the log that was just cut. This procedure is followed until all logs

have been obtained. Limbing and bucking ends at the point of the last buck cut.

4.3.12 Bucking times. Bucking time data, like felling times, can be obtained in the field. By timing the bucking operation and immediately measuring the diameter at the bucking point, the necessary relationship between diameter and bucking time can be derived. One must be careful to time and measure a sufficient number of cuts to insure that the relationship obtained is reliable. If no reliable mathematical relationship exists, raw empirical probability functions can be used.

4.3.13 Volume determination. Volumes are obtained as in Phase I, except that volumes, both cubic foot and board foot, will be obtained for each log in a tree and summed to give total tree volume. The estimated tree volumes from Phase I will be compared to the actual volumes for a check on consistency.

4.3.14 Travel to the next tree. Between-tree travel time in this study is considered to be the time required to move from the final bucking point to the next tree to be cut. To get to the next tree, the cutter is assumed to retrace his path along the stem (along the ground this time) from the first bucking cut to the stump before proceeding to the next tree to be cut. Thus, the distance to the next tree is the sum of the butt log length of a tree and the sample value of distance-between-trees obtained previously. Multiplication of this sum by the "on-ground" travel-time ratio estimate yields the desired expected travel time to the next tree.

Of course, the path of the cutter in the simulation only approximates the path he follows in practice. To be sure, this is the route

usually taken; however, variations undoubtedly occur. It must be understood that this procedure represents a typical situation.

4.3.15 On-ground travel times: On-ground travel time is probably best expressed as travel time per foot of distance traveled. By knowing this ratio and knowing the distance to be traversed, a simple multiplication yields the desired travel time for that distance. The travel time per unit distance, of course, varies with the conditions under which the travel is made. Ground relatively free of "litter" can be traversed more quickly than can ground that is covered with limbs, undergrowth, entanglements, and debris. Thus, rather than apply a constant value of travel time per foot or yard, it is more advantageous to record the times under a variety of conditions and use the data thus obtained in the form of a probability distribution.

Time recordings should be made of fellers in action. They should be equipped with their usual contrivances- chain saw, logger's tape, and wedge, if one is used.

In some areas the gas and oil containers, file, tools, and personal effects are carried from tree to tree. If so, the time to gather this apparatus should be recorded separately. In some cases, this data may be combined with travel times. In this area, though, these items are left in one spot until needed, at which time the feller must locate and travel to this storage place. Each method has its advantages, and care should be exercised in the recording of the travel times to insure that no error is made in interpretation of the results.

When gathering data, most of the distances over which the feller travels must be estimated rather than measured. This, of course,

represents a possible source of error.

The probability distribution for travel time was to be incorporated into the mainline program rather than reading it in as input.

4.3.16 Revenue. Revenue calculations are made by computing the net scaled board-foot volume and multiplying it by the going pay rate. This rate can, of course, be varied at will.

4.3.17 Cost. Total cost can be separated into fixed (independent of production) and variable (varies with production). Total cost is computed every hour and then again at the end of each day. It would be pointless to try to compute costs for anything less than a one-hour time limit.

4.3.18 Profit (Loss). Profit, or loss, naturally, is the difference between revenue and cost. If the revenue exceeds the cost, a profit is incurred. If, on the other hand, cost exceeds revenue a loss is accrued. The model computes profit or loss at the end of each day. Thus by varying the input and certain parameters within the model, the effect on cost, revenue and profit can be studied.

Since the cutter provides his own machine and assumes all the cost of fuel, maintenance, and repair, if his revenue does not exceed his cost of operation, it is senseless to go out to the woods. If he knew beforehand what his profit (or loss) might be, then his decision-making function would be eased considerably.

4.3.19 Output. Output from Phase II takes four different forms. The following information should be punched:

- (1) For each log,
 - (a) length
 - (b) diameter at both ends
 - (c) cubic foot volume
 - (d) board foot volume
- (2) For each tree,
 - (a) actual cubic foot and board foot volume
 - (b) expected cubic foot and board foot volume (from Phase I)
 - (c) differences between actual and expected volumes
- (3) At the end of each hour ,
 - (a) the day
 - (b) the hour of the day
 - (c) production rate
 - (d) total cost
 - (e) revenue
- (4) At the end of each day,
 - (a) the day
 - (b) production that day
 - (c) productive time
 - (d) unproductive time
 - (e) proportion of productive time spent in felling, limbing and bucking, travel, excess work time caused by cull
 - (f) total distance travelled
 - (g) income received
 - (h) total cost
 - (i) amount of profit or loss incurred

After each trial run this information would be compared and analyzed with results from other runs:

CHAPTER 5

A CASE STUDY

To show that the model "works," at least in theory, the removal of approximately three acres of timber will be simulated. Although the logging of one particular species, in one particular forest, in one particular area, is simulated, it will be seen that any given area could be studied in this same manner with suitable modifications.

The data used in the model were gathered from many different sources—field experiments, existing research reports, laboratory experiments, private and public agencies, and personal interviews. Data not obtainable from these sources had to be assumed (but reliable data is used wherever possible). This wide gamut of information sources posed the question of whether the resultant combination of data would result in an unreliable model. While this question is indeed a provocative one, no answer can be reached before the ultimate test, comparison with the "real-world," is conducted.

The FORTRAN II programs for Phases I and II are given in Appendix B. Section headings in this chapter correspond to the sections of the programs headed by "comment" cards. Thus the arguments should be easy to follow.

5.1 Basic Assumptions. The model was set up based on several simplifying assumptions. It was assumed that the logmaking would be carried out by one experienced feller working alone using a Homelite 770-D with a 16-inch bar. The clear cutting method of removal is employed. Stands contain only lodgepole pine. A tree is limbed and bucked immediately after being cut. The feller refuels, on the average, after 40 logs are cut; he

sharpens his chain after sawing approximately 80 logs. He carries enough fuel to last one whole working day.

The assumed mill specifications are as follows (taken from "spec" sheet of Yellowstone Pine Co., Belgrade, Montana)

Minimum dbh	=	7.0 inches
Minimum top diameter	=	5.6 inches
Minimum merchantable length	=	16.3 feet (sawlogs only)
Minimum gross soundness	=	50%
Maximum stump height	=	8.0 inches

Other necessary assumptions are discussed as they occur. Discussion of each Phase follows.

PHASE I

Input data to Phase I were collected in the Bear Creek area of the Gallatin National Forest. The "experimental plot" measured off to be about 3 acres. The number of trees in the sample was 108. The average diameter of the plot was 8.5 inches, the average height 70.6 feet, and the average limbage about 35 feet, or 46 percent of total height. This data would eventually be extrapolated to form a much larger "hypothetical" stand with the same characteristics. The stand would be "hypothetical" in the sense that it would be of the same statistical character as the sample, but each tree would not have been measured.

A small-stemmed stand was chosen because it is exemplary of the problems that plague lodgepole loggers - how does one make a profit on trees that average as low as 8 inches in diameter? The particular stand was chosen for several reasons. Among them are:

- (1) evenly spaced, clean stand, relatively free of underbrush
- (2) minimum number of dead trees
- (3) small stems
- (4) moderate slope (about 15 percent).

No provisions were made in this study to determine the effect of slope on logmaking. Although this would be a worthwhile endeavor, it is considered to be a sufficient problem for a separate investigation.

All of the measurements listed in section 4.2.1 were taken for each tree in the sample. The next step was to arrange the data in a form suitable for the ensuing computer analysis.

5.2 The Dbh Distribution.

5.2.1 Measurements. Tree diameters, in decimal inches, were measured with a standard diameter tape. The diameter tape, similar to the ordinary steel tape measure in appearance, is graduated so that the diameter of a cylindrical object at a point can be read directly by merely wrapping the tape around the object. The graduations are determined by using the relationship: $\text{circumference} = (\pi) (\text{diameter})$. The diameter inch divisions are thus inscribed on the tape at intervals of 3.1416 inches. As soon as each dbh measurement was taken, the tree was numbered with chalk to facilitate the height-measuring phase.

5.2.2 Distribution. The frequency distribution of diameters (rounded to the nearest inch) indicated that the stand was, as expected, somewhere between even-aged and uneven-aged (Fig. 5-1).

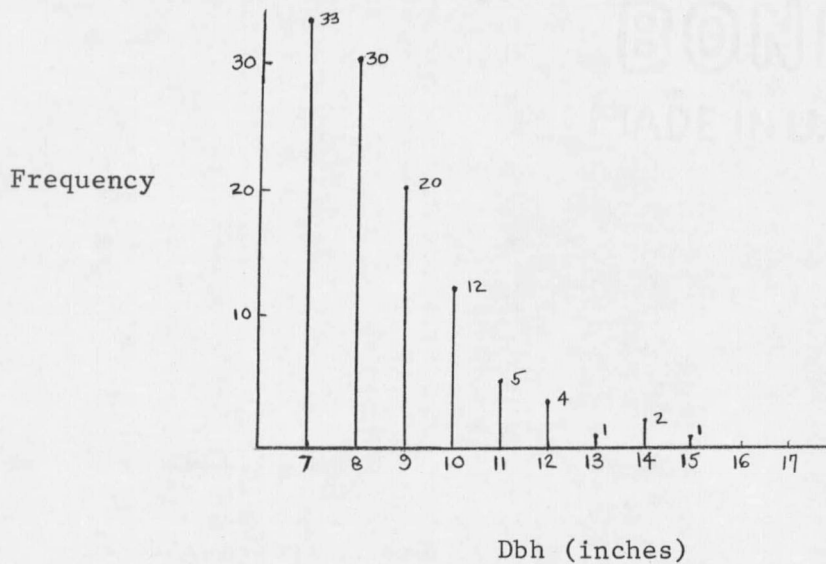


Fig. 5-1. Dbh Frequency Distribution of Experimental Plot

The cumulative probability distribution for dbh is shown in Fig. 5-2.

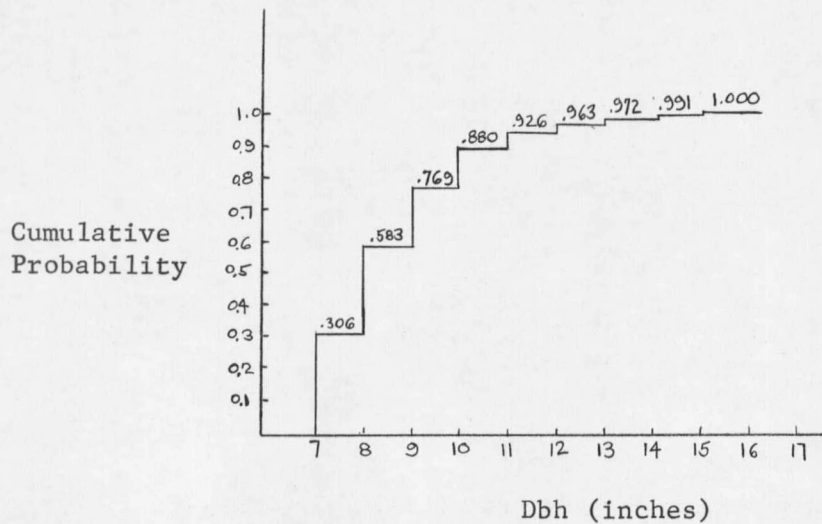


Fig. 5-2. Probability Distribution of Dbh in Experimental Plot

From this cumulative probability distribution, a probability table was constructed (Table 5-I).

Table 5-I. Probability Table for Dbh

Dbh	Cumulative Probability	Random Numbers
7	.306	001-306
8	.583	307-583
9	.769	584-769
10	.880	770-880
11	.926	881-926
12	.963	927-963
13	.972	964-972
14	.991	973-991
15	1.000	992-1000

Random numbers 01 through 306 correspond to a dbh of 7, random numbers 307 through 583 correspond to a dbh of 8, etc. This table will be useful when we are ready to draw samples.

5.3 The Distribution of Total Heights.

5.3.1 Measurements. Height measurements were taken on each tree with a Suunto O/Y clinometer. Since the trees had previously been numbered, tree height could easily be paired with diameter.

The clinometer determines the height of an object by the method of triangulation. The declination to the tree top is read in percent, and if the distance away from the tree is known, height can easily be determined. For instance, if one is 100 feet away from a tree and the clinometer gives a reading of 60% to the top of the tree, the tree is about 60 feet high. If one were only 50 feet away, and the height of the tree were 60 feet, the clinometer reading should be 120%. Although there is much room for human error in this method, the results obtained

by this measuring device are adequate for our purposes. A clinometer has an advantage over other height-measuring methods in that the instrument can be stored quite easily in one's pocket.

5.3.2 Distribution. The frequency distribution of total heights in the stand is shown in Fig. 5-3.

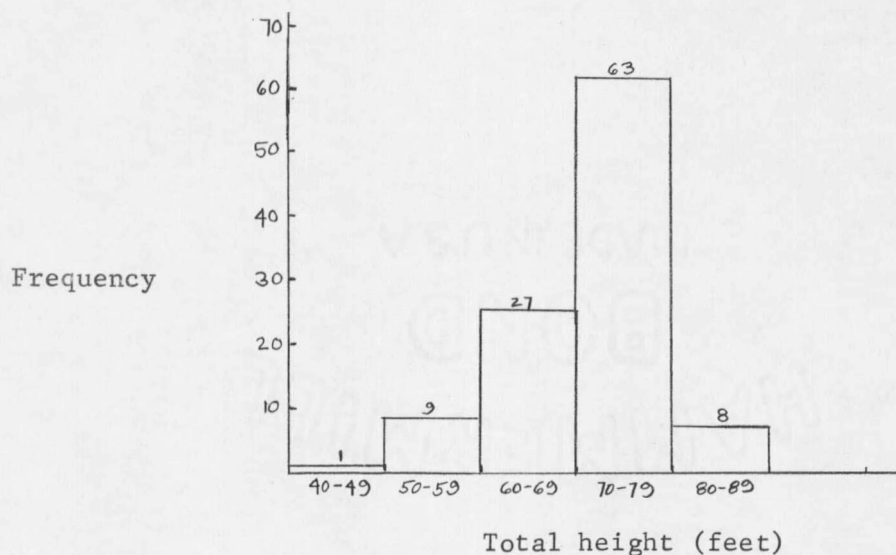


Fig. 5-3. Total Height Frequency Distribution in Experimental Plot

Before a probability table could be set up, a test was made to determine the relationship, if any, between height and diameter. Results of this test are deferred until a later section.

5.4 The Distributions of Crown Length.

5.4.1 Measurements. Length of live crown was measured at the same time as height. Length of live crown, in this study, means the length from the top of the tree down to the point on the bole which is considered, by estimation, to be the point at which limbing would begin. Dead limbs are usually not cut - they are expected to fall off during skidding - and need not be included in this measurement.

Thus, one reading is made to the top of the tree for height, and

another to the lowest point containing live limbs. The difference between the two is the live crown length.

If live crown length and height of all trees in the stand are known, crown/height ratios can be computed. This variable was found to be easier to work with, as will be shown later.

5.4.2 Distributions. The frequency distributions of crowns and crown/height ratios are shown in Figs. 5-4 and 5-5.

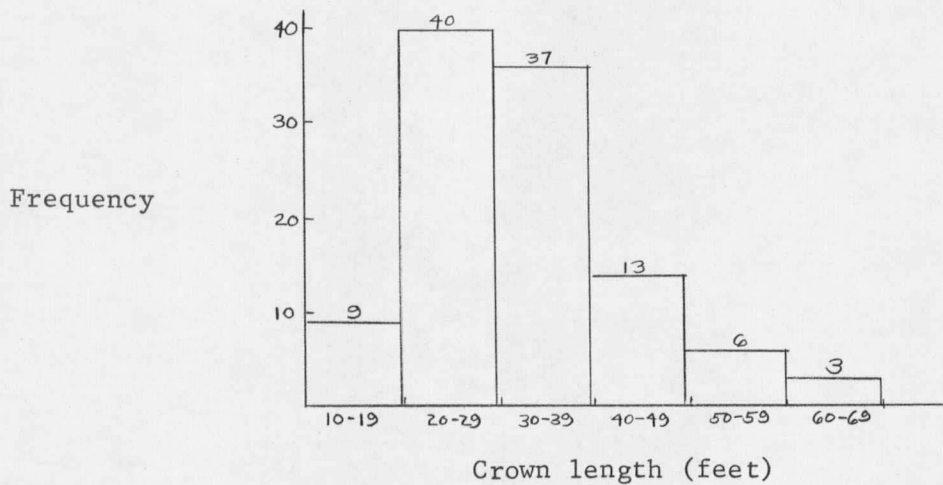


Fig. 5-4. Frequency Distribution of Crown Lengths in Experimental Plot

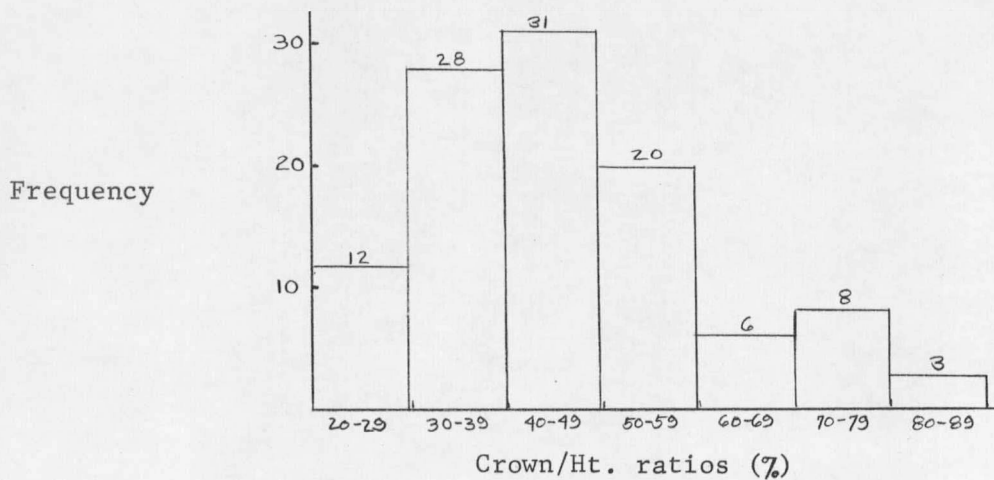


Fig. 5-5. Frequency Distribution of Crown/Height Ratios in Experimental Plot

Relationships of crown and crown/height with dbh and height were sought before any attempt was made to utilize the data in the model. The needed relationships were investigated by regression and correlation analysis.

5.5 Results of Regression and Correlation Analysis on Sample Data.

Regression and correlation analysis was applied to the data collected on the experimental plot. Since dbh is to be the initial tree characteristic determined in the simulation, it is considered to be an independent variable. The other variables, height and crown length were considered to be dependent on dbh.

Specifically, the purpose of the analysis was to determine the nature and degree of association between

- (1) height as a function of diameter
- (2) height as a function of crown length
- (3) crown as a function of diameter
- (4) crown as a function of diameter and height

The analysis was carried out with the help of a 1620 library program in the computing center. The results of the analyses are shown in Table 5-II. In all cases statistically significant results (at the 5 percent level) were obtained.

Table 5-II. Results of Regression and Correlation Analysis For Dbh, Total Height, and Crown Length

Dependent Variable, y	Independent Variables	Regression Equation	r^2	r	Std. Error
Height	Dbh	$y=38.54+1.47x_1$	.1287	.3473	6.83
Height	Crown Length	$y=43.32+0.31x_1$	.1161	.3407	6.85
Crown	Dbh	$y= 2.49+3.43x_1$	.5518	.7428	5.31
Crown	Dbh,height	$y= 6.53+3.28x_1+0.10x_2$	.5596	.7480	5.28

Similar regressions using crown/height ratios in place of crown length were made. Table 5-III gives the results of these runs.

Table 5-III. Results of Regression and Correlation Analysis
For Dbh, Total Height, and Crown/Height Ratios.

Dependent Variable	Independent Variables	Regression Equation	r^2	r	Std. Error
Crown/ht.	Dbh	$y=7.15+5.18x_1$	.3639	.6032	11.77
Crown/ht.	Total Height	$y=54.15-0.16x_1$	.0062	.0791	14.72
Crown/ht.	Dbh, Total Height	$y=33.48+6.17x_1-0.67x_2$	.4578	.6772	10.91

It can be seen that an estimate of the crown/height ratio of a tree can be made conditionally on dbh, without the inclusion of height since the correlation coefficient for crown/height as a function of dbh and height, .16772, is only slightly higher than that for crown/height as a function of dbh alone. Both relationships are significant at the 5 percent level. The coefficient for crown/height as a function of height alone is a mere .08, a statistically insignificant result, which suggests almost no association whatsoever.

It was decided against using the regression equations in the model to predict specific values of these variables, since the coefficients of variation were not exceptionally high.

Using the knowledge gained from the regression analyses, the model was constructed using empirical conditional probabilities of height and crown/height ratios on dbh. That is, "given a dbh, what is the corresponding tree height and crown/diameter ratio?" By using a finite empirical distribution in the sampling analysis an exact reproduction of the "hypothetical" stand would be obtained.

Data on height and crown/height ratios were grouped into individual diameter classes and conditional probability tables constructed from the sample data. These tables are given in Table 5-IV.

Table 5-IV. Conditional Probabilities of Height and Crown/Height on Dbh.

dbh	Total Height					Crown/Height Ratios						
	40-49	50-59	60-69	70-79	80-89	20-29	30-39	40-49	50-59	60-69	70-79	80-89
7	.03	.03	.39	.49	-	.22	.39	.33	.06	-	-	-
8	-	.10	.23	.63	.04	.14	.27	.33	.20	.03	.03	-
9	-	.10	.15	.65	.10	.05	.20	.25	.35	.10	.05	-
10	-	.08	.33	.33	.26	-	.25	.25	.17	.08	.17	.08
11	-	-	-	1.00	-	-	-	.40	.20	-	-	.40
12	-	-	-	.67	.33	-	-	-	.50	.25	.25	-
13	-	-	-	1.00	-	-	-	-	-	-	1.00	-
14	-	-	-	.50	.50	-	-	-	-	-	1.00	-
15	-	-	-	1.00	-	-	-	-	-	1.00	-	-

The distributions were then incorporated into the model.

5.6 Determination of Sample Values of Dbh, Height, and Live Crown Length.

The original sample data were assumed to represent 10% of the total number of trees in the stand. The data were adjusted so that the full 1080 were included in the probability distributions. In other words, each frequency was multiplied by a factor of 10. If 20 trees out of the 108 in the measured sample had a dbh of 10 inches, for example, it was assumed that 200 trees out of 1080 were of dbh 10. Thus, the probability of each dbh remains the same.

The computer program was set up to accept frequencies rather than probabilities. Frequencies within each height and crown/height subclass (e.g. the number of trees with a total height of 70, 71, 72...in height class 70-79) are also read in* so that selection of these variables can be made "to the foot," thereby achieving greater accuracy and realism (see data list in Appendix C for observed frequencies within subclasses).

Trees are defined in one possible random order in which they can be cut. A random number, RND, is generated, the cumulative dbh distribution is entered at the appropriate place,** and a sample value of dbh obtained. Another random number is generated, and the appropriate conditional probability distribution of height is entered to obtain a sample value of height. A crown/height ratio is similarly obtained.

After each sample value is drawn, the ordinate of the appropriate distribution is decreased by one, since we are dealing with a finite population. Thus, after 1080 trials, the distributions will have vanished.

5.6.1 Random number generation: Fortunately, a random number generator was incorporated in the FORTRAN II 1620 Subroutine Deck. This saved

-
- * In those subclasses containing only one or two trees in the sample, the extrapolated heights were spread out within the subclass on an "a priori" basis.
 - ** The method of doing this is to construct the cumulative probability function within the machine. As soon as the cumulative probability is equal to or less than RND, that value of the variable of interest is chosen. (See program instructions in Appendix B).

valuable programming time. By initiating the generator with an 8-digit, odd number not divisible by 5, a continuous stream of uniform random numbers can be generated.

5.6.2 Crown length. The product of height and crown/height yields a sample value of length of live crown, or limbage.

5.7 Computing Merchantable Height.

5.7.1 Merchantable height. Knowing the diameter and total height of the tree, merchantable height for each tree can be estimated by the use of taper tables. Merchantable height in this study, remember, is considered to be the height from the stump up to a point on the stem which is 5.6 inches in diameter.

The taper tables given in reference (32) were used. Although these tables are old (1915) and possibly may no longer hold, they are assumed to be adequate enough for this purpose. More recent tables are in the process of being published by the U.S. Forest Service, but they were not available at the time of this writing.

These tables purport to give the diameters at selected points along the stem for trees of a given dbh and height. Unfortunately, height is rounded off to the nearest 10 feet. Regressions were run first on each table, and next, on all tables combined. The results of these analyses are given in Table 5-V.

Table 5-V. Regression Analyses of Taper Tables.

y=diameter; x_1 =total height; x_2 = dbh; x_3 = distance up stem				
Run	Regression Equation	r^2	r	Std. Error
50' table	$y = 2.21 + 0.82x_2 - 0.14x_3$	.9870	.9935	0.17
60' table	$y = 4.85 + 0.63x_2 - 0.15x_3$	.9377	.9683	0.62
70' table	$y = 7.26 + 0.56x_2 - 0.18x_3$	.9495	.9744	0.83
80' table	$y = 7.10 + 0.56x_2 - 0.15x_3$	.9435	.9713	0.83
90' table	$y = 8.51 + 0.53x_2 - 0.16x_3$	.9451	.9722	0.90
all tables combined	$y=1.18+0.76x_1+0.57x_2-0.16x_3$	.9477	.9735	0.83

If, in the model, separate regression equations were used for each height class, the results would not be realistic. Take, for example, the 50-foot class, which includes trees of 45-54 feet in height. Assume we are interested in the diameter 25 feet up the stem of an 11-inch tree. The model would assign the value of 6.2 inches to every 11-inch tree having a height of anywhere from 46 to 54 feet. Rather, it was decided to use the regression results of the combined tables. While the results obtained may not exactly conform to reality, it will at least eliminate the above inconsistency.

Caution should be exercised in the use of this equation. For values of dbh outside the range of these tables merchantable height will sometimes exceed total height.

5.8 Cubic Foot and Board-Foot Volume Determination. Tree volumes were computed from regression equations given by Meyers (36) in a

publication of lodgepole pine volume tables. Although his data were gathered in Colorado and Wyoming, comparisons with tables published for U.S. Forest Service Region One showed no large differences between the two. Meyers' tables are used here because he supplies the equations from which they are derived.

The regression equations are:

For cubic foot volume (merchantable):

$$\begin{aligned} \text{CFV} &= 0.002798D^2H - 1.045780 & \text{for } D^2H &\leq 7000 \\ &= 0.002256D^2H + 2.836222 & \text{for } D^2H &> 7000 \text{ (eq.5.1)} \end{aligned}$$

where CFV = cubic foot volume

D = dbh

H = total height.

For board-foot volumes (Scribner):

$$\begin{aligned} \text{BFV} &= 0.012535D^2H - 20.190570 & \text{for } D^2H &\leq 15000 \\ &= 0.012893D^2H - 29.245660 & \text{for } D^2H &> 15000 \text{ (eq.5.2)} \end{aligned}$$

where BFV = Scribner Volume and D,H are as before.

Program variables corresponding to D and H are DBHX and THT, respectively.

