Date: 14 June 1967

RESEARCH PROJECT INITIATION

Project Title: The Systems Aspect of Harvesting and Transportation of Pulpwood

Project No.: E-1009

Project Director: Professor N. K. Rogers

Sponsor: Southern Executives Association

Agreement Period: From 26 June 1967 until 25 June 1969

Type Agreement: Memorandum of Understanding, dated May 2, 1967

Amount: $40,000 (Funded for one year)

Project Administrator
Mr. Fred C. Gragg
Southern Executives Association
Vice President and Assistant General Manager in Charge of Woodlands, Southern Kraft Division
International Paper Company
Mobile, Alabama 36601

Technical Liaison
Dr. T. A. Walbridge
Chief, Forestry Engineering and Development
Bowaters Southern Paper Corporation
Calhoun, Tennessee 37303

Reports Required
Quarterly - 1st report due 25 September 1967
Annual - Due 30 June 1968
Theses - As they occur
Final - Comprehensive report due by 25 August 1969

Assigned to: School of Industrial Engineering
GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF RESEARCH ADMINISTRATION
RESEARCH PROJECT TERMINATION

Date: April 20, 1972

Project Title: The Systems Aspect of Harvesting & Transportation of Pulpwood

Project No: E-24-601 (Old B-1009)

Principal Investigator: Prof. N. K. Rogers

Sponsor: Southern Executive Association; Mobile, Alabama

Effective Termination Date: 15 April 1972*


Clearance of Accounting Charges: All funds have been expended

Grant/Contract Closeout Actions Remaining:

Final Financial Report

Assigned to: School of Industrial & System Engineering

COPIES TO:
Principal Investigator
School Director
Dean of the College
Director, Research Administration
Director, Financial Affairs (2)
Security-Reports-Property Office
Patent and Inventions Coordinator

Library, Technical Reports Section
Rich Electronic Computer Center
Photographic Laboratory
Project File
Other

RA-4 (5-71)
December 29, 1967

Memorandum

To: The Southern Executives Association

From: The School of Industrial Engineering  
Georgia Institute of Technology

Subject: Second Quarterly Report, Project B-1009,  
"The Systems Aspect of Harvesting and Transportation of Pulpwood"

Time Period: This report covers the period of September 26 - December 25, 1967.

Participants:  
Mr. N. K. Rogers, Project Director, (1/4 Time), Georgia Tech  
Dr. Joseph Krol, Research Associate, (1/4 Time), Georgia Tech  
Dr. Peter Dyson, Research Associate, (1/4 Time), U. of Georgia  
Mrs. Elaine Ripley, Secretary, (1/8 Time), Georgia Tech  
Mr. Pietro Fenu, Graduate Assistant, (1/3 Time), Georgia Tech  
Mr. Walter Cosby, Graduate Assistant, (1/3 Time), Georgia Tech  
Mr. Harold Holliman, Graduate Assistant, (1/3 Time), Georgia Tech  
Lt. James Stark, Graduate Assistant, (Not funded), Georgia Tech  
U.S.A.F.  
Mr. John Bacon, Undergraduate Assistant, (Not funded), Georgia Tech  
Mr. Benny Baker, Undergraduate Assistant, (Not funded), Georgia Tech
The nature of the work performed was one of defining and initiating action in various systems engineering work areas. Graduate and Undergraduate Assistants were indoctrinated by the Research Associates at a series of nine weekly meetings in order that the students might select work areas of interest to them. With the exception of Lt. Stark, all student members of the project team were experiencing their first exposure to the pulpwood industry. Lt. Stark commenced his thesis work entitled, "A Simulation Model of the Common Pulpwood Harvesting System of the Southern Pine Region."

Various statistical analysis were made in order to familiarize the group with the nature of the industry being studied. In addition, each of the funded Graduate Assistants was required to design his own pulpwood harvesting business. Various levels of capital investment were chosen. Considerable insight was gained into the man-machine and money-time mix, although the depth of this work was insufficient for valid conclusions.

Towards the end of the quarter a considerable number of flow or process type analysis were made to aid in the description of the general system and to point up the inadequacies of the relationships in the flow in information and control systems, in physical process systems, and in financial systems, which contribute to the overall performance of the pulpwood harvesting and transportation business.

It was determined that three short range and three long range systems engineering treatments of the problem should be explored. These approaches were tenatively divided among the three principal
Research Associates for purposes of insuring adequate coverage. In addition, the Research Associates expressed a desire to work predominantly in the following areas:

Dr. Dyson: Prediction of Pulpwood Resource Areas of the Future.
Dr. Krol: Simulation of Pulpwood Harvesting Systems of the Future.

This appeared to give broad subject coverage in addition to the coverage of various analysis techniques mentioned above.

Mr. John Bacon produced a short paper regarding transportation of pulpwood by rail between various woodyards and various mills. Linear programming techniques were explored to arrive at a system which might possibly be useful to the industry.

Preparations were made for a joint Auburn, Georgia Tech, A.P.A. Research Meeting in January, as well as a meeting with the S.E.A. Steering Committee.

Contact with outside sources were made by members of the project team on an "as required" basis in order to obtain background material and analytical data for the work performed, as outlined above.

Two (2) paper mills, six (6) pulpwood yards, ten (10) harvesting sites, two (2) company owned forests, and various equipment distributors and dealers were visited. These locations were visited to provide the Graduate and Undergraduate Assistants with a cross section of various working environments.
Four (4) professional meetings were attended. (Three at no cost to S.E.A.). Mr. Rogers and Doctor Dyson spoke on areas of their interest at several meetings.

Publications:
Mr. John Bacon, Undergraduate Assistant, prepared a term paper entitled, "Minimization of Transportation Costs for the Hauling of Pulpwood by Rail". This paper is now under review by the Research Associates. Copies will be made available, if this paper is deemed to have useful application.

Remarks:
Mr. Harold Holliman resigned from the project group at the end of the Fall Quarter to accept a position in industry. An attempt will be made to replace him from the graduate group enrolling in the Winter Quarter.

Respectfully submitted,

N. K. Rogers
Project Director
December 29, 1967

Mr. Fred C. Gragg  
Southern Executives Association  
Vice President and Assistant  
General Manager, Woodlands  
Southern Kraft Division  
International Paper Company  
Mobile, Alabama  36601

Dear Mr. Gragg:

In accordance with our various discussions and the memorandum of understanding dated May 2, 1967, we submit our second Quarterly Report in letter memorandum form concerning Project E-1009, "The Systems Aspect of Harvesting and Transportation of Pulpwood".

We look forward to the meeting with the S.E.A. Steering Committee during the latter part of January for discussion and amplification of reported research activities.

Cordially,

N. R. Rogers  
Project Director

bjp

cc:  Dr. T. A. Walbridge, Project Liaison  
American Pulpwood Association  
Harvesting Research Project  

Dr. Peter Dyson, School of Forestry  
University of Georgia  

Mr. Harry Baker, Director  
Research Administration  

Dr. R. N. Lehrer, Director  
School of Industrial Engineering  

Dr. Joseph Krol  
School of Industrial Engineering  
Research Assistants
Memorandum

To: The Southern Executives Association

From: The School of Industrial Engineering
Georgia Institute of Technology

Subject: Third Quarterly Report, Project B-1009, "The Systems Aspect of Harvesting and Transportation of Pulpwood"


Participants: Mr. N. K. Rogers, Project Director, (1/4 Time), Georgia Tech
Dr. Joseph Krol, Research Associate, (1/4 Time), Georgia Tech
Dr. Peter Dyson, Research Associate, (1/4 Time), U. of Georgia
Mrs. Elaine Ripley, Secretary, (1/8 Time), Georgia Tech
Mr. Pietro Fenu, Graduate Assistant, (1/3 Time), Georgia Tech
Mr. Walter Cosby, Graduate Assistant, (1/3 Time), Georgia Tech
Mr. Terry Moore, Graduate Assistant, (Not funded), Georgia Tech
Lt. James Stark, Graduate Assistant, (Not funded), Georgia Tech
Mr. Michael Deisenroth, Graduate Assistant, (Not funded), Georgia Tech
Major James Bearden, Graduate Assistant, (Not funded), Georgia Tech
Lt. George Valente, Graduate Assistant, (Not funded), Georgia Tech
Mr. Adolfo Arias, Undergraduate Assistant, (Not funded), Georgia Tech
Mr. Benny Baker, Undergraduate Assistant, (Not funded), Georgia Tech

Work Time: Approximately 750 man hours were worked by various members of the research group divided approximately 300 hours - Research Associates, 300 hours - Funded Graduate Assistants, and 150 hours by Unfunded personnel.
Nature of Work Performed: The nature of the work performed was one of exploring areas of action and performing analysis in various systems engineering work areas. Graduate and Undergraduate Assistants met regularly with the Research Associates at a series of seven weekly meetings in order that the students and professors might report on their selected work areas and criticize each other’s work. With the exception of Lt. Stark, all student members of the project team were either experiencing their first exposure to the pulpwood industry or were in the second quarter of the research program. Lt. Stark continued his thesis work entitled, "A Simulation Model of the Common Pulpwood Harvesting System of the Southern Pine Region." He encountered considerable trouble in programming his work using two computer languages, but these problems began to be ironed out toward the end of the quarter.

Continuing statistical studies were made in order to familiarize the group with the nature of the industry being studied. Each of the funded Graduate Assistants outlined the area of his thesis work and Mr. Fenu completed several computer simulations regarding levels of future production. Dr. Krol spent a great part of his work time examining the literature and reached some tentative conclusions regarding land and wood values necessary to the research. Mr. Arias completed a brief study regarding mill location and geographic overlap of supply areas. This work will be continued by Mr. Deisenroth.
April 1, 1968

Mr. Fred C. Gragg  
Southern Executives Association  
Vice President and Assistant General Manager, Woodlands  
Southern Kraft Division  
International Paper Company  
Mobile, Alabama 36601

Dear Mr. Gragg:

In accordance with our various discussions and the memorandum of understanding dated May 2, 1967, we submit our third Quarterly Report in letter memorandum form concerning Project B-1009, "The Systems Aspect of Harvesting and Transportation of Pulpwood".

We look forward to the meeting with the S.E.A. Steering Committee during the coming week for discussion and amplification of reported research activities.

Cordially,

N. K. Rogers  
Project Director

cc: Dr. T. A. Walbridge, Project Liaison  
American Pulpwood Association  
Harvesting Research Project  
Dr. Peter Dyson, School of Forestry  
University of Georgia  
Mr. Harry Baker, Director  
Research Administration  
Dr. R. N. Lehrer, Director  
School of Industrial Engineering  
Dr. Joseph Krol  
School of Industrial Engineering  
Research Assistants
Towards the end of the quarter a number of additional graduate students joined the program and much of Mr. Rogers time was spent describing to them the general systems under study and pointing up the inadequacies of the management information and control systems, which determine performance in the pulpwood harvesting and transportation business.

The Research Associates continued to work predominantly in the areas heretofore selected:

Dr. Dyson: Prediction of Pulpwood Resource Areas of the Future.

Dr. Krol: Simulation of Pulpwood Harvesting Systems of the Future.


Major Bearden tentatively selected maintenance systems as his work area, and Mr. Moore decided to continue the earlier work of Mr. Bacon in systems for minimizing transportation costs. Mr. Benny Baker produced a short paper regarding the proper treatment of the accounting functions for a pulpwood producer. This paper provides a basis for further work by Mr. Rogers in attempting to define economic criteria for mechanization of the typical producer. Several other shorter papers were completed in connection with I.E. course work.

A joint Georgia Tech - A.P.A. Harvesting Research Meeting was held in January. This allowed members of both teams to become acquainted with each other's work area. Sources of data for future use were discussed in detail. Dr. Walbridge, our liaison member with S.E.A. was brought up to date regarding work during the Fall Quarter.
Personal Contact: Contact with outside sources were made by members of the project team on an "as required" basis in order to obtain background material and analytical data for the work performed, as outlined above.

Travel: One (1) paper mill, four (4) pulpwood yards, seven (7) harvesting sites, and quite a number of equipment distributors and dealers were visited. These locations were visited individually by the Graduate and Undergraduate Assistants to obtain insights necessary to their research. No professional meetings were attended. Mr. Rogers and Dr. Dyson felt the expense of their attending the A.P.A. meeting in New York was not justified.

Publications: Mr. Benny Baker, Undergraduate Assistant, prepared a term paper entitled, "Factors Which Make Up the Modified Income Statement". This paper will be used in future work by the Research Associates. Mr. Adolfo Arias, Undergraduate Assistant, prepared a project report entitled "Pulp Mills in the Southeastern United States". This will be used in future work. Lt. James Stark, Graduate Assistant, prepared a term paper entitled, "A Background Study of the Paper Industry". The bulk of this information will be found in his thesis or will be used by the Research Associates. Mr. Pietro Fenu, Graduate Assistant, prepared a term paper entitled, "A Dynamic Model of the Southern Paper Industry, 1950-2000". This paper presents an Industrial Dynamics model of the paper industry, and perhaps can be distributed in advance of his thesis work. Lt. George Valente, Graduate Assistant, prepared a term paper entitled,
"A Simulation of the Pulpwood Procurement System", outlining his proposed research area.

Remarks:

(1) Consultation with the Director of the School of Industrial Engineering resulted in tentative agreement for the scheduling in the Fall Quarter, 1968 of a three hour credit graduate seminar at the 700 level. This course consisting of ten three hour meetings, has been tentatively entitled "Seminar on Industrial Engineering Practices in Forestry and Paper Industries". The assistance of S.E.A. will be needed to make this a meaningful experience in the I.E. Curriculum.

(2) A third Funded Graduate Assistant was not selected to replace Mr. Holliman who resigned at the end of December. Instead, the funds scheduled for this position in the Winter and Spring Quarters will be used to keep Graduate work underway during the Summer Quarter for which funds were not originally allocated.

Respectfully submitted,

N. K. Rogers
Project Director
Research Seminar

S.E.A. Pulpwood Harvesting and Transportation Research Group
April 4, 1968

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CLOSED SESSION
Mr. Fred C. Gragg  
Southern Executives Association  
Vice President and Assistant  
General Manager, Woodlands  
Southern Kraft Division  
International Paper Company  
Mobile, Alabama  36601

July 8, 1968

Dear Mr. Gragg:

In accordance with our various discussions and the memorandum of understanding dated May 2, 1967, we submit our fourth Quarterly Report in letter memorandum form concerning Project B-1009, "The Systems Aspect of Harvesting and Transportation of Pulpwood."

The First Annual Report is in process of preparation and will be submitted shortly.

We look forward to the meeting with the S.E.A. at Point Clear, Alabama on October 31st for discussion and amplification of reported research activities.

Cordially,

N.K. Rogers  
Project Director

cc: Dr. T.A. Walbridge, Project Liaison  
American Pulpwood Association  
Harvesting Research Project  

Dr. Peter Dyson, School of Forestry  
University of Georgia  

Mr. Harry Baker, Director  
Research Administration  

Dr. R. N. Lehrer, Director  
School of Industrial Engineering  

Dr. Joseph Krol  
School of Industrial Engineering  
Research Assistants
Memorandum

To: The Southern Executives Association

From: The School of Industrial Engineering  
Georgia Institute of Technology

Subject: Fourth Quarterly Report, Project B-1009,  
"The Systems Aspect of Harvesting and Transportation of Pulpwood"

Time Period: This report covers the period of March 26, 1968 - June 25, 1968.

Participants:  
Mr. N. K. Rogers, Project Director, (1/4 Time), Georgia Tech  
Dr. Joseph Krol, Research Associate, (1/4 Time), Georgia Tech  
Dr. Peter Dyson, Research Associate, (1/4 Time), U. of Georgia  
Mrs. Elaine Ripley, Secretary, (1/8 Time), Georgia Tech  
Mr. Pietro Penu, Graduate Assistant, (1/3 Time), Georgia Tech  
Mr. Walter Cosby, Graduate Assistant, (1/3 Time), Georgia Tech  
Mr. Terry Moore, Graduate Assistant, (Not funded), Georgia Tech  
Lt. James Stark, Graduate Assistant, (Not funded), Georgia Tech  
Mr. Edward Jallouk, Graduate Assistant, (Not funded), Georgia Tech  
Mr. Michael Deisenroth, Graduate Assistant, (Not funded), Georgia Tech  
Major James Bearden, Graduate Assistant, (Not funded), Georgia Tech  
Lt. George Valente, Graduate Assistant, (Not funded), Georgia Tech  
Mr. Dan Plafcan, Undergraduate Asst., (Not funded), Georgia Tech  
Mr. James Stallings, Undergraduate Asst., (Not funded), Georgia Tech

Work Time: Approximately 900 man hours were worked by various members of the research group divided approximately 300 hours - Research Associates, 300 hours - Funded Graduate Assistants, and 300 hours by Unfunded personnel.
Nature of Work Performed: The nature of the work performed was one of narrowing the scope of action and refining work goals, as well as performing analysis in various systems engineering work areas. Graduate and Undergraduate Assistants met regularly with the Research Associates at a series of five weekly meetings in order that the students and professors might report on their selected work areas and criticize each other's work. All Research Associates and Assistants met with the S.E.A. Steering Committee on April 4, 1968 for a six hour presentation of the work in progress. The reception by the Steering Committee appeared to be favorable. Lt. Stark completed his thesis work entitled, "A Simulation Model for the Common Pulpwood Harvesting Systems of the Southern Pine Region." He encountered considerable trouble in programming his work using G.P.S.S. computer languages, but achieved two excellent validations toward the end of the quarter. His thesis was accepted by the Graduate Office.

Continuing statistical studies were made in order to familiarize the group with the nature of the industry being studied. Each of the funded Graduate Assistants prepared papers covering facets of the area of his thesis work and Mr. Fenu completed additional computer simulations regarding levels of future production. Dr. Krol continued his examination of the literature and Mr. Cosby catalogued all library resources regarding twenty two different subjects bearing on the research. Seven papers were prepared by Graduate and Undergraduate Assistants in addition to Lt. Stark's thesis.
Towards the end of the quarter a five hour presentation and critique session was held regarding these papers. Further areas of research were highlighted.

The Research Associates continued to work predominantly in the areas heretofore selected:

Dr. Dyson: Prediction of Pulpwood Resource Areas of the Future.

Dr. Krol: Simulation of Pulpwood Harvesting Systems of the Future.


Mr. Dan Plafcan produced a non-quantitative report describing the pulpwood supervisor or crew leader. Mr. Jim Stallings summarized the labor trends in the South for future use by members of the research group. Mr. Mike Deisonroth prepared a paper regarding the potential of pipelines for chip transportation. Lt. George Valente summarized in a paper the potential for helicopters in harvesting operations. Mr. Cosby prepared a lengthy report on the use of large capacity rough terrain forwarders which included design criteria. Mr. Fenu prepared a G.P.S.S. program to analyze Mr. Cosby's forwarder system and reported this in a paper. Mr. Jallouk took the Battelle Industrial Dynamics program and expanded and modified it to fit today's environment.

It was determined to survey the S.E.A. membership for data regarding the environment surrounding the single mill. Design of the proper forms of inquiry continued through June while
necessary approvals for this function were being sought. Tentative approval has now been obtained and submission of the survey forms to S.E.A. membership should occur about July 15th.

**Personal Contact:** Contact with outside sources were made by members of the project team on an "as required" basis in order to obtain background material and analytical data for the work performed, as outlined above.

**Travel:** One (1) paper mill, two (2) pulpwood yards, six (6) harvesting sites, and quite a number of equipment distributors and dealers were visited. These locations were visited individually by the Graduate and Undergraduate Assistants to obtain insights necessary to their research. The Forest Engineering meeting of the A.P.A. in Atlanta on April 24-25 was attended by all Research personnel and valuable contacts were made by group members regarding research data sources.

**Publications:** The following list of papers were prepared during the Spring Quarter. These papers will be abstracted in the Annual Report.

1. Walter W. Cosby, "Georgia Institute of Technology Library Sources for Pulpwood Harvesting."

2. Walter W. Cosby, "Improvements in Pulpwood Harvesting Operations with Large Capacity Rough Terrain Forwarders."


5. Edward Jallouk, "An Industrial Dynamics Model to Analyze the Problem of Smoothing the Flow of Pulpwood to Paper Mills in the Southeastern U.S."
6. Dr. Joseph Krol, "Some Aspects of Management Oriented Research in Forestry."

7. Dan J. Plafcan, "Pulpwood Harvesting, Supervisor or Crewleader: What Manner of Man is This?"


Remarks:

(1) Further consultation with the Director of the School of Industrial Engineering resulted in agreement not to schedule a three hour credit graduate seminar at the 700 level in the Fall Quarter, 1968. As the Research Group will be meeting with the S.E.A. at Point Clear in late October and as there will be a program at Georgia Tech for the "Friends of the School of Industrial Engineering" at about the same time; it was felt that exposure would be sufficient through these meetings and the normal Graduate Seminar activities of the School.

(2) A third Funded Graduate Assistant was selected for the Summer Quarter. He is Mr. Les Rue who will be in charge of the S.E.A. industrial survey mentioned previously. Sufficient funds were made available to keep the Graduate Research Program underway during the Summer Quarter although funds were not originally allocated for this purpose.

Respectfully submitted,

[Signature]

R. R. Rogers
Project Director
Mr. Fred C. Gragg  
Southern Executives Association  
Vice President and Assistant  
General Manager, Woodlands  
Southern Kraft Division  
International Paper Company  
Mobile, Alabama 36601

Dear Mr. Gragg:

In accordance with our various discussions and the memorandum of understanding dated May 2, 1967, we submit our fifth Quarterly Report in letter memorandum form concerning Project B-1009, "The Systems Aspect of Harvesting and Transportation of Pulpwood."

As no comments have been received regarding our First Annual Report, we particularly look forward to the meeting with the S.E.A. at Point Clear, Alabama on October 31st and November 1st, for discussion and amplification of reported research activities.

Cordially,

N.K. Rogers  
Project Director

cc: Dr. T.A. Walbridge, Project Liaison  
American Pulpwood Association  
Harvesting Research Project.

Dr. Peter Dyson, School of Forestry  
University of Georgia

Mr. Harry Baker, Director  
Research Administration

Dr. R.N. Lehrer, Director  
School of Industrial Engineering

Dr. Joseph Krol  
School of Industrial Engineering  
Research Assistants.
Memorandum

To: The Southern Executives Association

From: The School of Industrial Engineering
Georgia Institute of Technology

Subject: Fifth Quarterly Report, Project B-1009,
"The Systems Aspect of Harvesting and Transportation of Pulpwood"

Time Period: This report covers the period of June 25, 1968 - September 25, 1968

Participants:
- Mr. N.K. Rogers, Project Director (1/4 Time), Georgia Tech
- Dr. Joseph Krol, Research Associate, (1/4 Time), Georgia Tech
- Dr. Peter Dyson, Research Associate, (1/4 Time), U. of Georgia
- Miss Linda Owens, Secretary, (1/8 Time), Georgia Tech
- Mr. Pietro Fenu, Graduate Assistant, (1/3 Time), Georgia Tech
- Mr. Walter Cosby, Graduate Assistant, (1/3 Time), Georgia Tech
- Mr. Les Rue, Graduate Assistant, (1/3 Time), Georgia Tech
- Mr. Michael Deisenroth, Graduate Assistant, (Not funded), Georgia Tech
- Major James Bearden, Graduate Assistant, (Not funded), Georgia Tech
- Lt. George Valente, Graduate Assistant, (Not funded), Georgia Tech
- Mr. Neal Mercer, Graduate Assistant, (Not funded), U. of Georgia

Work Time: Approximately 880 man hours were worked by various members of the research group divided approximately 300 hours - Research Associates, 420 hours - Funded Graduate Assistants, and 160 hours by Unfunded personnel.
Nature of Work

Performed: The nature of the work performed was one of experimentation and analysis in various systems engineering work areas regarding pulpwood production. Graduate and Undergraduate Assistants met regularly with the Research Associates at a series of four weekly meetings in order that the students and professors might report on their selected work areas and criticize each other's work. All Research Associates and Assistants worked on the design of a "Mill Information Questionnaire," which was submitted to the S.E.A. membership. To date fourteen mills have responded, with another mill known to be in the process of completing the forms. Such response was most gratifying. The results of the survey and the uses for this information will be discussed at the fall meeting at Point Clear with the Steering Committee.

In addition to the "Mill Information Questionnaire," continuing statistical studies were made in order of familiarize the group with the nature of the industry being studied. Each of the funded Graduate Assistants spent much of his time studying order and work delays in the harvesting system and completed additional computer simulations regarding levels of future production. Dr. Krol continued his examination of the literature and Mr. Cosby made considerable progress regarding his evaluation of a design of large size harvesting components. Two papers were prepared by Graduate Assistants and a speech was made to a national conference by one of the Research Associates.
Towards the end of the quarter a three hour presentation and critique session was held regarding this work and other work performed by the Research group in their areas of interests.

The Research Associates continued to work predominantly in the areas heretofore selected:

Dr. Dyson:  Prediction of Pulpwood Resource Areas of the Future.


Personal Contact: Contact with outside sources were made by members of the project team on an "as required" basis in order to obtain background material and analytical data for the work performed, as outlined above. Several trips to national equipment manufacturers were made as part of the various investigations now underway.

Travel: Two (2) paper mills, two (2) pulpwood yards, four (4) harvesting sites, and quite a number of local equipment distributors and dealers were visited. These locations were visited individually by the Graduate and Undergraduate Assistants to obtain insights necessary to their research. The Forest Engineering meeting at Michigan State in East Lansing on September 25-27 was attended by two personnel from the project and valuable contacts were made by members regarding research data sources.
Publications: The following list of papers were prepared during the Summer Quarter. These papers will be abstracted in the Annual Report.


2. Dr. Peter Dyson, "Techno-Economic Restraints Dictate Future Industrial Forest Management."

3. Mr. Les Rue, "Procedural Outlines for a Sampling of Pulpwood Mills." (Profit Outline)

Remarks: (1) It is anticipated that M.S. Thesis production in the field of this research will be two per quarter for the next three quarters as original Research Assistants complete their academic requirements.

(2) Considerable rewriting for publication is necessary regarding earlier papers. This cannot be done until questions regarding publication policy is discussed at the Point Clear meeting.

Respectfully submitted,

N.K. Rogers
Project Director
Mr. Fred C. Gragg
Southern Executives Association
Vice President and Assistant
  General Manager, Woodlands
Southern Kraft Division
International Paper Company
Mobile, Alabama 36601

Dear Mr. Gragg:

In accordance with our various discussions and the memorandum of understanding dated May 2, 1967, we submit our sixth Quarterly Report in letter memorandum form concerning Project B-1009, "The Systems Aspect of Harvesting and Transportation of Pulpwood."

The members of the Project are most appreciative of the hospitality of the S.E.A. at the meeting at Point Clear on November 1st. The interest of the S.E.A. members and the guidance discussions with the Steering Committee were most beneficial to the Project members present.