5.9 Cull Assignment. The model assigns an NCULL value of "0" to a tree containing no defect; a "1" to a dead tree; a "2" to a tree with rot; and a "3" to a tree which will have defects sent to the mill. The probability of a tree containing one of these cull types is varied - a series of output decks having different cull factors is produced.

A tree containing no defects (i.e. NCULL=0) obviously receives a value for percentage of the tree affected by cull, PCT, of 0.

A tree which has been assigned an NCULL equal to 1 is assigned a PCT value of 100. That is, no part of a dead tree is usable. When NCULL = 2, PCT is assigned a value between 0 and 100. The assumption is made here that rot is uniformly distributed throughout the stand. In other words, once a tree has been found to have rot, it is equally likely that the tree is 90% infected as well as it is, say, 10% infected. This seems like a reasonable supposition, but it has yet to be proven. A uniform random number is generated and is taken to be the percentage, in terms of length, of tree infection.

A similar situation is encountered when NCULL = 3. The percentage of cull volume to be deducted from gross tree volume is assigned a value between 0 and 100 by generating a uniform random number as above.

The model at this point deviated somewhat from the "ideal" model given in Fig. 4-2. It was desired to run Phase I as a unit; however, due to the high cost of debugging Phase I without cull, the output cards containing no cull were used as input to a separate cull submodel. This submodel was later "joined" to the mainline model. Obtaining cull output is still cumbersome since one has to transfer output cards from the output hopper to the read hopper if a cull analysis is desired. This situation should be remedied by the user. Samples of 100 trees are presently obtained.

5.10 Output. A sample of the output from Phase I is given below.

(for assumed sound trees):

N	DBHX	THT	XMHT	CROWN	FREE	ECFV	EBFV	NCULL	PCT
1	8.	72.	34.5	21.6	50.4	11.8	47.6	0	0
2	7.	73.	31.4	25.5	47.4	9.0	34.6	0	0
3	8.	76.	36.4	22.0	54.0	12.6	50.8	0	0
4	8.	69.	33.1	35.2	33.8	11.3	45.2	0	0
5	8.	64.	30.7	26.2	37.8	10.4	41.2	0	0
6	8.	75.	36.0	34.5	40.5	12.4	50.0	0	0
7	8.	74.	35.5	38.5	35.5	12.2	49.2	0	0
8	9.	58.	31.4	35.4	22.6	12.1	48.7	0	0
9	7.	45.	18.0	13.9	31.0	5.1	17.4	0	0
10	10.	62.	36.9	34.1	27.9	16.3	67.5	0	0
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
1080	8.	73.	35.0	48.2	4.8	12.0	48.4	0	0

As the cull factor increases, only NCULL and PCT are altered. For example, following is a sample of the output when 15 percent of the trees are dead and 15 percent contain rot.

N	DBHX	THT	XMHT	CROWN	FREE	ECFV	EBFV	NCULL	PCT
1	7.	71.	30.5	24.9	46.2	8.7	33.4	1	1.000
2	11.	72.	45.2	57.6	14.4	22.5	99.0	0	0.000
3	7.	60.	25.2	19.2	40.8	7.2	26.7	2	.219
4	8.	61.	29.2	21.4	39.6	9.9	38.7	1	1.000
5	9.	57.	30.9	20.5	36.5	11.9	47.7	1	1.000
6	9.	76.	40.0	41.0	35.0	16.2	67.0	0	0.000
7	13.	73.	52.8	55.5	17.5	30.7	144.5	0	0.000
8	7.	67.	28.6	24.1	42.9	8.1	31.0	1	1.000
9	12.	73.	49.3	42.3	30.7	26.6	121.6	2	.506
10	9.	77.	40.5	38.5	38.5	16.4	68.0	0	0.000
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
100	10.	54.	33.0	21.1	32.9	14.1	57.5	0	0.000

This information, as punched, is the major input to Phase II.

5.11 Console Operation. Operation procedure and input order for

Phase I is

- (a) load object deck
- (b) load subroutine deck
- (c) data input
 - 1. An 8- digit odd number, DIGIT, not divisible by 5
 - 2. Number of merchantable trees, DBHS
 - 3. Diameter distribution
 - In two phases
 - a. Minimum and maximum diameter, IBEG, IEND.
 - b. The number of diameters in each diameter class I, (DBH (I), I = IBEG, IEND).
 - 4. Height distribution
 - In three phases
 - a. The number of heights contained in each diameter class, and the minimum and maximum values, HTS (II), JBEG (II), JEND(II), II = IBEG,IEND), rounded to the nearest 10.
 - b. The number of observations in each height class, (HTT (II,JAZ), JZ = JBEG (II), JEND (II)).
 - c. The number of height readings within the unit subdivisions of each height class, (HTU (II, JZ,K), K = 1,10).
 - 5. ...Crown/height ratios
 - In three phases
 - a. The number of crown/height ratios contained in each diameter class, and the minimum and maximum values, OIO (JJ), KBEG (JJ), (KEND (JJ), JJ = IBEG, IEND).
 - b. The number of observations in each height

class, (OIA (JJ, JZ), JZ = KBEG (JJ), KEND (JJ)).

- c. The number of crown/height ratios, in feet, within the unit subdivisions of each crown/height class, (OIB (JJ, JZ, K), JZ = 1,10).

The FORMAT statements governing this input can be gathered from examination of the program in Appendix B. The actual input for the case study is given in Appendix C.

PHASE II

The second phase of the simulation model, Phase II, performs the logmaking operations on the timber area defined in Phase I.

5.12 Input. The input to Phase II, and the order in which it is read in, consists of:

1. An 8-digit odd, initial random number, DIGIT, not divisible by 5.
2. The number of acceptable log lengths, JBUCK.
3. The acceptable log sizes, (X(I), I = 1, JBUCK), in descending order of magnitude.
4. Stand density, DSTY, total number of trees to be cut, TREES, and number of acres in the stand, ACRES.
5. On-log travel time distribution
 - In two phases
 - a. ONTOP (I), LBEG (I), (LEND (I), I = 7,15), the number of sample readings taken on logs of diameter I and their beginning and final values.
 - b. (ONTP (I,J), J = 1,10), the number of observations in each diameter class I.
6. Limbing time distribution
 - In two phases
 - a. The number of readings on logs of diameter I and their beginning and ending values, PLIMB (I), MBEG (I), (MEND (I), I = 7,15).

- b. The number of observations in each diameter class I, (PLMB (I,J) J = 1,10).
- 7. A control card specifying (a) production rate, NPR, (b) number of production hours at that rate, NHRS, and (c) the day, NTRIAL.
- 8. Output from Phase I
 - exactly as punched.

The FORMAT statements governing this input can be gathered from examination of the Fortran II program in Appendix B. The input is displayed in Appendix C. The trees must now be felled, limbed, and bucked..

5.13 Felling.

5.13.1 Felling times. The expected felling times for trees of a given dbh were obtained through field work. Five different operators were studied; three different types of saws were observed. In order to avoid rating the workers, only men who were considered to be 100%, or "average" workers were studied. The study technique relied heavily upon conventional stop-watch time study, but where applicable, time-lapse photography was used to advantage.

The studies were conducted entirely within the confines of the Gallatin National Forest, on slopes varying from 5 to 62 percent. Felling time was considered to begin when the saw was in position to start the cut and end when the tree started to topple. Note that by defining felling in this way, operations 5 and 6 in Fig. 2-3 have been combined. Periodic or irregular elements such as clearing obstacles and "pushing" stubborn trees were not included in the time-recordings. Times to fell trees that were "hung up" in branches of neighboring trees and required special attention were also eliminated, since it is assumed

in this thesis that the cutter is proficient enough to avoid this difficulty. One can not always make this assumption.

Cutting time (i.e. time to make the under-and back-cuts) in decimal minutes was recorded for each tree and a dbh measurement (o.b.) taken immediately after the cut. In some cases, when the path of the cutter was known in advance, it was possible to measure the trees before they were felled. This is the recommended procedure. In all, observations on 577 trees were taken. The dbh measurements on these trees ranged from 5.5 to 18.4 inches.

It was noted that several factors besides those previously mentioned seem to have an effect on the actual felling time of a tree. A complete list includes all the factors listed in section 2.1 plus five more:

- (1) Stump height
- (2) Tree height
- (3) Make and model of saw
- (4) Worker efficiency
- (5) Sharpness of the chain.

No attempt was made to quantify these factors; their individual effects are hidden in the resultant empirical felling time probability distributions.

The sale, location, and the number and percentage of trees cut in each sale, are shown in Table 5-VI. Each different sale represents a different cutter; therefore, the make and model of the saw used is also presented.

Table 5-VI. Vital Statistics of Felling Time Study,
Gallatin National Forest, 1964

Sale, cutter number	Sale Name	Approximate Location (District)	Saw Make and Model	Number of Trees	% of total
1	BearCreek#3	Gallatin	Homelite 770-D	60	10.4
2	Reservoir#8	Bozeman	McCulloch 1-53	76	13.2
3	BearCreek#2	Gallatin	McCulloch 1-53	172	29.8
4	BearCreek#3	Gallatin Hebgen	Homelite 770-D	219	37.9
5	CherryCreek	Lake	Homelite C-9	50	8.7
				577	100.0

Table 5-VII gives the average observed cutting time for each man/machine - dbh class combination along with the number of observations associated with each average value. The fellers are designated by $F_1, \dots, F_5$. A diameter class of any particular dbh measurement is obtained by rounding off the field diameter measurement to the nearest integer.

Table 5-VII. Average Felling Times for Each Man/Machine-Dbh Combination, and Number of Observations.

dbh class	man/machine					Number of Observations				
	F ₁	F ₂	F ₃	F ₄	F ₅	F ₁	F ₂	F ₃	F ₄	F ₅
6	.18	.14	.17	.18	—	4	1	13	1	—
7	.24	.21	.25	.24	.21	12	7	27	3	3
8	.29	.25	.29	.28	.27	18	14	32	15	4
9	.39	.32	.35	.33	.32	13	12	41	25	11
10	.43	.36	.44	.36	.33	8	14	30	30	5
11	.48	.47	.49	.46	.45	3	16	14	33	4
12	.51	.54	.59	.53	.49	2	7	11	42	6
13	—	.65	.72	.65	.70	—	5	3	35	6
14	—	—	.72	.72	.67	—	—	1	18	5
15	—	—	—	.77	.95	—	—	—	7	3
16	—	—	—	.72	1.22	—	—	—	6	1
17	—	—	—	.79	.82	—	—	—	2	1
18	—	—	—	1.03	1.63	—	—	—	2	1
						60	76	172	219	50

The information in Table 5-VII is plotted below in Fig. 5-6.

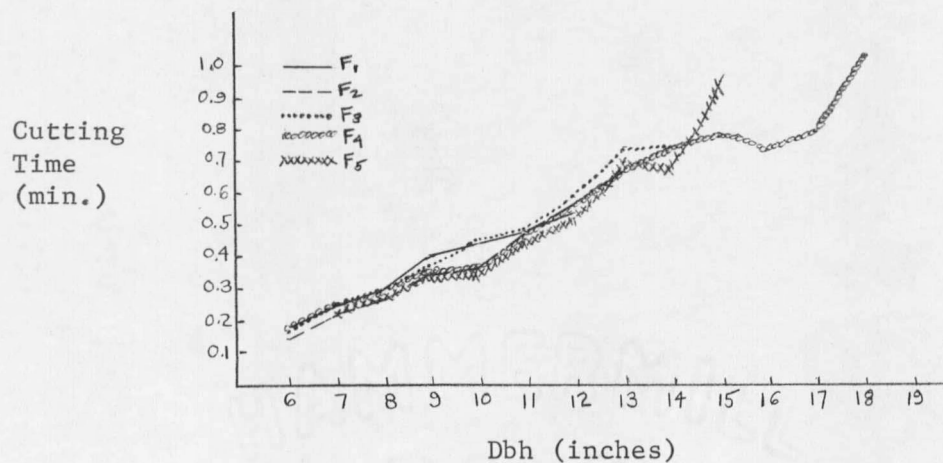


Fig. 5-6. Average Cutting Times for 5 Different Fellers.

This diagram could serve as an initial clue as to which groups of data could be pooled, the object being to get as many readings as possible into each diameter class.

An empirical curve was drawn up to represent the combined average cutting times for all cutters. A theoretical curve, based on the premise that the time to fell a tree varies as the square of the radius at the cutting level was determined and found to correlate very highly with the "average" curve ($r^2 = .82$). The equation for this curve is $y = 0.04x^2$ where y = cutting time and x = dbh, and is given in Fig. 5-7.

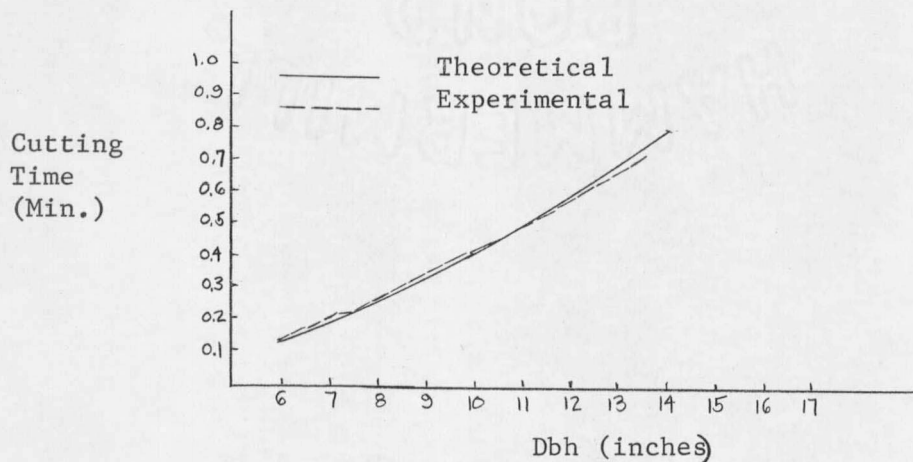


Fig. 5-7. Theoretical vs. Actual Felling Curve.

However, it was desired to account for the variability in cutting times in the model. Intuitively, we could say that felling times for each diameter class would be expected to be normally distributed about its mean; unfortunately this could not be proven with the limited data.

Frequency distributions of cutting times for each diameter class were constructed (see Appendix F). No conclusions could be reached regarding the particular mathematical distribution followed, if any.

More data is needed to characterize the nature of the distributions over such a wide range of values. The distributions seemed bi-modal in some cases and tri-modal in others. The variability in the size of the under-cut under different conditions, and the fact that many times it is necessary to manipulate the saw in such a manner that the tree is loosed from vibration, might be reasons for this.

Thus, instead of sampling from a theoretical probability distribution, which was next to impossible, sampling would be done from the raw empirical distributions of cutting times given in tabular form in Table 5-VIII below.

Table 5-VIII. Conditional Probability Distributions for Felling Times.

Dbh	Abcissas of Conditional Cumulative Probability Distributions (min.)									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
6	.167	1.000	-	-	-	-	-	-	-	-
7	.000	.577	.980	.980	1.000	-	-	-	-	-
8	.000	.277	.892	.988	1.000	-	-	-	-	-
9	.000	.039	.559	.902	.990	1.000	-	-	-	-
10	.000	.012	.288	.793	.942	.988	1.000	-	-	-
11	.000	.000	.057	.385	.813	.986	1.000	-	-	-
12	.000	.000	.000	.132	.6603	.867	.985	1.000	-	-
13	.000	.000	.000	.000	.102	.449	.857	.959	1.000	-
14	.000	.000	.000	.000	.042	.250	.708	.958	.958	1.000
15	.000	.000	.000	.000	.000	.000	.428	.714	1.000	-

However, this data cannot be "pooled" without some statistical evidence to support this action. One way to find out which data can be feasibly grouped together is to apply analysis of variance. Instead of conducting an analysis of variance on the set of data in Table 5-VII as a whole; (which would result in a disproportionate analysis

with unequal subclass numbers) replicate data in the individual diameter classes were analyzed. Any decisions made on validity of the data in this test would be consistent with its ultimate use. Table 5-VIX gives the results of this analysis at the 5% confidence level.

Table 5-VIX, Results of Analysis of Variance on Felling Time.

Dbh	F Experimental	F 0.05(df ₁ , df ₂)	Decision
7	0.84	2.56 (4,48)	Accept Ho
8	1.21	2.48 (4,79)	Accept Ho
9	2.33	2.46 (4,98)	Accept Ho
10	5.31	2.48 (4,83)	Reject Ho
11	0.40	2.52 (4,65)	Accept Ho
12	1.87	2.51 (4,64)	Accept Ho
13	0.84	4.24 (3,46)	Accept Ho
14	0.71	3.44 (2,22)	Accept Ho
15*	-	-	-

Since the analysis of variance assumes that the data being analyzed conform to the normal law, and no conclusions could be reached as to the nature of the distribution followed by the felling data, the Kruskal and Wallis nonparametric H-test was applied. If the nonparametric test yielded the same results as the analysis of variance, then any decisions made on whether the data constitutes one or several populations is reinforced. If the two tests do not agree, then the nonparametric results would be used. The results of the H-tests at the 5% level are given in Table 5-X.

* Only 2 cutters observed cutting 15-inch trees. T-test applied - Accept Ho.

Table 5-X. H-tests of Felling Data.

DBH	H	χ^2 (α ,df)	Decision
7	3.93	3.93 (.42,4)	Accept Ho
8	7.34	7.34 (.15,4)	Accept Ho
9	12.30	12.30 (.015,4)	Reject Ho
10	20.60	18.50 (.001,4)	Reject Ho
11	1.24	1.42 (.87, 4)	Accept Ho
12	5.17	5.17 (.28, 4)	Accept Ho
13	3.81	3.81 (.28, 3)	Accept Ho
14	3.00	3.00 (.24, 2)	Accept Ho
15	—	—	—

It can be seen that Ho was rejected under both tests for dbh 10. The data for dbh 9 was also rejected under the H test:

Since this was to be a preliminary model, it was decided to "pool" all the data in the face of strong evidence against the acceptance of the null hypothesis for either dbh = 9 or dbh = 10. In other words, the author has, in a sense, assumed that the discrepancy is attributable to chance causes. If this were the ultimate refined model, this situation would have been explored more fully. Since, in the final analysis, more data on felling would have to be obtained, this present decision is acceptable. The above analysis was meant to point out to potential users that model data should not be used indiscriminately.

The distributions as given in Table 5-VIII were used. A random number is generated, the proper distribution is entered, and a sample value of cutting time, FELLT, is obtained. This quantity is then added to the total felling time, TFELL:

5.13.2 Wait for tree to fall. The average time of tree fall was determined by experiment to be approximately 0.05 minutes. Some 157 observations were averaged to get this result. It is difficult and pointless to relate such a small time element to tree size because limbiness, lean, and slope of the area play such a big role. At the end of each day, the number of trees felled, CUT, is multiplied by 0.05 and added to TFELL to obtain an estimate of waiting time.

5.14 Cull. At this point, NCULL is examined and the subsequent course of action is governed by the value found there. These courses of action are given below.

If NCULL = 0:

This means that the tree contains no defect. The program proceeds to the section for determining the optimum log combination.

If NCULL = 1:

This means that the tree is dead. The program proceeds to the section on traveling to the next tree. Cull volume is increased by the amount of estimated volume in the dead tree.

If NCULL = 2:

This is the most complex case. Some rather striking assumptions have to be made in order to deal with this occurrence. Although the end result, in this case, may involve a large error, insights gained from the method of attack will be fruitful.

First, the assumption is made that when a tree has been found to contain rot, the infection takes the form of the shaded area in Fig. 5-8.

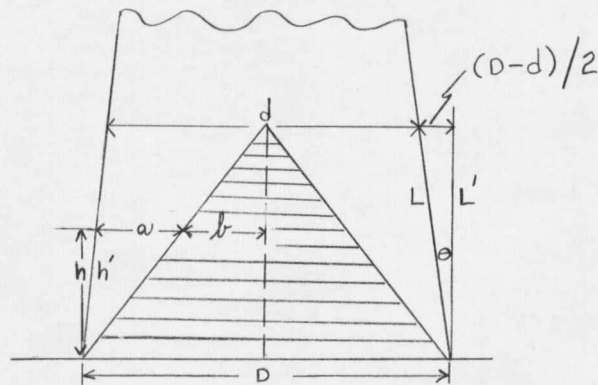


Fig. 5-8. Assumed Form of Cull Type II

That is, the rot always covers 100% of basal area and tapers to a point at $PCT \cdot XMHT = L$. (For simplification, a two-dimensional representation will suffice here.)

Since the mill will take anything over 50% sound, it is desirable to determine the point at which the diameter of rotten area is equal to half the diameter of bole. Thus, we want to know the point on the stem at which $a = b$, designated by h' .

From before, we know D , d , and L . We must find L' .

$$L = \sqrt{\left(\frac{D-d}{2}\right)^2 + L'^2}$$

$$\therefore L' = \sqrt{L^2 - \left(\frac{D-d}{2}\right)^2} \quad (\text{eq. 5.3})$$

Now, we want to find the distance h $\ni$ $a = b$

$$\frac{a}{d/2} = \frac{h}{L'}$$

$$\frac{b}{D/2} = \frac{L' - h}{L'}$$

$$a = \frac{hd}{2L'}$$

$$b = \frac{(L' - h)D}{2L'}$$

Set $a = b$

$$\begin{aligned} hd &= (L' - h)D = L'D - hD \\ h(d + D) &= DL' \end{aligned}$$

$$\therefore h = \frac{DL'}{d+D} \quad (\text{eq. 5.4})$$

Now, we can get h' from

$$h' = \frac{h}{\cos \theta}$$

where $\theta = \arctan \left(\frac{D - d}{2L'} \right)$

According to the bucking rules in 4.3.9, the logger begins making cuts at 4-foot intervals to a maximum of 4 cuts along the stem until

- (a) the length from the stump to the point at which he makes a cut is greater than L
- (b) his fourth cut falls at a point less than L but greater than h' along the stem
- (c) the difference between the original merchantable height and the length of stem cut off is less than the minimum acceptable merchantable height.

If (a) occurs, the cull volume, $PLEFT$, is increased by the board-feet of material cut off and the program proceeds to determining the optimum log combination. If (b) occurs, the same thing happens, only now, the first log contains cull type 3. A percentage deduction is made after determining the size of the first log. If (c) occurs, cull volume is increased by the estimated volume of the tree, and the program is sent to the section for traveling to the next tree.

If $NCULL = 3$:

In this case, the gross volume of a tree is deducted by that volume multiplied by PCT . The latter quantity is added to cull volume, $PLEFT$, and the program proceeds to the section on optimizing the log combinations.

In the program, variables given in Fig. 5-9 correspond to those in Fig. 5-8.

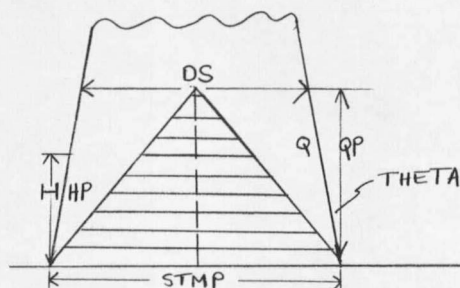


Fig. 5-9. Cull Type II Shape in Terms of Program Variables.

The argument following Fig. 5-8 remains the same, except for the changes in variable names.

5.15 Optimizing the Number and Sizes of Logs. The philosophy of bucking is given in Chapter 4. The proper combination of logs to minimize the amount of material left in the woods can be determined by iteration.

5.15.1 Theory. Given a stem of merchantable length, L , we wish to determine the proper combination of logs to minimize the waste, ΔL .

Fig. 5-10).

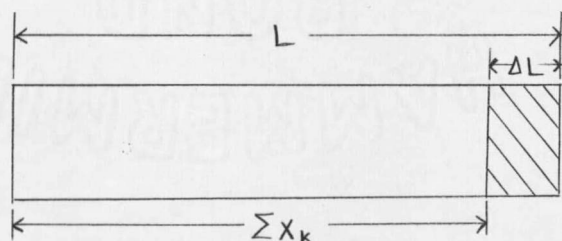


Fig. 5-10. Bucking Objective in Graphic Form.

Let n be the number of different sizes of acceptable logs and let $x_1, \dots, x_n$ be the accepted set of log lengths.

We require that $L \geq a_1x_1 + a_2x_2 + \dots + a_nx_n$ where $a_1, \dots, a_n$ are arbitrary integral constants. We wish to minimize $L - (a_1x_1 + \dots + a_nx_n) = \Delta L$, subject to the restriction that $\Delta L \geq 0$.

The problem can be reduced somewhat by noting that there are bounds on L ; $L_{\min} \leq L \leq L_{\max}$. A requirement on a_i , the number of logs of a given size is

$$\max_a \left\{ \begin{array}{l} \text{integers} \\ a \end{array} / 0 \leq a_i \leq \frac{L_{\max}}{x_i}, i = 1, \dots, n \right\}. \quad (\text{eq. 5.5})$$

An example should clarify this concept.

Example A. Specifications say that no tree under 16.3 feet in merchantable length can be cut. In the field measurements taken in a particular study, the height of the tallest tree was 75 feet.

$$\begin{aligned}\text{Let } L_{\min} &= 17 \\ L_{\max} &= 75\end{aligned}$$

$$\text{Then } L_{\min} = 17 \leq L \leq 75 = L_{\max}$$

Acceptable log lengths, in feet, are 33, 25, 17 = x_1, x_2, x_3 .

$$\begin{aligned}\text{Then } a_1 &\leq 2 \\ a_2 &\leq 3 \\ a_3 &\leq 4,\end{aligned}$$

and, of course, $m \leq a_3$, where m = the total number of logs cut from the tree.

5.15.2 Optimizing log combinations in the program. The program first determines the number of logs of size x_1 that can be cut from the given merchantable height, XMHT, and EXTRA, (i.e. ΔL) is computed. If no logs of size x_1 can be cut (i.e. $\text{XMHT} < x_1$), x_2 is tried, etc. until the first log size is found that is equal to or less than merchantable height. Of course, if no logs at all can be cut (i.e. $\text{XMHT} \leq x_1, \dots, x_n$) the feller proceeds to the next tree.

When the first log size that can be cut is found (note: this is the largest log possible for that tree), the number of logs of size x_{i+1} that can be cut from EXTRA, if any, are determined. If no logs of size x_{i+1} can be cut, i is increased by 1, and eventually it is found that either (1) no logs other than a_i of x_i can be cut, or (2) a_j of logs size x_j can be cut ($i < j$), from EXTRA.

If (1) occurs, a_i is decreased by 1, and the process of finding another size that will fit into $(\text{EXTRA} + x_i)$ is begun. The above procedure is reiterated until, eventually, a_i is reduced to zero. Now the process starts over again, with x_i now equal to x_{i+1} , until all possibilities have been exhausted.

If (2) occurs, EXTRA is computed and compared with the previous minimum EXTRA, and the minimum of these two is stored. Logs of size $x_{i+2}, \dots, x_n$ are examined to see if they can be cut from EXTRA, etc. and the whole process is repeated as before.

The combination of logs that minimizes ΔL , or EXTRA, is chosen. If two or more combinations yield the same EXTRA the combination composed of the least number of logs is chosen. If two or more combinations have identical EXTRA and number of logs, MAX, the combination that will effectuate bucking at the smaller diameters, (with the short log used as the butt log) is chosen. An example will make this all clear.

Example B.

Suppose XMHT = 50 feet
and $x_1 = 32.60$
 $x_2 = 24.45$
 $x_3 = 16.30$

- | | |
|------------------------------|---|
| (1) $\text{XMHT} - x_1 > 0$ | $a_1 = 1, \text{EXTRA} = 17.4$ |
| (2) $\text{EXTRA} < x_2$ | |
| (3) $\text{EXTRA} > x_3$ | $a_1 = 1, a_2 = 1, \text{EXTRA}' = 1.1$ |
| (4) $\text{XMHT} - 2x_2 > 0$ | $a_2' = 2, \text{EXTRA}'' = 1.1$ |
| (5) $\text{EXTRA} < x_3$ | |
| (6) $\text{XMHT} - 3x_3 > 0$ | $a_3' = 3, \text{EXTRA}''' = 1.1$ |

Three combinations result; all yielding an EXTRA of 1.1 feet:

$$(a) a_1 = 1, a_2 = 1$$

$$(b) a_2 = 2$$

$$(c) a_3 = 3$$

Clearly, we would choose (b). Since all three yield minimum ΔL , the next criterion to consider is the number of logs. This eliminates (c). The third criterion, smallest diameters at cutting points, indicates that (b) should be chosen because a cut made 25 feet from the butt will be at a smaller diameter than 17 feet from the butt.

The program assigns optimum log combinations to individual trees in the above manner, and stores the results.

5.16 Limbing and Bucking: It is extremely difficult to separate limbing time from bucking time because they are performed simultaneously. In this thesis, limbing and bucking are treated and grouped together under the variable name TLAB.

Limbing and bucking time includes the elements of time involved in removing live limbs from the stem and the sawing of the tree into logs, plus all other elements commonly associated with these primary tasks. Limbing and bucking begins immediately after the optimum log combination has been determined and ends after the last buck cut has been made.

5.16.1 Limbing and bucking equation. An equation for limbing and bucking time, l , might be:

$$l = h_{on} + h_{off} + \sum_{i=1}^n (s + w + f_i - d.e_i + r + m + b_i) + \sum_{i=2}^n g.p_i$$

(eq. 5.6)

where

l = total limbing and bucking time

n = the number of logs to be cut

h_{on} = the time required to mount the stem

h_{off} = the time to disembark from the stem

s = the time to hook the tape in the stem

w = walk time per foot of free stem

f_i = length of free stem of log i

d = limbing time per foot

c_i = length of log i that contains live limbs

r = the time to retract the tape

m = the time to make the reference cut

b_i = the time to buck log i

g = travel-time-on-ground ratio estimate

p_i = length of log i

Or, in terms of the variables used in the program

$$\begin{aligned}
 TLAB = HONOF &+ \sum_{j=1}^{MAX} (ONTOPT \cdot FREE + XLIMBT \cdot COMBO + 0.15 + 0.02 + BUCKT) \\
 &+ \sum_{j=2}^{MAX} TRAVT \cdot BNO(J)
 \end{aligned}
 \tag{eq. 5.7}$$

The index, J need not be explicitly defined in the program. Notice that

Case I (Section 2.1) is used for reeling in the tape.

5.16.2 Component times: The combined time to mount the log and disembark (HONOF) was averaged out to 0.09 minutes (i.e. 0.05 minutes to mount and 0.04 to dismount). FREE is originally obtained from Phase I and is adjusted each time a log is cut. COMBO is computed as the difference between the length of a log and its FREE portion. The average

time to hook and retract the tape has been determined to be 0.15 minutes (i.e. 0.05 minutes to hook and 0.10 minutes to reel in). It takes an average of 0.02 minutes to make the reference cut. The use of average times for the above variables will be adequate. Only on-log travel time (ONTOPT), limbing time (XLIMBT), on-ground travel time (TRAVT), and bucking times (BUCKT) remain to be explained. The determination of the log lengths (BNO (J)) was explained previously.

5.16.3 Limbing time ratio estimates. The manner of assigning a limbing time to a particular tree was, for a while, difficult to envision. The difficulty lay in selecting the unit of measure. Should limbing time be correlated with diameter, crown length, or height? Should limbing time be computed as a ratio estimate (i.e. limbing time per foot), or, should limbing time be expressed as a function of the number and size of limbs on a particular tree?

Of these possibilities, the first two seemed to be the most promising. Expressing limbing time as a function of the number and size of limbs is theoretically sound, but not practical. How can a prediction be made of the number and size of limbs to be found on a given tree? So many factors come into play that this would be almost impossible.

The second choice, computing a ratio estimate for limbing time, was chosen, with one modification. Expected limbing ratio estimates were computed for each diameter class. The reason for this is clear. On a larger tree we would expect more limbs per unit of length, or, if not, we would certainly expect larger limbs. Intuitively, this would tend to increase limbing time for larger trees. The suspicion

that limbing times per foot increases with the diameter of the tree was confirmed in the field-data analysis. Observations were made of 218 limbing times and the distances over which the limbing was performed. When a direct tape measurement could not be made, the limbing distance had to be estimated. At other times, the limbing distances could be read directly from the feller's tape measure. Average limbing time ratios for each diameter class were computed from the collected data. Partial results are shown in Fig. 5-11.

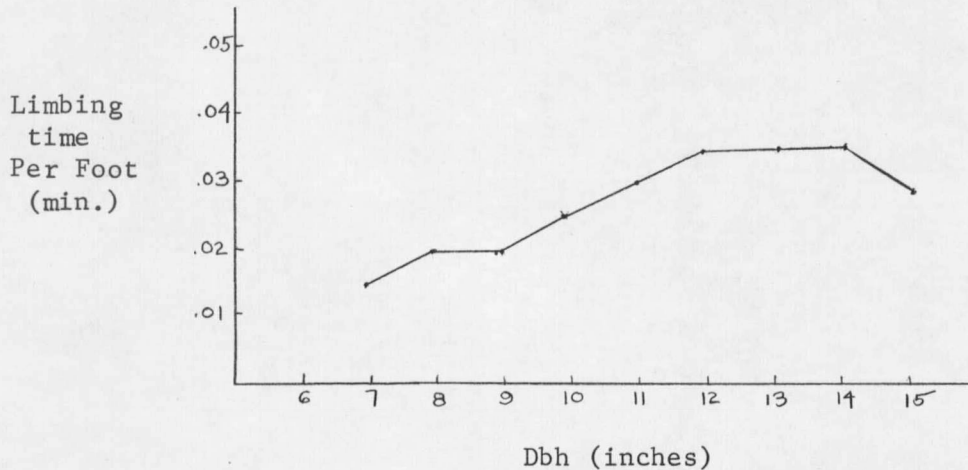


Fig. 5-11. Average Limbing Time Per Foot vs. Dbh

Data was collected only when the feller followed the procedure of walking on the stem in the process of limbing.

Each ratio estimate obtained does not represent the limbing of the entire tree. Many times only the limbing of portions of a tree could be observed.

The individual frequency distributions for limbing time are given in Table 5-XI.

Table 5-XI. Conditional Frequency Distributions for Limbing Times.

Dbh	Limbing Time Per Foot, in Decimal Minutes						Total Number Observed
	0.01	0.02	0.03	0.04	0.05	0.06	
7	12	8	4	-	-	-	24
8	10	8	6	2	-	-	26
9	9	5	5	2	-	-	21
10	5	13	9	5	1	-	33
11	6	15	11	8	4	-	44
12	-	10	10	6	5	2	33
13	-	6	5	7	5	-	23
14	-	1	4	2	2	-	9
15	-	1	3	1	-	-	5

218

5.16.4 On-log travel time. The time to traverse a stem free of limbs was analyzed in the same manner. Measurements were made of (1) the times to traverse "clean" logs of a given dbh and (2) the distances over which the travel was made. The total number of these sets of measurements was 176. Ratio estimates (travel time per foot) were computed and are considered to be conditional on diameter. The results are given in Table 5-XII.

Table 5-XII. On-Log Travel Time Ratios.

Dbh	On-Log travel Time Ratio Estimates, in Minutes Per Foot						$\bar{x}$	No. in Sample
	0.005	0.006	0.007	0.008	0.009	0.010		
7	-	-	2	4	5	4	.0077	15
8	-	2	4	5	5	3	.0081	19
9	-	3	7	8	6	2	.0079	26
10	2	5	9	12	5	1	.0073	35
11	3	7	7	13	2	-	.0071	32
12	2	3	3	11	-	-	.0072	19
13	2	2	1	6	-	-	.0070	11
14	3	4	4	1	-	-	.0063	12
15	3	4	-	-	-	-	.0056	7

These data will be used in a manner analagous to limbing times.

5.16.5 Bucking times. Data on bucking were obtained in a manner similar to felling data collection. Times for cutting through the logs at the bucking points were recorded along with the associated diameters (o.b.).

Two different operators were studied, each of whom used a different make and model saw. One of these men bucked his logs in the woods (our old F₃), and the other worker bucked at the landing. These are two of the alternatives shown in Fig. 2-3. Data obtained in this way would not only give an indication of whether the two saws cut differently, but in the analysis phase an indication would be gained on whether the time required to buck in the woods differs markedly from bucking time at the landing. It seems unlikely that the two effects would cancel each other out and thereby show no difference when in fact one did exist. Again, only workers who were considered to be average workers were studied.

Observations on 367 cuts were made on diameters ranging from 6 inches to 16 inches. Unlike the felling dbh measurements, which were recorded in decimal inches, diameters were measured in whole inches. This was done to facilitate the measuring technique. It must be remembered that while the analyst is measuring the bucking diameters, the cutter is often-times felling another tree. It is desirable to measure the stem as quickly as possible and seek asylum, for obvious reasons. Furthermore, many cuts are extremely difficult to get at once the tree is on the ground. The effect of this problem increases directly with number of trees already cut, since the trees often lie

criss-crossed on the ground.

A table similar to Table 5-VI for felling was worked up for bucking.
(Table 5-XIII).

Table 5-XIII. Vital Statistics for Bucking Time Study,
Gallatin National Forest, 1964.

Sale, Cutter Number	Sale Name	Location (District)	Saw Make & Model	Number of Cuts	% of Total
B ₁	BearCreek#2	Gallatin	Homelite 770-D	293	79.4
B ₂	BearCreek#3	Gallatin	McCulloch 1-53	76	20.6
				369	100.0

Table 5-XIV gives the average observed bucking time for each man/
machine-diameter combination along with the number of observations
collected for each average value. The buckers are denoted by B₁, B₂.

Table 5-XIV. Average Bucking Times for Each Man/Machine-Diameter
Combination and Number of Observations.

Diameter	Man/Machine		Number of Observations	
	B ₁	B ₂	B ₁	B ₂
6	0.06	0.06	48	24
7	0.08	0.09	48	27
8	0.11	0.11	36	6
9	0.15	0.15	38	8
10	0.20	0.21	46	3
11	0.23	0.29	40	2
12	0.28	0.31	20	3
13	0.34	0.28	6	1
14	0.36	-	7	-
15	0.63	-	2	-
16	0.43	-	1	-
			293	74

These data were also subjected to a statistical analysis. The information in Table 5-XIV is plotted in Fig. 5-12. Frequency distributions of bucking times for each diameter class are given in Appendix G.

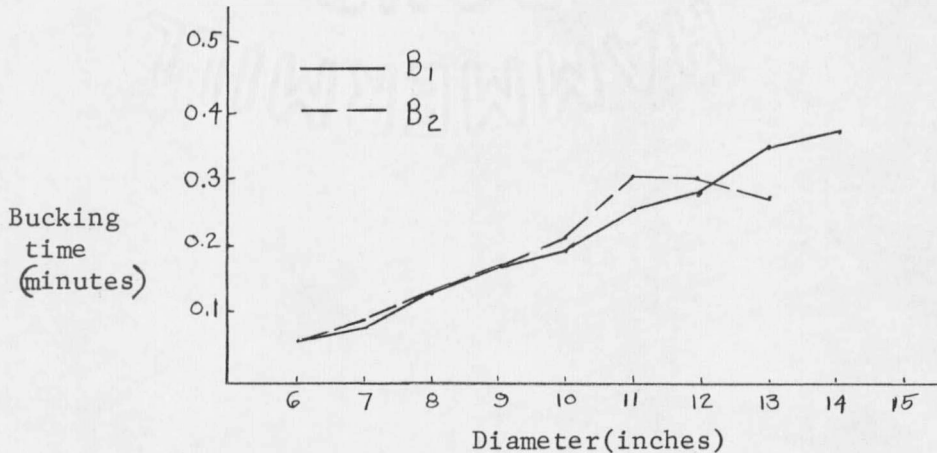


Fig. 5-12. Average Bucking Times for Two Different Buckers.

An empirical curve was drawn up to represent the combined average bucking times. A theoretical curve, based on the premise that the time to make a buck cut varies at the square of the radius at the cutting point, was determined. Its functional form is $y = .00179x^2$ where y = bucking time and x = diameter at the bucking point. The correlation coefficient for $x \leq 10$ was .88, highly significant, and for $x > 10$ it was .52. Lack of a sufficient quantity of data at this higher level was thought to be the reason for this discrepancy. The curves, theoretical vs. empirical, are given in Fig. 5-13.

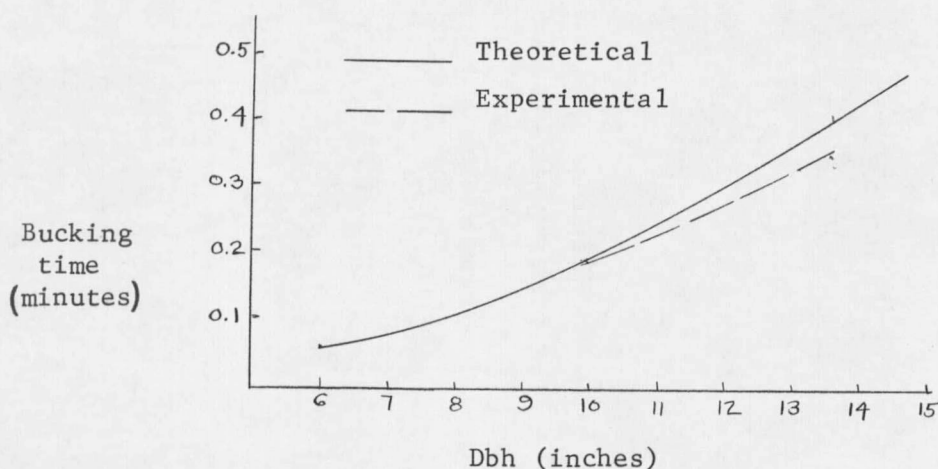


Fig. 5-13. Theoretical vs. Empirical Bucking Curves.

A series of t-tests were run on the data for each diameter class.

The results are given in Table 5-XV.

Table 5-XV. T-tests of Bucking Data.

Dbh	T Experimental	T .05 (df)	Decision
6	.210	2.00 (69)	Accept Ho
7	.880	1.99 (71)	Accept Ho
8	.179	2.03 (38)	Accept Ho
9	.066	2.01 (44)	Accept Ho
10	.101	2.01 (47)	Accept Ho
11	.207	2.02 (40)	Accept Ho
12	.250	2.37 (7)	Accept Ho
13	.071	2.57 (5)	Accept Ho
14(a)	-	-	-
15(a)	-	-	-

(a) B₂ not observed bucking this diameter

The null hypothesis is accepted in each case. There is no need to seek further refinement with the sum of ranks test, since the t-tests yielded such significant results. Bucking times should more nearly approach the normal distribution, anyway, since bucking consists of straight cuts

through the logs.

To obtain a sample bucking time, BUCKT, a random number, RND, is generated and the proper conditional probability distribution entered. This sample value is then added to TBUCK, the total bucking time.

5.17 Travel Time. Assuming felling, limbing, and bucking have been performed, a formula for travel time, V, might be

$$V = (m + d) g \quad (\text{eq. 5.8})$$

where
 m = length of the butt log in feet.
 d = distance from stump to the next tree in feet
 g = travel time per foot ratio estimate

Or, in terms of the computer variables

$$TTRAV = (BNO(1) + DIST) TRAVT \quad (\text{eq. 5.9})$$

The length of the butt log, BNO (1), has already been defined. Distance to the next tree, DIST, is obtained by generating a random normal deviate, DEV, multiplying it by the standard deviation of the distance-between-trees distribution, STD, and adding this quantity to the mean, AVE. Distance-between-trees is assumed to be distributed normally. A few experiments were performed to confirm this assumption, and a χ^2 test was performed on the data. In all cases, the assumption of a normal distribution was reasonable.

The mean of the distance-between-trees distribution, AVE, is computed from an equation given in (34):

$$AVE = \sqrt{\frac{45360}{TREES}} \quad (\text{eq. 5.10})$$

The assumed standard deviation is that deviation which would make

the lower bound of the distance between trees approximately zero, i.e.

$$\text{STD} = \text{AVE} / 3.0 \quad (\text{eq. 5.11})$$

A method for generating random normal deviates had to be found.

5.17.1 Random normal deviates: Random Gaussian, or normal, deviates were obtained by transforming a uniform random variable, R , to a normal random variable, Y , by the method of Teichroew (49).

We require that

$$R = F(t), \quad (\text{eq. 5.12})$$

where $0 < R < 1$, and $F(t)$ is the cumulative normal density function over the range $-\infty$ to Y , $\frac{1}{\sqrt{2\pi}} \int_{-\infty}^Y e^{-t^2/2} dt$. The problem is to determine the Y for which this is true. There are other, more accurate, methods for generating random deviates than that of Teichroew, but his method was chosen because of the relatively small computer storage space required. Other than the fact that this technique seldom results in a deviate greater than four standard deviations, it has much to recommend it, especially for smaller machines.

In this approach a fixed number of uniform variables is summed and an approximate normal deviate obtained by the use of an interpolating Chebychev polynomial. It is desired to find $Y = g(Z)$ where

$$\frac{1}{\sqrt{2\pi}} \int_{-\infty}^Y e^{-\frac{t^2}{2}} dt = \int_0^Z m_Y(t) dt \quad (\text{eq. 5.13})$$

and where m_Y is the density function of the sum of Y uniform variables. The range of Z is restricted to $Z_L \leq Z \leq Z_U$, and $Y = g(Z)$ is approximated by finding an interpolating polynomial. A Chebychev polynomial of degree $k - 1$ is fitted so that its values are the same as the value

of $g(Z)$ at the k roots of the Chebychev polynomial of degree k .

The case where $\delta = 12$ is used, since this δ value yields the most satisfactory results (39). Let $Z = \sum_{i=1}^{12} V_i$ so that $0 \leq Z \leq 12$.

Since Z must be restricted, Teichroew chooses $Z_L = 2$, $Z_U = 10$, where $P(Z_L \leq Z \leq Z_U) \geq 1 - 2(10)^{-5} = 0.9998$. If Z falls outside this range, it must be discarded.

Furthermore, let $r = (Z - 6) / 4$. Then an approximate normal deviate Y is obtained from

$$Y = \sum_{j=0}^9 d_{2j+1} T_{2j+1} r \quad (\text{eq. 5.14})$$

Rearranging the series in r , we obtain

$$Y = a_1 r + a_3 r^3 + a_5 r^5 + a_7 r^7 + a_9 r^9 \quad (\text{eq. 5.15})$$

where the coefficients $a_1, a_3, \dots, a_9$, are as follows:

$$\begin{aligned} a_1 &= 3.949846138 \\ a_3 &= 0.252408784 \\ a_5 &= 0.076542912 \\ a_7 &= 0.008355968 \\ a_9 &= 0.029899776. \end{aligned}$$

More explicit details can be found in reference (49). Since normal deviates were to be generated only once in a complete logmaking cycle, a special subroutine was not written. The instructions are incorporated in the mainline program. The computer variable SUMJ corresponds to Z , and XM corresponds to Y .

5.17.2 On-ground travel time. The on-ground travel time distribution was constructed and used in the same manner as the on-log distribution for all land travel. The resultant distribution of travel time ratios is shown in Fig. 5-14.

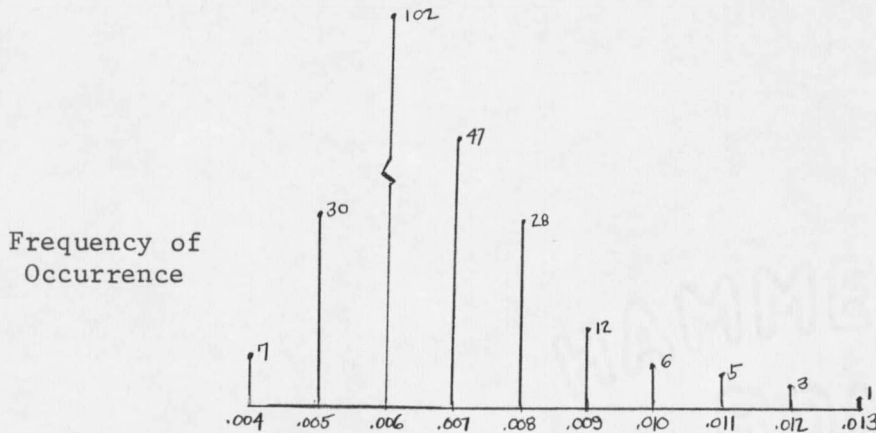


Fig. 5-14. Travel-Time-on-Ground Ratios

A cumulative probability distribution was constructed from this data.

This distribution is not read in as input like the others; ordinate values were incorporated into the mainline program.

5.18 Volume Determinations. After a log has been cut, its volume, both cubic-foot and board-foot, is computed.

5.18.1 Cubic-foot volumes. Smalian's formula is used to compute cubic-foot volumes. Since log length and diameters at both ends are known, cubic-foot volume can be computed from:

$$V_s = \pi \left(\frac{d^2}{(2)(144)} + \frac{D^2}{2(144)} \right) \frac{L}{2} \quad (\text{eq. 5.16})$$

where V_s = cubic-foot volume of a log, Smalian
 d = diameter at the small end, in inches

D = diameter at the big end, in inches

L = length of the log, in feet

Or, in terms of computer variables,

$$CFVL = 3.1416 \left(\frac{RDIAM(J)^2}{288.} + \frac{STUMP^2}{288.} \right) \frac{BNO(J)}{2.}$$

for the first log, and

$$CFVL = 3.1416 \left(\frac{RDIAM(J)^2}{288} + \frac{RDIAM(J00)^2}{288} \right) \frac{BNO(J)}{2.}$$

where J00 = J-1, for each succeeding log.

5.18.2 Board-foot volumes. There are provisions in the program for computing board-foot volumes of a log in five different ways. Any one of these estimation methods is likely to be used in any given area.

Method 1 - Volume by Weight

The "weight factor" commonly used in this area is 11 pounds per board-foot. In the model, the weight of a log is determined by multiplying its cubic-foot volume, CFVL, by its density factor, 28.2/ft³, given in Table 3-II. The estimated weight is then divided by 11 to arrive at the estimated volume in board feet, BFVWT.

Method 2 - Volume by Scribner (no allowance for taper)

Board-foot volume is also computed using a relationship derived for the Scribner rule. This relationship is given by:

$$V = 0.79d^2 - 4d - 2 \quad (\text{eq. 5.18})$$

where V = Scribner board-foot volume of a 16-foot log

d = diameter at the small end

Or, in terms of computer variables,

$$BFVS = 0.79 \cdot RDIAM(J)^2 - 4 \cdot RDIAM(J) - 2 \quad (\text{eq. 5.19})$$

Since this formula was developed for 16-foot logs, volumes of logs of a length other than 16 feet must be adjusted. One way to do this is to multiply the volume obtained with the above formula by ADJ, where $ADJ = BNO(J) / 16.3$. This method is consistent with the Scribner rule derivation.

Method 3 - Decimal C (no allowance for taper)

Volume in Scribner Decimal C, NDECC1, is computed by rounding off the volume obtained by Method 2 to the nearest 10 and dropping the zero.

Method 4 - Volume by Scribner (allowance for taper)

Another way to assign a Scribner volume to a log over 16.3 feet in length is to assume that the log is made up of one 16-foot log plus another log, the length of which is the difference between BNO(J) and 16.3 feet. Thus, a Scribner volume is assigned for a 16-foot log based on eq. 5.9 with RDIAM(J) as its small diameter. The diameter at the point where this 16-foot log would terminate, DIAMM, is inferred by "interpolation", i.e.

$$\frac{16.3}{BNO(J)} \left(RDIAM(JOO) - RDIAM(J) \right) + RDIAM(J) = DIAMM \quad (\text{eq. 5.20})$$

and the remaining volume obtained by "adjustment" and added to the first. Whenever the size of the actual log to be cut exceeds 16.3 feet, this method of estimation will always yield a greater volume than Method 2.

Method 5 - International 1/4" Log rule (allowance for taper)

Without considering losses or taper, the International board-foot volume of a log is given by the expression

$$V = .7854 d^2 L / 12 \quad (\text{eq. 5.21})$$

where V = volume in board feet, International rule
d = d.i.b. in inches at small end of a 4-foot section
L = log length, in feet

Corrections for losses and taper are subsequently made, and the final formula per 4-foot section, allowing for a 1/4" saw kerf is:

$$V = (.22d^2 - .71d) \quad (\text{eq. 5.22})$$

These log section volumes are totaled to give the volume of the entire log.

In the program, the number of 4-foot sections, CAN, is determined and the International volume, TV14, using eq. 5.22, is computed for each section. These partial volumes are then added to yield the total volume of the log, V14.

5.18.3 Stump diameters. In computing cubic foot volumes, it is desired to know the diameter at the stump, or level of cutting. This information is given in the publication by Mason (32). A partial reproduction of his table is given in Table 5-XVI.

Table 5-XVI. Butt Taper of Lodgepole Pine, 1' Stump Height.

Dbh (inches)	5	6	7	8	9	10	11	12	13	14	15	16	17
Stump diameter (inches)	5.5	6.6	7.8	8.9	10.1	11.1	12.2	13.3	14.4	15.6	16.8	18.0	19.3

A useful relationship can be derived from this table. It is

$$\text{STUMP} = \text{DBHX} + (\text{DBHX} + 2.) / 10. \quad (\text{eq. 5.23})$$

where STUMP = stump diameter
DBHX = dbh

Although this relationship does not exactly result in a table like Table 5-XVI, it is close enough so that no large error should be accrued by using it. One might say that eq. 5-23 would result in a diameter that was consistently greater than that given in Table 5-XVI, but, one must keep in mind that stump height assumed in this thesis is 8 inches, whereas

the table is based on a stump height of one foot. Eq. 5-23 should be adequate for this preliminary model.

5.18.4 Bark thickness. For computing cubic-foot and board-foot volumes, the bark thickness of the trees has to be known. The bark of a tree is unusable as far as ultimate product is concerned and cannot be included in any volume calculation. Bark thickness varies with diameter and with the tree species. In general, the bark thickness of lodgepole pine is not great. Table 5-XVII presents average bark thickness of lodgepole pine for trees of given diameter (24).

Table 5-XVII Bark Thickness of Lodgepole Pine, in Inches.