Cordially,

N.K. Rogers
Project Director

NKR/jp

cc: Dr. T.A. Walbridge, Project Liaison
American Pulpwood Association
Harvesting Research Project

Dr. Peter Dyson, School of Forestry
University of Georgia

Mr. Harry Baker, Director
Research Administration

Dr. R. N. Lehrer, Director
School of Industrial Engineering

Dr. Joseph Krol
School of Industrial Engineering

Research Assistants
Memorandum

To: The Southern Executives Association

From: The School of Industrial Engineering
Georgia Institute of Technology

Subject: Sixth Quarterly Report, Project B-1009,
"The Systems Aspect of Harvesting and Transportation of Pulpwood"

Time Period: This report covers the period of September 26, 1968 - December 25, 1968

Participants:

Mr. N.K. Rogers, Project Director (1/4 Time), Georgia Tech
Dr. Joseph Krol, Research Associate, (1/4 Time), Georgia Tech
Dr. Peter Dyson, Research Associate, (1/4 Time), U. of Georgia
Mrs. Jane Perry, Secretary, (1/8 Time), Georgia Tech
Mr. Pietro Fenu, Graduate Assistant, (1/3 Time), Georgia Tech
Mr. Walter Cosby, Graduate Assistant, (1/3 Time), Georgia Tech
Mr. Les Rue, Graduate Assistant, (Not Funded), Georgia Tech
Mr. Michael Deisenroth, Graduate Assistant, (Not Funded), Georgia Tech
Major James Bearden, Graduate Assistant, (Not Funded), Georgia Tech
Lt. George Valente, Graduate Assistant, (Not Funded), Georgia Tech

Work Time: Approximately 960 man hours were worked by various members of the research group divided approximately 360 hours - Research Associates, 300 hours - Funded Graduate Assistants, and 300 hours by Unfunded personnel.
Nature of Work Performed: The nature of the work performed was one of experimentation and analysis in various systems engineering work areas regarding pulpwood production. Graduate and Undergraduate Assistants met regularly with the Research Associates at a series of six weekly meetings in order that the students and professors might report on their selected work areas and criticize each other's work. All Research Associates and Funded Assistants attended the S.E.A. meeting at Point Clear, Alabama, on November 1, 1969, and took part in the program.

Fifteen mills responded to the Mill Information Questionnaire, submitted in late summer. Such response was most gratifying. The results of the survey and the uses for this information were discussed at the fall meeting at Point Clear with the Steering Committee. The Project group was asked to revise the type of survey originally submitted. This is in process and will be mailed out shortly. The original survey was returned via the proper channels to the originators. Publication policy was also determined by the Steering Committee at Point Clear.

Continuing statistical studies were made in order to familiarize the group with the nature of the industry being studied. Each of the funded Graduate Assistants spent much of his time performing the analytical tasks required by his assigned area of investigation. Mr. Fenu and Mr. Rue completed their thesis during the Fall quarter and Mr. Cosby made considerable progress regarding his evaluation of a design of large size harvesting components. The main presentations made by the Project members at the Point Clear meeting are listed in Appendix 1 attached.
Following the Point Clear meeting, a joint meeting was held by Georgia Tech, Auburn, and A.P.A. Harvesting Research management in order to assure coordination of effort. This meeting resulted in assurances that Project work at each location did not overlap.

Towards the end of the quarter a three hour presentation and critique session was held regarding this work and other work performed by the Research group in their areas of interests.

The Research Associates continued to work predominantly in the areas heretofore selected:

Dr. Dyson: Prediction of Pulpwood Resource Areas of the Future.


Late in December Mr. Rogers met with counsel for S.E.A. to clearly define nuances of publication policy and to receive approval of the form for future surveys.

Personal Contact: Contact with outside sources were made by members of the project team on an "as required" basis in order to obtain background material and analytical data for the work performed, as outlined above. Several trips to national equipment manufacturers were made as part of the various investigations now underway.

Travel: Two (2) paper mills, three (3) pulpwood yards, two (2) harvesting sites, and quite a number of local equipment distributors and dealers were visited. These locations were visited individually by the Graduate and Undergraduate Assistants to obtain insights necessary to their research. Members of the Project group attended
various professional meetings including A.P.A., A.I.I.E., and T.I.M.S. conferences of value to the research personnel.

Publications: The following thesis were prepared during the Fall Quarter.

These thesis will be abstracted in the Annual Report, and are being reviewed by S.E.A. for member distribution.

1. Mr. Pietro Fenu, "A Dynamo Simulation of Long-Term Growth of Southern Pulp and Paper Industry."

2. Mr. L.W. Rue, "A Simulation Model of the Southern Pulpwood Procurement System."

Remarks: (1) It is anticipated that M.S. Thesis production in the field of this research will continue to be two per quarter for the next three or four quarters as original Research Assistants complete their academic requirements.

(2) Considerable rewriting for industry publication of earlier papers is in process at present as a result of the determination of publication policy during the Fall Quarter.

Respectfully submitted,

N.K. Rogers
Project Director
Presentation by
School of Industrial Engineering Research Group - Project B-1009
"The Systems Aspects of the Harvesting and Transportation of Pulpwood"

Georgia Institute of Technology - Atlanta, Georgia
November 1, 1968

1. Goals and Objectives of the Research - Status Report
   Mr. N.K. Rogers - 15 minutes

2. Systems Analysis - Computer Simulation Techniques
   Mr. Pietro Fenu - 15 minutes

3. Systems Analysis - The Design of Physical Systems
   Mr. Walt Cosby - 15 minutes

4. The Mill Information Questionnaire - The Response and its Use
   Mr. Les Rue - 15 minutes

5. Systems Analysis - Policy Determination
   Dr. Joseph Krol - 15 minutes

6. Systems Analysis - Forestry Aspects of the Problem
   Dr. Peter Dyson - 15 minutes

7. Summary and Comments on the Program
   Dr. Robert N. Lehrer - 15 minutes

8. Questions and Answers To The Project Group - 15 minutes

One Hour Business Session to be conducted at a time set by the S.E.A. Steering Committee.
April 15, 1969

Mr. Fred C. Gragg
Southern Executives Association
Vice President and Assistant General Manager, Woodlands Southern Kraft Division
International Paper Company
Mobile, Alabama 36601

Dear Mr. Gragg:

In accordance with our various discussions and the memorandum of understanding dated May 2, 1967, we submit our seventh Quarterly Report in letter memorandum form concerning Project B-1009, "The Systems Aspect of Harvesting and Transportation of Pulpwood."

The members of the Project are most appreciative of the continuing interest of the S.E.A. expressed at the meeting at Georgia Tech on March 14th. The guidance discussions with the Steering Committee concerning the goals and objectives of a third year of research were most beneficial to the Project members present.

Cordially,

[Signature]

N. K. Rogers
Project Director

NKR/jp

cc: Dr. T. A. Walbridge, Project Liaison
American Pulpwood Association
Harvesting Research Project

Dr. Peter Dyson, School of Forestry
University of Georgia

Mr. Harry Baker, Director
Research Administration

Dr. R. N. Lehrer, Director
School of Industrial Engineering

Dr. Joseph Krol
School of Industrial Engineering

Research Assistants
Memorandum

To: The Southern Executives Association

From: The School of Industrial Engineering
Georgia Institute of Technology

Subject: Seventh Quarterly Report, Project B-1009,
"The Systems Aspect of Harvesting and Transportation of Pulpwood"

Time Period: This report covers the period of December 26, 1968 - December 25, 1969

Participants:

Mr. N. K. Rogers, Project Director (1/4 Time), Georgia Tech
Dr. Joseph Krol, Research Associate (1/4 Time), Georgia Tech
Dr. Peter Dyson, Research Associate (1/4 Time), U. of Georgia
Mrs. Jane Perry, Secretary (1/4 Time), Georgia Tech
Mr. Walter Cosby, Graduate Assistant (1/3 Time), Georgia Tech
Mr. Les Rue, Graduate Assistant (1/4 Time), Georgia Tech
Mr. Earl Maloney, Graduate Assistant (Not Funded), Georgia Tech
Mr. James Bearden, Graduate Assistant (Not Funded), Georgia Tech
Mr. George Valente, Graduate Assistant (Not Funded), Georgia Tech
Mr. Bert Bertils, Graduate Assistant (Not Funded), Georgia Tech
Mr. Larry Dix, Graduate Assistant (Not Funded), Georgia Tech
Mr. George Quaile, Graduate Assistant (Not Funded), U. of Georgia
Mr. John Gilbert, Graduate Assistant (Not Funded), Georgia Tech
Mr. Dave Hiland, Undergraduate Assistant (Not Funded), Georgia Tech

Work Time: Approximately 1100 man hours were worked by various members of the research group divided approximately 375 hours - Research Associates, 250 hours - Funded Graduate Assistants, 475 hours by Unfunded personnel.
Nature of Work
Performed: The nature of the work performed was one of experimentation and analysis in various systems engineering work areas regarding pulpwood production. Preparation of Research Reports in the Form of Master's Thesis or Project Reports continued as scheduled for the second year of work. Graduate and Undergraduate Assistants met regularly with the Research Associates at a series of five weekly meetings in order that the students and professors might report on their selected work areas and criticize each other's work. The Project Director and available Research Associates and Graduate Assistants met with the S.E.A. Steering Committee at Georgia Tech on March 14, 1969, to discuss current and future work in the program.

The Mill Information Questionnaire was revised in light of comments of counsel to the S.E.A. This revised Questionnaire was approved by reviewing authority and resubmitted to the participants for answering. Reviewing authority also approved the Research Reports of Mr. L. W. Rue and Mr. Pietro Fenu for distribution to S.E.A. membership. These will be mailed out shortly to the revised list of participants received during the quarter.

Continuing accumulation of economic and statistical studies were made in order to familiarize the new members of the research group with the nature of the industry being studied and the current status of research in the areas of their interest. Each of the funded Graduate Assistants spent much of his time performing the analytical tasks required by his assigned area of investigation. Mr. Bearden and Mr. Valente and Mr. Cosby substantially completed their research work during the Winter quarter and Mr. Cosby and Mr. Rogers made considerable progress regarding their reevaluation and revision of the earlier work by Mr. James Stark so that it can be distributed as a
research report. Mr. Rogers completed the first stage of his work concerning a technique for analyzing the financial decision making of the pulpwood producer.

Meetings were held on an individual basis between research workers at Georgia Tech, Auburn, U. of Georgia, and the A.P.A. Harvesting Research management in order to assure coordination of effort. Such meetings were mutually beneficial and reduced the amount of independent time spent in data gathering.

The Research Associates continued to work predominantly in the areas heretofore selected:

Dr. Dyson: Prediction of Pulpwood Resource Areas of the Future.


Throughout the reporting period Mr. Rogers corresponded with counsel for S.E.A. to insure clear definition of publication policy and to receive approval of the form for Survey information.

Personal contact:

Contact with outside sources were made by members of the project team on an "as required" basis in order to obtain background material and analytical data for the work performed, as outlined above.

Travel:

Three (3) paper mills, four (4) pulpwood yards, one (1) harvesting site, and a number of local equipment distributors were visited. These locations were visited individually by the Graduate and Undergraduate Assistants to obtain insights necessary to their research. Members of the Project group attended various professional meetings including A.P.A., A.I.I.E., and T.I.M.S. conferences of value to the research personnel.
publications: The following papers were prepared during the Winter Quarter. These papers will be abstracted in the Annual Report, and upon review and/or expansion will receive member distribution.

1. Mr. N. K. Rogers "The Development of a Pulpwood Producer's Financial Model."


remarks: (1) It is anticipated that M.S. Thesis production in the field of this research will continue to be two per quarter for the next three or four quarters as Research Assistants complete their academic requirements.

(2) Considerable rewriting for industry publication of earlier papers is in process at present as a result of the determination of publication policy during the Fall Quarter. In addition, speaking engagements for Research Associates are being arranged to publicize the work of the group.

Respectfully submitted,

[N. K. Rogers]
Project Director
July 15, 1969

Mr. Fred C. Gragg  
Southern Executives Association  
Vice President and Assistant General Manager, Woodlands Southern Kraft Division  
International Paper Company  
Mobile, Alabama  36601

Dear Mr. Gragg:

In accordance with our various discussions and the memorandum of understanding dated May 2, 1967, we submit our eighth quarterly Report in letter memorandum form concerning Project B-1009, "The Systems Aspect of Harvesting and Transportation of Pulpwood."

The members of the Project are most appreciative of the continued support by the S.E.A. for a third year of research activities. The Second Annual Report is now in process of preparation and will be forwarded for review by Mr. Armbrecht when completed.

Cordially,

N. K. Rogers  
Project Director

NKR/JRP

cc: Dr. T. A. Walbridge, Project Liaison  
American Pulpwood Association  
Harvesting Research Project  
Dr. Peter Dyson, School of Forestry  
University of Georgia  
Mr. Harry Baker, Director  
Research Administration  
Dr. R. N. Lehrer, Director  
School of Industrial and Systems Engineering  
Dr. Joseph Krol  
School of Industrial and Systems Engineering  
Research Assistants
Memorandum

To: The Southern Executives Association

From: The School of Industrial and Systems Engineering
Georgia Institute of Technology

Subject: Eighth Quarterly Report, Project B-1009,
"The Systems Aspect of Harvesting and Transportation of Pulpwood"

Time Period: This report covers the period of March 26, 1969 - June 25, 1969.

Participants:

Mr. N. K. Rogers, Project Director (1/4 Time), Georgia Tech
Dr. Joseph Krol, Research Associate, (1/4 Time), Georgia Tech
Dr. Peter Dyson, Research Associate, (1/4 Time), U. of Georgia
Mrs. Jane Perry, Secretary, (1/4 Time), Georgia Tech
Mr. Walter Cosby, Graduate Assistant, (1/6 Time), Georgia Tech
Mr. Richard Kessler Graduate Assistant, (1/4 Time), Georgia Tech
Mr. Earle Maloney, Graduate Assistant, (Not Funded), Georgia Tech
Mr. James Bearden, Graduate Assistant, (Not Funded), Georgia Tech
Mr. George Valente, Graduate Assistant, (Not Funded), Georgia Tech
Mr. Bert Bertils, Graduate Assistant, (Not Funded), Georgia Tech
Mr. Larry Dix, Graduate Assistant, (Not Funded), Georgia Tech
Mr. John Gilbart, Graduate Assistant, (Not Funded), Georgia Tech
Mr. Dave Hiland, Undergraduate Assist. (Not Funded), Georgia Tech

Work Time: Approximately 1050 man hours were worked by various members of the research group divided approximately 350 hours - Research Associates, 175 hours - Funded Graduate Assistants, 525 hours - Unfunded Personnel.
The nature of the work performed during the Spring Quarter was one of consolidation and refinement of the research effort performed prior to that time. Considerable effort was put forth to revise Mr. Bearden's work regarding the maintainability of pulpwood harvesting equipment. This was completed and is now being reviewed by counsel prior to distribution. Mr. Cosby and Mr. Rogers completed their revision of Mr. Stark's earlier thesis work and this also is being reviewed by counsel prior to distribution. Mr. Valente's work was given thesis approval but he was suddenly transferred to Vietnam prior to final revision and this work must await his forwarding certain revised portions from Saigon before publication.

A majority of the work is now being performed by researchers individually and the review and revision time required in joint meetings is great. Therefore, very few staff meetings for the entire research group were held during the Spring Quarter as only one new research member joined the group during the reporting period.

The revised Mill Questionnaire was forwarded and replies were received from thirteen of the seventeen members of the S.E.A. The bulk of the information received in these questionnaires is being examined to determine the wide degrees of variation found in the pulpwood operations supporting different paper mills.

Mr. Kessler and Mr. Rogers worked jointly on testing the economic model prepared earlier in the year by Mr. Rogers. The results were far from satisfactory and considerable simplification is required prior to publication for S.E.A. membership.
No joint meetings were held with Auburn or the A.P.A. research groups but one was scheduled for early July for coordination purposes.

Short papers were completed by Mr. Bertils, Mr. Hiland, and Mr. Gilbart concerning their research areas.

Personal Contact:

Contact with outside sources were made by members of the project team on an "as required" basis in order to obtain background material and analytical data for the work performed, as outlined above.

Travel:

Two (2) paper mills, two (2) pulpwood yards, three (3) harvesting sites, and a few equipment distributors were visited. These locations were visited individually by the Graduate and Undergraduate Assistants to obtain insights necessary to their research. Members of the Project group attended various professional meetings including A.P.A., A.I.I.E., and T.I.M.S. conferences of value to the research personnel.

Publications:

The following papers were prepared during the Spring Quarter. These papers will be abstracted in the Annual Report, and upon review and/or expansion will receive member distribution.

Mr. B. R. Bertils - "A Basis for a Statistical Analysis of Pulpwood Resource Lands to Determine Mobility Requirements"

Mr. David E. Hiland - "A Simulation Model of the Availability of Producer Crews in the Southern Pulpwood Procurement System"

Mr. Gordon John Gilbart - "Application of Markov Processes in Inventory Control in the Pulpwood Industry"

Mr. Jimmy Lane Bearden - "Maintainability Considerations for Pulpwood Harvesting Equipment"

Mr. James J. Stark, Mr. Walter W. Cosby, Mr. Nelson K. Rogers - "A Simulation Model for the Common Pulpwood Harvesting Systems of the Southern Pine Region (Revised)"
Remarks:

(1) It is anticipated that M.S. Thesis production in the field of this research will continue to be two per quarter for the next three or four quarters as Research Assistants complete their academic requirements.

(2) Speaking engagements for Research Associates are being sought to publicize the work of the group. Assistance from S.E.A. is required to gain the greatest publicity about the research effort.

(3) Dr. Krol will be absent from the research effort during the Summer Quarter. Dr. Stan Aaronson will assist the group during Dr. Krol's absence.

Respectfully submitted,

N. K. Rogers
Project Director
April 10, 1970

Mr. Fred C. Gragg
Southern Executives Association
Vice President and Assistant
General Manager, Woodlands
Southern Kraft Division
International Paper Company
Mobile, Alabama 36601

Dear Mr. Gragg:

In accordance with the memorandum of understanding dated May 2, 1967, and ensuing modifications, we submit a report of the Tenth and Eleventh Quarters Activities concerning Project B-1009, "The Systems Aspect of Harvesting and Transportation of Pulpwood." This report covers the period September 26, 1969 - March 25, 1970, and has been prepared for distribution to the S.E.A. Steering Committee at its meeting at the School of Industrial and Systems Engineering on April 17, 1970.

The members of the project are appreciative of the continued support provided by the S.E.A. during a third year of research activities at Georgia Tech. These participants in the 1969-1970 program are listed in Exhibit A.

An outline of the work to be accomplished during the 1969-70 year and a listing of work previously accomplished was submitted for S.E.A. use at the Point Clear meeting on October 2nd. This list has been revised and updated in Exhibit B. The status of research work not yet accepted is discussed in Exhibit C.

One of the objectives of the 1969-1970 program is added participatory activities of the Research Associates in off-campus programs to disseminate the knowledge obtained from the research. A listing of such external activities is presented in Exhibit D.
Although the project will officially conclude in September, 1970, The School of Industrial and Systems Engineering intends to continue on a reduced scale their effort in research regarding systems of harvesting and transporting pulpwood. There is still much benefit to be obtained from the publication and dissemination of the work performed under the S.E.A. research contract. Individual student support, individual research association with individual members of S.E.A., and S.E.A. support of our Corporate Associates program will be subjects of discussion at the April 17th meeting.

Cordially,

N. K. Rogers
Project Director

NKR/jrp

cc: Dr. T. A. Walbridge, Project Liaison
   American Pulpwood Association
   Harvesting Research Project

   Dr. Peter Dyson, School of Forestry
   University of Georgia

   Mr. Harry Baker, Director
   Research Administration

   Dr. R. N. Lehrer, Director
   School of Industrial and Systems Engineering

   Dr. Joseph Krol
   School of Industrial and Systems Engineering

   Research Assistants
## Project B-1009 - The Systems Aspect of Harvesting and Transportation of Pulpwood

### List of Participants 1969 - 1970

<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>School</th>
<th>Participation Level</th>
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<tbody>
<tr>
<td><strong>Project Staff</strong></td>
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<tr>
<td>Mr. N. K. Rogers,</td>
<td>Project Director</td>
<td>Georgia Tech</td>
<td>Full 1/4 1/4 1/4</td>
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<tr>
<td>Dr. Joseph Krol,</td>
<td>Research Associate,</td>
<td>Georgia Tech</td>
<td>0 1/4 1/4</td>
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<tr>
<td>Dr. Peter Dyson,</td>
<td>Research Associate,</td>
<td>U. of Georgia</td>
<td>1/4 1/4 1/4</td>
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<tr>
<td>Dr. Stan Aaronson,</td>
<td>Research Associate,</td>
<td>Georgia Tech</td>
<td>1/8 0 0</td>
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<tr>
<td>Mrs. Jane Perry,</td>
<td>Secretary,</td>
<td>Georgia Tech</td>
<td>1/4 1/4 1/4</td>
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<tr>
<td>Mr. Ed Chandler,</td>
<td>Undergrad. Assistant,</td>
<td>Georgia Tech</td>
<td>1/3 1/4 1/4</td>
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| **Graduate Students** |                       |                 |                     |
| Mr. Bert Bertils,    | Graduate Assistant    | Georgia Tech    | TC TC 0             |
| Mr. Walter Cosby,    | Graduate Assistant    | Georgia Tech    | 0 T T              |
| Mr. Larry Dix,       | Graduate Assistant,   | Georgia Tech    | TC TC TC            |
| Mr. John Gilbart,    | Graduate Assistant,   | Georgia Tech    | T 0 0              |
| Mr. Richard Kessler, | Graduate Assistant,   | Georgia Tech    | 1/3 1/3 1/3        |
| Mr. Earle Maloney,   | Graduate Assistant,   | Georgia Tech    | 0 T T              |
| Mr. John Owen,       | Graduate Assistant,   | Georgia Tech    | 0 1/10 1/10        |
| Mr. George Valente,  | Graduate Assistant,   | Georgia Tech    | 0 T T              |

**Full, 1/3, 1/4, 1/8 - Funded Participation**

**TC - On-Campus Thesis Participation**

**T - Off-Campus Thesis Participation**
List of Research Works

Work Published and Distributed to S.E.A.

1. Fenu, Pietro - "A Dynamo Simulation of Long-Term Growth of Southern Pulp and Paper Industry"
2. Rue, Leslie - "A Simulation Model for the Southern Pulpwood Procurement System"
3. Bearden, Jimmy - "Maintainability Consideration for Pulpwood Harvesting Equipment"
4. Stark, James; Cosby, Walter; Rogers, Nelson - "A Simulation Model for the Common Pulpwood Harvesting Systems of the Southern Pine Region"
5. Bertils, Bert - "A GPSS II Simulation Model to Evaluate Terrain Capabilities of Typical Pulpwood Harvesting Vehicles"

Work Accepted and In Process of Printing or Legal Review

6. Valente, George(1) - "Digital Simulation Models of Forest Investment and Forest Management"

Work Substantially Completed But Not Accepted


Work In Process

10. Krol, Joseph(1) - "Innovations in Research Applicable to Pulpwood Harvesting and Transportation"
11. Dyson, Peter - "An Analysis of the Future Growth of Silage Cellulose Production and Its Effect on Pulpwood Operation in the Southeast"
13. Maloney, Francis(1) - "A Model for Determination of Depreciation and Debt Retirement Policies for the Pulpwood Harvesting Enterprise"

Work Performed Not Resulting in a Research Report

14. Gilbart, John(1) - "Application of Markov Processes in Inventory Control in the Pulpwood Industry" Changed area of interest
16. Cosby, Walter - "A Comparison of Skidder Performance with the Performance of High Capacity and in Woods Forwarders" Too limited

(1) Work Interrupted 3-12 months by Military Requirements or Government Service.
Project B-1009 - The Systems Aspect of Harvesting and Transportation of Pulpwood

Status of Work Not Yet Accepted
(Numbered in Accordance with Exhibit B)

7. Dix: Mr. Dix has completed his draft of the research report and completed all experimental computer runs. After examination next week by his thesis committee, the work should be accepted subject to printing and legal review. Estimated completion - 60 days.

8. Cosby: Mr. Cosby found it necessary to leave Georgia Tech and go to work for the government at Warner Robbins A.F.B. He has been in the process of revising his ambitious research task to one which he can complete off-campus. His thesis committee has required him to reduce the scope of his original investigations. This required a draft revision of the research report and another set of experimental computer runs. Estimated completion - 120 days.

9. Rogers: Mr. Rogers developed his economic model during the summer of 1969. This was tested for sensitivity during the fall of 1969. Based on this computer experimentation, simplification of the model was made possible. This work will be completed during the summer of 1970. Estimated completion - 150 days.

10. Krol: Dr. Krol's work for the U.S. Army precluded heavy activity in individual research during the fall and winter quarters although he continued to serve as graduate student advisor and participate in meetings of the project group and advisory functions. Dr. Krol is now in the process of producing a research report which will discuss future innovations in research systems and approaches which may have great utility in the study of pulpwood procurement problems between now and the year 2000. Estimated completion - 120 days.

11. Dyson: Dr. Dyson continues his work regarding silage cellulose production. His workload in this area was reduced during the summer and fall of 1969 due to major surgery. The group is happy to again have him at full strength. Estimated completion - 120 days.
12. **Kessler:** Mr. Kessler has partially completed a draft of his work on mathematical determination of plant location in respect to resource area. The mathematical solution techniques are more complex than anticipated. Dr. Ed Unger and Dr. Dave Fyffe have contributed much time to this project and a concise solution technique has been found. The testing of the technique is in progress. Estimated completion - 90 days.

13. **Maloney:** Captain Maloney has been working on his thesis while serving a year's tour in Vietnam. At one point the project group was convinced this work had been lost. But computer program changes continue to arrive, are tested, and the results mailed to Vietnam. A letter has recently been received from Captain Maloney informing us that his initial draft has been completed and that he desires to return here during his next leave and complete his thesis requirements. Publication as a research report to S.E.A. would still have to be classified as doubtful.
Project B-1009 - The Systems Aspect of Harvesting and Transportation of Pulpwood

List of External Activities

Lectures and Speeches


"What the Schools are Doing to Prepare 'Logging Engineers'", Society of American Foresters, Miami, Florida, October, 1969.

"Panel on School Activities in the Preparation of Logging Engineers", American Pulpwood Association, Atlanta, Georgia, April, 1970.

Meetings Attended


Peter Dyson: Forest Engineering Meeting, Southeastern Region, American Pulpwood Association, Atlanta, Georgia, April, 1970.
FIRST ANNUAL REPORT

"THE SYSTEMS ASPECT OF HARVESTING AND TRANSPORTATION OF PULPWOOD"

Sponsored Research Project B-1009

Conducted by

The School of Industrial Engineering
Georgia Institute of Technology
Atlanta, Georgia

for

The Southern Executives Association

July 1, 1968
FIRST ANNUAL REPORT

"THE SYSTEMS ASPECT OF HARVESTING AND TRANSPORTATION OF PULPWOOD"

Sponsored Research Project B-1009

Conducted by

The School of Industrial Engineering
Georgia Institute of Technology
Atlanta, Georgia

for

The Southern Executives Association

July 1, 1968
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APPENDICES:

A  "What Will Our Forest Resource Be In the Future?"
   by Dr. Peter Dyson

B  "A Strategy of Research In Multiple Use of Forest Resources"
   by Dr. Joseph Krol

   by Pietro A. Fenu

D  "Minimization of Transportation Costs for the Hauling of
    Pulpwood by Rail"
   by John C. Bacon
I. NATURE OF THE RESEARCH PROGRAM

Objectives: The objective of the Research shall be the structuring of a systems model or models sufficient to validly represent the endeavors involved in the "Harvesting and Transportation of Pulpwood." Such model or models shall portray the significant characteristics and constraints on such systems as they now exist, and as they are likely to exist prior to the year 2000. Such model or models shall portray the compatibility or incompatibility of the various existing resource ownership patterns, silvicultural aspects, labor patterns, techniques of harvesting, and techniques of transportation; and such patterns and techniques anticipated prior to the year 2000. The resultant model or models shall have the ability of quantifying the productivity of the major resources utilized in the system and its relationship to economic investment and resource pricing.

Scope: The Research shall be limited to the "Southern Pines Producing" geographical region and shall consider the resource material for paper manufacturing from the time of the planting of the seed to the time of chemical treatment of the fiber in the paper-making process. The Research shall consider transportation of the resource material in any fiber form from stump to paper-making facility. For purposes of model construction, one paper-making facility and its resource area shall be the endeavor unit to be measured, providing its interfaces with other adjacent facilities and resource areas are firmly delineated. Non-typical facilities or resource areas shall be given due consideration. Provision in the model or models shall be made to quantify the social and political
interrelationships between the paper-making facility and its resource owners and processors, to equate them to the economic quantification of the model or models. Management techniques and business skills of the resource harvesters shall be given consideration in the model building processes.

Method of Approach: After an introductory and familiarization period necessary for the Research Group to become acquainted with the current state of the art, present characteristics and constraints on the system shall be defined and quantified using the systems approach for analytical purpose. Inputs, outputs, and levels will be explored for model compatibility and classification, and to define problem areas within the models. Various models of the present systems will then be designed for testing the present system, using simulation techniques apparently applicable. After problem areas have been minimized, then the most likely model or combination of models will be selected for testing the parameters for sensitivity. Further testing shall be made to insure the model or combination of models is responsive to the objectives of the research program. Results shall be reported in accordance with the schedule and format proposed by the Research Sponsor.
II. GOALS OF THE FIRST YEAR OF THE PROGRAM

Considering little prior work in the pulpwood harvesting and transportation field had been previously performed in the School of Industrial Engineering, the first two goals of the program were:

(A) Indoctrination, and

(B) Involvement.

Indoctrination was accomplished by the visitation programs outlined in Section V of this report coupled with literature searches as outlined in Section XII of this report and in the bibliographies of the papers abstracted therein. Attendance at professional meetings and joint meetings with the A.P.A. Harvesting Research Group, at Dr. Walbridge's suggestion, were most beneficial. Weekly meetings were held with the entire Project group in the early stages of the program to promote free exchange of information and resource information encountered. Various S.E.A. mills and forest management groups were extremely helpful during this indoctrination period.

Involvement was accomplished simply by putting people to work doing something in which they were particularly interested. Wide latitude was given all members of the Project group to study, analyze and report on facets of the general problem which, in their initial opinion, would result in new conclusions. Naturally, as this work was performed and more resource information became available, many of the participants found that their original ideas had already been well processed elsewhere, so they were forced to modify their original goals. Practically the only limitation
placed on these early projects was that the approach must be made from the systems viewpoint. This caused some difficulty as much of the resource information appeared to be concerned with one machine, or one crew, or one company. Both qualitative and quantitative works were produced, generally as term papers or term project reports. The quality ranged from excellent to poor as would be expected, but the results of creating active involvement, as reflected in Section III and IV of this report, was achieved.

Further goals of the first year of the program were to develop:

(C) Continuity, and

(D) Definition of scope.

Continuity of effort became more apparent in the latter part of the year. As non-funded Graduate and Undergraduate participants produced various works, the necessity for amplification or further study in areas of great potential became apparent. Thus the work currently being performed by funded Graduate Research assistants is now a foundation upon which they can build. A study of the abstracts in Section XII will demonstrate how this is slowly being accomplished. Programs and simulations developed with synthetic data have revealed what sort of "real world" data is necessary. This is now being gathered from the S.E.A. membership in order that there be a continuation from theoretical to applied results.

Definition of scope for the research effort is an area of major concern at the end of the first year. The variety of works performed by the Project group has, "so to speak", unlocked many more facets of the basic problem than initially were outlined to the original three Research Associates. Using the systems approach to the problem naturally broadens the research effort beyond the one forest, one producer, one woodyard pulpwood producing activities. Proofs of some of the tentative conclusions
reported in Section X of this report, even within the reference framework of one mill and its support systems, appear much more involved than originally anticipated. This can be revealed in a comment made by Lt. Stark upon submission of his Master Thesis, "Two more pages and this thesis would have made a fine Ph.D. dissertation." The Research Associates are now actively engaged in setting reasonable restrictions on the scope of work being performed. This could not be done until the "involvement" stage in the development of the program had been accomplished.

Goals for the second year of the program are discussed in Section XI.
### III. PERSONNEL GROWTH OF THE PROGRAM

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<tbody>
<tr>
<td><strong>Faculty</strong></td>
<td>3(1/4)</td>
<td>3(1/4)</td>
<td>3(1/4)</td>
<td>3(1/4)</td>
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<td>2(1/3)</td>
<td>2(1/3)</td>
<td>3(1/3)(1)</td>
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<tr>
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<td>1</td>
<td>5(2)</td>
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<tr>
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<td>2</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td><strong>Secretary</strong></td>
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<td>1(1/8)</td>
<td>1(1/8)</td>
<td>1(1/8)</td>
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<tr>
<td><strong>Total</strong></td>
<td>5</td>
<td>10</td>
<td>13</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>

(1) Not originally funded.

(2) Three of which joined the group more than half way into the quarter.
IV. MAN HOUR SUMMARY OF THE PROGRAM BY QUARTERS
(Excluding Secretarial and Clerical Assistance)

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>F</th>
<th>W</th>
<th>SP</th>
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<td>Faculty</td>
<td>80</td>
<td>160</td>
<td>240</td>
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<tr>
<td>Funded Students</td>
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<td>240</td>
<td>320</td>
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<tr>
<td>Unfunded Students</td>
<td>80</td>
<td>160</td>
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<td>320</td>
</tr>
<tr>
<td>Total Manpower</td>
<td>80</td>
<td>160</td>
<td>240</td>
<td>320</td>
</tr>
</tbody>
</table>

Av. 3(1/4)  Av. 2 1/3 (1/3)  Av. 4 (1/8)
V. VISITATION SUMMARY BY QUARTERS

<table>
<thead>
<tr>
<th>Producers</th>
<th>Woodyards or Chipyards</th>
<th>Forests or Research Station</th>
<th>Mills</th>
<th>Professional Meetings</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>25</td>
<td>10</td>
<td>7</td>
<td>11</td>
</tr>
</tbody>
</table>
VI. FACULTY INVOLVEMENT

Specific activities of the three Research Associates have been spelled out in the four Quarterly Reports previously submitted.

Dr. Dyson's area of particular interest, "Prediction of Pulpwood Resource Areas of the Future," is one where there is little consolidated data available. Most companies have complete programs outlining their own forest inventory and its anticipated productivity over the next thirty years. But these programs are not necessarily compatible for analytical purposes. In Appendix A, Dr. Dyson comments on his problem area and makes suggestions of different types regarding development in this area. This is a typical example of internal discussions within the Project group. Dr. Dyson has been particularly helpful to the Industrial Engineering students regarding forestry problems alien to their background.

Dr. Krol's area of particular interest, "Simulation of Pulpwood Harvesting Systems of the Future" is an area of primary interest to the graduate students. He has stimulated and refereed their work in this area. He additionally has been the primary member of the faculty group involved in literature search and compilation of background concepts and data upon which the entire Project group can draw. His papers have been primarily those which outline direction, approach, and methodology to be used in the research effort. In Appendix B, a paper prepared by Dr. Krol regarding such subject material is attached as being representative of effort at the faculty level in the Project.
Mr. Rogers' area of particular interest, "Formulation of Pulpwood Procurement Management and Financial Systems of the Future", lies primarily in the application of the theoretical research to simplified systems of potential use to management responsible for harvesting or transporting pulpwood. This naturally must follow the initial theoretical work of the Project group. In the first year his effort has been one of activating an organization for the research effort, managing the program, and reporting on its development. This report is indicative of his work as Project Director.

Each Research Associate worked approximately one hundred and five hours per quarter either on projects of his own choosing, or directing the activities of the graduate and undergraduate participants.
VII. GRADUATE STUDENT INVOLVEMENT

Graduate student activity falls into two categories: (a) Funded Work, and (b) Academic Work by Non-Funded Personnel. Funds were allocated for three graduate students to work for three quarters each year. An early decision was made to change this allocation to two graduate students on an annual basis plus an extra graduate student in the summer quarter. This allowed continuity of work throughout the year. Four funded graduate students have participated in the program to date. Each funded graduate student works approximately one hundred and forty hours per quarter on aspects of the program under the direction of the Research Associates.

Non-funded graduate students have become interested in the Project and eight have been involved to date for periods ranging from three to nine months. As such, they have performed work as members of the Project group for which they received academic credit. Each funded graduate student has also performed work for academic credit outside the scope of his funded work. Each non-funded graduate student works about forty to fifty hours per quarter on some project of interest to him under the direction of the Research Associates.

Project meetings, seminars, professional meetings, and site visitations to mills, forests and harvesting sites have been well attended by the twelve graduate students involved in the program to date.

It remains to be seen if graduate activity will remain at such levels as the effect of changes in draft status for graduate students has not yet been seriously felt.
A simple term project performed by Mr. Fenu in the winter of 1967 is attached in Appendix C as illustrative of the type of work being performed at the graduate level.
VIII. UNDERGRADUATE STUDENT INVOLVEMENT

Undergraduate involvement to date has been on a term project basis. Six seniors have worked at least one quarter or longer on specific projects of interest to them under the direction of the Research Associates.

Further undergraduate exposure has come about as the Research Associates, in executing their academic teaching responsibilities, have referred to the program and used illustrative examples from it at the junior or senior course levels.

At the present time there is no framework at the undergraduate level by which course work can be performed for a full quarter, treating only problems of Industrial Engineering in forestry and the paper-making industry.

A simple term paper performed by Mr. Bacon early in the program is attached in Appendix D as illustrative of the type of work being performed at the undergraduate level.
IX. PROBLEMS ENCOUNTERED IN THE RESEARCH EFFORT

The most basic problem in the first year was to create an interest at all levels in the School of Industrial Engineering in the problems of forestry and the paper-making industry. I would have been very easy to place four or five educators in a funded work situation and let them produce theoretical research about the long-range problems in the field. This would very likely have precluded any true amount of student involvement. We felt that this was not the prime goal of the S.E.A. contract.

We therefore funded graduate students and recruited non-funded students to establish a mixed group of students and faculty that perhaps has produced a different product in the first year than a purely professional group would have produced. At the same time it has been recognized in the School of Industrial Engineering that the S.E.A. Project group is one of two or three research groups in the School where "the action is happening." A base has been established on which the School, the S.E.A., and the industry as a whole can build.

A secondary problem was encountered during the initial exposure to the harvesting-transportation problem itself. In an industry noted for its free exchange of information (and which certainly has bent over backwards to extend help to the members of the Project group), we found that most information exchanges are very narrow in scope. True systems approaches to the problem simply have not been performed or, if performed, have not become available as "free" information.
Stated another way, there is a lot of free exchange of information regarding the performance characteristics of particular equipment but practically no information available about the interrelationship of that particular equipment and other equipment or work stages in the overall procurement system. The Project group hoped to learn quickly about some of these relationships by having access to the APA Producer Survey. This has not been completed after a year of preparation, so the Georgia Tech group has been forced to do their own "leg work", which has consumed more time than was earlier anticipated. The A.P.A. Harvesting Research Project staff has been especially helpful in bridging this gap and recommending sources of information not generally available to the public.

A third problem was strictly an internal one to the Tech campus. Our computer Center changed hardware in the middle of the year and the resultant revision of procedures and administrative processes created a time lag in progressing computer-oriented systems attacks on the general problem. This is a problem familiar to corporate operations and has corrected itself so that normal paths of information flow and responsive time cycles have now been created for the Project group.
X. APPARENT DIRECTION OF CONCLUSIONS

Aside from individual conclusions reached in the various works of the participants, the work of the Project group as a whole has not reached the point where generalizations may be made. However, the direction in which the resource procurement section of the industry is moving is beginning to become clear to the Project group. We therefore asked the Research Associates and Funded Graduate Research Assistants each to list the five most important aspects of the problem which they had encountered and to state the direction in which they believed the industry must move. Many items were listed more than once by the members of the Project group. The fifteen most significant points are listed, not necessarily in order of their importance, as follows:

1. The present system of procurement (a low rate of production from independent marginal producers harvesting poorly stocked lands) is in the long-run uneconomical. Such a system is unresponsive to fluctuating raw material demands as it inherently possesses built-in time lags which negate responsible management control.

2. An integrated system of procurement (an improved rate of production from company owned or quasi-controlled mechanized producers harvesting more productive plantings on controlled lands) will provide economies as a result of the efficiencies of increased scale, unit load handling and transport, and improved management control. Such an integrated system will be more responsive to fluctuating demand, and the control of the flow process will in reality rather than in theory become a responsibility of corporate
management.

3. Harvesting in excess of 100 cords per day per producing unit will become commonplace without exhorbitant investment, although substantial reshuffling of the subdivisions of the work tasks from tree to digester may be required.

4. Corporate management should be devoting considerable attention to the allocation of disposable capital in the future to fill in the investment gap now existing between company owned lands and their respective mills. Only in this manner can economies of increased scale be accomplished throughout the entire raw material procurement system.

5. Corporate management should be aware that if the land acquisition policies of the past twenty years are continued, then by 1990 they would have sufficient land to meet projected consumer demand. Whether continued land investment can be accomplished in the light of the additional investment required in paragraph 4, and in the light of the projected future changes in the national economic picture, should be researched in depth by an industry-wide financial study.

6. Some attention should be paid to other geographic regions of Central and northern South America as possible growing sites for raw materials to be transported in bulk to coastal mills of the Southeast region. This might reduce the amount of dollar investment in land noted in paragraph 5.
7. Harvesting and transportation labor in the pulpwood procurement systems of the Southeast will require:

   Higher wages,
   Improved working conditions,
   Union recognition, and
   Steady work guarantees.

In turn, mechanization of the systems in the industry will require:

   Better educated labor,
   Better motivated labor, and

   At least two shifts per day to maximize equipment utilization.

8. Non-productive rehandling of the raw material will be eliminated primarily by shifts in processing location and in the nature and unit quantity of the raw material being transported. (At present the Research group is divided into two camps "Chips from the stumps" and "Longwood to the mill". Both approaches may be wrong, but there appears to be general agreement at this writing that by the year 2000, shortwood processing will become completely antiquated.)

9. Harvesting equipment will physically increase in size and capacity, and its rate of performance will vastly improve. Standardization of equipment throughout the industry will become mandatory simply to reduce the manufacturing costs and hence lower the investment required by the procurement equipment system.

10. Consolidation of the individual mill's private resource area is desirable in order to minimize transportation distances and increase efficiencies in the management of the materials flow.
Once a mill's resource areas have been altered from a shotgun ownership or random independent pattern to a quasi-centralized area control, then transport forms other than the predominant rail system may become more economically attractive than at present. The redistribution of primary land to supply the individual mill might come about by lease, rental, or allocation of properties. This is fraught with difficulties unless approached on an industry-wide basis.

11. Mechanized artificial regeneration systems should be standardized throughout the industry, not only in an equipment sense, but also in a procedural sense. The many variations in regeneration systems used and planting patterns practiced at present will definitely complicate harvesting design efficiencies twenty to thirty years from now.

12. Corporate management of the entire forestry and paper-making industry from seed to paper sale must become more unified and its control systems improved substantially through computer information systems development and through an upgrading of management education and experience requirements in the forest management and resource procurement segments of the industry. In order to maximize return on investment through equipment utilization rather than labor utilization a different form of management talent than generally found at producer level today, will be required. Considerable increases in wage and salary scales will be necessary to attract the proper talent.
13. Considerably more attention must be devoted to input-output analysis of the land resource area and its products from the tree, as well as more integration of this type of analysis with the input-output analysis of the mill and its products. Product diversification by mills in the Southeast will continue to grow and product diversification from the forest lands also should grow.

14. In the light of paragraph 13, above, the complete usage of the "whole tree" will come under increasing scrutiny by the industry and harvesting systems formulated for use in the short term future must be adaptable to increases in stump and trimmings utilization in the long term future.

15. A centralized bank for computer information and management control systems planned or currently in use by the various corporations making up the industry might prevent duplication of effort in the future. Standardization of management information and control systems is as important as standardization of the physical equipment performing operational functions.

Again it should be pointed out that these fifteen comments merely outline the direction in which the Project group currently "sees" the industry is moving or in which it should move for economical solutions to the problem of procurement efficiencies.
XI. GOALS OF THE SECOND YEAR OF THE PROGRAM

Four goals have basically been established for the second year of the program. The first two of these are:

(A) Refinement, and

(B) Consolidation.

Refinement must occur in order to place the creative work already performed and underway at present into easily usable form. With scope fairly well defined, the basic individual work must be tested and evaluated and then revised to fit within the overall purposes of the Research Program.

Consolidation of various models created individually into one or more master models of the area under study will consume an ever increasing proportion of the time available to the Project group. At present these appear to be at least three general models necessary to be responsive to the purpose of the Research. These are:

(a) A Resource Flow Model,

(b) An Information Flow Model, and

(c) An Equipment Performance Evaluation Model.

Individual models of a restricted nature have been already created for type (a) and (c), while a limited model of type (b) is underway at present. However the current concern of the Project Director is the expansion of these single or dual purpose models into general purpose models reflecting the overall system being studied. Both refinement and consolidation stages of any research program always consume more man-hours than originally contemplated.
The second pair of goals for the second year are:

(C) Communications, and

(D) Sponsor Comprehension, and Acceptance.

Communications can cover a wide variety of methods of presenting research activities, ranging orally from informal presentation of research to a small group to the short course-seminar presentation open to industry attendance, and ranging verbally from the in-house written report for the sponsor group to the submission of refereed research papers to international publications. S.E.A. advice is requested in Section XII, concerning development of these lines of communications and the restriction attached to dissemination policy.

Sponsor comprehension and acceptance is paramount to a project of this nature. Having placed a research group in position to become involved in a new environment is one thing. Maintaining and amplifying involvement, particularly at the undergraduate and graduate levels is an entirely different problem as the participants constantly change from one year to the next, sometimes before they even learn of the sponsor's reaction. So, quite naturally, as work is produced and communicated to the sponsoring group, as in the abstracts found in Section XII, and in other presentations to them, the Project group is anxious for the sponsor feedback for this stimulates greater responsive effort. The Research group anticipates acceptance, but, as in all research programs, rejection of segments of the research or requests for modifications can occur. The Project group, therefore, must be able to gracefully modify those portions of its efforts to best fit the needs of the Sponsoring group. We look forward to increasing the opportunities for feedback from the S.E.A.
XII. ABSTRACTS OF PAPERS

Eighteen papers are abstracted in this section ranging from a report on a two-hour credit project for an undergraduate student to a Master's Thesis performed by a graduate student. These abstracts should be studied closely by the S.E.A. members for subject matter of interest to them.

The Project Director has commented on each paper and attempted to classify them as to their publication worth. One work could be published without revision. Eight works could be published with slight revision. Nine works either were not performed at the publication level or were performed for the discovery, collection, and dissemination of internal knowledge useful to the Project group. Quite a lot of the work done in the latter nine papers will be found in papers of a publishable level now in process.

It is the thought of the Project Director that after examination of the abstracts, the S.E.A. can advise us which works they wish to see in detail. Then such papers can be revised and prepared for dissemination at the Point Clear meeting scheduled for late October.

As the S.E.A. has no "in-house" communication organ by which these papers can be given general distribution, it might be possible at the end of the second year to take all publishable works and edit a text of sorts covering "The Systems Aspect of Harvesting and Transportation of Pulpwood." This question of publication needs further consideration by the S.E.A. Steering Committee in order not to spend money needlessly on duplication of papers having a limited audience.
At the same time some policy should be set regarding the preparation and publication in national journals, after S.E.A. clearance, of papers of general interest to the industry as a whole. Up to the present, the Project group has concentrated on the creative process but certainly in the second year refinement and communication of results will become a major concern.
Abstract of

Title: PULP MILL LOCATION IN THE SOUTHEASTERN UNITED STATES

Type of Paper: A Restricted Term Project

Author: Arias, Adolfo

Author's Title: Undergraduate Research Assistant

Purpose: This short project is performed to locate the paper mills of the Southeast and determine the interference between mills regarding supporting raw material resource areas.

Technique: The mills were geographically charted on a large scale map and interference was defined by: (1) 75 mile radius and (2) radii in proportion to mill capacity. Charting techniques emphasized the degree of interference.

Conclusions: Considerable interference exists. Many areas are subject to the requirements of six or more mills. Some thought should be given to land exchange between competing companies to reduce undue competitiveness in certain areas.

Project Director's Comments: Mr. Arias, a student from Panama, drew his conclusions in a straightforward monopolistic manner in accordance with his previous education. This general area may be explored further by Mr. Deisenroth on a non-funded basis.

Not performed at publication level.
Abstract of

Title: MINIMIZATION OF TRANSPORTATION COSTS FOR THE HAULING OF PULPWOOD BY RAIL

Type of Paper: A Term Paper

Author: Bacon, John C.

Author's Title: Undergraduate Research Assistant

Purpose: (1) To provide the members of the S.E.A. with an insight into the problems of the harvesting and transportation of pulpwood from a systems standpoint.

(2) To explore the rail transportation from woodyard to mill with the objective of minimizing the costs of transportation.

Technique or Analysis Used: Linear programming.

Conclusions and Recommendations: (1) In order to apply the techniques of linear programming, and open the door to substantial cost reductions, the hundreds of woodyards in the South must be considered as a fluid and flexible supply.

(2) Some method or methods must be devised to "free up" the pulpwood output of a given yard so that the proper allocation of the wood can be realized and the wasteful and inefficient practice of hauling wood for hundreds of miles be discontinued.

(3) If such a plan can be accomplished by a mutual agreement within the industry, the result will be a lower overall cost to the pulpwood industry as a whole.
Project Director's Comments: This is the first paper produced at the undergraduate level in the early stages of the program. Even though linear programming techniques are already in use in some mills, and Mr. Bacon's results are already out of date, the work was from his viewpoint, original. This demonstrates the principle of involvement desired in the early stages of the program. This work is the foundation for much more advanced work now being done at the thesis level by Mr. Moore.

Performed at publication level with revisions.
Abstract of

Title: FACTORS WHICH MAKE UP THE MODIFIED INCOME STATEMENT

Type of Paper: A Term Paper

Author: Baker, Benjamin R.

Author's Title: Undergraduate Research Assistant

Purpose: The purpose of the paper is to review those accounting factors which should make up the typical income statement of an independent pulpwood producer. Such items traditionally ignored by the small producer as taxes, interest, varying depreciation treatments, cash flow, debt retirement plans, etc. are set up in one equation form for possible computer programming. The need for such a program to determine production rates and harvesting price in respect to varying investment policies is necessary as mechanization is accomplished by the independent producer.

Technique: Approximately 36 factors are defined and their interrelationship is shown in equation form. Certain factors are subdivided by type and graphs have been drawn to indicate the policy choices open to the user.

Conclusions: Such a program can be used to predict the ultimate success or failure of any investment policy over the life of the asset. Changes in levels of productivity or price may be made to correspond to profit or loss or cash flow situations as encountered during the life of the endeavor.
Project Director's Comments: This paper is well thought out but presented poorly. The concepts expressed, resulting in a predictive analytical tool, are excellent, but the undergraduate treatment of their presentation leaves much to be desired. Mr. Rogers is in the process of rewriting the subject material and having it programmed for future use. This basic work is needed and should be made available at the dealer-producer level. Not performed at publication level.
Abstract of

Title:  IMPROVED MAINTENANCE OF PULPWOOD HARVESTING EQUIPMENT

Type of Paper:  A Term Paper

Author:  Bearden, Jimmy L.

Author's Title:  Graduate Research Assistant

Purpose:  This paper is a proposal to develop an orderly and scheduled program of maintenance for some of the more complex and costly equipments used in pulpwood harvesting and then to compare the cost-effectiveness of this maintenance program with that of the maintenance procedures now being followed.  The evaluation is proposed to be conducted on both new and used equipments.  The obvious intent is to reduce overall pulpwood harvesting costs.

Technique:  To conduct this evaluation, certain equipments would be selected as test items.  A recommended schedule of maintenance would be prepared and applied to equipments in this test group.  Data reflecting direct maintenance costs, production losses due to unscheduled maintenance, operating time until subsequent overhauls, and number of units produced would be recorded and compared between the test group and the control group.

Conclusions:  The quantitative results of this proposal could be presented as comparative tabulations of required costs for maintaining pulpwood harvesting equipment by two different methods.  These results would enable a pulpwood harvester to ascertain whether or not an
organized program of maintenance would reduce his operating costs and thereby directly increase his profits. They would also permit paper-producing companies to estimate any additional amounts of pulpwood that could be made available by adopting an improved maintenance program for existing equipments.

Project Director's Comments: Mr. Bearden's proposal is one of considerable interest to the industry, but one which is fraught with difficulty when it comes to data acquisition and test. Information sources conveniently available to Georgia Tech are lacking and it has been suggested to Mr. Bearden that he should study more the system necessary to conduct preventative maintenance operations in the harvesting and transportation areas of the industry.

Not performed at publication level.
Abstract of

Title: A LITERATURE SEARCH OF THE GEORGIA TECH LIBRARY FOR SOURCES OF INFORMATION RELATED TO PULPWOOD HARVESTING

Type of Paper: A Term Paper

Author: Cosby, Walter W.

Author's Title: Graduate Research Assistant

Purpose: The purpose of the research is to identify reference material related to pulpwood harvesting and harvesting equipment that is available in the Georgia Tech Library. Areas researched are listed as follows:

Tree Breeding   Motor Truck
Hardwoods       Motor Vehicle
Lumber          Machine Design
Plywood         Forestry
Timber          Agriculture
Particle Board  Soils
Paper           Land
Logging         Materials Handling
Pulpwood        Wood
Veneer          Pulp
Transportation  Woodwork

Technique: The technique utilized was a search of card catalogues and abstracts by subject for books, periodicals, indexes, abstracts,
bibliographies and directories. The volumes were then recorded in accordance with the Dewey Decimal System and the Library of Congress classification systems.

Conclusions: Reference materials identified were as follows:

1558 books classified under the Dewey Decimal System
155 books classified under the Library of Congress System
81 periodicals were subscribed to by the library
115 indexes, abstract journals, bibliographies, and directories were considered relevant.

Project Director's Comments: This work was necessary simply to find out what we had available in the Georgia Tech environment, and to make location of such material a simple process for the fifteen or more people involved in the research. Not performed at publication level.
Abstract of

Title: IMPROVEMENTS IN PULPWOOD HARVESTING OPERATIONS WITH LARGE CAPACITY ROUGH TERRAIN FORWARDERS

Type of Paper: A Major Term Paper

Author: Cosby, Walter W.

Author's Title: Graduate Research Assistant

Purpose: The major purpose of the paper is to describe and basically design large volume forwarders that could be capable of transporting tree length loads (approximately 20 cords) over natural terrain between the stump and improved roadside landings. In order to develop accurate figures for initial costs, weight, operating costs, and performance criteria, an effort is made to develop the forwarder as much as possible from components currently available on the market.

A second purpose is to determine the capabilities of the resulting forwarder as compared to those of a present day skidder system.