D.o.b.	5	6	8	10	12	14	16	18	20	22	24
D.i.b.	4.70	5.67	7.61	9.55	11.48	13.42	15.36	17.30	19.24	21.17	23.11

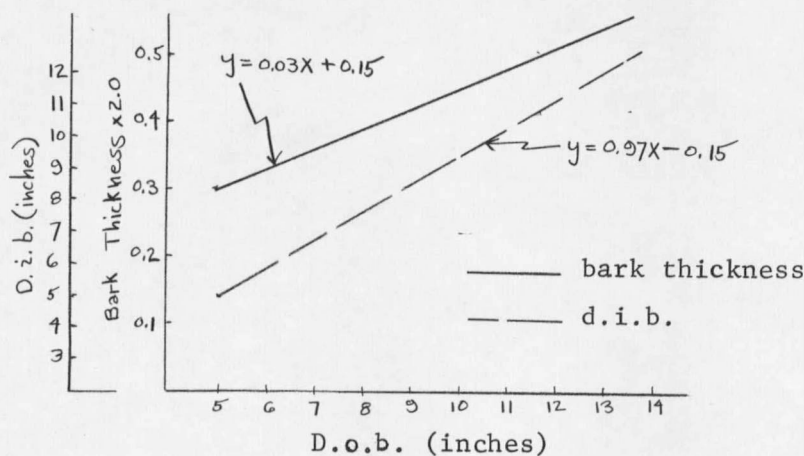


Fig. 5-15. Bark Thickness of Lodgepole Pine.

It must be remembered that these are average figures only - bark thickness, as does any physical variable, fluctuates about these mean values.

From this table, a useful relationship can be derived. Since the bark thickness vs. diameter curve is linear, a straight line adequately describes the relationship. By plotting the data (Fig. 5-15) computing $\Delta y / \Delta x$, and noting the y-intercept, it is seen that

$$y \cong 0.97X - 0.15 \quad (\text{eq. 5.24})$$

where $y = \text{d.i.b.}$
 $x = \text{d.o.b.}$

5.19 Refueling Times. The time to refuel is included in total productive work time. Times to refuel and reoil were obtained in the field and supplemented by laboratory experiment. Twenty experiments were performed. The average cycle for removing gas and oil caps, pour fuel and oil, and replace caps takes about 1.667 minutes. It is broken down as follows:

Remove gas cap	0.095 minutes
Remove oil cap	0.135 minutes
Pour gas-oil mixture	0.610 minutes
Pour oil	0.570 minutes
Replace gas cap	0.117 minutes
Replace oil cap	0.140 minutes
	<u>1.667 minutes</u>

Oil is put in on an average of every other refueling time. Therefore, the cycle time was broken down into two components, (1) refuel time, and (2) oiling time.

The average time to refuel, including removing and replacing tank cap, is 0.822 minutes, and average oiling time was determined to be 0.845 minutes.

In the model, refueling time per day is assigned according to the number of logs cut that day. A feller averaging 160 logs per day will refuel four times per day and fill the oil reservoir twice.

Therefore, the number of logs cut on any particular day is used as an indicator of how much time was spent in refueling.

The expression for refueling time per day was derived as follows:

Assume: Feller refuels after cutting 40 logs; puts oil in after 80 logs have been cut.

Then refuel time, in hours, REFUEL, is

$$\begin{aligned} \text{REFUEL} &= ((\text{BUT}/40.) .822 + (\text{BUT}/80.) .845) / 60. \\ &= .000518 \cdot \text{BUT} \end{aligned} \quad (\text{eq.5.25})$$

where REFUEL = Refueling time in hours
 BUT = Number of logs cut in any one day.

Refueling time is assigned at the end of a simulated day.

5.20 Sharpening the Saw. The feller who averages 5000 - 6000 board feet per day will usually sharpen his chain twice. Although improved sharpening methods have been developed in the last few years, the majority of fellers seem to prefer the old "hand" method of filing. The average sharpening time for a chain fitting an 18" bar, based on 10 observations, is 3.20 minutes. The standard deviation from this time was 0.51 minutes.

Since the average feller will cut 160 logs per day, the chain will be sharpened after approximately 80 logs have been cut. Thus sharpening time per day, SHARP, can be given by

$$\begin{aligned} \text{SHARP} &= \frac{\text{BUT}}{80} (.0533) \\ &= .000667 \text{ BUT} \end{aligned} \quad (\text{eq.5.26})$$

where SHARP = chain sharpening time per day, in hours
BUT = number of logs cut in that day.

SHARP is considered to be part of total productive time.

5.21 Cost of Operation: Total cost was broken down into its fixed and variable components. A complete cost breakdown is given in Appendix E. Fixed cost, FCOST, was determined to be \$0.23 per hour and variable cost, VCOST, was computed to be \$0.48 per MBF. At the end of each hour and each day, total cost, TCOST, is computed by multiplying the board-foot (Scribner) production in MBF by the variable cost rate and adding to the fixed cost for that time period.

5.22 Revenue: The amount of revenue received by the logger is, of course, determined by his production. A rate of \$4 per MBF (the going-rate) is used in the program to compute expected revenue for each of the five different methods of production estimation.

5.23 Profit (Loss): Profit or loss is, naturally, the difference between TCOST AND REV.

5.24 Output: A sample of the output from Phase II is given below. Assume acceptable log lengths are 33, 25, 17; cull factor = 0; and the feller cuts 10 trees per hour for 12 hours.

1. After each log has been cut: .

[illegible]

2. After each tree has been worked on:

[illegible]

3. At the end of each hour:

NTRIAL	LHR	NPR	TCOST	REV1	REV2	REV3	REV4	REV5
1	1	10	0.52	1.46	1.94	1.92	2.44	2.52
1	2	10	0.47	1.25	1.66	1.60	2.03	2.14
1	3	10	0.50	1.38	1.67	1.64	2.23	2.25
1	4	10	0.43	1.07	1.25	1.24	1.64	1.72
1	5	10	0.48	1.30	1.54	1.48	2.09	2.08
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.

4. At the end of each day:

NTRIAL	NCUT	PROD	UNPROD	TFELL	TLAB	TTRAV	CTIME	FACTOR	TDIST	TCOST	REV	PROFIT
1	120	3.33	8.67	0.65	1.44	0.54	0.00	0.20	4678.	5.54	23.20	17.66

5.25 Console Operation. Operation procedure and input order for Phase

II is

- (a) load object deck
- (b) load subroutine deck
- (c) data input

Several trial runs of the model were conducted and analyzed. The results indicated that this analysis method is very promising. It must be remembered that the model at this stage is still mainly conceptual--no attempt was, or should be, used to use the results as they stand. All through this thesis, the author has stressed the importance of the potential users' proper planning and implementation of data collection programs to augment and improve upon what is presented here.

PART III

This section is devoted to reviewing what has been accomplished in this thesis and providing a look into the future. It is composed of three chapters.

Chapter 6 gives the results of several trial runs of the simulation model. Chapter 7 is devoted to (1) a discussion of some of the refinements that could be synthesized into the preliminary model, (2) some of the limitations of the method, (3) a few pitfalls to be aware of, and (4) recommendations for further study. Finally, the conclusions reached in this study are given in Chapter 8.

CHAPTER 6

RESULTS OF SIMULATION RUNS

6.1 Checks. Before making the various trial runs, a few checks were made to see if the model would provide some reasonable results.

The first test conducted was a comparison between expected cubic-foot and board-foot volumes with volumes actually obtained in some trial Phase II runs. This was done for bucking sets 1, 4, and 5 in Table 4-III, assuming no cull. The results of this comparison are shown in Table 6-I.

Table 6-I. Comparison of Expected and Simulated Actual Volumes

Bucking Set	ECFV	CFV	DIFFA (%)	EBVF	BVF	DIFFB (%)
1	15,217	12,483	17.9	63,638	50,124	-21.2
4	15,217	12,806	15.8	63,638	49,593	-22.0
5	15,217	14,064	7.6	63,638	55,197	-13.3

In no case was the difference less than 7%. This test was to serve only as a guide to the plausibility of the data and model. Since expected cubic-foot and board-foot volumes were obtained from tables derived in Colorado, and actual volumes were based, in part, on separate tables published in 1915, the results of this test were encouraging. It is recommended that this area be investigated further; perhaps new and better original data needs to be collected.

There was no way to check cost data with other sources, since this is the first felling and bucking study devoted entirely to

lodgepole pine logging. In the debugging phase of running the FORTRAN programs, other checks were made on each part of the model for consistency between raw data and simulation results, to make sure that the programs were functioning properly and doing "all that they were supposed to." There is no need to belabor the point here, other than to say, woefully, that the programs took about a month to debug.

6.2 Simulation Runs. Several of the many possible options were analyzed. The criterion for selection of the set of alternatives was to present a cross-section of the various types of problems that can be investigated by simulation. The "modus operandi" and objective of each run are presented in Table 6-II.

Table 6-II: Simulation Runs

Run	"Modus Operandi"	Objective
1	Vary production rate	Determine optimum operating level
2	Vary acceptable log length	Note effect on cost, profit, and log distribution.
3	Vary cull	Locate BEP cull factor and isolate effects of different types of cull.
4	Vary board-foot estimation methods	Compare different rules to demonstrate need for a "standard" board-foot rule

The design and results of each run will be discussed separately. The results are by no means conclusive. They must be taken as preliminary. Each result should be investigated in the field and approp-

riate modifications made in the model.

6.3 Run 1- Vary Production Rate.

6.3.1 Design. The production rate, measured in trees cut per hour, was varied from 5 to 35 in steps of 5. In this run, log length, cull, and board-foot rule are kept constant, viz: the acceptable log lengths used in the run are 33, 25, and 17 feet; cull is simply the amount of waste left in the woods; and the board-foot rule used is the Scribner rule, allowing for taper.

6.3.2 Results.

a. Effectiveness. Production rate is directly under the control of the logger and can be used to measure worker effectiveness. Effectiveness, in this study, is the ratio of total productive time to total available time.

Effectiveness as a function of production rate is shown in Fig. 6-1. There is a 20 percent allowance for rest and delay built in.

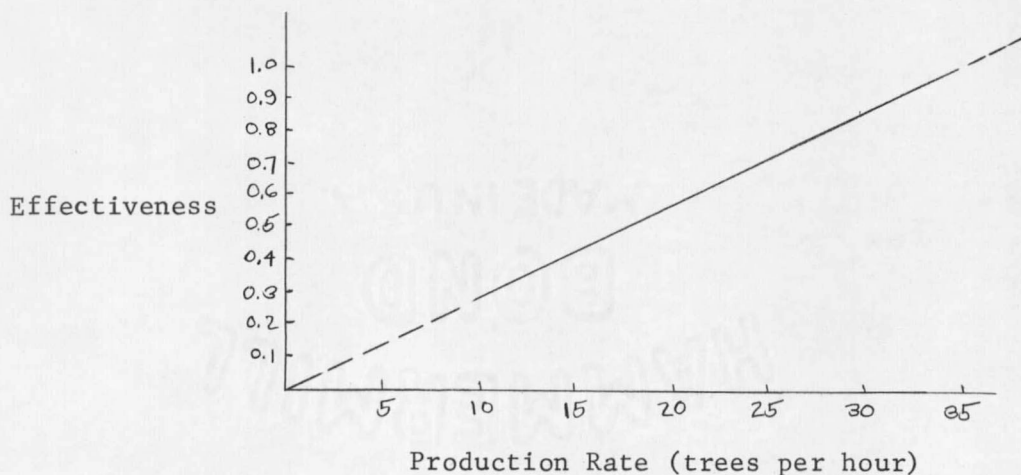


Fig. 6-1. Effectiveness vs. Production Rate

The "ideal" maximum production rate can be determined by extending the above curve to the point where effectiveness equals 1.0 (i.e. productive time exactly equals available time). In this case, the "ideal" maximum turns out to be about 38 trees cut per hour. Of course, this theoretical maximum will never be reached since the delays mentioned in 4.1 would come into play. That is, the actual maximum operating level would always be somewhat below this "ideal."

b. Profit. Average daily cost, revenue and profit for each production rate, assuming an 8-hour work day, are summarized in Fig. 6-2.

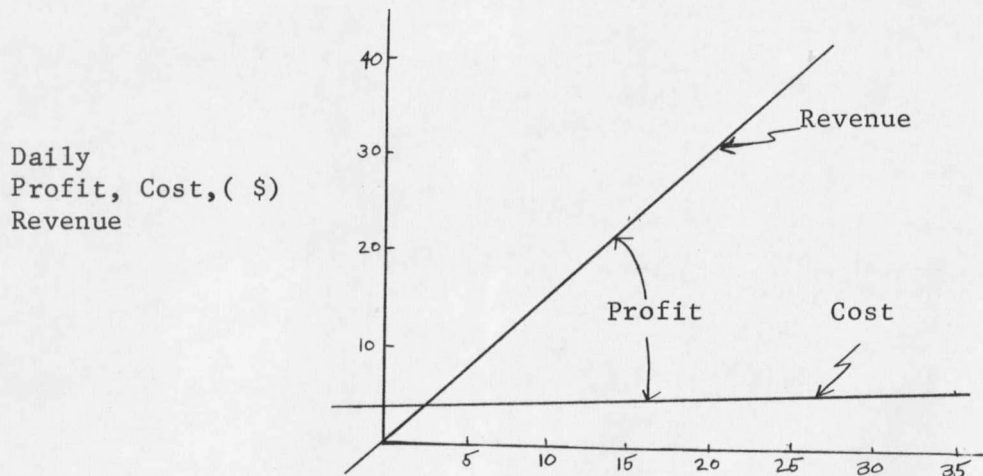


Fig. 6-2. Profit vs. Production Rate

The feller must average over 3 trees per hour to make a profit. Daily profit reaches an "ideal" maximum of about \$38.50 at 38 trees cut per hour.

This graph has an important function. From it, the logger can predict in advance what his expected cost and profit will be at a particular operating level. He will therefore know where to operate for desired profit; or, if at a particular operating level he sees he is making less than what is expected, he would begin to search for the reasons why.

c. Operational Times. Felling, limbing, and bucking, and travel time per MBF can also be predicted. This information would be useful in the preparation of time tables similar to the tables set up by Merz, Herrick, and Neebe by on-site observation.

Table 6-III is the matrix of operational times per MBF at the experimental production rates.

Table 6-III. Operational Time Matrix in Hours
(Including 20% rest and delay allowance)

Prod. Rate	Fell	Limb and Buck	Travel	Total Productive Time*
5	.135	.236	.111	.542
10	.138	.307	.114	.559
15	.138	.313	.112	.563
20	.145	.303	.111	.559
25	.140	.306	.113	.559
30	.143	.309	.109	.561
35	.140	.318	.112	.570

The variation within this array, of course, is due to the fact that this is a sampling procedure.

* exclusive of prorated elements such as refueling and sharpening the chain.

From these data, average productive time (including allowance for rest and delay) per MBF was determined to be 0.559 hours, or about 33.5 minutes, at an average cost of \$0.75.

The total logmaking time per MBF can be broken down into its components (Table 6-IV):

Table 6-IV. Logmaking Components

Component	Ave. Time per MBF, in Hrs.	% of Total Time
Felling	0.140	25.0
Limb and Buck	0.307	55.0
Travel	<u>0.112</u>	<u>20.0</u>
Total	0.559	100.0

Far more time is spent in the limbing and bucking phase than either in felling or travel. No attempt was made to separate limbing and bucking time.

The costs per MBF at the different production rates are shown in Fig. 6-3.

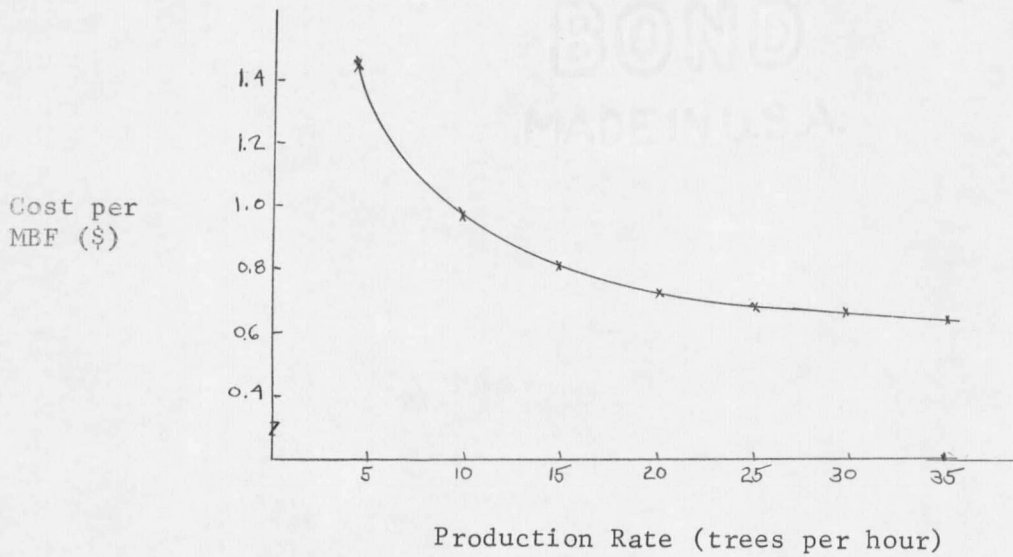


Fig. 6-3. Cost per MBF vs. Production Rate

Naturally, as production rate increases, unit cost decreases.

d. Distance Finally, distance traveled per hour as a function of production rate is given in Fig. 6-4.

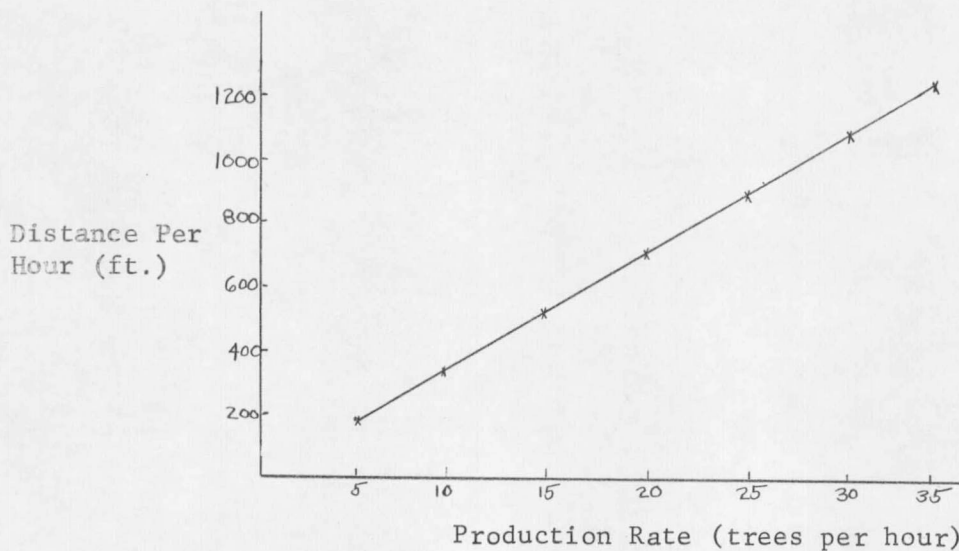


Fig. 6-4. Distance Traveled Per Hour vs. Production Rate

This information is not, in itself, too useful.

The factors that were kept constant in this run can be varied at will to correspond to local policies and conditions.

Run 2 Vary Acceptable Log Lengths.

6.4.1 Design. Bucking sets 1, 4, and 5 of Table 4-III were used in this run. Set 3, poles, was not considered since a different pay scheme is used by the pole companies. (This alternative could easily be handled by this model, however). An assumption was made as to the possible outcome of bucking set 2. The logger was assumed to be proficient enough to avoid "short-log" dockage.

The run was conducted in a manner similar to Run 1; that is, production rate, P, was varied while cull and board-foot estimation methods were kept constant at the same values. The results were then compared to those of Run 1.

6.4.2. Results.

a. Log length distributions.

The frequency table (Table 6-V) of log lengths resulting from each bucking policy shows that essentially the same total number of logs are garnered with policies I and II, and policy III yields substantially more logs than either I or II. This would be expected, since more combinations can be used when logs can be brought down to 8 feet.

Table 6-V. Frequency of Log Lengths.

Length	Policy I Sets 1 & 2	Policy II Set 4	Policy III Set 5
33	514	490	8
31	-	169	276
29	-	190	257
27	-	125	256
25	605	145	318
17	186	186	185
8	-	-	481
Total	1305	1305	1781

Results for bucking sets 1 and 2 (called Policy I) are assumed to be identical. These results would only differ if there were a substantial number of trees with a merchantable height falling between 8 and 16 feet. Otherwise it would always be more advantageous, cost-wise, to cut 16-foot logs. Since none of the 1080 trees in the "hypothetical" stand had a merchantable height less than 16 feet, this "sub run" (i.e. comparing sets 1 and 2) was not made.

b. Profits.

Average daily cost, revenue, and profit for each production rate, P, under each bucking policy, assuming an 8-hour work day, are compared to run 1 in Table 6-VI.

Tables 6-VI. Comparison of Costs with Various Sets of Log Lengths.

Set	P = 10			P = 15			P = 20		
	Cost	Revenue	Profit	Cost	Revenue	Profit	Cost	Revenue	Profit
1	3.65	15.05	11.40	4.51	22.30	17.78	5.31	28.91	23.61
2	3.65	15.05	11.40	4.51	22.30	17.78	5.31	28.91	23.61
4	3.63	14.94	11.31	4.48	22.03	17.55	5.26	28.53	23.27
5	3.95	17.54	13.59	4.98	26.14	21.15	5.80	32.99	27.19
	P = 25			P = 30			P = 35		
	Cost	Revenue	Profit	Cost	Revenue	Profit	Cost	Revenue	Profit
1	6.19	36.21	30.03	7.14	44.19	37.06	8.10	52.18	44.08
2	6.19	36.21	30.03	7.14	44.19	37.06	8.10	52.18	44.08
4	6.13	35.81	29.68	7.09	43.78	36.69	8.02	51.56	43.54
5	6.96	42.65	35.69	7.97	51.07	43.10	9.04	59.96	50.92

Although bucking set 5 is clearly the most profitable policy, Table 6-VI contains a very surprising result---in this timber stand it appears that bucking set 1 is slightly more profitable than bucking set 4! That is, it is not advantageous to the logger to cut in 2-foot increments between 25 and 33 feet. This result defies intuition, but it can be easily seen that under certain conditions (which prevail in this stand) this will always be true if the estimating is done by the method used in this thesis. The inadequacy of the Scribner board-foot rule in estimating the board feet of trees with considerable taper is at fault.

An illustration may help. Suppose that we have a tree with a dbh of 12 and a merchantable height of 29 feet (i.e. at 29 feet up the stem the diameter is 5.6 inches). Under bucking set 1, one 25-foot log would be obtained; under bucking set 4, one 29-foot log would be taken.

When expected board-foot volumes are computed by method 4 of section 5.18.2 the 25-foot log yields approximately 46.2 board feet while the 29-foot log yields an expected 45.0 board feet. This discrepancy is caused solely by the method of computing. Method 4 does not allow for taper for any length under 16 feet. Thus, when trees taper quickly (at a rate greater than 2 feet per 16 feet of length) a considerable underestimation results from using Scribner. Surely, mill tally will exceed log tally in this case. Some simple computations will show that if the trees taper at a rate of about 2 inches per 16 feet of length, more board feet will be obtained from the 29-foot log than from the 25-foot log. Our log tapers at a rate of about 3.8 inches per 16 feet of length. Thus, the "tradeoff" rate (i.e. the rate at which the board-feet of both logs would be identical) is somewhere between 2 and 3.8 inches. This analysis clearly shows that log taper and estimation method can severely affect revenues.

The total amount of waste material left in the woods that would otherwise have been marketable for each of the tested bucking policies is shown in Fig. 6-5.

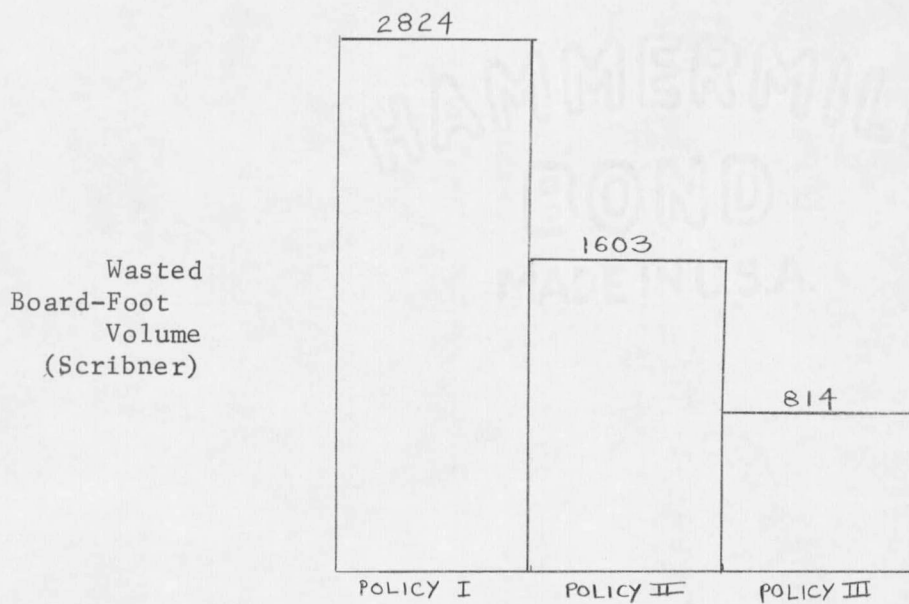


Fig. 6-5. Wasted Board Feet Under Each Bucking Policy.

With Set I, about 4.4 percent of the total volume of 63,638 board feet is wasted; with Set II about 2.5 percent; and, with Set III, about 1.3 percent. It would never be possible, using only discrete log lengths, to utilize all the available timber.

The evidence for overrun with bucking set 4 is startling. Since less waste is encountered than with bucking set 1, it must be concluded that more board-foot volume was obtained. This result adds support to the questioning of the contradictory results shown in Table 6-VI.

c. Effectiveness.

Relative effectiveness under each bucking policy can be studied (Fig. 6-6.)

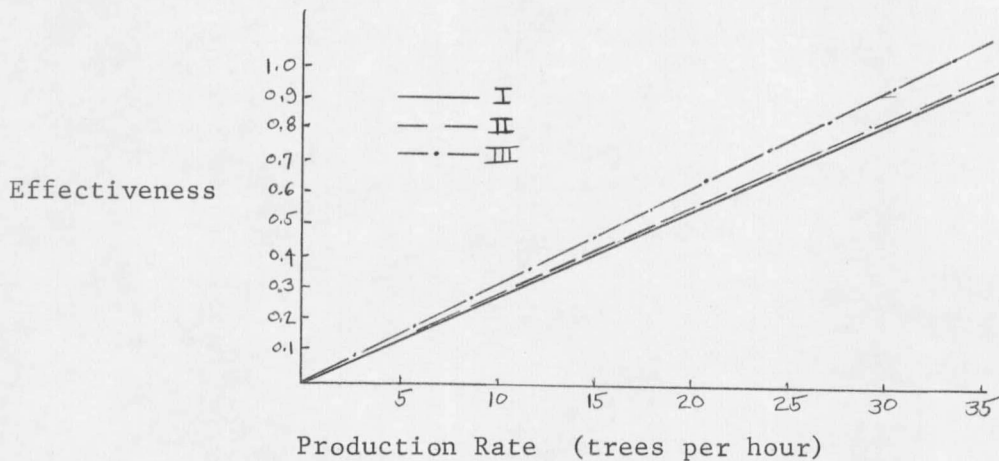


Fig. 6-6. Effectiveness Under Each Bucking Policy.