Finally, efforts are made to identify potentials for continued improvement of the forwarder's design and to determine the factors to be considered in introducing the forwarder into a harvesting improvement function. Determination of some of the effects of the forwarder on an continuing harvesting improvement function are made.

Technique: The forwarder is designed with consideration of the following factors:
(1) Minimum processing of trees prior to delivery at roadside.
(2) Mobility on natural terrain.
(3) Availability of components making up the forwarder, and the operating characteristics of such components.
(4) Working conditions of operations.
(5) Flexibility and simplicity.
(6) Ease of movement between sites.
(7) Production rates.

Criteria were developed upon which to compare the forwarder to a common skidder system. A comparison was then made between the two systems using standard economic analysis.

Conclusions: The forwarder system is believed to be superior to the skidder for transporting wood over natural terrain from the stumpage site to an improved roadside. The comparison by the paper indicated a single forwarder system has an average production rate 8.4 times that of a single skidder system. The initial cost of systems with equal production rates would be $150,000.00 for the forwarder system and $168,000.00 for the skidder system. The average operating cost of the skidder system would be 59% greater than that of the forwarder system. A $1.00 hourly increase in wages would result in a 10.3% production cost increase for the skidder system and a 1.79% production cost increase for the forwarder system. The forwarder system produces twice the ground pressure than that of the skidder system, but it is believed relative to ground pressure that the forwarder would be hampered only by very deep boggy swamps. Relative to gradeability, the forwarder has under most conditions 10% of grade more gradeability than the skidder system.
Project Director's Comments: Mr. Cosby wanted the experience of designing a machine for harvesting operations. He found it to be a very complicated task. His paper reflects his difficulty in solving the problem but the results will be most useful as his thesis work involves unit load handling and processing of the resource material. Mr. Cosby believes relocation of the "do" functions as well as a change in scale of operations in the harvesting and transportation problem is a must to meet future demands on the system.

Performed at publication level with revisions.
Abstract of

Title: WOOD-CHIP PIPELINES

Type of Paper: A Term Paper

Author: Deisenroth, Michael P.

Author's Title: Graduate Research Assistant

Purpose: Approximately 10 years ago, the pumping of solid materials through long-distance pipelines became a reality. A few years later, the practicality of transporting wood-chips to the paper mill via pipeline became a subject of study. This paper is a brief resume of the technical and operational studies that have been conducted. It also presents an example of how the economic feasibility for installation of a chip pipeline to serve a specific operation may be evaluated.

Technique: Technical consideration is given to: pipeline friction losses, velocities, concentration, size, pressure, corrosions, and start-shutdown procedures. The interrelationships of these problems are recognized and discussed. Attention is also given to some of the operational aspects that must be weighed. These include ancillary equipment, supply of a sufficient quantity of chips at input, and procurement procedures. An econometric model that considers all equipment and the labor directly involved in the operation of a pipeline system is then presented.
Conclusions: At present, most studies are technically directed with special emphasis given to hydraulics. Pressure head loss and the resulting power requirements for pumping various concentrations are in the sub-area of prime concern. Obviously, the widespread use of pipelines for transporting wood-chips will not be a practical reality for several years, if ever. However, advances in technology and the changing socio-economic structure of the world justify the continuance of experimentation in this area.

Project Director's Comments: This paper indicates that if a single mill's resource area was in one central location, then pipeline transport study should be accelerated. As long as the resource area is fragmented by a policy of producer independence then there is little hope for pipeline transport in the next ten to fifteen years. Companies with large plantation tracts should continue study in this area.

Performed at publication level with revisions.
Abstract of

Title: A DYNAMIC MODEL OF THE SOUTHERN PAPER INDUSTRY

Type of Paper: A Term Project

Author: Fenu, Pietro

Author's Title: Graduate Research Assistant

Purpose: The objective of the project is to attempt a dynamic approach to the simulation of the future growth of the paper industry in the Southern United States.

Related with this topic are the projections of paper and board consumption, pulpwood requirements and production, prices, etc., covering a period of 50 years. Part of the model, concerned with the land policy of the paper companies, should highlight the implications of today's policies concerning forest management, over the next few decades.

Technique: The paper identifies the dynamics of the system as an inter-relationship between the national economy, the paper industry, and forest management. Through the study of past statistical data it was possible to find rates, factors, and constants, for the buildup of a DYNAMO program defining the relationships. The projections given by the program, in the form of tabulated data and graphs, were checked with other works in this area, in order to establish the validity of the approach.
Conclusions and Recommendations: The DYNAMO compiler seems to fit well for this kind of forecasting works. A more complete collection of data, samples, etc., examined with standard statistical techniques can bring about a better formulation of the relationships between the different factors involved, and therefore bring more reliability to the results. Sensitivity tests of different values of assumed constants and growth patterns, are among the further steps required in order to give to the model full efficiency.

Project Director's Comments: This model is included as an Appendix to the Annual Report to give some indication of the preliminary quantitative treatments being made by members of the S.E.A. Project group. Mr. Fenw expects to develop this preliminary work into his graduate thesis, expanding the model as new parameters and variables are defined by the work of the group.

Performed at publication level with revision.
Abstract of

Title: A SIMULATION OF A PULPWOOD TRANSPORTATION SYSTEM

Type of Paper: A Term Project

Author: Fenu, Pietro

Author's Title: Graduate Research Assistant

Purpose: This paper presents a model for simulating an integrated pulpwood system from the stump to the mill.

The objective of the simulation is to supply data concerning the different conditions. The particular system analyzed was proposed and examined for economic criteria by another member of the S.E.A. project.

Technique: The system, composed of 2 skidders, 2 loaders, 3 trailers, 1 tractor, 4 trucks, is simulated in its different operations by a model written in the GPSS II computer language.

Flow of materials, utilization of machinery, time spans, etc., are determined by the computations.

Conclusions and Recommendations: The GPSS II language which includes the effects of random variations, seems particularly suited for analyzing these kinds of problems, because of its immediate relation with physical reality and its production of a great amount of information in the print out. Different integrated pulpwood systems (such as the one examined) could be easily compared on the basis of their efficiency, through similar simulations.
Project Director's Comments: This work performed independently of Stark's thesis which also uses GPSS, establishes the effectiveness of GPSS as a tool to analyze flow, efficiencies and utilization factors in pulpwood industries. It appears to be a far better technique than some of the present linear programming techniques which do not allow for the effects of random variation in the producing or transportation systems. As systems are developed in the S.E.A. Program, it now appears that their comparison will be in some form of GPSS analysis.

Performed at publication level with revisions.
Abstract of

Title: AN INDUSTRIAL DYNAMIC MODEL TO ANALYZE THE PROBLEM OF SMOOTHING THE FLOW OF PULPWOOD TO PAPER MILLS IN THE SOUTHEASTERN UNITED STATES

Type of Paper: A Term Project

Author: Jallouk, Edward

Author's Title: Graduate Research Assistant

Purpose: This project is an attempt to simulate the system of wood procurement in the Southeastern United States. The structure of the system (paper mills - wood dealers - wood producers) generates an information gap between the producers and the mills as there generally is not direct contact between the two. As a result, the mills are unable to maintain a smooth flow of wood. The program should define which variables can have a major impact on smoothing the fluctuations in the system.

Technique: The system analyzes the relationships between the three sectors (paper mills - wood dealers - wood producers), and the variables within each sector. The resulting detailed flow chart, translated into DYNAMO computer language, produces a program which was successfully run with trial data.

Conclusions and Recommendations: The logic of the program was accepted by the computer, but several changes in the initial conditions and constants are necessary to make the model run smoothly. The final model should test the reaction to consumption changes, seasonal inventory fluctuations, weather effects, etc.
Project Director's Comments: This model is an expansion of the DYNAMO program initially formulated by Battelle, and should provide a basic framework for an overall model of the procurement system in a typical mill. Mr. Jallouk's work needs refining. This is now being done by Mr. Fenu.

Performed at publication level with revision.
Abstract of

Title: PULPWOOD HARVESTING, SUPERVISOR OR CREWLEADER
 WHAT MANNER OF MAN IS THIS?

Type of Paper: A Term Paper

Author: Plafcan, Dan J.

Author's Title: Undergraduate Research Assistant

Purpose: The purpose of this paper was to provide information describing
the desired qualities of a pulpwood producer. Stemming from this
basic purpose, it was also pertinent to discuss particular char-
acteristics and qualities necessary for effective crew management.

Technique: Information was gathered through personal interviews and
extensive library research. Once this information had been gathered,
the resulting opinions and observations were coupled together in a
logical sequence in order to draw conclusions.

Conclusions and Recommendations: The day of a man, a bobtail truck week,
and a chain saw is rapidly disappearing. The future pulpwood pro-
ducer must possess basic managerial abilities, the technical know-
how, and personal motivation.

The future crewleader must learn how to position his men so
as to challenge their talents and at the same time maintain their
confidence.

Project Director's Comments: This undergraduate paper merely summarizes
in one location the comments regarding the foreman's task of in-
creasing "crew aggressiveness" and the ensuing discussion which
followed the release of the original Battelle reports on the sub-
ject. The paper is qualitative in nature and is reflective of the undergraduate level at which it was performed. Not performed at publication level.
Abstract of

Title: LABOR TRENDS IN THE SOUTH

Type Of Paper: A Term Paper

Author: Stallings, James B.

Author's Title: Undergraduate Research Assistant

Purpose: The purpose of the paper is to assemble in one ready reference the labor trends in the South for use by the Project group. Trends in the descriptive characteristics for Southern labor are to be established.

Technique: Consultation with Bureau of Labor Statistics personnel and review of census and employment resource information available in the Atlanta area. Charting and graphing presentation is made of summaries of such data.

Conclusions: Trends toward higher wages, increased union participation, better education, reduction in farm background and greater availability of negro and female labor supply are presented.

Project Director's Comment: This work is too general and too shotgunning to be anything more valuable than an assistance in locating resource information. Certain generalizations of the Project group are supported, however.

Not performed at publication level.
Abstract of

Title: PAPER INDUSTRY ANALYSIS
Type of Paper: A Term Paper
Author: Stark, James J.
Author's Title: Graduate Research Assistant

Purpose: The basic purpose of this paper was to provide a broad background and understanding of the entire paper industry. The paper was not intended to present highly technical information, but to familiarize the new members of the Project group with the environment in which they will be working.

Technique: The problem was approached by treating the entire paper industry as a whole.

Brief descriptions were given about the history of the paper industry, the products of the industry, the potential of the industry, and basic methods of production of the industry.

A systems viewpoint of the industry was also taken. A diagram was shown which well depicted the interrelationships of the various basic components of the system.

Detailed growth statistics and ratios were calculated. These ratios and statistics provide good insight as to the various trends presently taking place within the paper industry.

Conclusions and Recommendations: The information in the paper should provide a basic starting point for initiating research in the area of the pulp and paper industry.
Project Director's Comments: This paper was done in the fall of 1967 to familiarize the Project group with the environment. Lt. Stark was the only student participating in the summer of 1967. When he left in June 1968, fifteen people were involved in the program. Much of the growth must be attributed to Lt. Stark's early survey work and enthusiasm for the problems he encountered as he became familiar with the industry. Not performed at publication level.
Abstract of

Title: SOME ASPECTS OF MANAGEMENT-ORIENTED RESEARCH IN FORESTRY

Type of Paper: A Research Summary

Author: Krol, Dr. Joseph

Author's Title: Research Associate

Purpose: (1) To identify major areas of management-oriented research in forestry. (2) To identify the appropriate sources of reference. (3) To detect major trends and novel approaches to the solution of forest management problems.

Technique or Analysis Used: Literature search.

Conclusions and Recommendations: (1) Management-oriented research in forestry includes four major classifications:


   (b) Forest Management. Business Economics of Forestry. Administration and Organization of Forest Enterprises.

   (c) Marketing. Economics of Transport and the Forest Product Industries.

   (d) Forest Products and their Utilization.

(2) The most comprehensive source of reference is Forestry Abstracts published by Commonwealth Forestry Bureau, Oxford, England. The C.F.B. abstracts some 7,000 publications per year, about 8% of which are management-oriented.

(3) A major trend in harvesting is away from shortwood systems to tree-length and/or "whole tree" systems. One reason is that trees
are harvested not just for pulpwood.

(4) Another trend in harvesting is toward the complete utilization of each tree, i.e., including stumps and trimmings.

(5) Forest management techniques tend toward interdisciplinary approach based on silviculture, forest economics, marketing, systems analysis, optimization methods, and computer simulation.

Project Director's Comments: This is a report of the first massive literature search conducted by Dr. Krol. It consists of lists, charts, and graphs of use to the Project group in determining the many facets of the overall system. It is a sensible summary of the information sources available in published literature. Not performed at publication level.
Abstract of

Title: A STRATEGY FOR RESEARCH IN MULTIPLE USE OF FOREST RESOURCES

Type of Paper: Research Paper

Author: Krol, Dr. Joseph

Author's Title: Research Associate

Purpose: (1) To take a look at forestry as a whole. (2) To explore methodology suitable for research in multiple use of forest resources. (3) To review the state of the art in forest resource utilization.

Technique: Literature search.

Conclusions and Recommendations: (1) The methodology of research in forest resource utilization involves:

(a) Identification of feasible alternatives.

(b) Measurement.

(c) Analysis.

(d) Optimization.

(e) Decision.

(f) Sequential review.

(2) The elements of the above methodology have been expanded so as to show the interactions between general interrelated disciplines such as heuristics-oriented mathematics, general system theory, systems analysis, resource system modeling, forest economics and computer simulation.

(3) The policies of a large-scale forest product concern have been
reviewed as an illustration of a practical application of the theoretical concepts.

(4) The experience of this concern indicates the following policies:

(a) Development of new product lines.
(b) Aggressive marketing methods.
(c) Sales per employee at the level of $22,000 per year.
(d) Investment per employee at the level of $25,000.
(e) Gross rate of return on total investment at the level of 10%.
(f) Extensive use of management information systems.

Project Director's Comments: This paper tries to put into perspective forestry research activities with the objective of applying modern decision-making techniques in forest resource utilization. The main theme of the paper is to suggest direction and methodology for future research studies on the graduate level.

Performed at publication level with slight revision.
Abstract of

Title: A SIMULATION MODEL FOR THE COMMON PULPWOOD HARVESTING SYSTEMS OF THE SOUTHERN PINE REGION

Type of Paper: Master's Thesis

Author: Stark, James J.

Author's Title: Graduate Research Assistant

Purpose: The purpose of this thesis is to form the groundwork necessary for further research and study in the area of pulpwood harvesting and transportation, i.e., to study the basic systems commonly used at present by the majority of pulpwood producers. In order to achieve this objective the following specific goals were attained: (1) Characteristics and constraints presently imposed on the common systems of pulpwood harvesting were defined and quantified, (2) Three basic systems were defined, and (3) A general simulation program was developed which is representative of the common 5'3" pulpwood harvesting methods. The objective of the simulation program is limited to construction and validation of a basic computer program for the three systems defined.

Technique: The approach used in this study is that of system analysis. The systems analysis methodology consists of eight distinct parts: (1) system definitions, (2) reticulation, (3) abstraction, (4) identification, (5) measurement, (6) solution, (7) optimization, and (8) validation. This basic methodology is adapted for this study for two reasons. First, the pulpwood harvesting procedure is amenable to this approach and second, the methodology
allows for an orderly construction of the simulation model. The simulation model considers 12 basic pulpwood harvesting operations and allows for the assembly of any one of 28 possible, realistic systems. There are 19 variables which require data and probability distributions, and 15 parameters which can be set. The model is programmed in General Purpose System Simulator Language for system simulation on a Univac U-1108 digital computer.

Conclusions and Recommendations: Two conclusions are drawn directly from the sample program. First, the model does represent the system, and second, quantitative insight into the real world system can be obtained from the model with respect to system limiting operations.

Since this thesis is not considered a complete research study but a basis for further specific studies, it is recommended that statistical experimentation be conducted to obtain comparative data between systems, and to obtain data on the difference in system output from actual and hypothesized data. Systems tested with actual and hypothesized data could represent comparing present and future systems.

A second study is recommended to enlarge the computer program to allow for the paralleling of equivalent operations and the splitting of a system into two or more systems.

The final recommendation is that basic studies be made at an elemental level on harvesting operations. It is pointed out that there are many studies made on productivity of machinery but, a
man that costs 15 to 40 thousand dollars in five years has only
an assumed capability. It is proposed that the laborer, his
employer, and science would benefit from an application of stan-
dard industrial engineering method to this area.

Project Director's Comments: This is the first thesis produced under
the S.E.A. Research Program. It represents about six months work
by an unfunded Graduate student. It develops an excellent tech-
nique for analyzing today's systems of harvesting. The thesis is
a major building block for the entire project. Further amplifying
work is now being pursued by Mr. Cosby. **Performed at publication
level without revisions.**
Abstract of

Title: A SIMULATION OF THE PULPWOOD PROCUREMENT SYSTEM

Type of Paper: A Term Paper

Author: Valente, George A., Jr.

Author's Title: Graduate Research Assistant

Purpose: This research proposal outlined research which is to be carried out at a later date. The paper contains a section which, in a general manner, describes the present nature of the pulpwood procurement system. The basic problems of the present systems are described.

An extensive literature survey is also presented in the paper. The literature survey briefly explains what research has been done in the area of pulpwood procurement.

Technique: The author proposes an industrial dynamics approach to simulate the present pulpwood procurement system. By gaining a better understanding of the system, through simulation, the author hopes to improve the system. The author explains the objectives, the method of procedure, and the nature of the expected results of the proposed research.

Conclusions and Recommendations: It is felt that the major values to be gained from this research proposal are contained in the introduction and the literature survey. This is because the paper is a proposal, not an actual research paper.
Project Director's Comments: Mr. Valente hopes to continue this work as a basis for his thesis, but at present is being outdistanced by other members of the Research group. Therefore he will probably study in detail some sub-aspect of the system he discusses in his research proposal. Not performed at publication level.
Abstract of

Title: AN ANALYSIS OF THE POTENTIAL FOR HELICOPTER-BASED PULPWOOD HARVESTING OPERATIONS IN THE SOUTHEAST

Type of Paper: A Term Paper

Author: Valente, George A., Jr.

Author's Title: Graduate Research Assistant

Purpose: In some wood producing areas the helicopter has been employed for transporting logs from the stumps in the forests to loading areas that are easily accessible to land vehicles. This paper evaluated (primarily in terms of the economics involved) the potential of helicopter-based harvesting operations in the Southeast. Advantages and disadvantages of such operations are discussed.

Technique: The nature and scope of the helicopter's role in pulpwood harvesting is analyzed based on previous trials with helicopter logging operations conducted in the Pacific Northwest, Canada, and Russia. The results of these previous trials are related to pulpwood harvesting in the Southeast in terms of the systems aspect of the harvesting operation. Time and load factors are considered as the primary criteria that must be compared with total cost factors.

Conclusions: In general, there appears to be little potential for helicopter-based pulpwood harvesting in the Southeast in the foreseeable future. Economical helicopter operations depend primarily upon a high volume of wood to be moved in a small area within which other methods would be extremely costly. For the most part, the criteria of wood volume are not met due to the procurement system prevalent in the Southeast, i.e., harvesting performed by indivi-
dual producers and the wood then routed to the mills through dealers. Also, the costs associated with present methods of in-the-woods transport do not appear to be sufficiently high to justify use of the helicopter.

Project Director's Comments: A straightforward presentation of the current state of helicopter developments and their possible relation to harvesting in the Southeast. It was agreed by the Project group that potential is small for such systems. Performed at publication level with revisions.
APPENDIX A
WHAT WILL OUR FOREST RESOURCE BE IN THE FUTURE?

by

Dr. Peter Dyson

School of Forestry
University of Georgia

Prior to predicting a potential harvesting system to be used ten to twenty years in the future, it is mandatory that we speculate on what the pulpwood stands of the future will be like, or what they could be like.

To answer the first question of, "what they will be like," it is suggested that we might possibly look at the company stand descriptions as described by the continuous inventory cards as kept by our sponsor companies.

In speaking to Dr. Tom Wallbridge of the A.P.A., he informs us that he has placed in his budget for next year a request to get duplicate decks of I.B.M. cards which describe the stands of his member companies. This would report a total of approximately 10.5 million acres. It is my suggestion, as both Georgia Tech and Auburn compliment each other's work, that we should attempt to get one deck from each S.E.A. company for our use at a centrally located place. At the moment the most convenient location would be at A.P.A. in Atlanta where the S.E.A. resource file could reinforce the A.P.A. file.

It would be necessary to examine the input for each company and to write a separate program for each company's deck in order that the output
be standardized to give the information required by A.P.A. and the Auburn and Georgia Tech teams. This I believe would be one step in getting to know what there is liable to be on the stump in the next twenty years. It is suggested that we examine a mill like Rome Kraft first since its land patterns stretch from the mountains through the upper coastal plains. The cost of duplicating all the decks assuming we have 1 card/100 acres and every company had such a deck would be a considerable expense. The major problem would lie in getting permission from the seventeen sponsor companies. This data could give us a fair idea about the present condition of the stands and what they will be likely to produce in the future.

The second question regarding, "what the stands could be," depends, to a great extent, on what the various disciplines which contribute to our knowledge of how to grow and keep growing our trees have up their sleeves, and what it will cost to get the ideas from their sleeves into production. This problem is a far more difficult task for researchers who are reticent to revealing their secrets or findings before they can substantiate them at some arbitrary level.

The most interesting facets observed this year are silage sycamore and several known strains of seven year pine growing at the rate of 5 cords per acre per year. The first development has already been reported in the literature but the latter dumbfounded me. The researcher in question is not prepared to say what "his trees" will do in the future, but he does know what they have done in the past. At present he leaves it to the public to estimate what the trees will do in the future. These outplantings are available for all to see if they so desire. Therefore
I suggest that a group of vice presidents or upper echelon people should visit the plantings to see for themselves. The answer to the questions "What could our stands look like in the future?" and "What will we forfeit if we don't use existing technology?" are questions that A.P.A. and S.E.A. research groups could well compliment each other on for the coming year.

To this end A.P.A. has in their plans for next year a "think session" or two calling for a meeting of disciplines trying to break through the barriers of knowledge associated with tree growth and development. The individuals in these disciplines are a mixture of "prima donnas" and reticent people. Some talk loud and some don't talk at all. We believe much good could come from such a session in trying to answer "What could the stands of the future look like?" As such, we'd like to compliment and assist A.P.A.'s endeavors in this area of information exchange.

Project Director's Comments:

I do not believe a master card inventory of the resource area of seventeen companies is necessary to the research. However, I think that use of the six company file proposed by the A.P.A. Harvesting Research group might be of considerable assistance to Dr. Dyson and perhaps to the Auburn group. Perhaps some cost splitting arrangement can be worked out with Dr. Walbridge on the aspect of the comments reported above. In regards to the final comment regarding a "think task" session or two, the Georgia Tech group intends to participate and will attempt to work out within their budgetary limitations some form of assistance as Dr. Walbridge's plans are made more fully known.
A STRATEGY FOR RESEARCH IN MULTIPLE USE OF FOREST RESOURCES

by

Joseph Krol, Ph.D.

Introduction

The purpose of this paper is to formulate some guidelines that would be useful to research workers entering the field of harvesting systems. These men are in general well educated in the theoretical aspects of systems analysis but often lack the necessary background in forestry.

Forestry has been defined by the Society of American Foresters as "The scientific management of forests for the continuous production of goods and services." In other words, the products and services of forests are the goals toward which the scientific management of forests is directed.

The main source of financial income from forests are wood products. It is not surprising, therefore, that many persons think of forestry as being equivalent to timber production. Modern forestry subscribes to the concept of multiple use of forest resources. In addition to wood products, forests furnish water, wildlife, grazing grounds and a place for recreation. However, not every acre is expected to produce all possible goods and services in a given period of time. Some areas may be cut for wood products, some devoted to campgrounds, while some areas may be reserved for wildlife. Interspersed in the forest may be areas of grassland used for grazing domestic animals.
Whereas the total forest furnishes multiple goods and services, the policy of a particular owner may be directed toward one or a limited number of uses. Thus a paper company may be interested in growing the largest possible quantity of pulpwood.

Within recent years many changes have come about in harvesting and processing methods. One of the most promising concepts is that of integrated logging. Its main objective is diversified rather than single-purpose wood utilization. For example, the standing timber may be converted into a number of products such as (1) pulpwood, (2) saw logs, (3) poles, (4) posts, (5) veneer logs, and (6) fuelwood, whereas formerly the entire operation may have been conducted for the production of pulpwood. The number of different products removed from the same felling area depends upon species, site, quality and value.

The scientific management of forest is a complex undertaking involving physical, biological, social and economic considerations. Forestry, in the words of a prominent authority in that field "has to take account of air, water, earth, fire, plants, animals, property, human relationships, and the needs of people."

**The Case of Brown & Wall Company***

Before proceeding with a discussion of a general nature it will be helpful to review briefly the operations of the Brown & Wall Co., world's largest lumber product maker and distributor. The company's selected operating results are shown below:

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* The name is fictitious.
<table>
<thead>
<tr>
<th>Year</th>
<th>Net Sales in MM</th>
<th>Net Income in MM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967</td>
<td>$ 886.6</td>
<td>$ 60.3</td>
</tr>
<tr>
<td>1966</td>
<td>837.8</td>
<td>79.2</td>
</tr>
<tr>
<td>1965</td>
<td>727.5</td>
<td>83.4</td>
</tr>
<tr>
<td>1964</td>
<td>663.3</td>
<td>67.6</td>
</tr>
<tr>
<td>1963</td>
<td>581.9</td>
<td>44.2</td>
</tr>
</tbody>
</table>

Brown & Wall's sales are about equally divided between wood products (wherein home-building is the biggest market) and paper-based output. Lumber and container sales each account for about 25% of sales; paper 12%; pulp 11%; plywood 11%; paperboard 7%; hardwood products and logs 5%; chips 5%; timber 5%; and manufactured panels, the rest. Perhaps 10% of output is sold in export markets.

More than 100 manufacturing plants are operated domestically. Additional facilities are located in 17 countries abroad. Sales are made both direct to clients and through 70-odd distribution centers.

The company owns more than 3.7 million acres of U.S. timberland. About 2.8 million are in the Pacific Northwest, the remainder in the Southeast. In addition, the company holds rights to 9 million acres in the U.S., Canada and Southeast Asia.

Research also is actively pursued in the other end of the product line - in the forest. The recent big development is the fertilization by helicopter of tree farm lands as a part of the high-yield forest project. Brown & Wall officials predict that this program will eventually increase forest yield by 33%, and cover more than 500,000 acres in little more than a decade, thereby salvaging some $60 million in wood value which
otherwise would have been lost. At the same time, the company plans to plant more than 21 million seedlings by the end of 1968 - three times the number planted in 1967.

Capital outlays are expected to range between $125 - $150 million in 1968. The biggest share went for a 600-ton/day bleached kraft pulp mill at New Fern, North Carolina, and a second, a fine paper machine with 360-ton/day capacity at nearby Slymouth, North Carolina. Both are located close to some 600,000 acres of company timberland, and together cost over $75 million.

In its 1964 annual report the Brown & Wall Company is described as "a materials - flow company." Raw materials, primarily timber, flow into the various stages of the production process; they flow through the process, taking on new shapes, forms, or chemical composition, until they become finished goods; and then these finished products flow through distribution systems until they reach the ultimate consumer.