The difference in worker effectiveness under each policy is slight.

6.5 Run 3 - Vary Cull.

6.5.1 Design. The effects of the three major types of cull were investigated. These cull types are, for reference:

Type 1 - dead trees

Type 2 - stump-rotted trees

Type 3 - dockage

The different treatments were discussed in section 4.3.9.

The different types of cull were varied separately from 0 to 60% and the effect on profit noted. Then, combinations of the three types of cull were tried with the same objective. Production rate and log sizes were fixed at 20 trees per hour and set 1 (33,25,17)

respectively. Samples of 100 trees were used.

6.5.2 Results.

a. Profit.

Partial results of this run are given in Figs. 6-7 and 6-8.

First, the graph of daily profit vs. individual cull types.

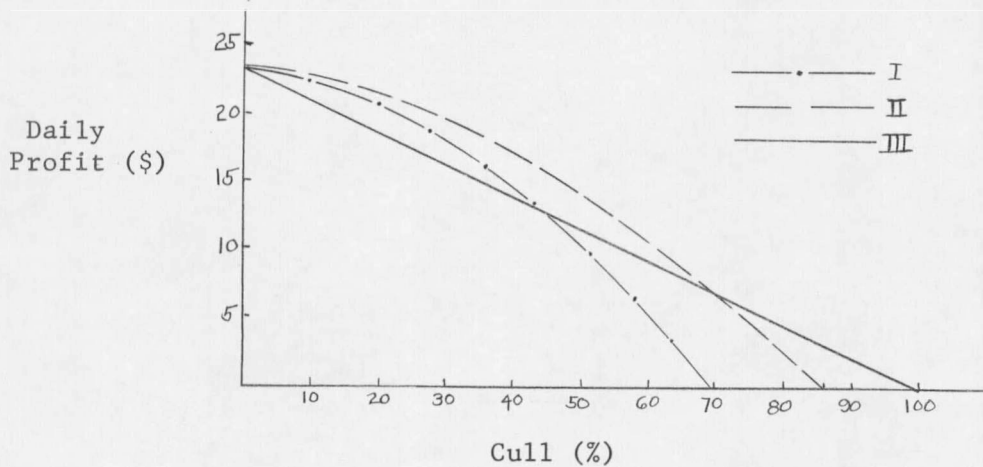


Fig. 6-7. Daily Profit vs. Cull.

Next, the graph of total profit vs. individual cull types and certain cull types in combination.

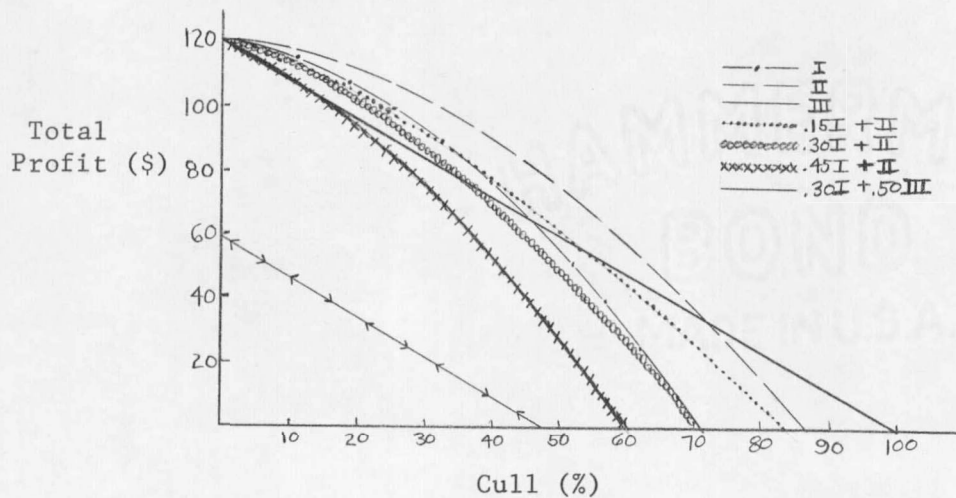


Fig. 6-8. Total Profit vs. Cull.

Overall, cull type II seems to have the most significant effect on profit. The reason for this is that costs are raised when extra cuts have to be made to remove rot. Sometimes the maximum 4 cuts are made before it is determined that a tree is useless. The cost to make these cuts is, naturally, a sunk cost. To shed insight on how the amount of this excess cutting time varies with the cull, see Fig. 6-9.

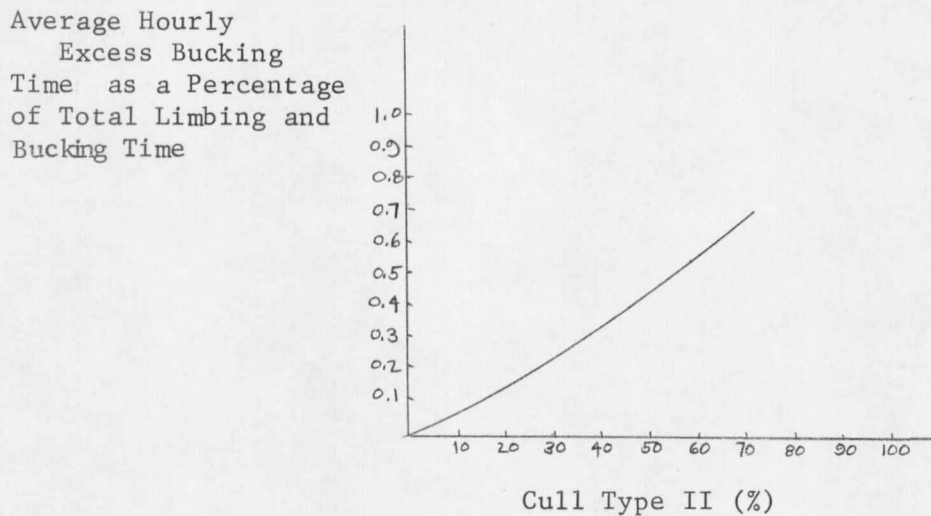


Fig. 6-9. Excess Bucking Time vs. Cull Type II.

At around 50 percent cull, the excess bucking time is 50 percent of the total limbing and bucking time!

b. Waste.

The amount of wasted merchantable volume in the samples of 100 under the different cull conditions can be shown. The samples each contained about 6000 board feet. (Figs. 6-10 and 6-11).

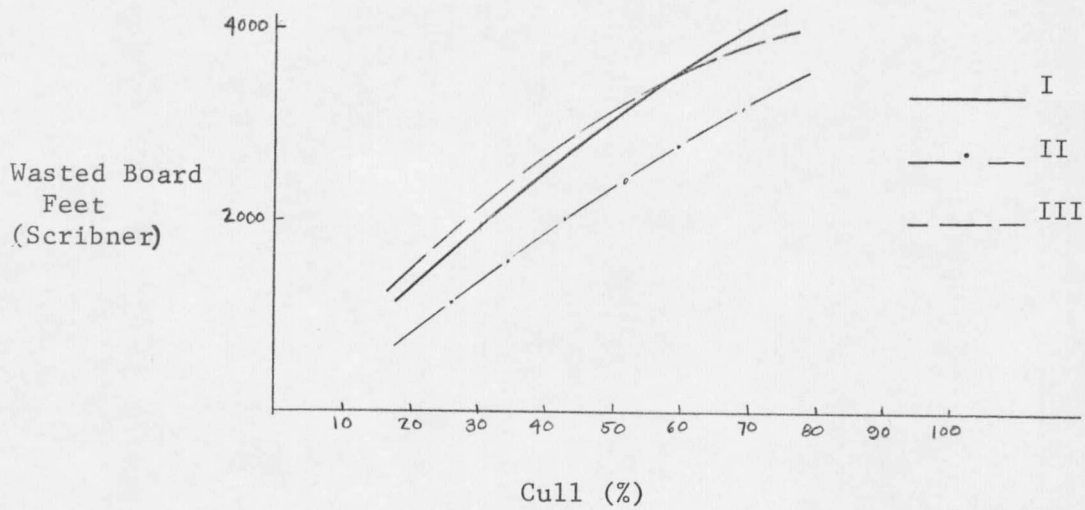


Fig. 6-10. Wasted Volume vs. Individual Cull Types ,

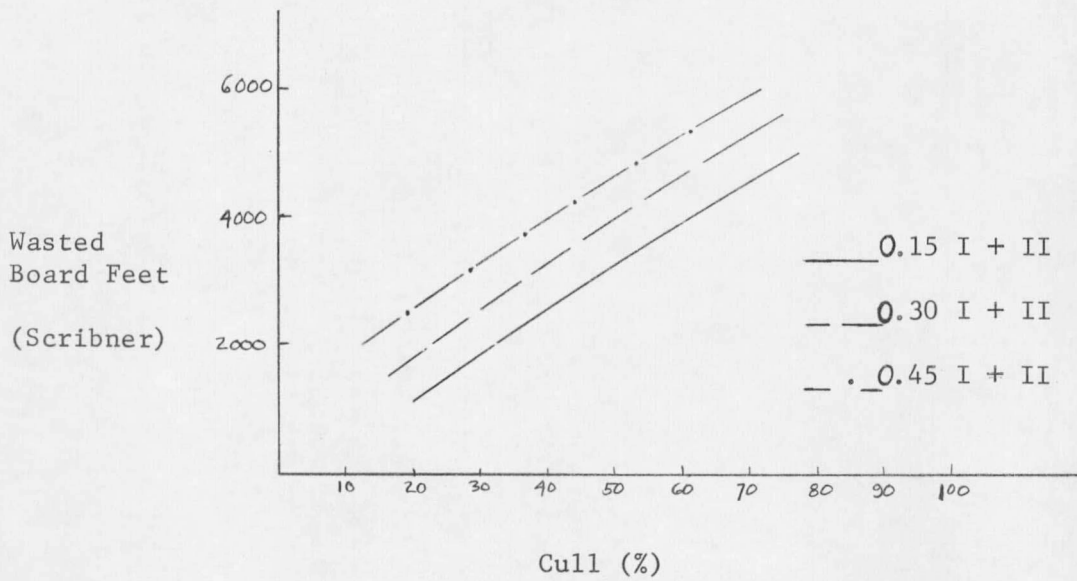


Fig. 6-11. Wasted Volume vs. Cull Types, in Combination.

Unlike cull types I and II, waste volume brought about by cull type III is not left standing in the woods; it is hauled into the mill and deducted there.

6.6 Run 4 - Vary Board-Foot Estimation Methods.

6.6.1 Design. As mentioned previously, there are over 40 different board foot rules in use in the United States at the present time. To show how the logger's profits can be affected by the various rules, the five different rules discussed in section 4.2.4 are compared. For reference, these are:

- (1) weight basis
- (2) Scribner (no allowance for taper)
- (3) Scribner Decimal C (no allowance for taper)
- (4) Scribner (allowance for taper)
- (5) International 1/4" (allowance for taper)

Production rate was varied as before; log sizes were kept at 33, 25, and 17; and cull, other than the usual trimming waste, was assumed to be negligible.

6.6.2 Results. The results of this analysis are shown in Fig. 6-12.

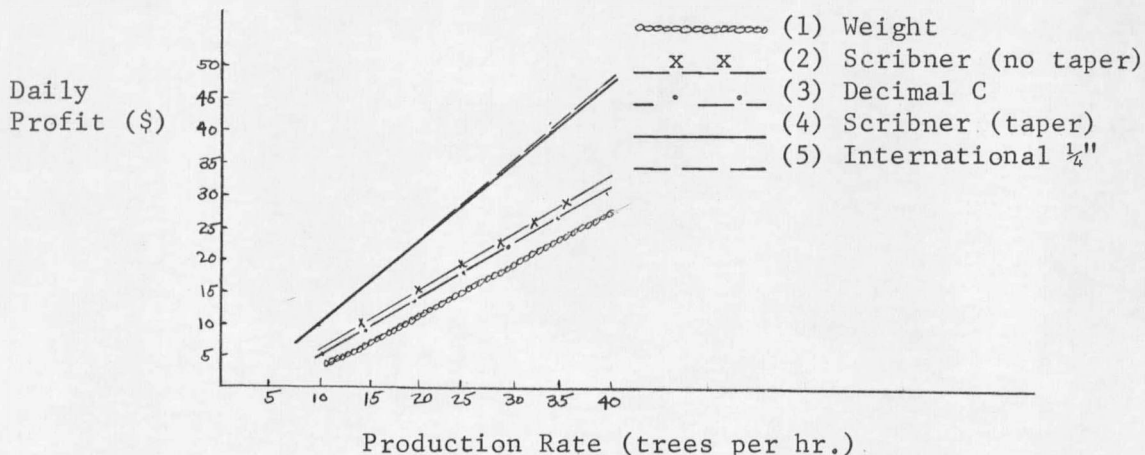


Fig. 6-12. The Effect of Various Board-Foot Rules on Profit.

The most advantageous payment schemes seem to be the Scribner rule, allowing for taper, and the International 1/4" rule. Unfortunately, when the Scribner rule is used in practice, no allowance is made for taper. Thus, a comparison between (2) and (5) is especially meaningful.

The main point here is that these are all payment schemes likely to be found in any part of the country today.

6.7. Summary.

Run 1 served to show the effect of production rate and effectiveness on cost and profit. Assuming that the model yields reliable results, the logger can predict in advance what his costs and profit will be at a particular operating level. He can then proceed to work at the level expected to yield desired profit. Loggers receiving less profit than anticipated should strive to find and eliminate the cause of the discrepancy. If the cutter is operating at a low level, with a low associated effectiveness, he should strive to eliminate idle time.

Run 2 served to uncover the effect of the log length restriction on cost and profit. It was seen that profit is increased when logs can be cut as short as 8 feet. The inadequacy of present log rules was also pointed out. The logger usually has no control over this restriction.

Run 3, varying cull, attempted to pinpoint the effect of different types of cull on profit. Cull type II, stump rot, seemed to be the most significant. The primary value of this run, of course, is its utility in governing the logger's actions. When

the logger has been cutting the area for a time judged long enough to provide significant results, he can estimate the cull factor in the stand. Then, by knowing what the model has determined to be the "breakeven" point, he can make a decision on whether it is profitable to continue cutting the stand or not.

Run 4, varying board-foot estimation procedures, served to further point out the inadequacy of present pay schemes. It pointed out that work should begin on developing either a uniform standard log rule, or a different method of payment, perhaps based on cubic-foot volume. Conjecturally, the latter seems to be more preferable.

CHAPTER 7

REFINEMENTS, LIMITATIONS, PITFALLS, AND RECOMMENDATIONS FOR FURTHER STUDY

In an initial study of this type, there are many things that get overlooked; there are inherent short-comings in method; there are certain precautions to be aware of; and there are new avenues opened for further investigation. We will call these four items (1) refinements, (2) limitations, (3) pitfalls, and (4) recommendations for further study, respectively.

REFINEMENTS

The preliminary model is "rough," and is by no means complete. Refinements can be made if one is willing to invest the time and the money necessary to bring them about. The extent of refinement is of course governed by the expected increase in savings that would result. A few of the possibilities for refinement are given below (with the exception of the need for a more intensive program of data collection, which was mentioned throughout):

7.1 Slope. The introduction of the effect of slope would make the model more realistic, especially in Montana. This is discussed more fully later. In the thesis model, slope was assumed to have no effect on production.

7.2 Accidents and Breakdowns. Although they were not included in this model, accidents and breakdowns could be incorporated in the model to make it more realistic. It has been shown (51) that with events such as accidents and breakdowns, where the probability

is small but the total number of chances is large, the frequency of incidents can be expected to follow the Poisson distribution. This study did not continue long enough to get adequate data on either of these two aspects. Several large paper companies contacted had no data on breakdowns, nor did saw manufacturers. Once the relevant parameters are known, it would be relatively simple to include the data in the model in the form of Poisson-distributed variables. Once an accident or breakdown occurred, the exact nature of each would have to be determined. In the case of an accident, the nature, seriousness, and effect of the injury would be determined; in the case of a saw breakdown, the nature, seriousness, and repair time would need to be found. Associated costs would be assigned.

7.3 Variable Costs. The method of computing felling costs used in the model seems adequate, but an even more accurate measure of variable cost could be gained by simulating actual fuel consumption. Fuel consumption data to incorporate into the model could be gathered through experimentation.

7.4 Felling and Bucking Times. Although it was not done in this study, due to lack of data, the felling and bucking time distributions could be transformed to conform to mathematical distributions. The resulting distribution functions would take up less storage space in the machine as well as be more reliable in the long run.

7.5 Stand Data. The method given in the thesis for obtaining input information is efficient when a simulation is to be made of the logging of one, two, or even a few particular areas. However, one

might be interested in knowing how the composition of the stand will affect felling and bucking costs. One could either assume different stand compositions to make test runs, or, to be more realistic, one could use a site index table in conjunction with studies like those of Holmes and Tackle (21), and Czarnowski (10), to predict expected diameters and heights in any given stand, from which to obtain results.

LIMITATIONS

Although computer simulation is a promising analysis tool, it does have its drawbacks.

7.6 Expense. Perhaps the most serious limitation is that the simulation approach can be expensive. Gathering the data is costly enough, but the computer time is even more expensive. However, once the model is set up, the former cost is almost eliminated. If many alternatives are to be evaluated, computer time builds up quickly. On the average, the typical run required about 50 minutes on the 1620. The amount of money involved may be small change to a large company, but to the many small loggers in this area, it is an exorbitant expense. With a bigger and faster computing machine, the costs may be lowered, however.

The author does believe, though, that over the long run the results obtained from a study of this type will result in savings far outweighing the costs incurred.

7.7 Delays. Another limitation is that delay time cannot be predicted by constituent. In work study, we are told to concentrate our efforts on the elimination of idle, or unproductive time. In

order to be able to eliminate it, we have to know what the idle time consists of. It was seen that the model can estimate total unproductive time. The amount of this unproductive time would be an indication of whether further study was required. This approach may be adequate enough for most purposes.

There are undoubtedly more limitations, but these two are considered to be the most important.

PITFALLS

There are a few pitfalls that must be kept in mind when constructing a simulation model, if one desires some reliable answers.

7.8 Misinterpretation. One pitfall is that although a model is an abstraction of the "real world" situation, it is not the "real-world," though ".....some scientists become so devoted to their model (mathematical or verbal) that they will insist that this model is the real world."(5) "It is an abstraction from the real world, and at best, it is useful."(4) A model must be looked at in these pragmatic terms.

7.9 Additivity of Data. Another pitfall may lie in the assumption of the additivity of data. This point cannot be overemphasized. Sometimes an accurate predicted cost of a given logging process cannot be made by summing various cost components (unless, of course, independence can be proved!). The effect of a given operating policy of one operation on other associated operations may materially change the cost of those other operations. For example, felling and bucking costs may not be additive. A feller who falls his trees in an orderly fashion will probably incur less bucking cost than one who falls trees in random.

directions, criss-crossing them as he goes. Clearly, the cost of bucking can be affected by the felling method.

This study assumed additive costs, and it may be that by doing so, large errors were incurred.

7.10 Interdisciplinary Approach. Another pitfall is seen to lie in the background of the analyst. As is so often the case, operations research problems are interdisciplinary. It was never more evident than in this study. The author sees the need for engineers in Forest Engineering Research to work hand-in-hand with foresters in solving mutual problems. There is no doubt that much lost time would have been saved and blind alleys avoided if the author was well-versed in some important aspects of forest technology.

7.11 Teams. Also, it is almost impossible for one man to gather the required data. The need has been emphasized for two- or three-man crews working together for the most efficient data collection.

7.12 Reliability. Perhaps the biggest pitfall is the tendency to make decisions on the basis of an unreliable model. A decision should be made with a certain amount of "confidence" as discussed previously.

As many trials as are statistically necessary should be run. Decisions can be made with a certain amount of "confidence," by computing the inherent variance in the system. That is, if two alternatives are being compared for cost and the data from them is seen to be distributed normally, statements concerning the band within which the true mean cost falls may be made with a given degree of confidence. Significant differences between means can be inferred from

one of the tests of Appendix A. Therefore, each time a decision is made concerning the choice of one alternative from many, the degree of confidence with which this decision is made should be computed and stated. In the preliminary model presented in this thesis, confidence statements were omitted for simplicity.

RECOMMENDATIONS FOR FURTHER STUDY

During the course of this undertaking, some new and rather interesting problem areas were exposed. Some of them have already been mentioned. In this section, a brief listing of these and other possible future studies will be presented.

7.13 Testing of This Simulation Model With the "Real-World."

The ultimate test of the validity of this model would be in a direct comparison with a real-world situation. The testing procedure would involve a large degree of coordination between analyst and logger. When an area to be cut was known in advance, the sample information to be used as input could be recorded as recommended. Then, the model would be run as usual adhering to local production policies. As a check, the analyst would record production data in the woods as this stand was in the process of being logged. The feller must log the area in the same manner as it was "logged" in the model. The results could then be compared.

7.14 Increasing Model Reliability.

It has been mentioned throughout that more data should be secured on several subsystems of logmaking. It was found that practically every phase of the process could warrant a special investigation. The proper amount of data to obtain should be determined statistically. In addition, many trials of each alternative to be evaluated should be run-- enough so that an estimate of the precision of the results could be made.

7.15 Devising a New Pay Scheme.

It was pointed out that present methods of payment are inadequate. A study to explore this problem in more detail is recommended. Perhaps

payment on the basis of cubic-foot volume cut, a more accurate measure of true volume, is a more equitable pay scheme than the methods in use at the present time. Payment based on the weight of logs brought in to the mill is practical and is used in several logging areas at the present time. However, this method of payment is subject to criticism by the loggers because of the large variation in weight one is likely to find in a given area. Little concern has been given this important problem.

7.16 The Effect of Slope.

In the rugged terrain characteristic of Montana logging, slope must surely have a significant effect on logging. Logging has been observed on slopes of up to 70%! On these slopes, it was very difficult to remain upright to study the fellers, let alone try to cut down trees. A study entirely devoted to this problem is needed.

Any new logging machines would have to be designed to cope with these slopes. On an intuitive basis, it would seem that many of these new large multipurpose harvesters and combines being designed would be unable to function effectively on some of the exceptionally steep slopes found here. This may mean that the only possible way to cut trees for some time to come is with a chain saw. If this is so, it should be resolved now so that research devoted to uncovering some other new revolutionary felling techniques can be initiated.

7.17 Evaluation of Chain Saws.

The determination of the relative desirability of all chain saws currently available seems like a worthwhile endeavor. Since no two chain saws can be exactly alike, and there is always a "one best way"

of doing a job, it stands to reason that for cutting a given tree species of a given hardness, size, and moisture content, one particular saw and bar size would be more efficient than the rest. It has been shown that the four saws observed in this study had approximately equal cutting abilities. However, since the effect of variations in workers was neglected, the proposed study, if conducted, should be carried out with one operator.

7.18 Simulation of Other Subsystems.

Logmaking is the initial subsystem in logging. Therefore, by following the procedure outlined in this thesis, the succeeding subsystems can be simulated and linked together until the entire system is modeled. In other words, the output from logmaking would serve as input to the skidding model; the output from the skidding model would serve as input to the loading model; etc. Then, interactions between subsystems could be studied as well as interactions between subsystem components.

CHAPTER 8

CONCLUSIONS

The conclusions reached in this study are directed more toward the approach to the problem, rather than the value of the results. Regarding the objectives of this project listed under I-4, though, the following conclusions can be reached:

Re Objective (a): Perhaps the most important benefit to be gained from this study is the exploitation of a new approach to logging analysis. By the use of simulation techniques, hundreds of acres of timber can be "harvested" in the office in just a few hours before any real logging activity takes place in the woods. Decisions can be made as a preventative measure (i.e. as a planning tool) rather than as a remedial one (i.e. solving existing problems).

Except for the work of Lussier, simulation has been slow to catch on in the logging field. It is hoped that as a result of this study, more attention will be given to this powerful new analysis tool. It was pointed out that there are other, more traditional ways of analyzing operations, each with its own particular pros and cons. Limitations of the simulation approach were pointed out. The choice of analysis technique must be made with these in mind. However, the author feels strongly that simulation offers more in the way of a complete analysis than do any of the other methods.

Re Objective (b): Insights into the relationships between log-making components were plentiful. Relationships between and among variables had to be isolated and measured in the model construction stage. Low correlations among stand factors found to exist in the "experimental plot" reinforced statements concerning the unpredictability

of lodgepole pine characteristics in any given area.

Data obtained on felling and bucking trees of a given diameter are reliable and can be useful in other applications. Many other important relationships were presented throughout the analysis.

Re Objective (c): More alternatives could have been evaluated by this simulation model than were examined in this thesis. For instance, (1) tree-length logging vs. felling and bucking in the woods, (2) felling and bucking one tree at a time vs. felling "x" trees in succession before limbing and bucking them, and (3) cutting for poles vs. cutting for logs are all alternatives that could have been evaluated, if it were not for time and cost limitations. The objective was to present a cross-section of possible analyses rather than the evaluation of each and every one.

Re Objective (d): Major cost factors and their respective importance were arrayed in Chapter 6. The greatest proportion of total cost was seen to lie in the limbing and bucking phase of logmaking. Cull was seen to have a significant effect on the cost of operation, especially cull type II-rot. Worker effectiveness, as suspected, was also a significant factor in regulating profit.

Re Objective (e): In the investigation of simulation runs 1 and 2 we have witnessed, in a sense, the determination of the optimum cutting policy given certain restrictions and external conditions. A misconception on the part of some people is that this optimal policy is the true and incontestible word to be followed "to the letter." However, an optimal solution is merely a deductive statement made within the context of the model. The only sense in which it is optimal is that it gives a solution to the model judged best according to some measure of effectiveness (cost or profit in this case). The extent to which

this solution is truly optimal depends on how well the model describes the system under study. It was mentioned before that an insufficient amount of data was secured to deem the thesis model reliable. A sensible approach to the problem is to view the optimal solution as a suggestion which might lead to process improvements.

Wrap-up. An attempt has been made in this thesis to present a new approach to logging analysis. It is only the beginning. The model is imperfect and needs to be refined. Validating the assumptions made is a necessary contingency. It is hoped that enough of the fundamentals were presented so that interested parties could use this model as a guide in the development of a more sophisticated structure. The main thing to remember is that the validity or preciseness of the data was not the major issue in this thesis, although it was not overlooked. Suggestions for improving the model reliability were given.

No new and startling cost-cutting improvements were discovered. Scientific selection of existing alternatives was stressed, instead.

Reducing the cost of logmaking would not be an easy chore. One of the major problems in improving this operation is that a good deal of time is spent in traveling from tree to tree. No one ever has or probably will ever be able to resolve this difficulty insofar as the trees are concerned. If the trees are too close together, stand growth is stunted. If they are too far apart, the logging costs are increased and the watershed and erodability of the soil are affected. The spacing must be optimized in relation to these factors. This is a problem in forest management.

As far as new machinery is concerned, any new machine developed for

felling would also have to be moved from tree to tree. Since the chain saw has proven to be an efficient tool, it seems unlikely that any major improvements in it will be found, although it must not be conceded that there is no further room for improvement. Of course, new machines that combine operations (Buschcombine, for example) may prove advantageous. This idea has been discussed.

About the only logmaking phase that can be improved immediately, in part at least, is the worker's choice of method and his aggressiveness. Since devising new machines and methods would be difficult, the only alternative is to improve on existing methods to make sure that the operations are being performed in the best possible way.

The Future. According to Bowman and Fetter (4), the use of the Monte Carlo method of analysis will increase in the next few years for three reasons:

- (1) More and more manufacturers are being exposed to the ideas involved.
- (2) The increased interest in uncertainty.
- (3) The advent of electronic computers.

The author has tried to incorporate these ideas in his presentation. He feels that this approach has unlimited potential. It is hoped that the next decade will see increased use of this powerful analysis tool in the logging field.

APPENDIXES

APPENDIX A

REVIEW OF STATISTICAL THEORY

A brief review and discussion of some of the statistical theory used in this thesis, especially on significance testing of measurements, is presented in this Appendix. Names and descriptions of the various concepts and tests used are given, along with appropriate equations. Derivations of these standard equations are not included; they can be found in practically any statistics text, for instance (13 and (42).

A.1 Population. A population, or universe, is the totality of all pertinent observations that might be made in a given problem. A population is finite if its members can be enumerated; if not, it is called infinite.

A.2 Sample. With a small finite population, it may be possible and practicable to measure every item if one is interested in knowing its characteristics. However, for a large number of individuals in a sizeable finite population, or for an infinite population, a study must be based upon measuring small, representative portions called samples.

Samples do not describe the parent population exactly, but allow inferences to be made about the population based on the characteristics of the sample. The probability of each individual variable must be proportional to its probability in the population, or, in the discrete case, each unit must have an equal chance of being selected.

Estimates of population parameters based on samples are subject to error. Sampling errors are reduced as the number in the sample increases. Estimates on the "precision" of a sample can be made.

A.3 Sample Space. For the analysis of an experiment, the outcome by itself is not of prime importance. It is only in relation to all the

possible outcomes for the experiment that the actual outcome takes on meaning. The aggregation of all possible outcomes for an experiment is called the sample space, and any possible outcome is called a sample point.

A.4 Random Variable: A random variable is a function defined on a sample space.

A.5 Mean, Variance, and Standard Deviation: Consider a set of sample measurements $X = (x_1, \dots, x_n)$.

The mean is defined as

$$\bar{x} = \frac{\sum_{i=1}^n x_i}{n} \quad (\text{eq. A.1})$$

and is an unbiased estimate of the population mean, μ .

The variance of the sample is defined as

$$s^2(x) = \sum_{i=1}^n \frac{(x_i - \bar{x})^2}{n-1} \quad (\text{eq. A.2})$$

and is an unbiased estimate of the variance of the population, σ^2 .

The standard deviation of the sample is defined as

$$s(x) = \sqrt{s^2(x)} \quad (\text{eq. A.3})$$

A.6 Probability: Probability is a quantitative measure of chance or likelihood. If N events are possible and n of them have an attribute A , and if we designate the probability of A as $P(A)$, then the probability of A occurring in a single event is

$$P(A) = \frac{n}{N} \quad (\text{eq. A.4})$$

When the probability of an event is set purely by the definition of a system, it is known as an "a priori" probability. When the numerical value of the probability is arrived at from accumulated data or experience, it is referred to as an empirical probability.

A.7 Dependent, Independent, and Conditional Probabilities. If A is an event for one experiment and C is an event for another experiment, independent of the first, then we have

$$P(AC) = P(A) P(C). \quad (\text{eq. A.5})$$

If, however, A and C are not independent and $P(C) \neq 0$, it is possible to define a probability for A, given that C has occurred, $P(A/C)$, and to have a multiplication rule

$$P(AC) = P(C) P(A/C). \quad (\text{eq. A.6})$$

Or, we define the conditional probability of A given C as

$$P(A/C) = P(AC) / P(C). \quad (\text{eq. A.7})$$

In the continuous case, suppose we have random variable (x_1, x_2) with probability function $f(x_1, x_2)$. Designating the conditional probability function for x_1 given x_2 by $f_1(x_1/x_2)$, we would have

$$f_1(x_1/x_2) = f(x_1, x_2) / f_2(x_2); f_2(x_2) \neq 0. \quad (\text{eq. A.8})$$

A.8 Frequency Distribution. A frequency distribution, perhaps the most commonly used data array, is simply a graphic presentation showing the relative frequency of occurrence of each point in the sample space. Frequencies can be converted to probabilities by dividing the frequency of occurrence by the total number of observations in the sample.

A.9 Probability Density and Distribution Functions. The function, $f(x)$, giving the probability for each sample point X , is called the probability density function. If an experiment were repeated a large number of times under essentially constant conditions, then $f(x)$ represents the proportion of outcomes that are equal to X .

Let $F(x)$ be the total probability up to and including the point " x ":

$$F(x) = \sum_{x' \leq x} f(x') \quad (\text{for a discrete variable})$$

$$= \int_{-\infty}^x f(x) dx \quad (\text{for a continuous variable})$$

(eq. A.9)

This function is called the distribution function or cumulative probability distribution and is defined for all points on the real line. $F(x)$ represents the proportion of outcomes that are less than or equal to " x ".

In general, let X be a real-valued random variable with discrete sample space ($w_1, w_2, \dots$). The probability distribution can be described by a probability function $f(x)$ giving the probability in the interval $X + \Delta X$. Alternatively, it can be described by a distribution function $F(x)$, giving the total probability up to and including the value x .

A.10. Simulated Sampling. A "sample" value can be drawn from any probability distribution by generating a random number and entering an ordinate of the probability distribution at the appropriate place. In other words, each random number is used as a decimal value of the cumulative probability. In this artificial process, each value of the

variable of interest will occur with about the same relative frequency as in the "real world," but their arrangement will be randomized.

As an example, consider the following. Assume that we are interested in a variable "t," which can take on integral values from 1 to 5. By experimentation, it is discovered that "t" has the following probability distribution (Fig. A.1).

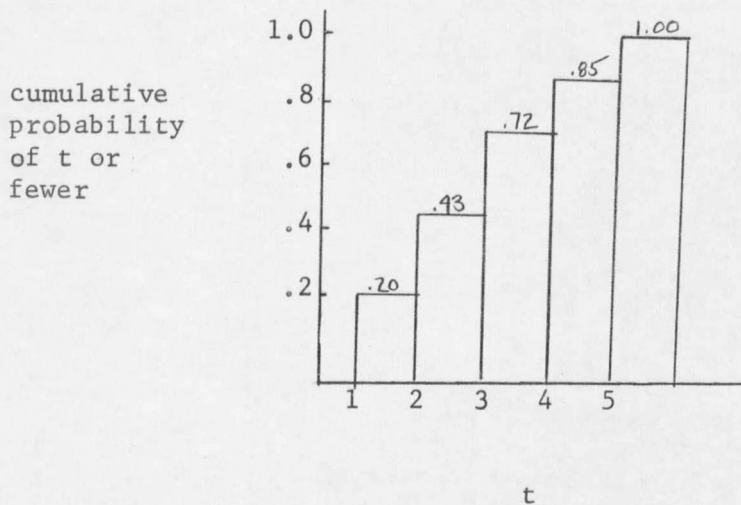


Fig. A-1. Probability Distribution of t

According to our hypotheses, random number 01 through 20 will correspond to a t-value of 1, random numbers 21 through 43 correspond to a t-value of 2; etc. A table can be set up to correspond with the above scheme (Table A-I).

Table A-I Sampling Table for t

t=	1	2	3	4	5
P (t≤T)	.20	.43	.72	.85	1.00
Random number	01-20	21-43	44-72	73-85	86-100

Thus, a set of random numbers can be used to generate sequences of

variables which are of the same statistical character as the simulated experiences.

Of course, the probability function need not be discrete. If desired, continuous variable data can be transformed to the discrete case, or it can be used as continuous, whichever suits the analyst.

Simulated sampling, of course, requires a suitable random number generator. If just a few samples are taken, a roulette wheel, dice, or one of the many available random number tables may be used. However, with very large samples, a computer subroutine is the most efficient random number generator. Thousands of samples can be drawn in just a few minutes.

A.11 The Normal Distribution. The familiar bell-shaped probability distribution is known as the "normal" distribution. In this case, "normal" is strictly a mathematical term and does not have its usual connotation. The normal curve is symmetrical about a single peak and is characterized by having its average, or mean, value exactly equal to the peak of the curve (Fig. A-2).

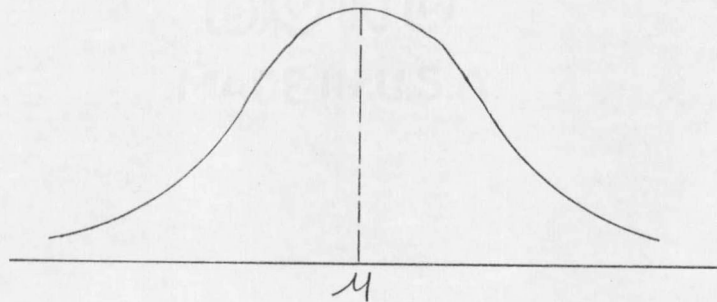


Fig. A-2. The Normal Distribution

While many distributions encountered in practice approach the normal, no distribution of actual measurements is ever identical with the normal, as a distribution of finite measurements can only approximate the continuous function of the normal distribution. Also, some degree of irregularity, or "skewness," is usually encountered.

The equation of the normal curve in terms of the probability density, y , is

$$y = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (\text{eq. A.10})$$

The mean, $\bar{x}$, is equal to μ and the variance, $S^2(x)$, equals σ^2 .

The total area under the normal curve is equal to 1.0. The relative frequency of occurrence of the variable between any two values of x , say x_1 and x_2 , is measured by the fraction of area under the curve between these values times the total frequency, N . Since the total area is equal to 1.0, the area between any two values of x can be taken as the probability of a normally distributed variable falling within this range.

$$P(x_1 \leq x \leq x_2) = \frac{1}{\sigma\sqrt{2\pi}} \int_{x_1}^{x_2} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx \quad (\text{eq. A.11})$$

The area under the normal curve has been carefully calculated and tables of the area for various measurements are available in many handbooks.

A.12. Other Distributions. In addition to the normal distribution, other distributions are of importance at times. A few of them are included here.

DISCRETE DISTRIBUTIONS

(a) Binomial

Range of x	:	0, 1,, n	
Probability function	:	$P(k) = C_n, k P^k (1-p)^{n-k}$	
Mean	:	$\bar{x} = np$	
Variance	:	$S^2(x) = np(1-p)$	(eq. A.12)

(b) Poisson

Range of x	:	0, 1,, x	
Probability function	:	$P(k) = \frac{\lambda^k e^{-\lambda}}{k!}$	$\lambda > 0$
Mean	:	$\bar{x} = \lambda$	
Variance	:	$S^2(x) = \lambda$	(eq. A.14)

(c) Uniform

Range of x	:	0, 1,, n	
Probability function	:	$P(k) = \frac{1}{n+1}$	
Mean	:	$\bar{x} = \frac{n}{2}$	
Variance	:	$S^2(x) = \frac{n^2}{12} + \frac{n}{6}$	(eq. A.14)

CONTINUOUS DISTRIBUTIONS

(a) Rectangular (Fig. A-3)

Range of x	:	0 to a	
Density	:	$f(x) = \frac{1}{a}$	
Mean	:	$\bar{x} = a/2$	
Variance	:	$S^2(x) = a^2/12$	(eq. A.15)

(b) Exponential (Fig. A-4)

Range of x	: 0 to ∞	
Density	: $f(x) = ae^{-ax}$	
Mean	: $\bar{x} = 1/a$	
Variance	: $S^2(x) = 1/a^2$	(eq. A.16)

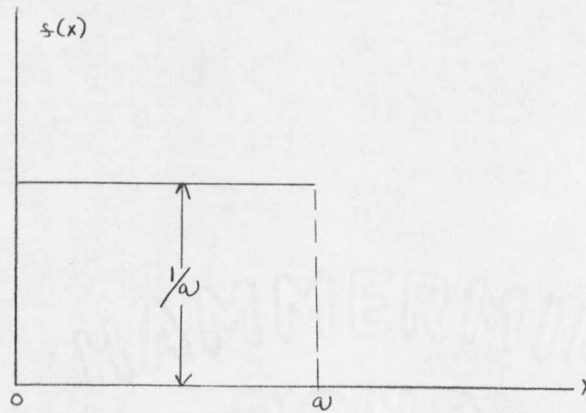


Fig. A-3. Rectangular Distribution

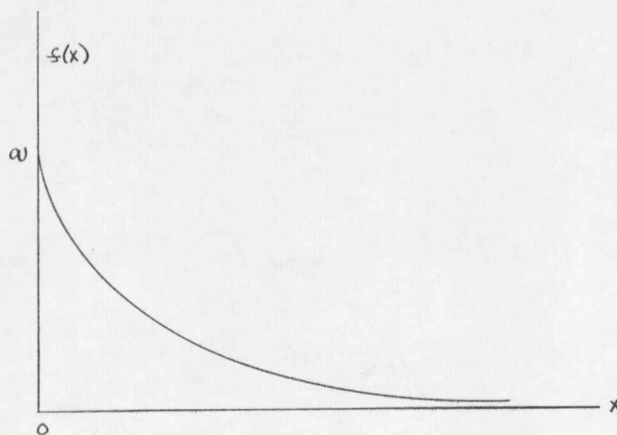


Fig. A-4. Exponential Distribution

A.13 Standard Deviate. Each value of a normally distributed x can be expressed in units of the number of standard deviations it deviates from the mean: $x = \mu + Z\sigma$. The variable Z is called the standard deviate:

$$Z = \frac{|x - \mu|}{\sigma}$$

(eq. A.17)

Tables are available that give the area under the normal curve for different values of Z . These areas represent the probabilities for normally-distributed variables of the occurrence of values deviating from the mean from $-\infty$ to Z times the standard deviation.

A.14 Significance Level: In a procedure with results that are distributed normally, $1-2 [1-F(Z)]$, called the confidence level, represents the symmetrical probability for results in the range $\mu \pm Z\sigma$. The quantity $2 [1-F(Z)]$, designated by α , is called the significance level of the test. If the hypothesis states that certain results have a normal distribution with mean μ and standard deviation σ and a result is observed that deviates from the mean by as much as $Z\sigma$, then if we say that the observed result is significantly different from the hypothesized results, there is only an α probability of being wrong (i.e. the test rejects with probability α when the hypothesis is true). The probability of rejecting the hypothesis when it is not true is called the power of the test. This probability varies inversely with the variance of the data.

A.15 Null Hypothesis. In tests of significance, a hypothesis is stated concerning the expected results. This hypothesis to be tested is

called the null hypothesis, usually depicted by H_0 . The null hypothesis, essentially, is an assumption that there is no difference between an observed and an expected result. After the null hypothesis has been stated, evidence is then sought to either support or reject it.

A.16 Tests Based on the Normal Distribution.

A.16.1 The t-test. The t-test deals with the estimation of a true value from a sample and the establishing of confidence ranges within which the true value can be said to lie. The statistic t can be defined in a manner similar to the definition of a standard deviate of the normal distribution. It is the difference between the mean of a sample and the true mean of the population from which the sample was drawn, divided by the estimated standard deviation of the mean,

$$t = \frac{\bar{x} - \mu}{S(\bar{x})} \quad (\text{eq. A.18})$$

The t distribution becomes equivalent to the normal distribution when the number in the sample, n , becomes infinite. The number n enters the formula for t in the form of the "degrees of freedom" (number of independent observations) available for the calculation of the standard deviation. Tables are available that give the probability level with a given number of degrees of freedom.

The t test can be used to test any one or all of 3 null hypotheses:

- (1) $\mu = \bar{X}$
- (2) $\mu = 0$
- (3) $\mu_1 = \mu_2$

Only hypothesis (3) is investigated in this thesis. This tests

whether the means of two different samples could have come from the same population or from populations with the same means. In order to apply this test, it is necessary to have a "pooled" estimate of the standard deviation of the measurements.

The expression to test the difference between two means is as follows:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\bar{s}(x) \sqrt{1/n_1 + 1/n_2}} \quad (\text{eq. A.19})$$

The pooled estimate of the standard deviation is calculated from

$$\bar{s}(x) = \sqrt{\frac{\sum (x_1 - \bar{x}_1)^2 + \sum (x_2 - \bar{x}_2)^2}{n_1 + n_2 - 2}} \quad (\text{eq. A.20})$$

The value of t is calculated from eq. (A.19) and is compared with tabulated values at the degrees of freedom equal to $n_1 + n_2 - 2$, the sum of the total degrees of freedom available for calculating the pooled estimate of the standard deviation. If the calculated t is larger than the tabulated t at the preselected probability or significance level, α , then we conclude that the null hypothesis, $\mu_1 = \mu_2$, is false, and the population mean estimated by $\bar{x}_1$ is significantly different from the population mean estimated by $\bar{x}_2$, with α chance of being wrong.

A.16.2 The F-test for variances. It was pointed out that means of several samples will vary over a range which can be approximated for any desired probability level. The same is true of variances. If several groups of samples are drawn from the same parent population,

the estimated variance of the parent population will not be identical. The F-test provides a method for determining whether the ratio of two variances is larger than might be expected by chance if they had been drawn from the same population.

The null hypothesis is:

$$H_0 : \sigma^2(x_1) = \sigma^2(x_2).$$

The test statistic is:

$$F = \frac{S^2(x_2)}{S^2(x_1)} \quad (\text{eq. A.21})$$

F means the difference, in the form of a ratio, of two variance estimates that can be expected to occur, depending on the number of degrees of freedom available for the calculation of each estimate. If $S^2(x_1)$ and $S^2(x_2)$ are calculated with df_1 and df_2 degrees of freedom, respectively, and the ratio written with the larger estimate in the numerator, the F-value at the α level indicates that there is only a 2α probability of observing a ratio this large if the two variance estimates were obtained from the same population or from two populations with the same variance. Again, tables are available with this information tabulated.

A.17 Regression and Correlation Analysis. There are two aspects to problems involving decisions by association. One aspect concerns itself with the degree of relationship, or the extent to which decisions are enhanced by taking an associated variable into consideration. The second aspect concerns itself with the nature of the relationship, or the functional relationship

between the variables which enables us to predict the value of a dependent variable from the value of an independent variable.

Statisticians refer to problems concerning the degree of relationship as correlation problems and to those involving the nature of relationship as regression problems.

A.17.1 Regression. Regression analysis can be of two types - linear and curvilinear. An example of a linear relationship between two variables, x and y , is given by Fig. A-5.

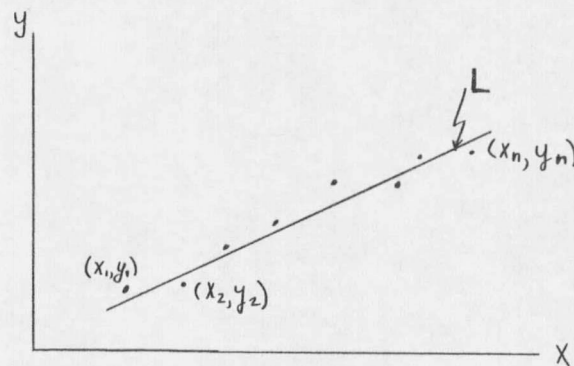


Fig. A-5. Linear Regression Scatter Diagram

This is called a "scatter diagram," and the line of best fit, L , is called the "regression line of y on x ." The set of data points (x_i, y_i) are plotted on a scatter diagram to see if a relationship is suspected to exist. If the outlook is promising, a mathematical analysis is called for.

A curvilinear relationship between x and y might look like Fig. A-6.

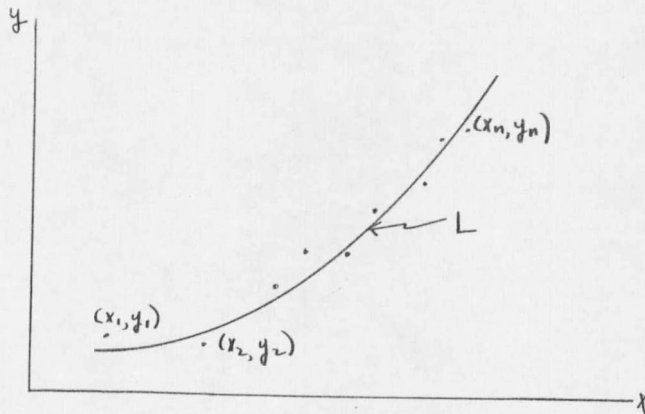


Fig. A-6. Curvilinear Regression Scatter Diagram

The usual procedure for testing whether a relationship is linear or curvilinear is to fit the linear regression line, find out what percentage of the variance was explained by the line of regression, and then see if the introduction of curvilinearity adds any refinement. Curvilinear relationships can be transformed into linear form by logarithmic transformations.

The theory behind the fitting of the regression curve is commonly called the theory of "least squares." The best fit of the curve is that position which will make the sum of the squared deviations of the observed x values from the regression line a minimum.

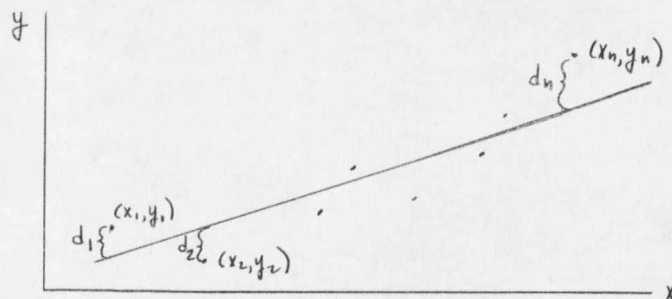


Fig. A-7. Fitting a Curve by Least Squares

Consider Fig. A-7, in which the data points are given by $(x_1, y_1), \dots, (x_n, y_n)$. For a given value of x , say x_1 , there will be a difference between the value y_1 and the corresponding value as determined from the curve, C . Denote this difference by d_1 , and call it the "deviation" of (x_1, y_1) from the true value.

Corresponding to value $x_2, \dots, x_n$ we can obtain $d_2, \dots, d_n$.

(Note that the d_i may be positive, negative, or zero.)

The curve, C , having the property that $d_1^2 + d_2^2 + \dots + d_n^2 = \sum_{i=1}^n d_i^2$ is a minimum is called a "best-fitting" curve, and is said to fit the data in the "least-squares" sense.

The least squares solution to the bivariate linear regression line yields the following "normal" equation:

$$\begin{aligned} \sum y &= Na + b \sum x \\ \sum xy &= a \sum x + b \sum x^2, \end{aligned} \quad (\text{eq. A.22})$$

which can be solved for a and b to fit in the regression equation

$$\hat{y} = a + bx. \quad (\text{eq. A.23})$$

If the curve hints at being parabolic, the normal equations are

$$\begin{aligned} \sum y &= a N + b \sum x + c \sum x^2 \\ \sum xy &= a \sum x + b \sum x^2 + c \sum x^3 \\ \sum x^2 y &= a \sum x^2 + b \sum x^3 + c \sum x^4 \end{aligned} \quad (\text{eq. A.24})$$

One then solves for a, b, and c to fit into the model

$$\hat{y} = a + bx + cx^2. \quad (\text{eq. A.25})$$

Extensions to equations of a higher degree can be made easily by observing that they can be obtained formally by multiplying eqs. A.24 by 1, x, and x^2 respectively and summing on both sides of the resulting equations. This technique can be extended to obtain normal equations for least-square quadratic curves, and, in general, any least-square curve of higher degree.

A.17.2. Correlation. The degree of association between variables is commonly measured by the correlation coefficient. The correlation coefficient, r, can have a numerical value varying between the limits of -1 and +1. When $r = 0$, there is no correlation at all; when $r = \pm 1$ there is perfect correlation, either positively or negatively.

The correlation coefficient, r, for two variables is computed from the equation

$$r = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}} \quad (\text{eq. A.26})$$

where

r = correlation coefficient

x = individual sample value of variable x

y = individual sample value of variable y

$\bar{x}$ = mean of x sample

$\bar{y}$ = mean of y sample

Correlation coefficients can often be misleading. One must be careful to observe the proper "cause-and-effect" relationships.

A.18 Multiple Regression and Correlation. Multiple regression

and correlation differ from simple bivariate correlation and regression in that the degree and nature of association between one dependent variable and two or more independent variables is measured. The concepts do not differ appreciably, although the derivations of the normal equations and correlation coefficient equation become more rigorous.

As the number of variables increases, it is necessary to fit a form of the dimension of the number of independent variables + 1 to the data. In other words, if the number of independent variables is 2, then a least-squares plane must be passed through three points; if the number of independent variables is 3, we must pass a polygon of degree 4 through the points, etc.

The normal equations for the regression coefficients using one dependent and any number of independent variables are determined from:

$$\begin{aligned}
 Na + b_1 \sum x_1 + b_2 \sum x_2 + b_3 \sum x_3 + \dots &= \sum y \\
 a \sum x_1 + b_1 \sum x_1^2 + b_2 \sum x_1 x_2 + b_3 \sum x_1 x_3 + \dots &= \sum x_1 y \\
 a \sum x_2 + b_1 \sum x_1 x_2 + b_2 \sum x_2^2 + b_3 \sum x_2 x_3 + \dots &= \sum x_2 y \\
 \vdots & \\
 a \sum x_n + b_1 \sum x_1 x_n + b_2 \sum x_2 x_n + b_3 \sum x_3 x_n + \dots &= \sum x_n y
 \end{aligned}$$

(eq. A.27)

As would be expected, these calculations can easily be done on a digital computer. The method used for solving these equations involves matrix theory, a subject that will not be dealt with here.

A.19 Analysis of Variance: The analysis of various attempts to answer two questions:

- (1) whether all the means from the groups under a source of variation classification come from a single population,
- (2) which of the means differ significantly from the others.

In other words, the null hypothesis, $H_0 : \mu_1 = \mu_2 \dots = \mu_k$, is tested. (The t-test for testing the hypothesis $H_0 : \mu_1 = \mu_2$ is a special case of this larger test.) The total variation in a set of measurements is separated into components and assigned to possible sources or causes. The total variation in the analysis of variance consists of the sum of squared deviations about the general mean of the entire array of measurements. The component sums of squares attributable to treatments or external influences are removed from this total sum of squares. Any remainder not assigned to a specific source of variation is the residual or experimental error and is an estimate of the average amount of variation contributed by the several populations or treatments. It is a measure of the variation which is considered representative of all the items under observation when no external treatments or influences are present.

Each of the component sums of squares is then used to estimate a variance, resulting in a series of variance estimates, one or more for external sources and one or more for the residual. These variance estimates then are subjected to an F-test to see if any significance difference exists. When the variance attributable

to a source of variation is shown to be significant, it indicates that there is a significant difference in the means of the groups classified under the given source of variation. Table A-II illustrates symbolically a series of replicate data taken at different conditions of some factor M, and gives the analysis of variance formulas.