Coupled with the material flow are energy and information flows. Electrical and other forms of energy facilitate production processes throughout the system. Human energy also flows through the system on a continuing basis. Information is the most important factor in coordinating a dispersed and diversified operation such as the Brown & Wall Company. The company's computerized management information system integrates operations carried out in some 25 states.

Complexity and Heuristic Attitude

The operations of the Brown & Wall Company give us a good idea of the complexity of the modern forest products industry. Without being too accurate in our estimates let us summarize the elements of complexity involved in the production and harvesting of wood products.
<table>
<thead>
<tr>
<th>Item</th>
<th>Estimated Numbers of Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood products</td>
<td>$10 + \alpha$</td>
</tr>
<tr>
<td>Type of terrain</td>
<td>$5 + \beta$</td>
</tr>
<tr>
<td>Type of soil</td>
<td>$5 + \delta$</td>
</tr>
<tr>
<td>Type of planting equipment</td>
<td>$5 + \sigma$</td>
</tr>
<tr>
<td>Type of species</td>
<td>$5 + \varepsilon$</td>
</tr>
<tr>
<td>Length of rotation</td>
<td>$5 + \mu$</td>
</tr>
<tr>
<td>Basic types of harvesting systems</td>
<td>$2 + \kappa$</td>
</tr>
<tr>
<td>Degree of mechanization in harvesting systems</td>
<td>$5 + \lambda$</td>
</tr>
<tr>
<td>Types of minor transport equipment</td>
<td>$5 + \omega$</td>
</tr>
<tr>
<td>Types of major transport equipment</td>
<td>$5 + \iota$</td>
</tr>
<tr>
<td>Types of chipping equipment</td>
<td>$2 + \phi$</td>
</tr>
</tbody>
</table>

In the above classification, greek symbols $\alpha$, $\beta$, $\delta$ and so forth, represent alternatives potentially feasible but relatively unimportant in the present state of the art. Although it is recognized that some alternatives are mutually exclusive, the theoretical number of possibilities can be estimated as being of the order of:

$$(10 + \alpha)(5 + \beta)(5 + \delta)(5 + \varepsilon)(5 + \sigma)(5 + \mu)(2 + \kappa)(5 + \lambda)(5 + \omega)(5 + \iota)(2 + \phi)$$

If $\alpha = \beta = \delta \ldots = 0$, we will arrive at the figure of $(10)(5^5)(2^2)$ theoretical possibilities. This example illustrates the highly combinatorial nature of complexity and the need for a proper scientific attitude. Rigorous mathematical methods do not appear to be very helpful for dealing with very complex problems. The correct attitude seems to be the heur-
istic attitude which is a mixture of inventive intuition, logic and mathematics. The philosophy of the heuristic approach has been supported by a number of great mathematicians such as Descartes, Leibnitz, Bolzano and Pólya. In more recent years, Professor Herbert Simon (33) has been associated with this school of thought.

The steps involved in the heuristic problem solving can be identified thus:

1. Identification of feasible alternatives.
3. Analysis.
4. Optimization.
5. Decision.
6. Sequential review.

Heuristic approach is used by Professor Kaufman (23) in developing a science of action, or "praxeology" (from the Greek praxis = action); and by Johnson et al. (21), who used the term "rhochematics" understood as the science of managing material flow. In the remaining sections of this paper the elements of heuristic approach (as applied to forest management) will be discussed some detail.

**Identification of Feasible Alternatives**

Ideally, it would be desirable to consider all feasible methods employed in processing a tree from the moment of planting to the moment of delivery to the ultimate consumer. Such an approach would call for an encyclopedic knowledge of forestry and is beyond the scope of this paper. Consequently, we will limit our discussion to one subsystem used in the flow of forest materials, namely transportation of logs. This
operation constitutes a major part of harvesting expense and is very suitable for illustrating certain aspects of heuristic approach to the analysis of complex systems.

It is convenient to distinguish two subsets of log transportation, namely minor transportation and major transportation. In general, minor transportation takes place between the felling site and the loading site, while major transportation involves movement of logs from the loading site to the mill.

Minor transportation is concerned with log assemblage or skidding. Skidding methods are numerous and may involve animal skidding, tractor skidding or overhead cable-hauling systems. Research is being carried out in the use of helicopters and balloons.

Major land transportation may involve the use of chutes, sleds, tractors, motor trucks and forest railroads. Major water transportation involves floating and driving of logs by means of river and lake rafts, barges and flumes.

Table I (adapted from Brown\(^4\)) shows the region, leading species, principal methods of minor and major transportation, and principal products in a selected number of forest regions. Looking at this table we can conclude that environmental conditions dictate the choice of most feasible methods of transportation. Furthermore, we note that methods suitable for region X may not be appropriate for region Y. On the basis of results shown in Table I, we can generalize that in a complex system involving transformations of materials, energy and information, many diversified processes can be employed at the same time within the system.
<table>
<thead>
<tr>
<th>Region and Leading Species</th>
<th>Minor Transportation</th>
<th>Major Transportation</th>
<th>Principal Products</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2. Cold deck ing and swinging to railroads or truck roads.</td>
<td>2. Railroads.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Skyline systems.</td>
<td>3. Raffing.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Tractors and arches.</td>
<td>4. Combinations of 2 or more above.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5. Combinations of 4 and others.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Animal bunching.</td>
<td>3. Wagons.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Combinations of above.</td>
<td>3. Tractors.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Flumes.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Chutes.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7. Combinations of above.</td>
<td></td>
</tr>
<tr>
<td>Region</td>
<td>Methods</td>
<td>Products</td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------------------------------------------------------------------------</td>
<td>-----------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Northeast (White pine, yellow birch, hemlock, beech, spruce, and Basswood)</td>
<td>1. Tractor skidding. 2. Horse skidding.</td>
<td>Saw logs, pulpwood, veneer logs, cross ties, piling and fuelwood.</td>
<td></td>
</tr>
<tr>
<td>Eastern Canada (Spruce and balsam fir, white and red pines, yellow birch, hard maple and cedar.)</td>
<td>1. Horse skidding. 2. Tractors.</td>
<td>Pulpwood, saw logs, fuelwood, cross ties, veneer logs, poles, mine props and piling.</td>
<td></td>
</tr>
</tbody>
</table>
Webster (39) developed an economic analysis of timber-production possibilities in Elk State Forest in Pennsylvania. His analysis proved efficient for ranking management opportunities and for determining priorities within a given budget, but of limited value in determining how large the budget should be. Webster's work may be used as a guide in the identification of feasible alternatives in a particular forest region.

**Measurement**

Scientific management of forests requires reliable data. In particular, information is required with reference to the measurement of: (a) continuous forest inventory, (b) operating costs and revenues, (c) structural relationships, and (d) marketing data.

**Continuous Forest Inventory.** Inventory control methods used in forestry are quite refined. The company that owns 500,000 acres of woodlands may have a permanent sample of one-fifth acre plots throughout the property. The number of plots needed to give a reliable representation of the whole forest is statistically determined. Experience shows that one sample plot for every 500 acres may give satisfactory results. On these sample plots all individual trees are identified and complete information on each is recorded on IBM cards. Data recorded include species, diameter, height, condition, sawlog and pulpwood content, and so on. In addition, a separate card is prepared summarizing a wealth of information about the fifth-acre plot itself. The objective of these permanent sample plots is to record changes between two successive inventories. The plots themselves are harvested exactly as the surrounding forest. All plots are reinventoried every five years. One fourth of the sample plots are
remeasured annually. With the use of an electronic computer and the vast array of information available from the IBM cards, the management has at its fingertips accurate information on timber volumes in various categories, growth, mortality and its causes, or any other type of information recorded on the punched cards in the inventory.

Forestry Abstracts (25 No. 3951; 27 No. 1077) show that at least 105 CFI Systems are currently in operation covering more than 85 million acres; a further 67 CFI Systems are planned. Data are given on costs, remeasurement intervals, recording methods, uses, and limitations.

Operating Costs and Revenues. The determination of financial yield from forest operations is not simple. Since both costs and revenues occur at various times during the rotation, provision must be made for the effect of time value of money. Let us assume that the schedule of operations during the rotation is as follows (all figures refer to one acre):

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>Land</td>
<td>L</td>
<td></td>
<td>$100</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Planting</td>
<td>P</td>
<td></td>
<td>$ 25</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>Weeding</td>
<td>W</td>
<td></td>
<td>$ 20</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>Thinning (1)</td>
<td>A</td>
<td>$ 40</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>Thinning (2)</td>
<td>B</td>
<td>$ 60</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>Thinning (3)</td>
<td>C</td>
<td>$ 75</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>25</td>
<td>Harvesting</td>
<td>H</td>
<td>$400</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>All</td>
<td>Annual Expense</td>
<td>E</td>
<td></td>
<td>$2/year</td>
</tr>
</tbody>
</table>
The present worth (PW) of these transactions can be written as follows:

\[ PW = -L - P \left( pf' - i\% - 1 \right) - \frac{W(pf' - i\% - 5)}{1} + A(pf' - i\% - 10) \]
\[ + B(pf' - i\% - 15) + C(pf' - i\% - 20) + H(pf' - i\% - 25) \]
\[ - E(pf - i\% - 25) \]

where

\[(pf' - i\% - n) = \text{present work factor for single payments}\]
\[(pf - i\% - n) = \text{present work factor for a uniform series of payments}.\]

It is apparent that the present worth of the net revenues depends on five major factors:

1. Prices realized from the sale of thinnings and of final harvest.
2. Physical yield of timber thinned and harvested.
3. Cost of land, planting, weeding, thinning, harvesting and annual expense.
4. Choice of the interest rate \(i\%\).
5. Choice of the length of rotation \(n\).

A few general comments on the nature of the operating costs and revenues will be in order.

The cost of land \((L)\) covers the initial cost of buying the land together with the expense which may be required to put it in a condition fit for planting. It is important when possible to get good land because it may be more profitable to plant good land costing $100 per acre than poor land costing next to nothing.

The cost of planting \((P)\) includes the cost of site preparation, drainage, fencing (where necessary), plants and planting. The cost of planting varies with the size of the plants, the method of planting
(particularly spacing), the nature of soil, and the efficiency of organization.

The cost of weeding (W) is necessitated by the rank weed vegetation which otherwise suppresses the young trees.

Thinning (A, B, and C) consists of taking out certain species and generally smaller sizes that should be harvested first or would be injured or broken later in the normal logging operations. Thinning is sometimes referred to as prelogging and is considered to be an income producing operation.

Harvesting (H) consists of preparation of logs for transport (felling and bucking), minor log transportation (skidding), loading for transport, and major land or water transportation.

Annual expenses (E) involve items such as administration, forest protection and taxes.

Careful measurement of the above factors is essential for the financial success of forest enterprise.

**Structural Relationships.** The financial structure of a business enterprise is usually stated by the fundamental equation of accounting: assets = liabilities plus net worth. A typical balance sheet follows the form of this equation and is supposed to represent the financial structure of a business at a particular date. An important technique of financial statement analysis is that of measuring the ratios of the significant parts of a balance sheet for the purpose of testing whether they are reasonable.

The use of the ratio analysis is not widely practiced in forest management. However, Fitzgerald(13) applied this method to the analysis
of forest product industries. Sixteen applicable ratios are discussed in his paper, and averages are given for a sample taken from members of the Michigan Forest Product Cooperative.

Marketing Data. It was pointed out earlier that the present worth of net revenues obtainable from forest operations depends on prices realized from the sale of forest products. A few decades ago the problem of pricing forest products was relatively simple since in many product lines the variety of colors, sites, and shapes was kept at a minimum. As the size of the market has grown, segments of the market have become large enough to justify the development of separate products to meet specific needs. As an example, let us examine the list of products manufactured by the Brown & Wall Company:

<table>
<thead>
<tr>
<th>Product Category</th>
<th>Varieties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumber (4 - Square)</td>
<td>22</td>
</tr>
<tr>
<td>Softwood plywood</td>
<td>16</td>
</tr>
<tr>
<td>Laminated products</td>
<td>8</td>
</tr>
<tr>
<td>Hardwood products</td>
<td>14</td>
</tr>
<tr>
<td>Manufactured panels</td>
<td>20</td>
</tr>
<tr>
<td>Paper products</td>
<td>13</td>
</tr>
<tr>
<td>Pulp and paperboard</td>
<td>16</td>
</tr>
<tr>
<td>Containers and cartons</td>
<td>4</td>
</tr>
<tr>
<td>Other products</td>
<td>14</td>
</tr>
</tbody>
</table>

The above example shows clearly that marketing data are used by the Brown & Wall Company as a primary basis for planning and organizing the entire company operation.
Analysis

Analysis of forest operations rests on two foundations, namely:
(a) forest economics, and (b) use of computers.

Forest Economics. Forest economics provides a body of knowledge
that helps guide every forestry activity in the right direction. It deals
mainly with costs, returns and profitability of forestry as related to
(1) environmental conditions (e.g. public policies, marketing practices,
prices, rates of interest), and (2) operation of the forest enterprise.
It supplies answers to such problems as the economics of planting, thin-
ning, harvesting, and wood product utilization.

A comprehensive source of information on forest economics can be
found in a selected bibliography of the subject compiled by Professor
Rumsey (32) of New York State College of Forestry. This bibliography con-
tains references published since the beginning of 1963, and classified
under the following main headings: (1) Forestry economics at large;
(2) Agents of production in forestry; (3) Forest management; (4) Forest
industry; (5) Forest - product demand, prices, marketing and trade, and
(6) Transport. The latest issue of this bibliography has 50 pages. It
lists, in a special appendix, 81 theses and dissertations on forest eco-
nomics in progress at North American Universities.

Readers wishing to gain some experience in economics of forestry
are referred to a manual of 36 exercises published by Duerr and Chris-
tiansen (11).

An important phase of forest economics is the determination of
profitability. For example, using the data shown on page 11, the follow-
ing values of the present worth will be obtained when the interest rate
is taken at 4%, 6%, and 8% respectively:
<table>
<thead>
<tr>
<th>Item No.</th>
<th>Year</th>
<th>Symbol</th>
<th>PW at 4%</th>
<th>PW at 6%</th>
<th>PW at 8%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>L</td>
<td>-$100.00</td>
<td>-$100.00</td>
<td>-$100.00</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>P</td>
<td>-$24.10</td>
<td>-$23.60</td>
<td>-$23.10</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>W</td>
<td>-$16.36</td>
<td>-$14.80</td>
<td>-$13.40</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>A</td>
<td>+$26.80</td>
<td>+$21.60</td>
<td>+$18.00</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>B</td>
<td>+$33.00</td>
<td>+$24.35</td>
<td>+$18.00</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>C</td>
<td>+$33.80</td>
<td>+$25.50</td>
<td>+$15.10</td>
</tr>
<tr>
<td>7</td>
<td>25</td>
<td>H</td>
<td>+$150.00</td>
<td>+$93.20</td>
<td>+$54.00</td>
</tr>
<tr>
<td>8</td>
<td>All</td>
<td>E</td>
<td>-$31.24</td>
<td>-$25.56</td>
<td>-$20.76</td>
</tr>
</tbody>
</table>

**Total PW**

|                  | +$71.90 | +$0.69  | -$52.16 |

The above example illustrates three aspects of profitability analysis. First, it can be seen that profitability of forestry is very sensitive to the magnitude of interest rates used in the determination of present worth. At present, most of the forestry profitability calculations are based on 4% rate of interest. Since inflation is progressing at the rate of about 3% per year it is clear that 4% interest rate used in discounting calculations is grossly inadequate. The second point is that time dimension is of critical importance in forest operations. Our example is based on a total period of 25 years with some operations occurring every five years. This assumption is only one of many possible management strategies. The third point is that in order to optimize the problem of profitability, hundreds and perhaps thousands of calculations should be made for varying prices, costs and yields. Such calculations can be most effectively carried out on digital computers.
Use of Computers. Use of computers in forestry can be classified under three headings, namely: (a) silvicultural applications, (b) forest economics applications, and (c) system simulation.

Silvicultural applications of computers involve: (1) statistical analysis of experiments and surveys, (2) compilation of forest inventory, (3) construction of volume and yield tables, and (4) silvicultural research. The analysis of results of designed experiments and surveys is not limited to forestry and there are many papers discussing this application of computers. Notable among these is a set of programs known as the "B.M.D. package" \(^{(9)}\). There are many published case histories on the use of computers in forestry inventory. For example, Rivard \(^{(30)}\) describes the experience of the Canadian International Paper Company in this field. The construction of volume and yield tables has been generally recognized as being a straight-forward computer task. Cunia \(^{(8)}\) has summarized the essential features of volume-table calculations from a statistical point of view and the implementation of these calculations has been brought up to a successful conclusion by many workers in forest mensuration. The use of computer-based simulation is one of the most interesting aspects of silvicultural research. Smith et al. \(^{(35)}\) considered the distribution of mortality in plantations and natural stands, and simulated the effects of various patterns of plant mortality on the computer. The model developed gives valuable data about optimum spacing of seedlings. In another study, Stiteller and Borden \(^{(36)}\) developed a Fortran II program for generation of forest models for an even-aged and uneven-aged oak stands and two mixed hardwood stand.
The impact of computers on forest economics has been considerable. Chappelle\(^{(5)}\) wrote a general paper on the use of simulated models in forest economics and outlined the steps in the model-building process. Actual economic models have been described by Row\(^{(31)}\), Howard\(^{(19)}\), and Chappelle\(^{(6)}\). Row\(^{(31)}\) developed a program in Fortran designed to evaluate simultaneously six complex forest investment alternatives and to perform analyses repetitively for many cost and price situations. Howard\(^{(19)}\) developed a Fortran IV program for use with IBM 7090 computer for computing the bare land values and optimum rotation of a stand of trees by means of a Faustman formula for various combinations of regeneration costs, interest rates and production functions. Chappelle\(^{(6)}\) developed a large-scale model by means of which individual trees are evaluated for cutting in a thinning operation and where the objective is to maximize net revenue per unit of time. The decision process is examined from the viewpoint of four types of timber growing firms: pulpwood stumpage sellers; sawtimber stumpage sellers; firms producing dressed and graded lumber; and firms producing dressed and graded lumber and saleable bark-free slabs. Inter-firm variations in tree growth, logging and milling costs, and product recoveries are examined by computer simulation. This study exemplifies the potential of the computer approach in the formulation of economic guides to decision-making in forest management.

System simulation approach to forest management problems appears to be very promising. It was originated by O'Regan et al.\(^{(29,14)}\). These two papers represent a significant contribution to the state of the art. In the first paper, Gould and O'Regan discuss the economic consequences
of 70 years of forest management by two alternative policies, the first aimed at sustained yields and second responsive to price changes. The model is activated by a "wood generator" and incorporates harvesting and maintenance costs, interest on loans and deposits, and fire and storm damage. In the second paper, O'Regan et al. discuss an approach to two problems faced by foresters: (1) the search for effective methods of gathering data, and (2) the development of simulation to clarify management options. The first problem is mainly concerned with sampling, and especially with the objective of maximizing the amount of information about the forest obtainable on a fixed budget, or alternatively minimizing the cost of a given level of information. The second problem relates to the construction of realistic forest model regarded as "wood generator". Drawing on the work of Balderston (3), Hitch (16), Hoag (17), Hufschmidt (20), Maas (26), and Simon (34), the authors succeeded in developing a sophisticated "wood generator" known as HUFFS (Harvard University Fortran Forest Simulator). This program includes the effects of site, stocking, species, and quality variables, and responds to silvicultural practices as well as to harvesting methods and management policies.

Clutter and Bamping (7) extended the work of Gould and O'Regan (14) in a model involving a considerably larger enterprise and a somewhat more sophisticated treatment of the biological and economic factors involved. The simulation program is designed for an IBM 7094 computer and is known as FOPS (Forestry Operations Simulator).

In the field of wood utilization, two interesting studies should be mentioned. Manetsch (27) describes simulation studies of the U.S. softwood plywood industry. Wodzinski and Hahm (40) describe a Fortran 63 program for use with the CDC 1604 computer for optimization of sawmill production and of cutting schedules.
As a final comment on system simulation, mention should be made of the work of Professor Watt who published two important books dealing with systems analysis in ecology\(^\text{(37)}\), and resource management\(^\text{(38)}\).

Optimization

We will now discuss some aspects of optimum policies in forest management. An optimal policy is a set of values decided for certain variables under the control of management. The primary objective of forest management is to conserve and maintain the soil and an appropriate volume of growing stock. These two resources constitute the basic natural forest capital which can yield perpetual timber crops. The continued maintenance of this capital can be assured by applying "best" policies to the following objectives:

1. Protection and improvement of soil productivity.
2. Concentration of efforts on better sites.
3. Improvement of the composition of the forest by favoring the most valuable and fast-growing species.
4. Developing optimum spacing and distribution of trees so that each has room to grow but no space is wasted.
5. Removal of substandard trees in order to avoid waste.
6. Removal of over-mature trees in order to channel soil fertility to younger trees.
7. Weeding in order to eliminate the suppression of valuable young trees by inferior vegetation.
8. Protection of forest from fire.
9. Protection of forest from damage by disease, insects and animals.
10. Protection of immature trees from damage during logging.

11. Developing optimal thinning methods for the dual purpose of profitably harvesting the wood removed and increasing the growth of the trees which remain.

12. Developing optimal harvesting systems for felling, skidding and transportation operations.

13. Developing optimal programs of forest products utilization.

14. Developing optimal scheduling of forest operations.

15. Developing criteria for the optimal rate of return.

We can see that the problem of finding optimum policies in forest management is very complex. There are many heterogeneous variables (i.e. silvicultural, technological and economic) of varying degree of importance and interdependence, which have to be optimized under the constraints of a limited budget and limited information.

Research dealing with optimal policies in forest management can be grouped into three classes: (1) Special problem studies, (2) linear programming studies, and (3) dynamic programming studies.

Special problem studies in forest management can be exemplified by the work published by the U.S. Department of Agriculture\(^{(41)}\), Anderson\(^{(1)}\), Baird\(^{(2)}\), Farquhar\(^{(12)}\), Greenleaf\(^{(15)}\), Jones\(^{(22)}\), Kurimura\(^{(25)}\), and Muhlenberg\(^{(28)}\). Agricultural Handbook No. 304\(^{(41)}\) describes a procedure (including a computer program) for economic evaluation of reforestation and stand improvement projects, and indicates a method for allocating available funds to projects that will yield the highest rate of financial return. Anderson\(^{(1)}\) developed a model for determining priorities of investment in improvement of timber and stands under Georgia conditions.
It was found that stand improvement required a low net capital outlay per acre and, under suitable conditions, yielded high rates of return in short investment periods. Baird\(^{(2)}\) developed methods for (1) making an economic stratification of existing commercial forest land; (2) evaluating the potential investment returns of alternative wood-growing processes on the same land; and (3) defining the existing and potential forest economy in terms of the general economy of a region. Farquhar\(^{(12)}\) developed an approach to the economic allocation and use of forestry resources. An input-output relationship is studied in a simplified form using only four output groups (i.e., stumpage, forage, recreation, and water), and the conclusions are summarized in the form of a linear program for obtaining maximum output. The problems of decision-making are discussed in detail. Greenleaf\(^{(15)}\) conducted a financial analysis of the timber production and recreation potential of a consolidated area of about 110,000 acres under different levels of use. Jones\(^{(22)}\) used the principle of "guiding rate of interest" to study the profitability of three types of forest ownership. He concludes that "marginal farmers" require 12% rate of interest, whereas "commercial farmers" and institutional owners" require 6% and 3% respectively. Kurimura\(^{(25)}\) developed a theoretical analysis of "guiding rate of interest" in determining financial rotations. Muhlenberg\(^{(28)}\) proposed a method for considering forest multiple-use alternatives within the framework of the joint-output models of traditional economic theory. Examples are given with reference to a two-product case (i.e., wood, deer). A four-product matrix (i.e., wood, deer, water, amenity) is considered in a review of more complex multiple relationships.
Linear programming studies in forest management can be exemplified by the work of Donnelly (10) and Kidd et al. (24). Donnelly (10) describes the construction of a linear programming model that represents conditions in a hypothetical woodlands department in Maine. Kidd et al. (24) discuss the application of linear programming to the regulation of timber harvests from a given forest. The main conclusion is that linear programming can be used to provide optimum solutions to forest regulation problems. Linear programming can also enable a forest manager to predict the effect of a change in managerial constraints.

Dynamic programming is a relatively new discipline dealing with the optimization of the sequential processes of decision. These processes are closely related to processes of adaptation in a changing environment. Hool (18) developed what is probably the most complex tool thus far proposed for the optimization of forest management policies. His method combines dynamic programming with Markov chains in order to analyze the effects of incompletely controlled events on the behavior of renewable natural resources. The method allows, at any point during the planning interval, and for any condition of the system, the determination of the optimum control activity to achieve some specified management objective. The continuous forest inventory system can produce some of the data for such a program.

### Decision

In the opinion of psychologists and economists, the conversion of objectives into criteria is the most difficult problem facing a decision-maker. Professor Kaufman (23) states that the choice of a criterion of decision requires not only a profound investigation of the problem itself
but also an analysis of the person or the group having the power of decision. We will illustrate this important statement by means of two examples.

**Example 1.** A company is planning to install a data processing device. Three machines, 1, 2, and 3 are suitable with the following information available:

\[
\begin{align*}
I_1 &= 400, \\
I_2 &= 700, \\
I_3 &= 1000,
\end{align*}
\]

\[
\begin{align*}
e_1 &= 60, \\
e_2 &= 36, \\
e_3 &= 24
\end{align*}
\]

where \( I_n \) = investment cost

\( e_n \) = annual operating expense

To simplify the problem, it is assumed that the three machines will be compared on the basis of the capitalized cost method which requires the use of the following expression:

\[
\text{Capitalized Cost} = \frac{I_n}{i} + \frac{e_n}{i}
\]

where \( i \) = rate of interest indicating the minimum attractive rate of return.

Three executives, A, B, and C, have been asked to submit their recommendations. Executive A is conservative by nature and selects \( i = 0.03 \). Executive B is more progressive and selects \( i = 0.06 \). Executive C is aggressive and selects \( i = 0.12 \).

The summary of capitalized cost calculations computed by the three executives appears below:

<table>
<thead>
<tr>
<th>Executive A</th>
<th>Executive B</th>
<th>Executive C</th>
</tr>
</thead>
<tbody>
<tr>
<td>( i = 0.03 )</td>
<td>( i = 0.06 )</td>
<td>( i = 0.12 )</td>
</tr>
<tr>
<td>Device 1: $400 + $60/0.03= $2,400</td>
<td>$400 + $60/0.06= $1,400</td>
<td>$400 + $60/0.12= $900</td>
</tr>
</tbody>
</table>
Device 2: $700 + $36/0.03 = $700 + $36/0.06 = $700 + $36/0.12 = $1,900 = $1,300 = $1,000

Device 3: $1,000 + $24/0.03 = $1,000 + $24/0.06 = $1,000 + $24/0.12 = $1,800 = $1,400 = $1,200

If it is desired to minimize the capitalized cost then we are faced with the following recommendations:

Executive A: Machine 3
Executive B: Machine 2
Executive C: Machine 1

All three recommendations are perfectly valid. They are all different because each of the three executives has a different sense of values. We are faced with the problem of resolving which executive has the "best" sense of values.