Table A-II. Analysis of Variance Table

Groups	M_1	M_2	$M_3 \dots \dots M_n$
Item	x_{11}	x_{12}	$x_{13} \dots \dots x_{1n}$
	x_{21}	x_{22}	$x_{23} \dots \dots x_{2n}$
	x_{31}	x_{32}	$x_{33} \dots \dots x_{3n}$
	$\vdots$	$\vdots$	$\vdots$
	x_{j1}	x_{j2}	$x_{j3} \dots \dots x_{jn}$
No. of Observations	k_1	k_2	$k_3 \dots \dots k_n$
Total No. of Observations	$N = \sum_{i=1}^n k_i$		
Over-all mean	$\bar{X} = \sum_{i=1}^n \sum_{j=1}^k \frac{x_{ij}}{N} = \frac{\sum X}{N}$		
Total SS	$\sum_{i=1}^n \sum_{j=1}^k (x_{ij} - \bar{X})^2 = \sum X^2 - \frac{(\sum X)^2}{n}$		
Between Groups SS	$\sum_{i=1}^n k_i (\bar{x}_i - \bar{X})^2 = \frac{\sum (\sum_{j=1}^k x_{ij})^2}{k_i} - \frac{(\sum X)^2}{n}$		
Within Groups SS	$\sum_{i=1}^n \sum_{j=1}^k (x_{ij} - \bar{x}_i)^2 = \sum X^2 - \sum_{i=1}^n \frac{(\sum_{j=1}^k x_{ij})^2}{k_i}$		

To test whether the factor M has a significant effect on the variation of x, the variance estimates within the replicates are compared with the variance estimate of the sample means. The variance estimates are obtained by dividing the sums of squares by the degrees of freedom. Variance estimates so obtained are called "mean squares." We test the existence of $\sigma^2 (M)$ by the ratio of the between-group mean square and the within-group mean square. If this ratio exceeds the tabulated F-value for the degrees of freedom corresponding to n-1 and N-n, we can reject the hypothesis that two mean squares estimate the same variance, σ^2 , and can accept the existence of a contributing factor M.

The significance of a regression relationship can be tested by the analysis of variance in this manner.

A.20 Nonparametric Statistics. In many problems, the assumption that samples have been drawn from a normal population is quite unreasonable. Methods are available for making inferences without any assumption as to the form of the distribution in the population.

A.20.1 χ^2 (Chi-Square). The statistic known as χ^2 , or chi-square, measures the discrepancy between observed and hypothetical frequencies.

Let f_i be the numbers, or frequency, observed in the "i-th" class, and F_i be the number, or frequency, expected in the "i-th" class in accordance with the proportions indicated by the hypothesis.

Then, the χ^2 statistic is

$$\chi^2 = \sum_{i=1}^k \frac{(f_i - F_i)^2}{F_i} \quad (\text{eq. A.28})$$

Note that if there were no deviation, χ^2 would be zero.

In using the χ^2 distribution to establish the significance of deviations, some basis is required for setting the "expected results." These may be set by previous experience, or from data themselves in tests of homogeneity, or on an "a priori" basis as when a distribution is assumed to be binomial or normal. On whatever basis the expected results are established, the hypothesis is established so that the observed results conform to some expected distribution:

$$H_0 : f_i = F_i$$

While it is not possible to establish H_0 to be true, it is possible to calculate the probability of its being false.

Tables are available that give maximum values of χ^2 for different degrees of freedom (number of independent observations) that can be expected with some indicated probability if the null hypothesis is true. If larger values are obtained, the null hypothesis is rejected with the corresponding probability of being wrong. The probability level at which the null hypothesis is rejected is called the significance level of the test.

A.20.2 Sum-of-ranks test: The sum-of-ranks test can be used to test the equality of means when the assumption of normality cannot be made. It is more commonly known as the Mann-Whitney test. The hypothesis " N_1 values of x_1 and N_2 values of x_2 are samples from a common population" can be tested.

Ranks from least to greatest are assigned to the $N_1 + N_2$ measurements and the sum of the ranks obtained for each group separately. If two measurements are equal, they are both assigned the mean of the ranks which those measurements would have received had there been

no ties. The sum of ranks for group i will be denoted by R_i . As a check, it should be noted that

$$R_1 + R_2 = \frac{N(N+1)}{2} \quad (\text{eq. A.29})$$

If N_1 and N_2 are each as large as 8, the statistic

$$\frac{2R_i - N_i(N+1)}{\sqrt{\frac{N_1 N_2 (N+1)}{3}}} \quad (\text{eq. A.30})$$

has a distribution that is approximately unit normal. If the null hypothesis states that the x_1 median is not greater than the x_2 median, we should reject only when R_2 is significantly large (i.e. R_1 is small), and vice-versa. If the number in either sample is small, a table (See 17) may be used to obtain exact probabilities.

A.20.3 Sum-of-ranks test for comparing K samples. The extension of the two-sample comparison by ranks to problems in which there are K samples is due to Kruskal and Wallis (26). The samples are merged and a rank of 1 assigned the lowest sample value, 2 to the next lowest, and so on. Then, the sum of the ranks is found for each of the K samples. Let N_i be the number of observations in the " i th" sample, R_i the sum of the ranks assigned to the observations in that sample, and $N = \sum_{i=1}^k N_i$. The test statistic to be computed if there are no ties is

$$H = \frac{12}{N(N+1)} \sum_{i=1}^k \frac{R_i^2}{N_i} - 3(N+1) \quad (\text{eq. A.31})$$

If there are ties in rank because two or more observations are equal, each observation is given the mean of the ranks which those observations would have received, as before, and H is divided by

$$1 - \frac{\sum T}{N(N^2 - 1)} \quad (\text{eq. A. 32})$$

If t is the number of observations in one tied set, $T = (t-1)(t)(t+1)$ for that set. The $\sum T$ is taken over all groups of ties.

If the K samples come from identical populations, and the N_i 's are not very small, H is distributed approximately as χ^2 with $k-1$ degrees of freedom. The hypothesis is rejected for large values of H .

APPENDIX B FORTRAN II PROGRAMS

```

C      PROGRAM FOR SIMULATING LOGMAKING(I.E. FELL, LIMB, BUCK)
C      THE PROGRAM MUST BE RUN IN TWO PARTS
C      THE FIRST PART (PART I) SETS UP THE FOREST AND GENERATES THE ORDER
C      IN WHICH THE TREES ARE TO BE CUT, AS WELL AS DETERMINING THE DBH,
C      TOTAL HEIGHT, MERCHANTABLE HEIGHT, AND CROWN LENGTH OF EACH TREE.
C      THE SECOND PART (PART II) USES THE OUTPUT FROM PART I TO LOG THE
C      AREA IN QUESTION. THE TREES ARE CUT DOWN, THE OPTIMUM LOG COMBO
C      IS DETERMINED, AND EACH TREE IS THEN LIMBED AND BUCKED.
C      PART I
C      START THE LOGS ROLLING-
      DIMENSION      DBH(10),HTS(10),JBEG(10),JEND(10),HTT(10,10),
1HTU(10,10,10),OIO(10),KBEG(10),KEND(10),OIA(10,10),OIB(10,10,10)
1000  FORMAT(55H N DBH THT MHT CRWN FREE CFV BFV CULL PCT )
1002  FORMAT(1X)
1004  FORMAT(14,2F4.0,3F5.1,2F6.1,15,F6.0)
      11  FORMAT (F10.8)
      24  FORMAT(2I2)
      25  FORMAT(10F4.0)
      32  FORMAT(F5.0,2I3)
350   FORMAT(5HECFV=E14.8,5HEBFV=E14.8,7HAVEDBH=F6.2,6HAVEHT=F6.2)
      PUNCH1000
      PUNCH1002
      READ 11,DIGIT
      NCULL = 0
      PCT = 0.0
      CFV = 0.0
      BFV = 0.0
      N=0
      BSDBH=0.0
      STHT=0.0
C      THIS SECTION READS IN THE DBH DISTRIBUTION
      READ32,DBHS
      NDBHS = DBHS
      READ 24,IBEG,IEND
      IBB=IBEG-6
      IEE=IEND-6
      READ 25,(DBH(I),I=IBB,IEE)
C      THIS SECTION READS IN TOTAL HEIGHTS (AS A FCT OF DBH)
      DO 33 II=IBB,IEE
      READ 32,HTS(II),JBEG(II),JEND(II)
      IIB=JBEG(II) / 10
      IIE=JEND(II) / 10
      READ25,(HTT(II,JZ),JZ=IIB,IIE)
33  READ25,((HTU(II,JZ,K),K=1,10),JZ=IIB,IIE)
C      THIS SECTION READS IN PERCENT CROWNS (AS A FCT OF DBH)
      DO 43 JJ=IBB,IEE
      READ 32,OIO(JJ),KBEG(JJ),KEND(JJ)

```

```

JJB=KBEG(JJ) / 10
JJE=KEND(JJ) / 10
READ25,(OIA(JJ,JZ),JZ=JJB,JJE)
43 READ25,(IOIB(JJ,JZ,K),K=1,10),JZ=JJB,JJE)
C THIS SECTION GENERATES A DBH
2000 RND=RANDF(DIGIT)
SDBH=0.0
DO 27 I=IBB,IEE
IF(RND-((SDBH+DBH(I))/DBHS))29,29,30
30 SDBH=SDBH+DBH(I)
27 CONTINUE
29 DBHX=I+ 6
BSDBH=BSDBH+DBHX
N = N + 1
NDBH=DBHX - 6.
DBH(I)=DBH(I)-1.0
DBHS=DBHS-1.0
C THIS SECTION GENERATES A TOTAL HEIGHT
RND=RANDF(DIGIT)
HT1=0.0
LOW=JBEG(NDBH) / 10
KOW=JEND(NDBH) / 10
DO 38 L1=LOW,KOW
IF(RND-(HTT(NDBH,L1)+HT1)/HTS(NDBH))34,34,97
97 HT1=HT1+HTT(NDBH,L1)
38 CONTINUE
34 RND=RANDF(DIGIT)
HT2=0.0
DO 35 J=1,10
IF(RND-(HTU(NDBH,L1,J)+HT2)/HTT(NDBH,L1))94,94,88
88 HT2=HT2+HTU(NDBH,L1,J)
35 CONTINUE
94 HTS(NDBH)=HTS(NDBH)-1.0
HTT(NDBH,L1)=HTT(NDBH,L1)-1.0
HTU(NDBH,L1,J)=HTU(NDBH,L1,J)-1.0
THT = L1 * 10 + J - 1
HHT=THT-20.
STHT=STHT + HHT
NTHT=THT+5.0
C THIS SECTION GENERATES A CROWN/HT RATIO (RELATED TO DBH)
RND=RANDF(DIGIT)
OIO1=0.0
LIT=KBEG(NDBH) / 10
KIT=KEND(NDBH) / 10
DO 75 L2=LIT,KIT
IF(RND-(OIA(NDBH,L2)+OIO1)/OIO(NDBH))90,90,91
91 OIO1=OIO1+OIA(NDBH,L2)
75 CONTINUE
90 RND=RANDF(DIGIT)
OIO2=0.0

```



```

DO 92 K=1,10
  IF(RND-(OIB(NDBH,L2,K)+OIO2)/OIA(NDBH,L2))87,87,93
93 OIO2=OIO2+OIB(NDBH,L2,K)
92 CONTINUE
87 OIO(NDBH)=OIO(NDBH)-1.0
  OIA(NDBH,L2)=OIA(NDBH,L2)-1.0
  OIB(NDBH,L2,K)=OIB(NDBH,L2,K)-1.0
  OIOX = L2 * 10 + K - 1
  CROWN=OIOX*HHT/100.
  FREE=HHT-CROWN
C THIS SECTION COMPUTES MERCHANTABLE HEIGHT
  TMHT=(1.1786842+.076004589*(HHT      )+.56697106*DBHX-5.6)/.1587845
  XMHT=TMHT-0.67
C THIS SECTION COMPUTES EXPECTED TREE VOLUMES
  2 QUAN = DBHX**2*HHT
    IF(QUAN - 7000.) 409,409,410
409 ECFV = 0.002798*QUAN - 1.045780
    GO TO 411
410 ECFV = .002256*QUAN + 2.836222
411 IF(QUAN -15000.) 412,412,413
412 EBFV = .012535*QUAN - 10.190570
    GO TO 414
413 EBFV = .012893*QUAN - 19.245660
414 CFV = CFV + ECFV
    BFV = BFV + EBFV
    PUNCH 1004,N,DBHX,HHT,XMHT,CROWN,FREE,ECFV,EBFV,NCULL,PCT
    IF(N - NDBHS) 2000,500,500
500 DBHSY=NDBHS
    ADBH=BSDBH/DBHSY
    ATHT=STHT/DBHSY
    PUNCH 350,CFV,BFV,ADBH,ATHT
C ASSIGNING CULL FACTORS TO SAMPLES OF 100 CULL 1=DEAD,CULL2=ROT,CULL3=DEF
C YOU MUST LOAD PRIOR OUTPUT INTO READ HOPPER
    DEAD=0.0
    ROT=0.0
    OTHER=0.0
51 DEAD=DEAD+0.15
    PROB=DEAD
    IF(PROB-0.7)1,1,15
  1 DO 5 I=1,100
    READ 1004,N,DBHX,THT,XMHT,CROWN,FREE,ECFV,EBFV,NCULL,PCT
    RND=RANDF(DIGIT)
    IF(RND-PROB)3,3,4
  4 PUNCH 1004,I,DBHX,THT,XMHT,CROWN,FREE,ECFV,EBFV,NCULL,PCT
    GO TO 5
  3 NCULL=1
    PCT=1.0
    PUNCH 1004,I,DBHX,THT,XMHT,CROWN,FREE,ECFV,EBFV,NCULL,PCT
  5 CONTINUE
    GO TO 51

```

```
15 DEAD=0.0
16 ROT =ROT+.15
   PROB=ROT
   IF (PROB-0.7) 17,17,62
17 DO 10 I=1,100
   READ 1004,N,DBHX,THT,XMHT,CROWN,FREE,ECFV,EBFV,NCULL,PCT
   RND=RANDF(DIGIT)
   IF (RND-PROB) 14,14,13
13 PUNCH 1004,I,DBHX,THT,XMHT,CROWN,FREE,ECFV,EBFV,NCULL,PCT
   GO TO 10
14 NCULL=2
   PCT=RANDF(DIGIT)
   PUNCH 1004,I,DBHX,THT,XMHT,CROWN,FREE,ECFV,EBFV,NCULL,PCT
10 CONTINUE
   GO TO 16
62 OTHER = OTHER + 0.15
   PROB = OTHER
   IF (PROB-0.7) 61,61,77
61 DO 63 I=1,100
   READ 1004,N,DBHX,THT,XMHT,CROWN,FREE,ECFV,EBFV,NCULL,PCT
   RND=RANDF (DIGIT)
   IF (RND-PROB) 100,100,101
101 PUNCH 1004,I,DBHX,THT,XMHT,CROWN,FREE,ECFV,EBFV,NCULL,PCT
   GO TO 63
100 NCULL=3
   PCT=RANDF(DIGIT)
   PUNCH 1004,I,DBHX,THT,XMHT,CROWN,FREE,ECFV,EBFV,NCULL,PCT
63 CONTINUE
   GO TO 62
77 OTHER=0.0
12 ROT=0.0
   DEAD=DEAD+0.15
   IF (DEAD-0.5) 60,60,88
60 ROT=ROT+0.15
   IF (ROT-0.5) 70,70,12
70 PROB=DEAD+ROT
   DO 55 I=1,100
   READ 1004,N,DBHX,THT,XMHT,CROWN,FREE,ECFV,EBFV,NCULL,PCT
   RND=RANDF(DIGIT)
   IF (RND-PROB) 6,6,31
31 PUNCH 1004,I,DBHX,THT,XMHT,CROWN,FREE,ECFV,EBFV,NCULL,PCT
   GO TO 55
6 RND = RANDF(DIGIT)
   IF (RND-(DEAD/PROB)) 40,40,41
41 PCT=RANDF(DIGIT)
   NCULL=2
   PUNCH 1004,I,DBHX,THT,XMHT,CROWN,FREE,ECFV,EBFV,NCULL,PCT
   GO TO 55
40 NCULL=1
   PCT=1.0
```

```
PUNCH 1004,I,DBHX,THT,XMHT,CROWN,FREE,ECFV,EBFV,NCULL,PCT
55 CONTINUE
GO TO 60
88 STOP
END
```

C PART II

```
1 FORMAT(3I4)
2 FORMAT(I4,I2,F6.2,F6.1,2F5.1,3F6.1, I4,F6.1)
10 FORMAT(7F8.4)
11 FORMAT(F10.8)
25 FORMAT(10F4.0)
32 FORMAT(F5.0,2I3)
169 FORMAT(2F7.0)
600 FORMAT(I4,F4.0,F4.0,3F5.1,3F6.1,F6.1,I2,4F6.2)
612 FORMAT(2I3,I4,6F8.2)
614 FORMAT(I3,I4,6F5.2,F7.2,F6.0,3F7.2)
1004 FORMAT(I4,2F4.0,3F5.1,2F6.1,I5,F6.0)
2002 FORMAT(I2)
    DIMENSION ONTOP(10),LBEG(10),LEND(10),ONTP(10,10),PLIMB(10)
    DIMENSION MEND(10),PLMB(10,10),Y(12),WALK(4),TLIMB(4),DIAM(4)
    DIMENSION MOP(10),A(10),LOP(9),B(9),KOP(8),C(8),JOP(7),D(7)
    DIMENSION X(7),BNO(4),RDIAM(4),MBEG(10),XNO(4),VDIAM(9)
1111 READ 11,DIGIT
C READ IN STANDARD LOG LENGTHS
    READ2002,JBUCK
    READ 10,(X(I),I=1,JBUCK)
    READ169,DSTY,TREES
C COMPUTE MEAN AND STANDARD DEV OF DIST BETWEEN TREES DISTRB
    AVE=SQRTF(43560./TREES)
    STD=AVE/3.0
C THIS SECTION READS THE WALK ON LOG DISTRIBUTION (AS A FCT OF DBH)
    DO 89 KK=1,9
    READ32, ONTOP(KK),LBEG(KK),LEND(KK)
    KKB=LBEG(KK)
    KKE=LEND(KK)
89 READ25,(ONTP(KK,JZ),JZ=KKB,KKE)
C THIS SECTION READS IN LIMBING TIME DISTRIBUTION(PER FT REL TO DBH)
    DO 53 LL=1,9
    READ 32,PLIMB(LL),MBEG(LL),MEND(LL)
    LLB=MBEG(LL)
    LLE=MEND(LL)
```

```
53 READ25,(PLMB(LL,JZ),JZ=LLB,LLE)
   READ 1,KOKE
C   READ PRODUCTION RATE INFO
700 READ 1,NPR,NHRS,NTRIAL
   NCUT = NPR*NHRS
   CUT = NCUT
   THRS=NHRS
C   SET REGISTERS = 0
   VBF=0.0
   BUT=0.0
   CTIME=0.0
   TFELL=0.0
   TLMB = 0.0
   TBUCK=0.0
   TLAB=0.0
   TTRAV=0.0
   TDIST = 0.0
   LBJ = 0
   TTCOST = 0.0
   TVSCB = 0.0
641 VOLWT = 0.0
   VSCB1 = 0.0
   VSCB2 = 0.0
   NDECC1 = 0
   RVI4=0.0
   LBBJ = 0
C   READ OUTPUT FROM PHASE I
1032 READ 1004, N, DBHX, THT, XMHT, CROWN, FREE,ECFV,EBFV,NCULL,PCT
   TV=0.0
   TRE=0.0
   CFV=0.0
   BFV = 0.0
   LBJ = LBJ + 1
   LBBJ = LBBJ+1
   VBF=VBF+EBFV
C   THIS SECTION CUTS DOWN THE TREE
C   FIRST CHECK FOR CULL I
   IF(NCULL-1)616,613,616
613 XMHT=0.0
   MAX=1
   BNO(1)=0.0
   PLEFT=EBFV
   PRE=0.0
   GO TO 854
616 MDBH=DBHX-6.
   RAN=RANDF(DIGIT)
   GO TO(100,101,102,103,104,105,106,107,108,109),MDBH
100 IF(RAN-.167)300,300,301
101 IF(RAN-.577)301,301,200
200 IF(RAN-.980)302,302,304
```

```
102 IF(RAN-.277)301,301,201
201 IF(RAN-.892)302,302,202
202 IF(RAN-.988)303,303,304
103 IF(RAN-.039)301,301,203
203 IF(RAN-.559)302,302,204
204 IF(RAN-.902)303,303,205
205 IF(RAN-.990)304,304,305
104 IF(RAN-.012)301,301,206
206 IF(RAN-.288)302,302,207
207 IF(RAN-.793)303,303,208
208 IF(RAN-.942)304,304,209
209 IF(RAN-.988)305,305,306
105 IF(RAN-.057)302,302,210
210 IF(RAN-.385)303,303,211
211 IF(RAN-.813)304,304,212
212 IF(RAN-.986)305,305,306
106 IF(RAN-.132)303,303,213
213 IF(RAN-.603)304,304,214
214 IF(RAN-.867)305,305,215
215 IF(RAN-.985)306,306,307
107 IF(RAN-.102)304,304,216
216 IF(RAN-.449)305,305,217
217 IF(RAN-.857)306,306,218
218 IF(RAN-.959)307,307,308
108 IF(RAN-.042)304,304,219
219 IF(RAN-.250)305,305,220
220 IF(RAN-.708)306,306,221
221 IF(RAN-.958)307,307,309
109 IF(RAN-.428)306,306,222
222 IF(RAN-.714)307,307,308
300 FELLT=0.1
    GO TO 13
301 FELLT=0.2
    GO TO 13
302 FELLT=0.3
    GO TO 13
303 FELLT=0.4
    GO TO 13
304 FELLT=0.5
    GO TO 13
305 FELLT=0.6
    GO TO 13
306 FELLT=0.7
    GO TO 13
307 FELLT=0.8
    GO TO 13
308 FELLT=0.9
    GO TO 13
309 FELLT=1.0
    13 TFELL = TFELL + FELLT/60.
```



```

C      THIS SECTION DETERMINES NUMBER AND SIZE OF LOGS
C      CHECK FOR CULL
      IF(NCULL-1) 5,5,800
800  Q=PCT*XMHT
      STMP=DBHX+((DBHX+2.)/10.)
      DS=1.1786842+.076004589*(THT      )+.56697106*DBHX-.1587845*Q
      QP=SQRTF(Q**2-((STMP-DS)/24.)**2)
      H=(STMP*QP)/(STMP+DS)
      THETA=ATANF((STMP-DS)/(24.*QP))
      COS=COSF(THETA)
      HP=H/COS
      MAX=4
      PRE=0.0
      GO TO 803
5  LOGS1 = 0
      LOGS2=0
      LOGS3=0
      LOGS4=0
      MAX=0
      PRE=0.0
      EXTRA = 1000.
      DO 18 I=1,JBUCK
      MOP(I)=XMHT/X(I)
      A(I)=MOP(I)
      REG1 = 0.0
6  DIFF1 = XMHT - ( A(I) - REG1)* X(I)
      IF(DIFF1-XMHT)78,18,78
78  IF(DIFF1-EXTRA)8,49,55
49  KLOGS = A(I) - REG1
      IF(KLOGS-MAX)15,15,18
8  EXTRA = DIFF1
15  LOGS1=A(I)-REG1
      MAX = LOGS1
      DO 171 II=1,MAX
171 XNO(II)=X(I)
      IF(DIFF1)8,19,55
55  IO = I + 1
      IF(IO-JBUCK)82,82,19
82  DO 17 K = IO,JBUCK
      LOP(K) = DIFF1 /X(K)
37  B(K) = LOP(K)
      REG2 = 0.0
46  DIFF2 = DIFF1 - ( B(K) - REG2)* X(K)
      IF(DIFF2 - DIFF1) 77,17,77
77  IF(DIFF2-EXTRA)23,16,56
16  KLOGS = A(I) - REG1 + B(K) - REG2
      IF(KLOGS-MAX)23,23,17
23  EXTRA=DIFF2
      LOGS1=A(I)-REG1
2050 LOGS2=B(K)-REG2