Example 2. A company wishes to choose between two plant locations. The management wants to minimize the following three objectives: (1) distance to markets, (2) unit cost of production, and (3) labor turnover. Let us suppose that the following information is available:

<table>
<thead>
<tr>
<th>Distance to Markets</th>
<th>Unit Cost</th>
<th>Labor Turnover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location 1</td>
<td>50 Miles</td>
<td>$4</td>
</tr>
<tr>
<td>Location 2</td>
<td>100 Miles</td>
<td>$3</td>
</tr>
</tbody>
</table>

Two executives, A and B, have been asked to submit independent evaluations. In this case, the units are not commensurate and some weighting method has to be used. Suppose now that the two executives rate the objectives as follows:

<table>
<thead>
<tr>
<th>Distance to Market</th>
<th>Unit Cost</th>
<th>Labor Turnover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executive A</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Executive B</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>
Executive A obtains the following preference functions for the two locations:

\[ A(1) = (50)^3 (4)^1 (20)^1 = 10,000,000 \text{ (miles $\times$)} \]
\[ A(2) = (100)^3 (3)^1 (10)^1 = 60,000,000 \text{ (miles $\times$)} \]

Executive B obtains the following results:

\[ B(1) = (50)^1 (4)^3 (20)^1 = 64,000 \text{ (miles $\times$)} \]
\[ B(2) = (100)^1 (3)^3 (10)^1 = 9,000 \text{ (miles $\times$)} \]

Thus, executive A favors location 1, whereas executive B favors location 2.

These two examples show that, theoretically, objectives and criteria can be related to each other by means of value functions or preference functions. However, the formulation of value functions is one of the most difficult problems of scientific decision-making. Value functions are influenced by physiological, temperamental and environmental factors. For example, an older single person will generally have short-term aims, whereas a young married man will be planning ahead for at least a generation. Some persons would rather spend their money immediately, whereas others tend to make long-term investments. Some tend to be politically liberal whereas other tend to be conservative.

Professor Kaufman summarizes the difficulty of the problem by asking the following question:

"In the age of the flexible world, when everything is being reappraised in less than a generation, when sociological context, social mystiques, philosophical ideas, individual and mass psychology have lost even a temporary stability, what measuring instruments can we use that will also be acceptable to other members of our social group?"
He has no answer but suggests that:

"Logic and a concern for human relationships should be the two basic ingredients of human nature, the latter giving us the good intentions which the former allows us to put into practice."

**Sequential Review**

The last step in the heuristic problem solving is the sequential review of past decisions. The sequential processes of decision-making imply adaptation to changing conditions.

The general pattern of adaptive behavior could be compared to the behavior of the driver of a car, with the exception that the events happen in a discrete manner. Whereas the driver adapts himself continuously to the new conditions, a decision-maker in a business enterprise revises his decisions periodically. In addition, the problems facing the decision-maker are much more difficult because the changes in his environment may be caused by competitive decision-makers. Professor Kaufman\(^{(23)}\) states that in our present state of knowledge we do not have any theoretical methods applicable to the study of such complex, through very real situations. The work of Hool\(^{(18)}\), referred to in the earlier part of this paper, indicates a possible approach to this problem. In the absence of reliable analytical methods it is possible to acquire some experience by means of simulation techniques.

A forest-based enterprise is a dynamic system with complex flows of materials, information, energy, manpower and money. The dynamic changes affecting forestry in the future will result from a number of factors such as general economic growth, advancing technology, and changing
managerial concepts. Since it is difficult to make exact predictions of the developments occurring between the present and the year 2000 - the correct approach seems to be that of sequential revision of future goals.

The problem of response to change can be illustrated by the experience of the Brown & Wall Company during the decade between 1956 and 1965. The pertinent data are tabulated below:

<table>
<thead>
<tr>
<th>Item</th>
<th>1965</th>
<th>1956</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sales:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulp, paper and pulpwood</td>
<td>$210 MM</td>
<td>$106 MM</td>
</tr>
<tr>
<td>Containers and cartons</td>
<td>$164 MM</td>
<td>$115 MM</td>
</tr>
<tr>
<td>Lumber</td>
<td>$180 MM</td>
<td>$178 MM</td>
</tr>
<tr>
<td>Softwood plywood</td>
<td>$ 58 MM</td>
<td>$ 16 MM</td>
</tr>
<tr>
<td>Hardwood plywood</td>
<td>$ 42 MM</td>
<td>--------</td>
</tr>
<tr>
<td>Manufactured panels</td>
<td>$ 14 MM</td>
<td>$ 5 MM</td>
</tr>
<tr>
<td>Logs and other products</td>
<td>$ 61 MM</td>
<td>$ 19 MM</td>
</tr>
<tr>
<td><strong>Total Sales</strong></td>
<td><strong>$721 MM</strong></td>
<td><strong>$438 MM</strong></td>
</tr>
<tr>
<td>Other income</td>
<td>$ 13 MM</td>
<td>$ 9 MM</td>
</tr>
<tr>
<td><strong>Total Income</strong></td>
<td><strong>$734 MM</strong></td>
<td><strong>$447 MM</strong></td>
</tr>
<tr>
<td>Total costs</td>
<td>$651 MM</td>
<td>$382 MM</td>
</tr>
<tr>
<td><strong>Net Income</strong></td>
<td><strong>$ 83 MM</strong></td>
<td><strong>$ 65 MM</strong></td>
</tr>
</tbody>
</table>
Additional Data:

<table>
<thead>
<tr>
<th></th>
<th>1956</th>
<th>1965</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total assets</td>
<td>$808 MM</td>
<td>$574 MM</td>
</tr>
<tr>
<td>Wages and salaries</td>
<td>$226 MM</td>
<td>$184 MM</td>
</tr>
<tr>
<td>Number of employees</td>
<td>33,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Number of stockholders</td>
<td>24,000</td>
<td>7,000</td>
</tr>
</tbody>
</table>

Significant ratios:

<table>
<thead>
<tr>
<th></th>
<th>1956</th>
<th>1965</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total sales/total assets</td>
<td>0.894</td>
<td>0.594</td>
</tr>
<tr>
<td>Net income/total assets</td>
<td>0.103</td>
<td>0.113</td>
</tr>
<tr>
<td>Total sales/No. of employees</td>
<td>$21,850</td>
<td>$21,900</td>
</tr>
<tr>
<td>Total assets/No. of employees</td>
<td>$24,500</td>
<td>$28,700</td>
</tr>
<tr>
<td>Total wages/No. of employees</td>
<td>$6,850</td>
<td>$5,200</td>
</tr>
</tbody>
</table>

Several observations can be made on the changes which occurred between 1956 and 1965. In particular we note:

(1) Growth and diversification of sales effort.
(2) Significant improvement in the efficiency of marketing methods as indicated by about 50% increase in the total sales/total assets ratio.
(3) Virtually constant sales per employee.
(4) About 20% decrease in the level of investment per employee.
(5) More than 30% increase in the average wages and salaries.
(6) Slight reduction in the rate of return on the total investment.

The decrease in the level of investment per employee is particularly interesting because the company's operations became highly mechanized and computerized in the period between 1956 and 1965.
Concluding Remarks

The area of forest resource utilization is still in its infancy and much remains to be done. This paper reviewed some of the techniques of scientific decision-making in the management of forest resources. The concepts presented have been drawn from the ideas of several interrelated disciplines such as heuristic-oriented mathematics, general system theory, systems analysis, resource system modeling, forest economics and computer simulations. In addition, the policies of a large-scale forest-product industrial concern have been described as an illustration of a practical application of the theoretical concepts.
REFERENCES


A DYNAMIC MODEL OF THE SOUTHERN PAPER INDUSTRY

1950 - 2000

by

Pietro A. Fenu

INTRODUCTION

The objective of the present work is to attempt a dynamic approach to the simulation of a model for the paper industry in the South, covering a period of fifty years from 1950 to 2000.

The use of the DYNAMO compiler is suggested by its successful applications in industrial, economic, social, political, environmental, and military problems, where it has demonstrated its possibilities as a powerful tool in the simulation of dynamic systems.

Time constraints made impossible a more complete collection of data, samples, etc., which if carefully examined with standard statistical techniques could have brought to a more precise formulation of the relationships between different factors involved. The expansion of the model through sectors not covered in this work, and the sensitivity tests of different values of assumed constants and growth patterns, are among the further steps required in order to give the model full efficiency.

DYNAMIC OF THE SYSTEM

The structure of the paper industry discloses two main connections with the outside world, roughly represented by the following diagram:
The general situation of the national economy influences the paper industry in its present and future production plans, while it in turn is influenced by the share of GNP produced by the industry. Forest management (of any kind or level) affects the behavior of the industry as supplier of raw materials, while the industry attempts its own control by means of various policies of planting, pricing, and land-ownership determinations.

The dynamic impulse of this closed system is given by the population growth, which together with the consumption rate, brings about the production forecasts and related considerations.

The DYNAMO flow diagram is shown on figure 1.

PAPER AND PAPER BOARD CONSUMPTION

The U.S. resident population is taken under assumption "C" of the Bureau of Census, which is the most reasonable according to the trend of the past few years.

The data used in the DYNAMO program for the equations 59A POP.K = TABLE (PTAB, YEAR. K, 0, 50, 5)
C PTAB*=...............  
corresponds to the following Table 1:
### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>POP</td>
<td>Population</td>
</tr>
<tr>
<td>CONS</td>
<td>Consumption per capita</td>
</tr>
<tr>
<td>DEM</td>
<td>Demand of paper</td>
</tr>
<tr>
<td>GNPC</td>
<td>GNP per capita</td>
</tr>
<tr>
<td>INC</td>
<td>Increment of GNPC (4.42%)</td>
</tr>
<tr>
<td>GNP</td>
<td>Gross National Product</td>
</tr>
<tr>
<td>PAPS</td>
<td>Sales (paper)</td>
</tr>
<tr>
<td>PRC</td>
<td>Price per ton</td>
</tr>
<tr>
<td>USP</td>
<td>Utilization (cords per ton of paper)</td>
</tr>
<tr>
<td>DEMP</td>
<td>Demand of pulpwood</td>
</tr>
<tr>
<td>GRS</td>
<td>Growth factor in Southern Pulpwood Production</td>
</tr>
<tr>
<td>SPULP</td>
<td>Southern Pulpwood Production</td>
</tr>
<tr>
<td>ACRES</td>
<td>Acres, paper company forests</td>
</tr>
<tr>
<td>CFG</td>
<td>Incremental factor</td>
</tr>
<tr>
<td>GRFA</td>
<td>Growth factor in land value</td>
</tr>
<tr>
<td>VLAND</td>
<td>Land value (acre)</td>
</tr>
<tr>
<td>TOLAN</td>
<td>Total value of company acres</td>
</tr>
<tr>
<td>GREX</td>
<td>Growth factor in acre expenditures</td>
</tr>
<tr>
<td>AEXP</td>
<td>Acre expenditures</td>
</tr>
<tr>
<td>TEXP</td>
<td>Total expenditures</td>
</tr>
<tr>
<td>TAX</td>
<td>Taxes</td>
</tr>
<tr>
<td>ABCD</td>
<td>Boxcar function</td>
</tr>
<tr>
<td>TMI</td>
<td>Capital invested</td>
</tr>
<tr>
<td>VTM1</td>
<td>Value of capital invested (30 years)</td>
</tr>
<tr>
<td>VLI</td>
<td>Value of company acres (30 Years)</td>
</tr>
<tr>
<td>TOTB</td>
<td>Return</td>
</tr>
<tr>
<td>CORD</td>
<td>Cords</td>
</tr>
<tr>
<td>PRI</td>
<td>Price per cord</td>
</tr>
</tbody>
</table>
Table 1. Population (x 1000)

<table>
<thead>
<tr>
<th>Year</th>
<th>Population (x 1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td>152271</td>
</tr>
<tr>
<td>1955</td>
<td>165931</td>
</tr>
<tr>
<td>1960</td>
<td>180684</td>
</tr>
<tr>
<td>1965</td>
<td>194572</td>
</tr>
<tr>
<td>1970</td>
<td>206039</td>
</tr>
<tr>
<td>1975</td>
<td>219366</td>
</tr>
<tr>
<td>1980</td>
<td>235212</td>
</tr>
<tr>
<td>1985</td>
<td>252871</td>
</tr>
<tr>
<td>1990</td>
<td>270770</td>
</tr>
<tr>
<td>1995</td>
<td>289632</td>
</tr>
<tr>
<td>2000</td>
<td>309520</td>
</tr>
</tbody>
</table>

The values of the consumption per capita of paper and paperboard are given by a smoothed exponential graph, constructed considering the 1.91% average annual growth shown during the years 1950 to 1965. This graph is reported on Figure 2, the equations are:

59A CONS.K = TABLE (CTAB, YEAR.K, 0, 50, 5)

C CTAB*=.............

The demand for paper and paperboard is given by:

13A DEM.K = (POP.K)(CONS.K)(COST2)

C COST2 = 0.0005

The GNP per capita is computed at a regular growth of 4.42%, average rate from 1950 to 1965.

1L GNPC.K = GNPC.J + (DT)(INC.JK + 0)

12R INC.KL = (GNPC.K)(COST1)

C COST1 = 0.0442

Initial condition in 1950 is

6N GNPC = COST4

C COST4 = 1878
Figure 2. Consumption per capita

<table>
<thead>
<tr>
<th>Year</th>
<th>lbs/capita</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td>319.1</td>
</tr>
<tr>
<td>1955</td>
<td>363.2</td>
</tr>
<tr>
<td>1960</td>
<td>381.4</td>
</tr>
<tr>
<td>1965</td>
<td>452.7</td>
</tr>
<tr>
<td>1970</td>
<td>500.5</td>
</tr>
<tr>
<td>1975</td>
<td>555.5</td>
</tr>
<tr>
<td>1980</td>
<td>615.0</td>
</tr>
<tr>
<td>1985</td>
<td>698.0</td>
</tr>
<tr>
<td>1990</td>
<td>780.5</td>
</tr>
<tr>
<td>1995</td>
<td>865.0</td>
</tr>
<tr>
<td>2000</td>
<td>980.5</td>
</tr>
</tbody>
</table>
The GNP is given by

$$12A\quad GNP.K = (POP.K)(GNPC.K)$$

It is related to the total amount of sales for paper and paperboard through the equations

$$12A\quad PAPS.K = (COST3)(GNP.K)$$

$$C\quad COST3 = 0.02883$$

This relation comes from an observed almost constant share of the GNP by the paper industry, as shown in the following TABLE 2. The constant factor is the mean value.

<table>
<thead>
<tr>
<th>Year</th>
<th>SALES (x 10^6)</th>
<th>% of GNP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1953</td>
<td>10413</td>
<td>2.85</td>
</tr>
<tr>
<td>1954</td>
<td>10481</td>
<td>2.87</td>
</tr>
<tr>
<td>1955</td>
<td>11808</td>
<td>2.96</td>
</tr>
<tr>
<td>1956</td>
<td>12843</td>
<td>3.06</td>
</tr>
<tr>
<td>1957</td>
<td>13114</td>
<td>2.97</td>
</tr>
<tr>
<td>1958</td>
<td>12975</td>
<td>2.90</td>
</tr>
<tr>
<td>1959</td>
<td>14403</td>
<td>2.97</td>
</tr>
<tr>
<td>1960</td>
<td>14619</td>
<td>2.90</td>
</tr>
<tr>
<td>1961</td>
<td>14856</td>
<td>2.85</td>
</tr>
<tr>
<td>1962</td>
<td>15770</td>
<td>2.81</td>
</tr>
<tr>
<td>1963</td>
<td>16263</td>
<td>2.75</td>
</tr>
<tr>
<td>1964</td>
<td>17116</td>
<td>2.70</td>
</tr>
<tr>
<td>1965</td>
<td><strong>19385</strong></td>
<td>2.84</td>
</tr>
<tr>
<td>1966</td>
<td>21765</td>
<td>2.94</td>
</tr>
</tbody>
</table>

The level

$$1L\quad YEAR.K = YEAR.J + (DT)(COST6 + 0)$$

$$C\quad COST6 = 1$$

is used as time-variable for tabulating data during the program.

The average price per ton of paper and paperboard is given by
20A \( PRC.K = \frac{PAPS.K}{DEM.K} \)

All the values in \$ are at current prices, and over the long run they heavily reflect the inflationary effect.

**NATIONAL PULPWOOD CONSUMPTION AND SOUTHERN PRODUCTION**

Data concerning pulpwood consumption, and production of paper and paperboard, discloses an amazing increase in rate of utilization (cords/ton). This phenomenon can be related to different causes; the explanation here assumed is that of a diminishing age of the trees utilized, due to the sharp demand increase. Consequence of this decrease is a reduction in efficiency of the chemical process. The following Table 3 covers the period 1950 to 1965.

<table>
<thead>
<tr>
<th>Year</th>
<th>PULPWOOD (x 1000 cords)</th>
<th>PAPER AND BOARD (tons)</th>
<th>UTILIZATION (cords/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td>23626217</td>
<td>24300178</td>
<td>0.972</td>
</tr>
<tr>
<td>1951</td>
<td>26521795</td>
<td>26048000</td>
<td>1.018</td>
</tr>
<tr>
<td>1952</td>
<td>26460730</td>
<td>24413212</td>
<td>1.083</td>
</tr>
<tr>
<td>1953</td>
<td>28140922</td>
<td>26540000</td>
<td>1.060</td>
</tr>
<tr>
<td>1954</td>
<td>29002415</td>
<td>26656631</td>
<td>1.088</td>
</tr>
<tr>
<td>1955</td>
<td>33356476</td>
<td>30140000</td>
<td>1.106</td>
</tr>
<tr>
<td>1956</td>
<td>35748582</td>
<td>31428000</td>
<td>1.137</td>
</tr>
<tr>
<td>1957</td>
<td>35745543</td>
<td>30678853</td>
<td>1.165</td>
</tr>
<tr>
<td>1958</td>
<td>35248367</td>
<td>30775000</td>
<td>1.145</td>
</tr>
<tr>
<td>1959</td>
<td>38690519</td>
<td>34007000</td>
<td>1.137</td>
</tr>
<tr>
<td>1960</td>
<td>40484683</td>
<td>34461000</td>
<td>1.174</td>
</tr>
<tr>
<td>1961</td>
<td>41191483</td>
<td>35585000</td>
<td>1.195</td>
</tr>
<tr>
<td>1962</td>
<td>44070226</td>
<td>37684000</td>
<td>1.169</td>
</tr>
<tr>
<td>1963</td>
<td>46435000</td>
<td>39231000</td>
<td>1.183</td>
</tr>
<tr>
<td>1964</td>
<td>49710000</td>
<td>41478000</td>
<td>1.198</td>
</tr>
<tr>
<td>1965</td>
<td>52827505</td>
<td>44049000</td>
<td>1.199</td>
</tr>
</tbody>
</table>
The equations giving the pulpwood consumption are:

12A \[ \text{DEMP.K} = (\text{DEM.K})(\text{USP.K}) \]

59A \[ \text{USP.K} = \text{TABLE(UTAB,YEAR.K,0,50,5)} \]

C \[ \text{UTAB*} = \quad \ldots \ldots \ldots \ldots \ldots \ldots \]

The data for the UTAB* are from the graph shown in Figure 3, made under the assumption of asymptotic pattern in the phenomenon earlier referenced. Normalization of trees age and size, is a consequence of the increasing percentage of pulpwood coming from scheduled plantations.

Southern pulpwood production had developed, during the past 35 years, the trend shown in Figure 4. As trial assumption, this trend is supposed to hold during the period 1950 to 2000. The equations are:

28A \[ \text{SPULP.K} = (\text{COST8})\text{EXP(GRS.K)} \]

12A \[ \text{GRS.K} = (\text{YEAR.K})(\text{COST9}) \]

C \[ \text{COST8} = 12.5E6 \]

C \[ \text{COST9} = 0.061 \]

**LAND POLICY**

An increase in the land ownership of the paper industry characterizes its policy during the past two decades. This policy is suggested by the necessity of keeping a hedge against increases in pulpwood prices and assuring the availability of raw material required by the huge future demand.

The many competitive uses of the land (urban, industrial, recreational, etc.) created by a booming population, forecasts a stationary or even decreasing amount of acres devoted to commercial forest land, while the share owned by the companies seems destined to increase. The follow-
Figure 3. Utilization

<table>
<thead>
<tr>
<th>Year</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td>1.018</td>
</tr>
<tr>
<td>1955</td>
<td>1.106</td>
</tr>
<tr>
<td>1960</td>
<td>1.165</td>
</tr>
<tr>
<td>1965</td>
<td>1.200</td>
</tr>
<tr>
<td>1970</td>
<td>1.238</td>
</tr>
<tr>
<td>1975</td>
<td>1.265</td>
</tr>
<tr>
<td>1980</td>
<td>1.285</td>
</tr>
<tr>
<td>1985</td>
<td>1.305</td>
</tr>
<tr>
<td>1990</td>
<td>1.318</td>
</tr>
<tr>
<td>1995</td>
<td>1.330</td>
</tr>
<tr>
<td>2000</td>
<td>1.338</td>
</tr>
</tbody>
</table>
Figure 4. Growth in Southern Pulpwood Production

<table>
<thead>
<tr>
<th>Selected years</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
<td>20270300</td>
</tr>
<tr>
<td>1958</td>
<td>20233000</td>
</tr>
<tr>
<td>1960</td>
<td>23551000</td>
</tr>
<tr>
<td>1962</td>
<td>25586300</td>
</tr>
<tr>
<td>1964</td>
<td>28825800</td>
</tr>
<tr>
<td>1966</td>
<td>33061200</td>
</tr>
</tbody>
</table>
ing data in Table 4, concerning the South, show this trend during the period 1956 to 1966.

Table 4.

<table>
<thead>
<tr>
<th>Year</th>
<th>Acres Commercial Forest Land</th>
<th>Acres Paper Companies Forests</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
<td>193288000</td>
<td>18492400</td>
</tr>
<tr>
<td>1958</td>
<td>193288000</td>
<td>20385600</td>
</tr>
<tr>
<td>1960</td>
<td>193288000</td>
<td>21809600</td>
</tr>
<tr>
<td>1962</td>
<td>197469000</td>
<td>21888500</td>
</tr>
<tr>
<td>1964</td>
<td>201069000</td>
<td>23058500</td>
</tr>
<tr>
<td>1966</td>
<td>201069000</td>
<td>25169300</td>
</tr>
</tbody>
</table>

Acres owned by paper companies are given by the equations

1L \[ ACR\_K = ACR\_J + (DT)(CFG\_JK + 0) \]

12R \[ CFG\_KL = (COS10)(ACRES\_K) \]

C \[ COS10 = 0.032 \]

where COS10 is the mean value of the percentage increase during the period 1956 to 1966.

Assuming an average initial value of $65 per acre, and given an exponential growth as from 1940 to 1959, the total value of land owned by companies is computed through the equations

28A \[ VLAND\_K = (NLAND)\exp(GRFA\_K) \]

C \[ NLAND = 65 \]

12A \[ GRFA\_K = (GRCOE)(YEAR\_K) \]

C \[ GRCOE = 0.055 \]

12A \[ TOLAN\_K = (VLAND\_K)(ACRES\_K) \]
CAPITAL INVESTED

The importance of capital in timber growing results from the length of the production process. With a harvesting cycle-period of 30 years, the annual total expenditures in improving company forests are given by the equations

28A \[ A_{\text{EXP.K}} = (N_{\text{EXP}}) / EXP(G_{\text{REX.K}}) \]

C \[ N_{\text{EXP}} = 0.705 \]

12A \[ G_{\text{REX.K}} = (G_{\text{RC}})(Y_{\text{EAR.K}}) \]

C \[ G_{\text{RC}} = 0.047 \]

12A \[ T_{\text{EXP.K}} = (A_{\text{EXP.K}})(A_{\text{CRES.K}}) \]

The assumption of an exponential path of the expenditures per acre is based on the 1956 - 1966 data shown in Table 5.

Table 5.

<table>
<thead>
<tr>
<th>Year</th>
<th>TOTAL EXPENDITURES</th>
<th>EXPENDITURES PER ACRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
<td>16779200</td>
<td>0.9084</td>
</tr>
<tr>
<td>1958</td>
<td>25792500</td>
<td>1.2652</td>
</tr>
<tr>
<td>1960</td>
<td>34301600</td>
<td>1.5727</td>
</tr>
<tr>
<td>1962</td>
<td>26818900</td>
<td>1.2252</td>
</tr>
<tr>
<td>1964</td>
<td>32610100</td>
<td>1.4142</td>
</tr>
<tr>
<td>1966</td>
<td>36092300</td>
<td>1.4339</td>
</tr>
</tbody>
</table>

Taxes are computed on a general 4% basis, and given by

12A \[ T_{\text{AX.K}} = (T_{\text{PER}})(T_{\text{OLAN.K}}) \]

C \[ T_{\text{PER}} = 0.04 \]

The capital represented by land value, expenditures, and taxes, in a given year

8A \[ T_{\text{MI.K}} = T_{\text{OLAN.K}} + T_{\text{EXP.K}} + T_{\text{AX.K}} \]
is loaded in a boxcar function

6A \[ A_{BCD} \times 2.K = T_{MI}.K \]

37B \[ A_{BCD} = BOXLIN(31,1) \]

and computed at its actual value after a 30 years period, with com-
pound interest of 6%

12A \[ V_{TMI}.K = (A_{BCD} \times 31.K)(INTC) \]

C \[ INTC = 5.743 \]

This value, together with the actual value of land given by

6A \[ A_{BCE} \times 2.K = A_{CRES}.K \]

37B \[ A_{BCE} = BOXLIN(31,1) \]

12A \[ V_{LI}.K = (A_{BCE} \times 31.K)(V_{LAND}.K) \]

is used in order to determine, after a period of 30 years, what
should be the total return from the related harvesting crop.

7A \[ T_{TMB}.K = V_{TMI}.K - V_{LI}.K \]

Assuming a production per acre of 2 cords, in order to obtain the
total return covering expenditures and interest, the stumpage market-price
should be given by

12A \[ C_{ORD}.K = (APR)(A_{CRES}.K) \]

C \[ APR = 2 \]

20A \[ P_{RI}.K = T_{TMB}.K/C_{ORD}.K \]

RESULTS

The values obtained are tabulated with a time interval of one year.
The most representative figures are then plotted on two diagrams.

From time 0 (1950) to time 35 (1985) the results show quite accept-
able trends. Then some situations become explosive. Trial runs, with
smoothing factors, or under different assumptions, could lead to control these situations. The data available for check (1950 - 1966), and reported in the previous pages, match well with the results obtained through the DYNAMO program. The results available from other forecasts, such as the projected production of paper and board in the year 2000 (149 millions versus 151.75), seem to support the stated assumptions.

The price trend, determined under the minimum goal for a profitable investment (capital return and 6% interest), indicates how the almost constant stumpage price, which characterized the past ten years, sooner or later will rise considerably above such levels. Before 1980 the price is set equal to zero only for programming reasons.

The present trend of the Southern pulpwood production will result in equalization with the national consumption levels in 1989. This over-capacity, together with the results concerning company acres and prices, seems to indicate a totally changes structure of the supply system. The transformation which took place in other sectors of the industry and resulted in almost total control of the sources of raw materials by the manufacturer (steel, copper, rubber, etc.), will probably reach the paper industry in the coming decade.
<table>
<thead>
<tr>
<th>0.04</th>
<th>177.6m</th>
<th>69.0m</th>
<th>100.0m</th>
<th>150.0m</th>
<th>200.0m</th>
<th>250.0m</th>
<th>300.0m</th>
<th>350.0m</th>
<th>400.0m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>177.6m</td>
<td>69.0m</td>
<td>100.0m</td>
<td>150.0m</td>
<td>200.0m</td>
<td>250.0m</td>
<td>300.0m</td>
<td>350.0m</td>
<td>400.0m</td>
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<tr>
<td>0.0</td>
<td>177.6m</td>
<td>69.0m</td>
<td>100.0m</td>
<td>150.0m</td>
<td>200.0m</td>
<td>250.0m</td>
<td>300.0m</td>
<td>350.0m</td>
<td>400.0m</td>
</tr>
<tr>
<td>0.0</td>
<td>177.6m</td>
<td>69.0m</td>
<td>100.0m</td>
<td>150.0m</td>
<td>200.0m</td>
<td>250.0m</td>
<td>300.0m</td>
<td>350.0m</td>
<td>400.0m</td>
</tr>
<tr>
<td>0.0</td>
<td>177.6m</td>
<td>69.0m</td>
<td>100.0m</td>
<td>150.0m</td>
<td>200.0m</td>
<td>250.0m</td>
<td>300.0m</td>
<td>350.0m</td>
<td>400.0m</td>
</tr>
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<td>0.0</td>
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<td>100.0m</td>
<td>150.0m</td>
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<td>250.0m</td>
<td>300.0m</td>
<td>350.0m</td>
<td>400.0m</td>
</tr>
<tr>
<td>0.0</td>
<td>177.6m</td>
<td>69.0m</td>
<td>100.0m</td>
<td>150.0m</td>
<td>200.0m</td>
<td>250.0m</td>
<td>300.0m</td>
<td>350.0m</td>
<td>400.0m</td>
</tr>
<tr>
<td>0.0</td>
<td>177.6m</td>
<td>69.0m</td>
<td>100.0m</td>
<td>150.0m</td>
<td>200.0m</td>
<td>250.0m</td>
<td>300.0m</td>
<td>350.0m</td>
<td>400.0m</td>
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<tr>
<td>0.0</td>
<td>177.6m</td>
<td>69.0m</td>
<td>100.0m</td>
<td>150.0m</td>
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<tr>
<td>0.0</td>
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<tr>
<td>0.0</td>
<td>177.6m</td>
<td>69.0m</td>
<td>100.0m</td>
<td>150.0m</td>
<td>200.0m</td>
<td>250.0m</td>
<td>300.0m</td>
<td>350.0m</td>
<td>400.0m</td>
</tr>
</tbody>
</table>
APPENDIX D
MINIMIZATION OF TRANSPORTATION COSTS
FOR THE HAULING OF PULPWOOD BY RAIL

by

John C. Bacon
This paper was done in fulfillment of the requirement of I.E. 451-3, a Senior course at the Georgia Institute of Technology, for scholastic credit. However, the source material, primary information, and professional guidance were derived largely from participating members of the Southern Executives Association. Therefore, the basic purpose of this work was to provide the members of the S.E.A. with useful information relating directly to their objectives in gaining an insight to the harvesting and transportation of pulpwood from a systems standpoint.

The information contained herein is not intended to represent the operating characteristics of any company or group of companies within the pulpwood industry. All models and cases are hypothetical, being based on average industry statistics only to the extent that the following discussions will assume a more feasible identity.
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INTRODUCTION .................................................. 1
PROPOSAL ....................................................... 3
ANALYSIS ......................................................... 4
  Definition of the Activity Set ......................... 4
  Definition of the Item Set .............................. 4
  Determination of the Exogeneous Flows ............... 5
  Statement of Problem .................................. 5
SOLUTION ....................................................... 7
APPLICATION ................................................... 11
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Figure 1: "Graphical Representation of Model"
Figure 2: "Solution Matrices - Distribution Problem"
Figure 3: "Starting Matrix - Weighted Distribution"

Table 1: "Transportation Cost Array"
Table 2: "Schedule of Woodyard Capacities"
Table 3: "Interpretation of Solution"
INTRODUCTION

An examination of the Southern Pines Producing Area, a twelve state area, reveals a total of 87 mills using pulpwood as the primary input resource. These mills are serviced by a total of 838 outlying concentration woodyards - stockpile and shipping centers to which the cut pulpwood is brought to be loaded onto railroad cars and hauled to the mill. This phase of activity is common to all the pulpwood industry, with various mills hauling form 50% to 90% of their pulpwood by rail. Thus, with the total output of the Southern Region expected to reach 41 million cords by the end of 1968, the economic significance of rail transportation to the industry is obvious. Moreover, it is acknowledged that the greatest variable in wood cost per cord at the mill is the freight rate paid for its transportation from the woodyard. For a typical mill's procurement area (which may have a span of 250 miles) the cost per cord at the woodyard seldom varies over $.50 on the usual $18 to $21 scale.

It is a common sight in an area of pine forests to watch two freight trains, each with a heavy percentage of wood rack cars, pass each other heading for a point near the other train's origin. To the uninitiated it may seem strange that pulpwood is hauled 150 miles through pine forests to a mill in the midst of these forests, while the wood surrounding that mill is being cut for shipment to a second mill which itself is 100 miles away.

There are, however, many factors which influence the location of a pulp mill and the subsequent determination of its supplying woodyards.
All mills are not in the heart of their resource areas, but may be located on the seacoast, thus having to range inland to find adequate sources of pulpwood. Other inland mills may be in sparse timber areas and thus have to go far afield to secure enough wood to keep the mill operating at capacity. Perhaps available labor patterns are such that nearby timber would be difficult to harvest with any assurance of regularity. Local economic factors, weather conditions, rail service facilities, terrain—all these conditions must be carefully weighed by the procurement manager when selecting woodyard locations. Even then his job is not completed. The presence of competitors' woodyards in an area may eliminate the region for consideration.

Thus it is understandable that as the pulpwood industry in the South grew, and more and more mills were constructed, the patterns of woodyards became quite complex, with a great deal of "interlocking" or overlapping of procurement areas developing. Pulpwood companies purchased large tracts of land for wood supply, and these, too, became spread over a large area. These are some of the reasons, then, for a tree standing 50 miles from one mill being cut and shipped 100 miles to a different mill at a freight cost of several dollars per cord.

The effect of this is obvious. The entire industry is suffering from a general inefficiency in this phase of activity because almost everyone must pay the higher rail rates. The reasons for this inefficiency may have been sufficiently valid in the past to escape scrutiny, but they need now to be placed under the harsh and revealing light of increasing costs and the necessity for better utilization of resources. The pulpwood industry as a whole has spent considerable time and money on the problem
of reducing procurement costs, and has generally been pleased with a cost reduction measured in cents per cord obtained through the application of harvesting techniques improvement, minimization of handling, etc. Certainly, a reduction of several cents per cord is significant when evaluated in terms of the 33 million cords produced in the South in 1966, but reductions of several dollars per cord are remaining unrealized. The minimization of transportation costs on a large scale could release great sums of money with which to expand operations, open new procurement areas, and more effectively utilize both natural and capital resources.

PROPOSAL

It shall be the purpose of this paper to explore the rail transportation of pulpwood from woodyard to mill with the objective of minimizing the costs of transportation. The approach taken will be from the systems viewpoint, with the area under study to be represented by a mathematical model or models. A method or methods will be developed to be used as an illustration of the conclusions, and to serve as a tool for the evaluation of economic alternatives to indicate an optimum solution.

No attempt will be made to present a short course in model formulation or linear programming techniques. Since this work is of an exploratory nature, no attempt will be made to develop a computer program for the results of this analysis, although a discussion of efforts in this direction is included.
ANALYSIS

Definition of the Activity Set

The system under study consists of an established pulpwood mill(s) capable of processing either chips or roundwood. This mill was constructed to have a rated output which must be met in order to insure economic operation. Therefore it must be serviced by woodyards with sufficient aggregate supply capacity to satisfy mill demands. The mill demand quantities will be adjusted to exclude that proportion of trucked wood reaching the mill, so that the only transportation function is that of rail movement. Activity shall be considered to begin at the woodyards after the wood has been loaded onto rail cars. Activity shall end after transportation to the mill is complete.

The cost of pulpwood at the mill is comprised of stumpage cost, handling and storage costs, and transportation costs. These transportation or hauling costs are a function of distance almost exclusively. For model construction purposes, the assumption will be made that all rail links are on a "one haul line", i.e., no charges are included for switching of cars from one line to another. Therefore, the two most meaningful criteria for woodyard locations are supply capacity and distance from the mill (transportation cost).

Definition of the Item Set

The item to be measured in all cases is the cord of wood, which is the actual unit upon which the freight rates, as well as other cost factors, are based.
Determination of the Exogeneous Flows

The woodyard - rail transport - pulp mill model as presented here will have no net inputs or outputs of items between the system, as a whole, and exterior regions.

Determination of the input-output coefficients in the form of factors of proportionality between activity levels and internal flows will be determined in following paragraphs.

Statement of Problem

The problem formulation may be generally stated as follows: There exist certain sources of supply (woodyards) geographically distributed, and certain other locations (pulp mills) where a need exists for the materials available at the sources. Depending upon the relative geographical locations and freight rates, there is a certain cost associated with transporting a unit of wood from a given source to a given destination. Given these transportation costs, the resources at each source, and the requirements at each destination, the problem is to determine the minimum cost shipping program. The solution will state what quantities are to be shipped from each source to each destination.²

This problem statement immediately suggests some form of the distribution problem widely encountered in the literature of linear programming. There are a number of advantages in applying a standardized algorithm in this case, the most obvious being ease of computation and ready availability of reference material.

Application of the standard transportation (distribution) problem imposes a constraint that should now be investigated. Specifically, the
\[ \sum_{i=1}^{m} a_i = \sum_{j=1}^{n} b_j \]  

(1)

The assumptions are made here, and will be extended throughout, that all functions are subject to the conditions of proportionality, nonnegativity, additivity, and linear objective function.

In reality, there is nothing exact about the shipment of pulpwood to a mill from its various woodyards. The quantities vary dependent upon weather conditions, supply of labor, and other factors; the often followed rule is to simply cut and ship as many cords as possible. The mill maintains a sizeable stockpile of wood to fill in during slack harvesting periods. Thus, in the short run of, say, one month, the foregoing supply-demand relationships may not actually be satisfied from the shipment standpoint. However, consider now a year’s span of time. Even though there may be variations within that interval, the net result is that the mill gets enough wood to satisfy its demand (capacity). An entirely correct model would substitute a mathematical function for the supply factor. This function could, with proper inputs, accurately approximate the actual situation where weather and other elements come into play. For the present, however, the supply-demand relationships will be used as initially formulated.
SOLUTION

Consider the network of woodyards and mills depicted in Figure 1. The system shown, though purely hypothetical, could represent any one of a number of regions in the South. The woodyards, six in number, do not by any means represent the total number of yards required by the three mills shown; they could well be yards under consideration to add to existing supply from other locations. The increase could be needed because of expansions in mill pulping facilities. The stipulation is made here that the yards are already built and in service, thus having fixed locations. For the present, the assumption will be made that the mills all belong to one company which wishes to minimize rail transportation costs in acquiring the facilities. The demand figures to be set forth for each of the mills are the marginal demands only, i.e., the amount by which each mill wishes to increase production.

It is emphasized here that this model is simplified for the purpose of illustration only. The computational techniques involved are valid regardless of the rank of the matrix. An actual situation could very well have a 6 x 120 matrix - obviously not feasible for hand calculation, but applicable to computer solution. This topic of extension to computer programming will be discussed later.

Figure 1 is a graphical representation of the model, which will now be formulated algebraically. The three mills denoted by 1, 2, and 3 have corresponding marginal increase requirements of 27,000, 31,000, and 24,000 cords per year. They are to be supplied by woodyards whose capacities (based on past history) are shown in Table 2. Table 1 is a cost
TABLE 1

<table>
<thead>
<tr>
<th></th>
<th>$C_{11}$ = $2.25</th>
<th>$C_{21}$ = 1.50</th>
<th>$C_{31}$ = 1.70</th>
<th>$C_{41}$ = 2.60</th>
<th>$C_{51}$ = 2.05</th>
<th>$C_{61}$ = 4.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{12}$</td>
<td>1.85</td>
<td>$C_{22}$ = 2.60</td>
<td>$C_{23}$ = 3.00</td>
<td>$C_{24}$ = 2.05</td>
<td>$C_{52}$ = 3.75</td>
<td>$C_{62}$ = 2.05</td>
</tr>
<tr>
<td>$C_{13}$ = 4.10</td>
<td>$C_{23}$ = 3.20</td>
<td>$C_{33}$ = 2.40</td>
<td>$C_{43}$ = 2.25</td>
<td>$C_{53}$ = 1.75</td>
<td>$C_{63}$ = 2.60</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 2

<table>
<thead>
<tr>
<th>WOODYARD</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPACITY CORDS/YEAR</td>
<td>13,000</td>
<td>11,000</td>
<td>16,000</td>
<td>18,000</td>
<td>9000</td>
<td>15,000</td>
</tr>
</tbody>
</table>
array of freight rates from each yard to each mill. If the number of cords to be shipped from yard \( i \) (\( i = 1-6 \)) to mill \( j \) (\( j = 1-3 \)) is denoted by \( x_{ij} \), then the function to be minimized (the objective function) will be:

\[
Z = \sum_{i=1}^{6} \sum_{j=1}^{3} c_{ij} x_{ij}
\]

(2)

Additional constraints are encountered in the form of

\[
\sum_{j=1}^{3} x_{ij} \leq s_i
\]

(3)

i.e., the amount shipped cannot exceed the supply available at that yard.

\[
\sum_{i=1}^{6} x_{ij} \geq d_j
\]

(4)

i.e., mill requirements must be satisfied.

The matrices and solution appear in Figure 2. The method of solution is straightforward, appearing in any book on linear programming. (An excellent treatment on the basic transportation method can be found in *Linear Programming and Extensions*, by George B. Dantzig.) For this reason the work is not explained in detail. The final tableau does represent an optimal solution, and these results are displayed in Table 3.

An extension of the preceding method, often referred to as the "weighted distribution" problem, has certain characteristics which are of interest when considering the woodyard to pulp mill transportation problem. In the previous model, the assumption was made that a given woodyard would be capable of supplying equal quantities of wood to all mills.
**FIGURE 2**

<table>
<thead>
<tr>
<th>$x_{11}$</th>
<th>$x_{12}$</th>
<th>$x_{13}$</th>
<th>$a_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{11}$</td>
<td>$c_{12}$</td>
<td>$c_{13}$</td>
<td>$u_1$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$x_{21}$</th>
<th>$x_{22}$</th>
<th>$x_{23}$</th>
<th>$a_2$</th>
</tr>
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<tr>
<td>$c_{21}$</td>
<td>$c_{22}$</td>
<td>$c_{23}$</td>
<td>$u_2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$x_{31}$</th>
<th>$x_{32}$</th>
<th>$x_{33}$</th>
<th>$a_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{31}$</td>
<td>$c_{32}$</td>
<td>$c_{33}$</td>
<td>$u_3$</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>$x_{41}$</th>
<th>$x_{42}$</th>
<th>$x_{43}$</th>
<th>$a_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{41}$</td>
<td>$c_{42}$</td>
<td>$c_{43}$</td>
<td>$u_4$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$x_{51}$</th>
<th>$x_{52}$</th>
<th>$x_{53}$</th>
<th>$a_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{51}$</td>
<td>$c_{52}$</td>
<td>$c_{53}$</td>
<td>$u_5$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$x_{61}$</th>
<th>$x_{62}$</th>
<th>$x_{63}$</th>
<th>$a_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{61}$</td>
<td>$c_{62}$</td>
<td>$c_{63}$</td>
<td>$u_6$</td>
</tr>
</tbody>
</table>

$\begin{align*}
b_1 & \quad b_2 & \quad b_3 & \quad \text{IMPLICIT PRICES} \\
V_1 & \quad V_2 & \quad V_3 & \quad \end{align*}$

**Table 1**

<table>
<thead>
<tr>
<th></th>
<th>13 K</th>
<th></th>
<th>13 K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.25</td>
<td>1.85</td>
<td>4.10</td>
</tr>
</tbody>
</table>

1. $x_{21} = 11K$  
   2. $x_{31} = 16K$

<table>
<thead>
<tr>
<th></th>
<th>18 - $\Theta$</th>
<th>0 + $\Theta$</th>
<th>18K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.60</td>
<td>2.05</td>
<td>2.25</td>
</tr>
</tbody>
</table>

|    | 2.05          | 3.75         | 1.75 | 1.75 |

|    | 4.50          | 2.05         | 15 - $\Theta$ (Drop) 2.60 | 15K |

<table>
<thead>
<tr>
<th></th>
<th>15K</th>
</tr>
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<tbody>
<tr>
<td>$b_1 = 27K$</td>
<td>31K</td>
</tr>
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<table>
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<tr>
<th></th>
<th>24K</th>
</tr>
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<tbody>
<tr>
<td>$\Theta = 15$</td>
<td>-0.70</td>
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TABLE 3

<table>
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<tr>
<th>WOODYARD</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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</thead>
<tbody>
<tr>
<td>CAPACITY</td>
<td>13,000</td>
<td>11,000</td>
<td>16,000</td>
<td>18,000</td>
<td>9,000</td>
<td>15,000</td>
</tr>
<tr>
<td>CORDS/</td>
<td>YEAR</td>
<td>CORDS/</td>
<td>YEAR</td>
<td>CORDS/</td>
<td>YEAR</td>
<td>CORDS/</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>11,000</td>
<td>16,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>13K</td>
<td>0</td>
<td>0</td>
<td>3000</td>
<td>0</td>
<td>15,000</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>15,000</td>
<td>9,000</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

OPTIMAL SOLUTION

3

TABLE 3
in the system. In practice, however, this situation is sometimes altered by any of a number of factors. The most prevalent condition is that when a single rail line connects the woodyard with two mills, for example, but a "two-line haul" would be required for transportation to the third mill. This would decrease the number of cords shipped at the given overall cost, because of the expense of transfer from one line to the next. Or perhaps the Railroad involved claims that they simply cannot supply the required number of rack cars to satisfy the demand; here again, the supply function would be altered by an external factor. The weighted distribution problem can take into account these variations, and still yield an optimum solution with a minimum of computation.

The following quantities will be defined:

\[ a_i = \text{total number of cords available at woodyard of type } i. \]

("Type" of woodyard could be a distinction as to a company owned and operated yard, a dealer operated yard, etc., or it could refer to the actual company owning the yard; it is a flexible definition.)

\[ b_j = \text{total number of cords required at mill } j. \]

\[ c_{ij} = \text{cost of transportation per cord from woodyard to mill.} \]

\[ p_{ij} = \text{total number of cords that can be shipped by one woodyard } i \text{ assigned to mill } j. \]

\[ x_{ij} = \text{total number of cords from yard } i \text{ assigned to mill } j. \]

Thus the associated objective function is:

\[
\text{minimize } z = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} x_{ij} \quad \& \quad x_{ij} \geq 0 \quad (5)
\]

and the corresponding constraints are written:
\[
\sum_{j=1}^{n} x_{ij} \leq a_i, \quad j = 1, 2, \ldots n \tag{6}
\]

and
\[
\sum_{i=1}^{m} p_{ij} x_{ij} \geq b_j, \quad i = 1, 2, \ldots n \tag{7}
\]

From (6), the total quantity of wood available must not exceed the total shipped, and from (7), the total quantity from each yard times the amount assigned must meet or exceed mill demand.

The starting matrix set-up for this problem is illustrated in Figure 3, with inputs being based on data presented in the first model (Figure 1). As seen from the tableau the second woodyard, for example, could supply the first mill with 10,000 cords per year, and mills 2 and 3 with 11,000 cords per year.

The Dual of the weighted distribution problem is: Find \(u_i\), \(v_j\) and maximum \(q\) such that
\[
u_i + p_{ij} v_j x_{ij} \tag{8}
\]

where
\[
\sum_{i=1}^{m} u_i a_i + \sum_{j=1}^{n} v_j b_j = q(\text{Max.})
\]

The criterion of optimality is given by a set of \(x_{ij}\) satisfying the primal problem if there are \(u_i\) and \(v_j\) satisfying the Dual such that:
**FIGURE 3**

**STARTING MATRIX**

<table>
<thead>
<tr>
<th>( \mathbf{X} )</th>
<th>( a_i = 13 )</th>
<th>( b_j )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_{11} )</td>
<td>13</td>
<td>1.75</td>
</tr>
<tr>
<td>( x_{12} )</td>
<td>13</td>
<td>1.50</td>
</tr>
<tr>
<td>( x_{13} )</td>
<td>11</td>
<td>2.50</td>
</tr>
</tbody>
</table>

| \( x_{21} \) | 10 | 2.00 |
| \( x_{22} \) | 11 | 1.50 |
| \( x_{23} \) | 11 | 1.50 |

| \( x_{31} \) | 14 | 3.75 |
| \( x_{32} \) | 15 | 1.75 |
| \( x_{33} \) | 16 | 1.75 |

| \( x_{41} \) | 18 | 1.25 |
| \( x_{42} \) | 16 | 3.00 |
| \( x_{43} \) | 17 | 1.50 |

| \( x_{51} \) | 9 | 1.00 |
| \( x_{52} \) | 9 | 2.25 |
| \( x_{53} \) | 8 | 2.25 |

| \( x_{61} \) | 15 | 1.75 |
| \( x_{62} \) | 13 | 3.75 |
| \( x_{63} \) | 15 | 1.50 |

| \( v_1 \) | 27 | 31 |
| \( v_2 \) | | 24 |
| \( v_3 \) | | |
\[ x_{ij} > 0 \rightarrow u_i + p_{ij} v_j = c_{ij} \]

and

\[ u_i + p_{ij} v_j < c_{ij} \rightarrow x_{ij} = 0 \] (9)

A complete treatment of the preceding topic may be found in *Linear Programming and Extensions*, by George B. Dantzig.

**APPLICATION**

The problems just presented were set forth in the mode of the transportation algorithm not only because of the suitability of the method, but also because of the ease of solution. Despite, however, the relative simplicity of calculation, the linear program becomes a massive system of equations when tailored to the actual needs of problems of the type discussed. For example, no man or calculating department could ever hope to solve a 200 x 30 matrix. Therefore, the use of computers must be considered as the only feasible method of solution. Their primary characteristics of speed, accuracy, and memory are essential.

A number of facts are now pointed out to the advantage of the analyst. First is the fact that there are no division operations in the two methods discussed. Since division is by far the slowest of arithmetic calculations on the computer, valuable machine time is minimized. Second, the answers given appear as integers, providing that the inputs are also integers. And third, because of the frequency of recurrence and structural peculiarities of the problem, standard routines have been developed which further allow reduction in both programming and computer time.
It is recommended that problems of the type stated be programmed according to the Ford-Fulkerson flow method because of that method's advantages for large matrices. The minimum machine requirements include a 4K storage, and problem restrictions are:

\[ n \leq 600, \text{ no restrictions on } m. \]

\[ 618 + m(n + 1) + 2(m + n) \leq \text{ high speed storage available.} \]

A 220 x 30 matrix with numbers not exceeding \(10^{10} - 1\) in magnitude can be solved (exclusive of input and output) in five minutes on an IBM 704 machine.\(^3\)

**DISCUSSION**

The relationships between pulp mills and their supplying woodyards which have been dealt with have had one common element, in that the supply points (woodyards) have been fixed in geographical location, but not constrained as to allocation of output. Rather, the problem has been to determine the optimum distribution of wood from a number of yards.

The obvious conclusion in this case is that to apply the mathematical methods presented, and open the door to substantial cost reductions, the hundreds of woodyards in the South must be considered as a fluid and flexible supply. Some method or methods must be devised to "free-up" the pulpwood output of a given yard so that the proper allocation of the wood can be realized, and the wasteful and inefficient practice of hauling wood for hundreds of miles discontinued. If this plan can be accomplished by a mutual overall cost to the pulpwood industry as a whole, with every individual company benefitting.
FOOTNOTES


BIBLIOGRAPHY


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SUMMARY

The rapid advances in technology which have occurred during recent years have resulted in machines that perform many tasks much more efficiently than ever before. Such machines, however, are usually complex and are expensive to acquire and operate. Operational costs are affected greatly by the direct and indirect costs of maintaining the equipment. Reliability has become a very important factor in reducing maintenance costs by reducing failure rates. Maintainability is a related factor that is concerned with restoring a system to effective useable condition after a failure occurs. It has not yet received sufficient attention from the manufacturers or purchasers of pulpwood harvesting equipment.

The failure rate of many kinds of equipment may be predicted by use of the exponential distribution function. Analysis of failure data recorded for a power saw is shown to follow such a distribution. In this report, the lognormal distribution is found to be applicable for describing empirical repair time data that was collected for a multifunction pulpwood harvester.

The report indicates characteristics that pertain to reliability and maintainability such as availability, downtime, and the different types of maintenance. Graphical aids are used to describe reliability and maintainability quantitatively.
CHAPTER I

INTRODUCTION

The Maintainability Problem

The ability of a system to be maintained—that is, retained in or restored to effective useable condition—is often as important to the system's usefulness as is its ability to perform its intended function. Even though this might be so, system designers are often too deeply concerned with the system's performance features. In a study of maintainability problems, Rigby and Cooper (1) noted that "The primary goal of the designer is to obtain an output that will satisfy a series of specific performance requirements. Additional requirements, such as maintainability*, are apparently seen as secondary to this goal." This seems to be especially true when applied to pulpwood harvesting equipment. The wide variety of equipment in this field encourages a designer to meet the competition by producing equipment that will "do more faster." He has not been sufficiently aware of the need of or logic for a maintainability requirement. This is due in part to the acceptance of such equipment by purchasers who themselves are uninformed about the techniques and concepts associated with maintainability. The result is that comparatively minor pressure is fed back to the designer for improving maintainability. Such improvements are often seen as burdensome, irksome, and costly and under the stress of time and cost pressures, then, maintainability requirements are among those most likely to be compromised.

* Maintainability is a characteristic of design and installation which is expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time when the maintenance is performed in accordance with prescribed procedures and resources.
The rapid advances which have occurred in technology in recent years, together with the increasing use of automation, have placed greater emphasis on the need for efficient and effective design in terms of system performance, cost, and schedule of operation. The preceding statement is obviously true but too often such a declaration is taken as being applicable only to sophisticated, complex, and glamorous equipment. This is unfortunate because it is now recognized that, in many cases, a more effective system from a cost viewpoint can be obtained by trading off some other design feature in order to obtain an easier maintained system; and for those systems which are required to have a long operational life with repeated usage, maintainability is indeed as significant a parameter as reliability.

This means that improvements in system effectiveness might be achieved by expending time and money toward providing higher maintainability in harvesting equipment design, rather than trying to obtain great improvement in reliability, and that this may be more readily feasible within the present state-of-the-art of this equipment. Contractors who manufacture very complex systems for the Department of Defense have recently begun to concern themselves with finding means for injecting maintainability design requirements into early design phases much as reliability design requirements are now considered. This concern is based on studies that show alarming increases in system operating costs that are due to failures and maintenance problems. Hall(2) stated that one-third of all Air Force operating cost is for maintenance, and one-third of all Air Force personnel are engaged in maintenance even though

* Reliability is the probability that an item will perform its intended function for a specified interval under stated conditions.
a large portion of the maintenance is done by contract. In the forest products industry, for every dollar spent on acquisition of harvesting and handling equipment, it has been predicted that one dollar and a quarter will be spent on maintenance over the equipment's useful life(3). These are maintenance costs only, and are exclusive of gas, oil, operator's wages, insurance, licenses and so forth. It is readily seen therefore, that an original investment to increase maintainability during system development may produce a manifold saving in operating costs and a substantial improvement in system effectiveness.