```

```
DO2051 JL=1,LOGS1
2051 XNO(JL)=X(I)
      JJ=LOGS1+1
      MAX=LOGS1+LOGS2
      DO 172 JK=JJ,MAX
172  XNO(JK)=X(K)
      IF(DIFF2)8,36,56
56  I1=I+2
      IF(I1-JBUCK)81,81,36
81  DO2004L=I1,JBUCK
      KOP(L)=DIFF2/X(L)
7   C(L)=KOP(L)
      REG3=0.0
47  DIFF3=DIFF2-(C(L)-REG3)*X(L)
      IF(DIFF3-DIFF2)76,2004,76
76  IF(DIFF3-EXTRA)80,99,39
99  KLOGS=A(I)-REG1+B(K)-REG2+C(L)-REG3
      IF(KLOGS-MAX)84,84,2004
80  EXTRA=DIFF3
      LOGS1=A(I)-REG1
      DO1031 LJ=1,LOGS1
1031 XNO(LJ)=X(I)
      LOGS2=B(K)-REG2
      LJJ=LOGS1+1
      LJJJ=LOGS1+LOGS2
      DO1030 MJ=LJJ,LJJJ
1030 XNO(MJ)=X(K)
84  LOGS3=C(L)-REG3
      LL=LOGS1+LOGS2+1
      MAX=LOGS1+LOGS2+LOGS3
      DO 173 JM=LL,MAX
173  XNO(JM)=X(L)
      IF(DIFF3)8,41,39
39  I2=I+3
      IF(I2-JBUCK)40,40,41
40  DO 45 M=I2,JBUCK
      JOP(M)=DIFF3/X(M)
42  D(M)=JOP(M)
      DIFF4=DIFF3-D(M)*X(M)
      IF(DIFF4-DIFF3)2005,45,2005
2005 IF(DIFF4-EXTRA)86,85,45
85  KLOGS=A(I)-REG1+B(K)-REG2+C(L)-REG3+D(M)
      IF(KLOGS-MAX)83,83,45
86  EXTRA=DIFF4
      LOGS1=A(I)-REG1
      DO1012 LU=1,LOGS1
1012 XNO(LU)=X(I)
      LOGS2=B(K)-REG2
      LJJ=LOGS1+1
      LJJJ=LOGS1+LOGS2
```

```
DO1005 MJ=LJJ,LJJJ
1005 XNO(MJ)=X(K)
LOGS3=C(L) - REG3
JLJ=LOGS1+LOGS2+1
LW=LOGS1+LOGS2+LOGS3
DO1011 J=JLJ,LW
1011 XNO(J)=X(L)
83 LOGS4=D(M)
MM=LOGS1+LOGS2+LOGS3+1
MAX=LOGS1+LOGS2+LOGS3+LOGS4
DO 174 JN=MM,MAX
174 XNO(JN)=X(M)
45 CONTINUE
41 REG3=REG3+1.0
IF(REG3-C(L))47,36,36
2004 CONTINUE
36 REG2=REG2+1.0
IF(REG2-B(K))46,19,19
17 CONTINUE
19 REG1=REG1+1.0
IF(REG1-A(I))6,18,18
18 CONTINUE
SMAX=MAX
BUT=BUT+SMAX
IF(MAX) 175,54,791
791 DO 175 J=1,MAX
MREV=MAX +1-J
175 BNO(J)=XNO(MREV)
C THIS SECTION COMPUTES LIMBING AND BUCKING TIMES
C TRAVEL TIME ON LOG RATIO ESTIMATE
RND=RANDF(DIGIT)
ONTOP1=0.0
LAW=LBEG(MDBH)
KAW=LEND(MDBH)
DO 26 J=LAW,KAW
IF(RND-(ONT P(MDBH,J)+ONTOP1)/ONTOP(MDBH))95,95,96
96 ONTOP1=ONTOP1+ONT P(MDBH,J)
26 CONTINUE
95 V=J
ONTOP=V/1000.
C LIMBING TIME (PER FT) RATIO ESTIMATE
RND=RANDF(DIGIT)
XLIMB1=0.0
JAW=MBEG(MDBH)
JIW=MEND(MDBH)
DO 149 K=JAW,JIW
IF(RND-(PLMB(MDBH,K)+XLIMB1)/PLIMB(MDBH))59,59,60
60 XLIMB1=PL MB (MDBH,K) + XLIMB1
149 CONTINUE
59 Z=K
```



```
C      XLIMBT=Z/100.
      LIMBING TIME
      PRE=0.01
803 DO168 J=1,MAX
      IF(NCULL-1) 804,804,889
889 IF(PRE) 805,805,804
804 IF(FREE)44,44,155
155 IF(FREE-BNO(J))111,110,110
110 WALK(J)=BNO(J)*ONTOPT
      TLMB = TLMB + WALK(J) /60.
      FREE=FREE-BNO(J)
      GO TO 150
111 COMBO=BNO(J)-FREE
      WALK(J)=FREE*ONTOPT
      TLMB = TLMB + WALK(J) /60.
      TLIMB(J)=COMBO*XLIMBT
      TLMB = TLMB + TLIMB(J)/60.
      FREE=0.0
      GO TO 150
44 TLIMB(J)=BNO(J)*XLIMBT
      TLMB = TLMB + TLIMB(J)/60.
150 TOTAL=BNO(J)+PRE+TRE
      DIAM(J)=1.17868+.076005*(THT      )+.56697*DBHX-.1587845*TOTAL
      PRE=PRE+BNO(J)
      GO TO 48
805 TV=TV+.028
      TRE=TRE+4.
      CMHT=XMHT-TRE
      IF(CMHT-X(JBUCK))1613,2222,2222
2222 DIAM(J)=1.17868+.076005*(THT      )+.56697*DBHX-.1587845*TRE
48 LDIAM=DIAM(J)+.5
      JDIAM = LDIAM- 5
C      GENERATE A BUCK TIME
      RAN=RANDF(DIGIT)
      IF(JDIAM) 500,500,705
705 IF(JDIAM-7) 701,701,516
701 GO TO(500,501,503,505,508,512,516),JDIAM
500 IF(RAN-.438)400,400,401
501 IF(RAN-.040)400,400,502
502 IF(RAN-.827)401,401,402
503 IF(RAN-.464)401,401,504
504 IF(RAN-.952)402,402,403
505 IF(RAN-.043)401,401,506
506 IF(RAN-.638)402,402,507
507 IF(RAN-.978)403,403,404
508 IF(RAN-.224)402,402,509
509 IF(RAN-.591)403,403,510
510 IF(RAN-.877)404,404,511
511 IF(RAN-.959)405,405,406
512 IF(RAN-.095)402,402,513
```

```
513 IF(RAN-.357)403,403,514
514 IF(RAN-.738)404,404,515
515 IF(RAN-.952)405,405,406
516 IF(RAN-.086)403,403,517
517 IF(RAN-.348)404,404,518
518 IF(RAN-.741)405,405,519
519 IF(RAN-.871)406,406,520
520 IF(RAN-.917)407,407,408
400 BUCKET=.03
    GO TO 14
401 BUCKET=.08
    GO TO 14
402 BUCKET=.13
    GO TO 14
403 BUCKET=.18
    GO TO 14
404 BUCKET=.23
    GO TO 14
405 BUCKET=.28
    GO TO 14
406 BUCKET=.33
    GO TO 14
407 BUCKET=.38
    GO TO 14
408 BUCKET=.43
    14 IF(NCULL-1) 807,807,890
890 IF(PRE) 808,808,807
808 CTIME=CTIME+ ( TV+BUCKET) /60.
    IF(TRE-HP)888,810,810
888 IF(J-4) 168,613,613
810 XMHT=XMHT-TRE
    FREE = FREE-TRE
    IF(TRE- Q) 1112,5,5
1112 IF(J-4) 168,5,5
    807 TBUCK = TBUCK + BUCKET /60.
    JOO=J-1
    IF(JOO)168,3001,3002
3001 IF(NCULL-1) 815,815,891
891 IF(TRE) 815,815,816
C    DETERMINE ACTUAL VOLUMES
816 TUMP=1.17868+.076005*(THT      )+.56697*DBHX-.1587845*TRE
    STUMP=.97*TUMP-.15
    GO TO 817
815 STUMP = .97*( DBHX + (DBHX+2.0)/10.) - 0.15
817 RDIAM(J) = .97*DIAM(J)-.15
    CFVL = BNO(J)/2.*((RDIAM(J)/2.))**2+(STUMP/2.))**2)*3.1416/144.
    GO TO 3003
3002 RDIAM(J)=.97*DIAM(J)-.15
    RDIAM(JOO)=.97*DIAM(JOO)-.15
    CFVL=BNO(J)/2.*((RDIAM(J)/2.))**2+(RDIAM(JOO)/2.))**2)*3.1416 /144.
```

```

3003 CFV=CFV + CFVL
    BFVWT=CFVL*28.2/11.0
    VOLWT = VOLWT + BFVWT
    ADJ=BNO(J)/16.3
    BFVS1=(0.79*RDIA(J)**2-2.0*RDIA(J)-4.0)*ADJ
    VSCB1 = VSCB1 + BFVS1
    LDECC1 = ( BFVS1 + 5.0) / 10.
    NDECC1 = NDECC1 + LDECC1
    RDECC1 = NDECC1
    IF(BNO(J)-16.3) 603,603,161
161 IF(JOO)168,3004,3005
3004 DIAMM = 16.3/BNO(J) * ( STUMP - RDIA(J)) + RDIA(J)
    GO TO 3006
3005 DIAMM = 16.3/BNO(J) * ( RDIA(JOO) - RDIA(J)) + RDIA(J)
3006 ABFV = .79*RDIA(J)**2 - 2.0*RDIA(J) - 4.0
    ADJ=( BNO(J)-16.3)/16.3
    BBFV =(0.79* DIAMM **2-2.0* DIAMM -4.0)*ADJ
    BFVS2=ABFV + BBFV
    GO TO 675
603 BFVS2 = BFVS1
675 VSCB2 = VSCB2 + BFVS2
    BFV = BFV + BFVS2
    CAN=BNO(J)/4.
    MIN=CAN
    RUN=MIN
    VI4=0.0
    VDIAM(1)=RDIA(J)
    DO 999 KOO=1,MIN
    TVI4=( .22*VDIAM(KOO)**2 - .71*VDIAM(KOO)) *.905
    VI4=VI4+TVI4
    KOI=KOO+1
999 VDIAM(KOI)=VDIAM(KOO)+0.25
    VDIAM(9)=VDIAM(MIN)+0.25*((CAN-RUN)/4.)
    OI4=( .22*VDIAM(9)**2 - .71*VDIAM(9))* .905*(CAN-RUN)/4.
    VI4=VI4+OI4
    RVI4=RVI4+VI4
    IF(JOO) 168,3,4
C   OUTPUT FOR A LOG
30PUNCH2,N,J,BNO(J),DIAM(J),STUMP,CFVL,BFVWT,BFVS1,BFVS2,LDECC1,
    1VI4
    GO TO 168
40PUNCH 2 ,N,J,BNO(J),DIAM(J),DIAM(JOO),CFVL,BFVWT,BFVS1,BFVS2,
    1LDECC1,VI4
168 CONTINUE
    ETC=0.0
    DO 833 K=1,MAX
833 ETC=ETC+BNO(K)
    MAN=ETC/50. +1.0
    BAN=MAN
    TLAB=TLAB+BAN*.15/60.

```

```
HONOF=.09
TLAB=TLAB+.09/60.
CHOP=MAX*2
TBUCK=TBUCK+CHOP/100./60.
ADJ = EXTRA/16.3
PLEFT = 10.6544*ADJ
854 DIFFA = ECFV - CFV
    DIFFB = EBFV - BFV
C   OUTPUT FOR A TREE
    PUNCH600,N,DBHX,THT,ECFV,CFV,DIFFA,EBFV,BFV,DIFFB,PLEFT,MAX,(BNO(J
1),J=1,MAX)
54  SUM J=0.0
    DOL22 J=1,12
    Y(J)=RANDF(DIGIT)
122 SUM J=SUM J + Y(J)
    R=(SUMJ-6.0)/4.0
    IF(ABSF(R)-1.)43,43,54
430 XM=3.949846138*R+0.252408784*R**3+0.076542912*R**5
    1 +0.008355968*R**7+0.029899776*R**9
    DEV = XM
    DIST = DEV*STD+AVE
C   TRAVEL TIME ON GROUND RATIO ESTIMATE
    RND = RANDF(DIGIT)
    IF(RND-.029)61,61,62
62  IF(RND-.153)63,63,64
64  IF(RND-.576)65,65,66
66  IF(RND-.771)67,67,68
68  IF(RND-.888)69,69,112
112 IF(RND-.938)113,113,114
114 IF(RND-.963)115,115,116
116 IF(RND-.984)117,117,118
118 IF(RND-.996)119,119,120
61  TPFT=.004
    GO TO 121
63  TPFT=.005
    GO TO 121
65  TPFT=.006
    GO TO 121
67  TPFT=.007
    GO TO 121
69  TPFT=.008
    GO TO 121
113 TPFT=.009
    GO TO 121
115 TPFT=.010
    GO TO 121
117 TPFT=.011
    GO TO 121
119 TPFT=.012
    GO TO 121
```

```
120 TPFT=.013
121 DISTT= PRE+DIST
    TDIST = TDIST + DISTT
    TRAVT=DISTT*TPFT
    TTRAV = TTRAV + TRAVT /60.
    IF(LBBJ-NPR) 1032,610,610
610 LHR = LBJ/NPR
    FCOST = 0.23
    VCOST = VSCB2*0.48/1000.
    TCOST = FCOST + VCOST
    REV1 = VOLWT/1000.*4.
    REV2 = VSCB1/1000.*4.
    REV3=RDECC1/100. *4.
    REV4 = VSCB2/1000.*4.
    REV5=RVI4/1000.*4.
C   OUTPUT AT END OF HOUR
    PUNCH612,NTRIAL,LHR,NPR,TCOST,REV1,REV2,REV3,REV4,REV5
    TVSCB = TVSCB + VSCB2
    FACTOR=1.-( TVSCB/VBF)
    TTCOST = TTCOST + TCOST
    REV = TVSCB /1000.*4.
    IF(LHR-NHRS)641,611,611
611 PROFIT = REV - TTCOST
    SHARP = (BUT/80.*3.2)/60.
    WAIT = (CUT*.05)/60.
    REFUEL = (.0225*BUT)/60.
    TFELL=TFELL+WAIT
    TLAB=TLAB+TLMB+TBUCK
    WORK=TFELL+TLAB+TTRAV+SHARP+REFUEL
    PROD = WORK + WORK*.20
    UNPROD = THRS-PROD
C   OUT PUT AT END OF DAY
    PUNCH614,NTRIAL,NCUT,PROD,UNPROD,TFELL,TLAB,TTRAV,CTIME,FACTOR,TDI
    1ST,TTCOST,REV,PROFIT
    IF(NTRIAL-KOKE) 700, 1111, 1111
162 STOP
    END
```


1 1 2 1 3 1 0 1 0
 20 70 80
 10 10
 1 2 0 1 1 2 1 1 0 1
 2 0 2 1 1 0 1 2 1 0
 10 70 70
 10
 1 2 0 0 1 3 0 0 2 1
 C THIS IS BASIC CROWN DATA
 330 20 50
 70 130 110 20
 1 2 0 3 10 10 12 10 11 11
 13 11 9 7 12 21 19 13 10 15
 16 12 9 11 6 9 14 11 13 9
 5 5 3 0 1 2 0 2 2 0
 300 20 70
 40 80 100 60 10 10
 3 1 1 10 6 2 0 5 5 7
 8 6 5 10 11 12 7 6 6 9
 12 13 15 10 7 8 9 6 11 9

7 8 9 10 5 9 0 3 6 3
 2 1 0 3 1 1 1 0 1
 1 2 1 3 0 0 1 2 0 0
 200 20 70
 10 40 50 70 20 10
 1 0 3 2 2 2
 3 7 3 0 5 3 7 4 5 3
 6 7 8 4 2 3 5 6 4 5
 8 6 5 11 4 9 6 9 7 5
 4 4 0 3 2 0 1 3 2 1
 1 3 0 2 1 1 1 1 0 0
 120 30 80
 30 30 20 10 20 10
 1 0 3 6 4 1 5 3 4 3
 3 1 4 0 5 2 4 6 2 3
 2 3 4 0 1 2 3 1 2 2
 1 0 2 2 1 1 0 2 1
 2 3 4 0 3 0 2 1 3 2
 1 1 1 3 2 1 0 1 0 0
 50 40 80
 20 10 0 0 20
 3 4 3 2 2 3 1 2
 1 0 2 2 0 1 3 0 1 0
 3 0 3 4 1 2 2 0 4 1
 40 50 70
 20 10 10
 3 1 2 2 2 3 5 2
 1 2 2 1 0 0 1 1 1 1

1	1	0	1	4	2	0	1	0	0
10	70	70							
10									
1	2	1	0	0	3	1	1	1	0
20	70	70							
20									
3	1	1	4	2	1	3	0	2	3
10	60	60							
10									
1	5	1	1	2	0	0	0	0	0

C DATA PRINTOUT FOR PART II

C AN 8 DIGIT ODD NUMBER
15603211

C NUMBER AND SIZES OF LOGS

3
326000 244500 163000
C READ DENSITY, NUMBER OF TREES TO CUT
1350 1080
C WALK ON LOGS
15 7 10
2 4 5 4
19 6 10
2 4 5 5 3
26 6 10
3 7 8 6 2
35 5 10
2 5 9 12 5 2
32 5 9
3 7 7 13 2
19 5 8
2 3 3 11
11 5 8
2 2 1 6
12 5 8
3 4 4 1
7 5 6
3 4

C LIMBING TIME DISTRIBUTION

24	1	3
12	8	4
26	1	4
10	8	6 2

21	1	4		
9	5	5	2	
33	1	5		
5	13	9	5	1
44	1	5		
6	15	11	8	4
33	2	6		
10	10	6	5	2
23	2	5		
6	5	7	5	
9	2	5		
1	4	2	2	
5	2	4		
1	3	1		

C NUMBER OF SIMULATED DAYS

17

C FOLLOW WITH OUTPUT FROM PART I

APPENDIX D

CHAIN SAW SPECIFICATIONS (from manufacturers' literature)

Homelite 770-D Specifications

Bore	2 3/16"
Stroke	1 35/64"
Displacement	5.8 Cubic Inches
Fuel Tank Capacity	41 Ounces
Oil Tank Capacity	14 Ounces
Maximum Engine RPM	No Load 7500, Load 6000/6500
Sprocket	404" pitch 7 Tooth
Chain Speed - Load - f.p.m...	2828
Weight	Dry--less bar, chain, 20 lbs.
Bar Sizes	14", 17", 21", 25", 30"
Approximate Price	\$285.00

Homelite C-9 Specifications

Handle Bar Type	Flush cut, plastic grip
Weight Less Bar and Chain	19 lbs.
Bar Sizes	14, 17, 21, 25, 30
Attachments	Bow, Clearing & Utility Guides
Chain Type	.404 Pitch
Sprocket	7 Tooth .404 Pitch
Chain Speed under Load	2828 Feet per Minute
Chain Oiler Type and Capacity.	Positive Manual 8. oz. reservoir w/ filter
Engine Type	Single cylinder, two cycle loop scavenged
Bore	2 1/16"
Stroke	1 9/16"

Displacement	5.22 cubic inch
Intake Valve	High Performance Pyramid Reed
Compression Ratio	6.7:1
Ignition Timing	30° BTDC Static
Engine Speed	Under load - 6000-6500 RPM
Clutch Engaging Speed and Type	2800 RPM - 6 shoe double spring centrifugal
Fuel Type and Mixture	Regular Grade Gasoline with a ½ pint per gallon (16:1) Homelite 2 cycle oil
Fuel Tank Capacity	42 oz. with pressure sensitive replaceable automatic vent
Breaker Point Setting and Location.....	.015" - protected in sealed box under the flywheel
Magneto	High tension - water and dust proof with protected coil
Spark Plug Type and Gap	Champion J-6-J -- .025"
Throttle Control	Trigger in handle with throttle lock
Bearings	Needle and Ball Bearings
Carburetor	Tillotson All-Position Diaphragm with integral fuel pump and fuel strainer
Fuel Filter	All-Position Felt Pick-up in fuel tank, screen in carburetor
Air Filter	Protected Phenolic Impregnated Polyester Fiber (Micro Mesh) for long service life
Muffler	Quiet Type - with baffled spark arrestor
Approximate Price	\$250.00

McCulloch 1 - 53 Specifications

Type of Engine Single cylinder, two-cycle aircooled
crankcase scavenged

Displacement 5.3 cubic inches

Carburetor diaphragm all-position

Starter Automatic rewind with nylon rope

Clutch Automatic four metal shoe,
centrifugally operated

Drive Direct

Weight Dry - less bar, chain, 20 lbs.

Bar Sizes 12", 15", 18", 24", 30"

Approximate Price \$230.00

APPENDIX E

CHAIN SAW COST ANALYSIS

Fixed Costs.

	<u>Annual</u>	<u>Hourly</u>
Depreciation	\$190.00	0.19
Interest	17.10	0.02
Insurance	<u>21.00</u>	<u>0.02</u>
	\$228.10	\$0.23

Variable Costs.

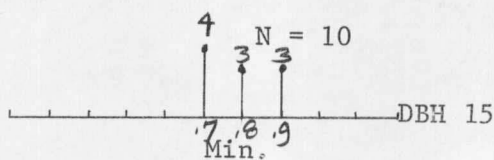
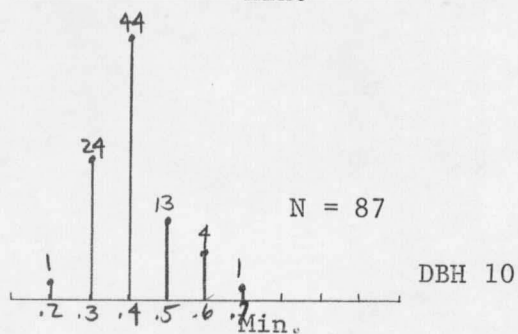
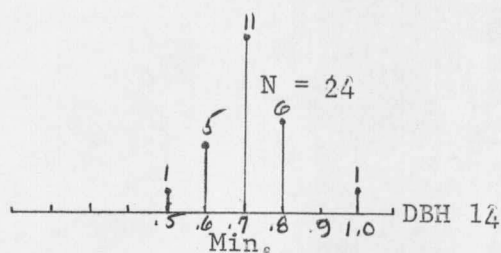
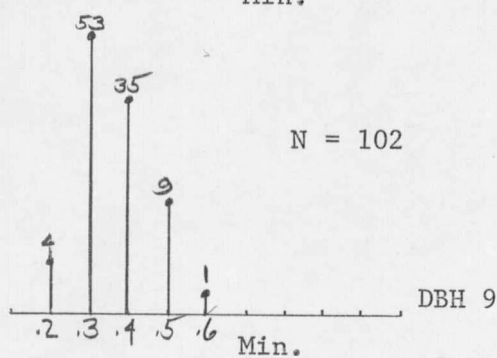
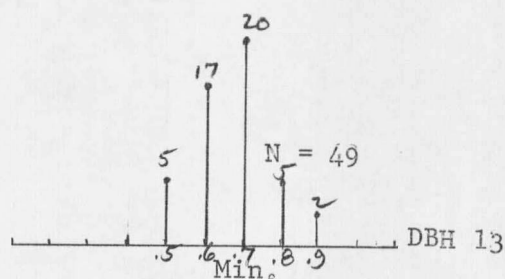
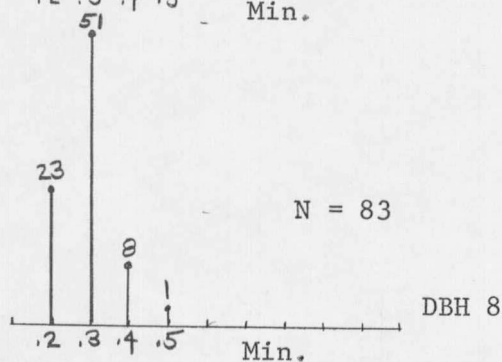
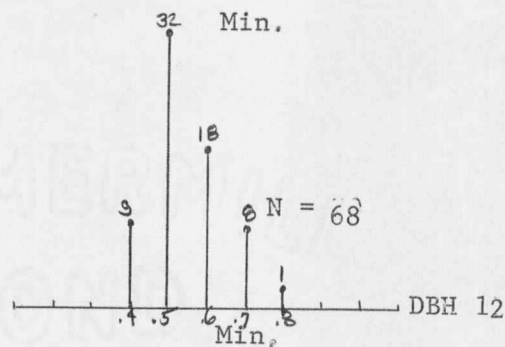
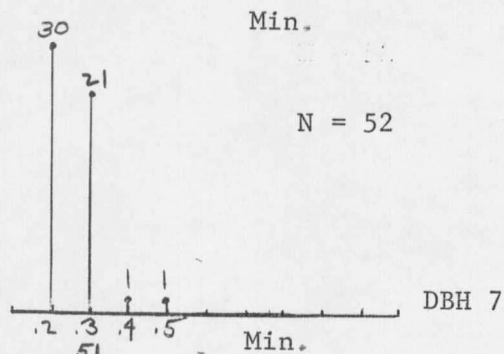
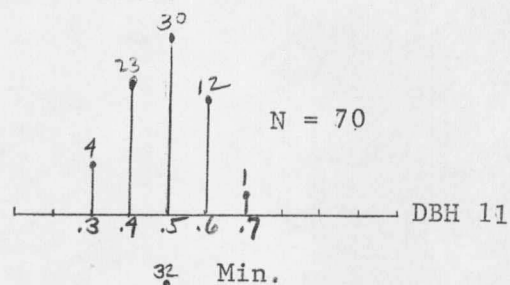
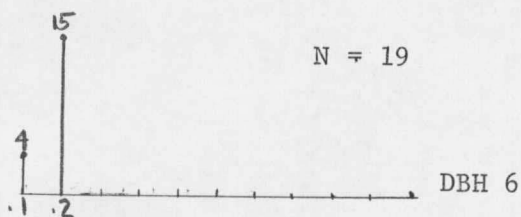
	<u>Daily</u>	<u>Per MBF</u>
Fuel (Gas and Oil)	\$1.56	0.26
Maintenance and Repair	<u>1.32</u>	<u>0.22</u>
	\$2.88	\$0.48

Assumptions.

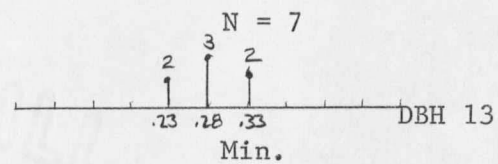
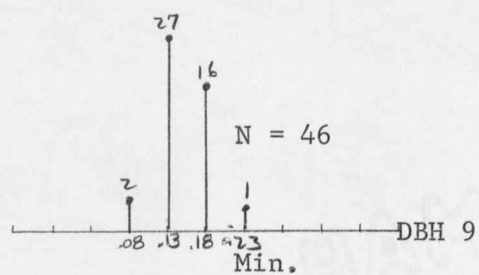
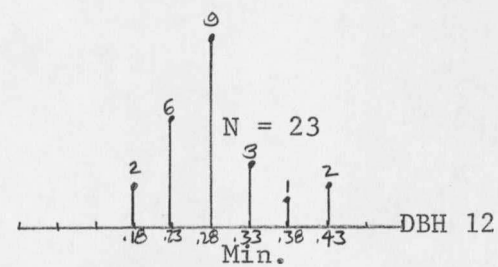
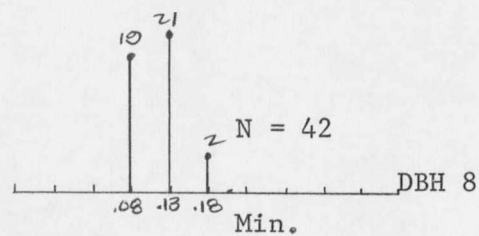
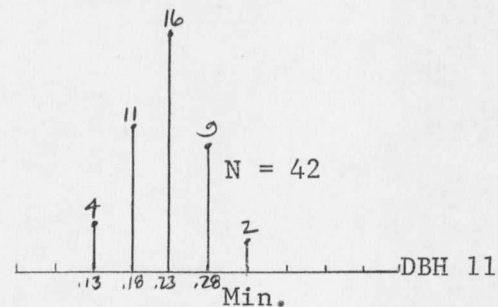
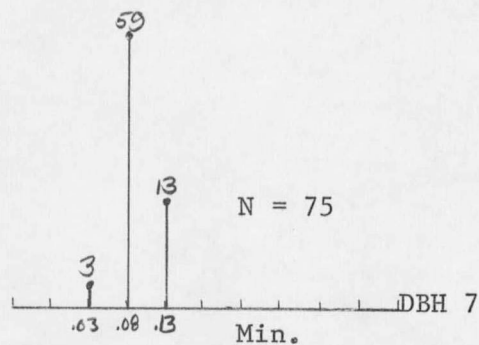
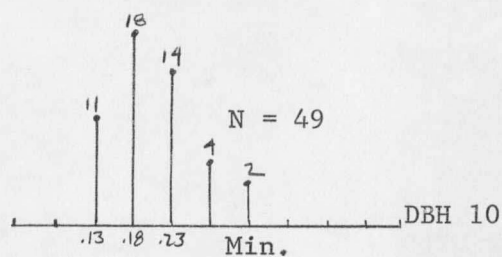
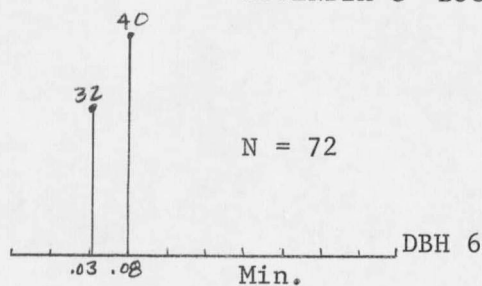
- (1) Initial cost of \$285.00.
- (2) Trade-in value of \$95.00
- (3) Useful life of 1 year.
- (4) Operating time is 1000 hrs./ yr.
- (5) Interest, 6% of average annual investment.
- (6) Gasoline costs \$.30/gal; oil costs \$2.40/gal.
- (7) Maintenance labor is \$100/yr; repair parts cost \$230/yr.
- (8) Average cutter will cut 1500 MBF/yr. (6000 BF/day) at 16 trees/MBF.

Assumptions were made on the basis of personal interview, intuition, and information presented in references.

APPENDIX F FELLING FREQUENCY DISTRIBUTIONS



APPENDIX G BUCKING FREQUENCY DISTRIBUTIONS



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