A recent Air Force report on system effectiveness (4) states:

The high cost and complexity of modern military systems require the most efficient management possible to avoid wasting significant resources on inadequate equipment. Efficient systems management depends on the successful evaluation and integration of numerous different but interrelated systems characteristics such as reliability, maintainability, performance, and cost. If such evaluation and integration is to be accomplished in a scientific rather than intuitive manner, a method must be formulated to assess quantitatively the effects of each system characteristic on overall system effectiveness (4).

Maintainability is today receiving increasing attention from both users and producers of systems, for the most part as a result of the emphasis given by the Department of Defense. Such industry groups as IEEE, ASME, and SAE have formed maintainability working groups and committees and have sponsored symposia and sessions at national and regional meetings on the subject of maintainability.

**System Effectiveness**

Considerable attention has been paid to the relationship of maintainability to other system parameters in recent years, and many concepts have been proposed. Of these concepts, Systems Effectiveness has perhaps
been elevated to the position of highest rank. The notion of effectiveness and measures of effectiveness are not new. Such measures have been used for many years for determining how well a device performs or for comparing one device with another. The use of figure-of-merit comparison is well known; for example, rated-horsepower of an engine and mach number for aircraft speed.

The extension to measuring system performance on some overall job task basis is, however, relatively recent. Many of the operations research or systems analysis efforts which have become prominent starting in World War II were initiated in order to find quantitative methods for assessing and optimizing a system's effectiveness. Cost effectiveness considerations have become a major item of system design in defense and space systems.

A system is designed to perform a function or set of functions (meet a need). System Effectiveness is a measure of how well the system performs its intended function. In order to be a useful measure, it is necessary to express system effectiveness in quantitative terms. A number of such measures have been derived, most utilizing a probability scale.

One of the more useful definitions of Systems Effectiveness and the one used throughout this report is: Systems Effectiveness is the probability of the extent to which a system may be expected to achieve a set of specific job requirements and is a function of operational readiness, dependability, and capability. This definition may be expressed in probability terms as:
SE = ODC

where

SE is the probability that the system can meet an operational demand.

O is operational readiness: the probability that the system will be ready to operate when required or is presently operating satisfactorily.

D is dependability: the probability that the system will operate within the required specification for the entire job duration.

C is capability or design adequacy: the probability that the job will be accomplished if the equipment is operating within specification.

Each of these parameters is, in turn, a function of other parameters as can be seen from Figure 1. The terms availability, operational readiness, and dependability have similar connotations but operational readiness includes total calendar time while availability includes only desired use time. These are usually termed point concepts, since they refer to the ability of the system to operate at any given point in time when called upon to do so. Dependability is used to depict the ability of the system to operate effectively for a specified time period if it is operable at the start of the period (5). A more detailed discussion of the complete systems effectiveness model is beyond the scope of this report which will concentrate on the maintainability and availability parameters that contribute so much to it.
Figure 1. Concepts Associated With System Effectiveness (5)
Objectives

General Objectives

A system that is inexpensive to maintain is a worthy goal toward which every engineer should design. Such a system is always desired by its users. Unfortunately, these users do not always make their demands for these qualities specific enough or state them with sufficient vehemence; consequently, they are often forced to purchase equipment that is not really effective but only "better than anything else around."

Two things militate strongly against maintainability. First, it can't be put into a complex machine after the machine has been designed and built without expensive redesign and modification. This quality has to be in the design from the very beginning, and this means engineering work, engineering expense. Second, maintainability does not improve performance. A mechanized harvester with good maintainability won't cut a larger tree or lift a heavier load than it would if it were very difficult to maintain. Thus, the question arises as to how to motivate management and engineers to design maintainability into the machine.

How can the purchaser and user of the machine be convinced that his desire for an easily, rapidly, and inexpensively maintained machine can be satisfied, at least partially, by making use of the disciplines and techniques of reliability and maintainability? How can he be convinced that these factors can be quantified and specified? How can everyone concerned with pulpwood harvesting equipment be made aware of the studies, work, and results which have been accomplished by other industries who have recognized the maintainability role?

The general answer to the above questions is, of course, by
explaining and demonstrating maintainability concepts, practices, and results in a manner that can be easily understood. The general objectives of this report, then, are to contribute toward the knowledge of maintainability concepts in respect to pulpwood harvesting equipment, to demonstrate the applicability of maintainability concepts to selected pulpwood harvesting equipment, and to present quantitative techniques for pulpwood harvesting equipment designers or purchasers.

**Specific Objectives**

To accomplish the general objectives, the following tasks are considered as specific objectives:

1. Present a general survey of literature that deals primarily with maintainability of mechanical equipments. Examples of two different maintainability programs are included in this survey.

2. Present a simplified explanation of the three concepts of availability that are presently recognized and accepted by persons concerned with maintainability. These are intrinsic availability, achieved availability, and operational availability.

3. Present the concept of job availability. This concept provides a more realistic measure of the actual effects of maintainability and reliability on job accomplishment.

4. Present a simplified explanation of maintenance process requirements and downtime considerations. Downtime is used as the fundamental measure of maintainability. Its component parts of fault recognition, location, correction, and checkout are defined and explained.

5. Investigate the reliability characteristics of a typical machine used in pulpwood harvesting. The exponential distribution function
will be presented and a determination made regarding its applicability
to the observed failure history of one of the typical types of pulpwood
harvesting machinery.

6. The general lognormal distribution function will be presented
and some of its characteristics that are important when used to describe
or predict maintainability will be pointed out.

7. Examine the repair times and actions that were recorded for
a complex multifunction pulpwood harvester and determine whether the
lognormal distribution is applicable.

8. Develop a hypothetical simplified example that will illustrate
some of the techniques that are suggested in this report. The results
of this example will be analyzed as to their meaning and usefulness.

9. Prepare graphical aids to assist in calculating the various
factors of reliability, maintainability, and availability.

Methods

Graphs and nomographs are used throughout the report to calculate
the different measures of reliability, maintainability, and availability.
The computational graphs are normalized so that they may be used for dif-
ferent groupings of data. Similarly, all of the nomographs are presented
on equally spaced vertical scales that have cyclical gradations. This
permits the range of the nomographs to be extended if necessary. Also,
any block segment of the nomographs may be expanded or magnified to pro-
vide more accuracy.

The chi-square goodness of fit test is used to determine how well
the lognormal distribution fits the empirical distribution of maintain-
ability data and how well the exponential distribution fits the empirical
distribution of reliability data.
CHAPTER II

LITERATURE SURVEY

General

The concept of including maintainability as a quantifiable design parameter has been in existence for only approximately ten years, but a search of applicable literature reveals that it has already become a most popular topic. Very little was written prior to 1960 but published literature on the subject is now increasing in an exponential fashion doubling about every two to three years (13). The vast majority of this literature deals with electronic or aerospace equipment and results from the heavy emphasis placed on maintainability by the Department of Defense. The automotive industry has expanded its interest in both reliability and maintainability and this has contributed to the longer warranties provided on many new vehicles. Most of the literature concerning heavy machinery such as pulpwood harvesting equipment stresses reliability and only occasionally mentions maintainability. Even when mentioned, the concept is treated in only subjective terms.

Belying the increase in the volume of literature on the subject is the fact that maintainability is a very difficult subject about which to write. This difficulty is largely attributable to the human element that is a major part of the maintenance process. It is also complicated by the dissimilar logistics and environmental conditions that exist between different users and locations.

A lack of communication between operators, maintenance personnel, and design engineers limits the amount of feedback which is so useful in
the verification of design features. Further complications in writing about maintainability are caused by a lack of common agreement on the precise meaning of the term. A number of different definitions have been presented in various publications, each tailored by authors to convey their particular interpretation.

Investigation into why equipment and material was not reliable and what should be done to make it so was started shortly after World War II. It took about two decades of work on the subject before reliability found its way into consumer products. Lipson, Sheth, and Sheldon from the University of Michigan offer the following explanation (6):

There are two major reasons why the techniques used to assure reliability have taken so long to reach individual consumer products: 1). Most of the pioneering work was done in the field of electronics while consumer industry products are concerned largely with mechanical components, 2). Until recently, industry, unlike the military was not interested in expensive reliability analysis. While studies of the reliability of electronic equipment began in the 1940's, analysis of mechanical components is largely a product of the 1960's.

Today at least 90 per cent of maintainability research is devoted toward electronic and aerospace equipment. It could be several years before the manufacturers and purchasers of heavy industrial machinery will receive any really significant benefits from such industry efforts.

As so often happens when a subject becomes popular, many articles on maintainability simply restate what others have already said. This fact has been recognized by some of the professional organizations and efforts are being made to reduce this practice.

The literature described in the remainder of this chapter and in Appendix A exemplifies some of the articles and publications that should be of interest to all personnel that are associated with pulpwood har-
vesting equipment. The list of OTHER REFERENCES appearing at the end of this report consists of publications that are not directly cited but do provide material that is applicable to the subject.

Démonstration of Vehicle Maintainability

A maintainability program that should prove especially interesting to purchasers and operators as well as to designers of pulpwood harvesting equipment was conducted and reported by the U.S. Army and the Michigan Division of Ling-Temco-Vought Corporation (7).

The Equipment

A six-wheel-drive, articulated, two-body high performance 1-1/4 ton utility truck was the product that was involved. Designated the XM-561, it is powered by a multifuel diesel engine. Its cross-country performance is practically comparable to that of a full tracked vehicle, while its highway performance is fully compatible with today's road and traffic conditions; its top speed exceeds 50 mph and fuel consumption is superior to that of existing utility vehicles. The vehicle is amphibious; controls, gauges, and accessories must be watertight; so, accessibility problems are compounded.

The Program

The development contract for this vehicle included an incentive clause that required a maintainability demonstration. The incentive requirement was that when operated under specific conditions, the unscheduled maintenance wasn't to exceed 100 man-hours for 20,000 miles of operation, and that total maintenance would not exceed 500 man-hours. Maintenance required by accidental damage or by government furnished components was excluded. The existence of this contract incentive
generated interest on the part of top management and this assured emphasis on maintainability in design.

**Design Considerations**

Maximum use of standard components and low cost, off-the-shelf assemblies was also required. Obviously, these constraints placed certain restrictions on attainable reliability and, as can be seen by referring to Figure 1, maintainability had to play a major role in defining the availability of the product. During the preliminary design phase, predictions of maintenance time requirements of the designs by component, and by system were recorded. As a result of these records, and by using experience gained on component tests, it was possible to influence design and achieve significant maintenance savings. As an example, in designing engine mounts and electrical disconnects, it was possible to show a reduction for power plant removal and replacement time from 207 man-minutes to 90 man-minutes. The simple expedient of listing maintenance tasks versus required time, for design and project discussions proved quite effective.

**Tests and Results**

Test rigs were used wherever possible to determine actual maintenance times that had been predicted during early design and the data was collected by subsystem. These tests were analyzed and a total of 142 man-hours of unscheduled maintenance in 20,000 miles of operation was predicted. Six of the subsystems, including the steering system and brakes were responsible for over one-half of these maintenance hours. Design engineers concentrated on improvements in maintainability and reliability for these subsystems and reduced predicted unscheduled
maintenance man-hours to 95 for 20,000 miles of operation. Field tests of the first vehicles off the assembly line verified these predictions and the XM-561 completed its durability test schedules satisfactorily.

Department of Defense Policies

The Department of Defense has issued three documents which are directed toward the management, demonstration, and prediction of maintainability. These are:

MIL-STD-470 Maintainability Program Requirements
MIL-STD-471 Maintainability Demonstration
MIL-HDBK-472 Maintainability Prediction

The philosophy that prevails throughout the Defense Establishment is, that having established the system or equipment operational requirements, it is essential that the maintainability of the system or equipment be predicted in quantitative terms as early in the design cycle as is possible. It is also required that maintainability predictions be updated on a continual basis as the design progresses to assure a high probability of compliance with established requirements which will become evident during demonstration testing. The Maintainability Prediction Handbook provides the medium, within the present state-of-the-art, toward achieving these Department of Defense objectives.

DC-9 Design Requirements

Two easily read papers describing the reliability and maintainability programs that were followed during design of the DC-9 aircraft were presented by Douglas Aircraft Company engineers at the 1965 Reli-
ability and Maintainability Conference(8,9). Purchasers of larger multifunction pulpwood harvesting equipment should find these technical papers quite enlightening concerning the possible benefits of a practical program.

The DC-9 program emphasized simplicity and improvement of already proven components as well as commonality of design. The qualitative maintainability design objectives included the following:

1. Simplification of systems by elimination of components, which in turn resulted in elimination of tasks.

2. Use of components with service proven reliability, and further improvement of the components selected.

3. Rapid access to areas requiring frequent maintenance.

4. Rapid replacement of components by use of Quick Attach Detach Devices (QADs), plate nuts, and simple attachments.

5. Minimization of special tool requirements.

In addition to simplification of the design itself, an operations analysis of all maintenance tasks was performed. Tasks were analyzed for possible elimination or simplification. Designers were instructed to survey all of the equipment that was in operational use in the field, on Douglas aircraft and others, to learn where the best equipment was located; that is, the best equipment by its current MTBF records. Such records are more easily available to the aircraft industry than they are to producers of pulpwood harvesting equipment and the aircraft company intelligence network is considerably better organized. Still, enough information to permit such an operation is available to heavy equipment producers.
A very substantial contribution to reliability and maintainability in design was made by the airlines. One of the first things that Douglas did upon going to work on the DC-9 was to set up a conference and all potential customers were invited to attend. In order to establish what would be generally a standard airplane, the airlines were asked for their preferences and experiences with various types of equipment so that the major equipment selections could be made based on this broad operational background. Such a conference advised the design engineers of the peculiar requirements of the different airlines and also their experiences, good or bad, with particular types of equipment.

After the components and assemblies had been selected, estimates were made of the times required to perform maintenance tasks and design goal times were formulated, with the final quantities favoring pessimism. By careful attention to the maintainability details of system design, actual task time verification in all instances bettered the goals, in some cases by as much as 50 per cent. Some of the design goals and verified task times for the powerplant are shown in Table 1. A comparison of powerplant task times of the DC-9 with similar tasks on in-service jet airplanes shows a significant reduction in clock time and man-hours favoring the DC-9. For instance, an engine change can be accomplished on the DC-9 by four men in less than 30 minutes while four men require up to four hours to accomplish an engine change on comparable aircraft installations.

Fleet service records, kept for over three years of operation, verify that the DC-9 is one of the most maintainable and effective jet transports ever built.
Table 1. Task Times for DC-9 Powerplant Maintenance

<table>
<thead>
<tr>
<th>Maintenance Task</th>
<th>DESIGN GOAL</th>
<th></th>
<th>TASK TIME VERIFICATION</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clock Time</td>
<td>Man Minutes</td>
<td>Clock Time</td>
<td>Man Minutes</td>
</tr>
<tr>
<td>Engine Change</td>
<td>60</td>
<td>240</td>
<td>30.0</td>
<td>120.0</td>
</tr>
<tr>
<td>Engine Conversion- Neutral to LH or RH</td>
<td>57</td>
<td>104</td>
<td>34.5</td>
<td>69.0</td>
</tr>
<tr>
<td>Nose Cowl Change</td>
<td>30</td>
<td>60</td>
<td>20.0</td>
<td>40.0</td>
</tr>
<tr>
<td>Generator Change</td>
<td>30</td>
<td>60</td>
<td>25.0</td>
<td>50.0</td>
</tr>
<tr>
<td>Constant Speed Drive Change</td>
<td>60</td>
<td>120</td>
<td>45.0</td>
<td>90.0</td>
</tr>
<tr>
<td>Starter Change</td>
<td>30</td>
<td>30</td>
<td>13.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Starter Valve Change</td>
<td>18</td>
<td>18</td>
<td>12.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Hydraulic Pump Change</td>
<td>30</td>
<td>30</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Fire Detector Change</td>
<td>30</td>
<td>30</td>
<td>13.5</td>
<td>13.5</td>
</tr>
<tr>
<td>Thrust Reverser Actuator Change</td>
<td>48</td>
<td>48</td>
<td>15.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>
CHAPTER III

AVAILABILITY, MAINTAINABILITY, AND MAINTENANCE

General

As noted in Chapter II, several different definitions and concepts of maintainability have been presented in the technical literature. The factors of reliability, availability, and maintenance have also been described in various ways. Reliability concepts have been the most thoroughly investigated and consequently have merged toward a common definition and set of criteria. It is generally agreed that reliability is a quantifiable parameter that deals with how long a product or a component will operate before failing and that it can be described or predicted for most equipment (5,10). The remainder of this chapter discusses these factors as they might be applied to pulpwood harvesting equipment or similar heavy duty outdoor industrial machinery.

Availability

Availability expresses a relationship between the time a system is capable of performing its intended function and the time when it is not. By expressing this relationship as a ratio, a measure of availability may be expressed. This sounds quite simple and almost superfluous but in order to use this ratio for any practical purpose, further qualification is necessary. At least three kinds of availability have been defined. These are intrinsic (inherent) availability, achieved availability, and operational availability. This report also defines job availability.
Intrinsic Availability

Intrinsic or inherent availability takes into account, in the calculation of the availability ratio, only those items which are inherent in the system design. It assumes that tools, parts, manpower, manuals, etc. are instantly available to effect any necessary unscheduled maintenance. It does not consider any scheduled or preventive maintenance time. Thus, it is a measure only of the intrinsic design variables controllable by the system designer. It is expressed as:

\[ A_i = \frac{MTTF}{MTTF + MTTR} \]

where

MTTF = the mean-time-to-failure

MTTR = the mean-time-to-repair

This concept of availability is useful primarily to the design engineer. It represents the maximum availability attainable under ideal conditions. Figure 2 presents a nomograph based on the above relationship. It provides an easy solution when two of the factors are known or can be estimated. Derating factors are necessary for field use because of the environment, necessary scheduled maintenance, and the inefficiencies of operations.

Achieved Availability

Another measure of a system's availability that takes into account preventive and scheduled maintenance times is referred to as achieved availability \( A_a \). It also assumes that any necessary tools, parts, man-
Figure 2. Intrinsic Availability Nomograph
power, manuals, etc. are instantly available. It may be expressed as:

\[ A_a = \frac{MTBM}{MTBM + MADT} \]

where

\( MTBM = \) mean-time-between-maintenance

\( MADT = \) mean-active-downtime

This measure may be calculated from the nomograph of Figure 2 by substituting the value of MTBM for MTTF and the value of MADT for MTTR.

**Operational Availability**

This type of availability (Figure 3) is applicable when the actual operating environment and all delay times are considered. It is expressed as:

\[ A_o = \frac{MTBM}{MTBM + MDT} \]

where

\( MDT = \) actual-mean-downtime

**Job Availability**

The fourth type of availability has been called by many names, confused with other parameters, and defined in a multitude of ways. For systems that produce easily measurable outputs in a length of unit time (for example, cords of wood per shift) the name of "job availability \((A_J)\)" is suggested. This concept takes into account the fact that, for some systems, a failure which occurs during an operating period, may be
Figure 3. Operational Availability
acceptable if it can be repaired during a specified period of time. It also considers the actual operating environment and all delay times. It may be represented in probability terms as:

\[ A_j = P_R(1-R_t) + R_t \]

where

\[ R_t = \text{the probability that the entire system will operate within tolerances for the job duration} \]

\[ P_R = \text{the probability that if the system fails, it can be repaired within an acceptable time limit.} \]

Methods for computing and predicting these factors are presented in later chapters. If any two of the factors appearing in the above equation are known or can be estimated, the nomograph presented in Figure 4 may be used to compute the remaining factor.

In all four of the above definitions, the time under consideration is operational demand time. When non-operational times (free time and storage and transit time) are included in the time to be considered, thus becoming total calendar time, availability becomes operational readiness as shown in Figure 1.

**Maintainability and Maintenance**

**General**

Maintainability may be subjectively defined as the inherent ability of a system or piece of equipment to be maintained, i.e., restored to acceptable operating condition within a specified period of time. It is obviously a parameter of design and, therefore, is a part of the systems engineering discipline. If good maintainability
Figure 4. Job Availability Nomograph
is not designed into production equipment, it can only be provided later by afterthought design that results in costly modifications.

Maintenance may be subjectively defined as all actions taken which retain or restore system effectiveness, or which will retard system degradation. It is, to a large degree, a result of design. It is associated with the utilization of a system and its optimization is a subject of operations research; however, in order to determine what techniques and information is of importance in designing for maintainability it is necessary to examine those factors which, when combined, make up maintenance tasks or actions.

Types of Maintenance

Maintenance activities are generally divided into two major categories; preventive maintenance and corrective maintenance. Preventive maintenance is that maintenance performed, preferably on a scheduled basis, for the purpose of retaining an item in satisfactory operating condition. It includes servicing and inspection activities. Corrective maintenance is that maintenance performed to return an equipment to service after a failure or other malfunction has occurred. It includes recognition (although recognition of a fault might also occur during preventive maintenance), location, correction, and checkout. The relationships among these divisions of maintenance are illustrated in Figure 5.

Although designing for maintainability must include both preventive and corrective maintenance considerations, the critical problems usually center around corrective maintenance since it involves the restoration of a failed system to an operable state. Further,
Figure 5. The Maintenance Process
considerably more attention has been paid in the past to optimum preventive maintenance policies involving such factors as spare parts stockage, logistics, and queuing problems. These studies, in general, have been less concerned with design for ease and rapidity of corrective maintenance than with design for economic spares provisioning, economic module size for replacement, and repair-discard policies (10).

Recognition. The recognition phase of maintenance is obviously the first to be considered. During this phase, any fault that may have occurred must be detected through the analysis of symptoms or symptomatic responses. When dealing with pulpwood harvesting equipment, most faults are obvious but this is not always true. The fault may occur in one of three ways. First, the fault may be one that reduces performance or efficiency; this is called degradation or deterioration. Degradation is a result of time, temperature, friction, dirt, etc. It is oftentimes accelerated by a lack of proper servicing or by improper operation. When the gradual changes, considered collectively, reach a point where system performance is below acceptable limits, another phase of corrective maintenance is entered. Excessive oil consumption due to worn piston rings in an engine is an example of this type of fault.

The second type of fault occurs when a part suddenly becomes completely inoperative or exhibits a gross change in characteristics. This is called a catastrophic failure. This type can be repaired by further maintenance actions. Common examples are a broken wire, a stuck valve, or a blown fuse. Proper equipment design will minimize such failures; however, for parts with a finite reliability, such
faults will eventually occur and the designer should minimize the time required to repair them.

The third type is called a disastrous fault. No maintenance action can repair such a fault and the equipment or part must be replaced. An example is a burned out lamp filament.

Location. The second time phase of corrective maintenance includes diagnosis, localization, and isolation of the fault. As in the recognition phase, this may be a completely obvious process when applied to industrial machinery but it is very important that the true reason for failure be determined. A discharged battery is sometimes replaced without any consideration being given toward the actual reason for its discharged condition. The primary fault might very well be a malfunctioning generator or voltage regulator. Entry into this phase may be made from either the recognition phase of a corrective maintenance action or from the inspection phase of a preventive maintenance action.

Correction. The third time phase of corrective maintenance is that in which something actively is done to restore the system to acceptable performance. This can be done only for the degradation or catastrophic type failure. In the case of pulpwood harvesting equipment, this usually consists of opening the machine, through disassembly if necessary or by other accessible means, removing and replacing the faulty items with operable items, or repairing them, and then closing the equipment in preparation for returning it to service.

Checkout. The fourth phase of corrective maintenance is called the checkout or verification phase. It assures that the equipment has
been restored to normal performance capability. It may also include optimizing adjustments or calibration of the system.

**Downtime**

Total downtime may be defined as the number of calendar hours during which a system is scheduled for use but is not available for use (12). This includes active repair time, during which repair actions are being taken by maintenance personnel, and delay time during which the mechanic may be able to do little or nothing toward actively restoring the equipment. The average of active repair time is the mean-time-to-repair (MTTR). The average of the sum of active and delay times is the actual-mean-downtime (MDT).

Active repair time is easier to treat quantitatively than is delay time and is more readily controllable by engineering design. It is the summation of the times required in each of the phases of corrective maintenance that were described above. Delay time or total downtime includes logistic time, which is the number of downtime hours consumed in awaiting parts or technical assistance, and administrative time which is a function of the structure of the operational organization and environmental factors. Overnight or weekend times may be considered as administrative delay times if desired; however, a more useful appraisal of maintainability is usually gained when these times are not included.

Since active repair time is usually of more interest to the design engineer and mean or total downtime is of more importance to the possessor of harvesting equipment, it is meaningful to investigate each of these separately. This is the reason why the separate concepts
of intrinsic availability ($A_i$), involving only active repair time, and operational availability ($A_0$), which includes both active maintenance time and delay time, were introduced earlier. As a result, specifications or design tradeoff decisions generally utilize MTTR as a maintainability criterion and systems effectiveness calculations usually include MDT.

**Maintainability in Design**

The ease with which a maintenance task can be performed is directly related to the way in which a system has been put together, the number of indicators provided, the number of fasteners to be removed, the clarity of instructions and drawings which must be referred to in accomplishing each part of the task, etc. Each designer must place himself in the role of the maintenance technician in order to understand his point of view. At the same time, he must consider that maintainability design affects, and in turn is affected by, all other system parameters. It interacts with system performance requirements through the requirements for monitoring system performance, test, and alignment. It interacts with safety with regard to safety of access, protection of the mechanic from electrical shock, heat, and other environmental hazards. It interacts with packaging (configuration) with regard to such items as access for maintenance, location of test points, controls, adjustments, tools, connectors, handles, and mounting. It interacts with environmental requirements with regard to the ability of the system to be maintained under the required environmental conditions. It interacts with cost with regard to the cost of maintenance and support versus the cost of maintainability design. In particular,
it reacts with reliability in terms of job availability (13).

To meet overall system requirements, it will obviously be necessary to perform tradeoffs among the major system parameters. Before any effective tradeoff decisions involving maintainability can be made by the designer, he must make an attempt to predict how maintainable the system will be and how various design changes might affect its maintainability.

**Maintainability Prediction**

Undoubtedly, the most difficult task necessary for effective application of the maintainability parameter during design is prediction. It would be ideal if maintainability could be accurately predicted in the conceptual stage. To date, the only approach that has been thought of has been to use historical information obtained from other systems, and to adapt this information to the proposed system. This severely restricts design engineers who hope to use completely new components or assemblies. Fortunately, this restriction is not often encountered by designers of pulpwood harvesting equipment. For such equipment the vast majority of subassemblies and components are either improved, extended, or modified versions of previously tested hardware.

Several prediction methods have been tried by engineers and each of them assumed that a degree of commonality existed. The major attempts at maintainability prediction have included:

1. extrapolation methods
2. time summation schemes
3. checklist schemes
(4) simulation methods
(5) "Expert" judgement
(6) matrix tabulation

A complete analysis of each of these techniques, their advantages, and their disadvantages has been performed by Rigney and Bond (14). Their analysis of a weighted checklist method of prediction should be of particular interest to the designers of industrial consumer machinery. A study performed by the American Institute of Research (15) resulted in a checklist of 241 design features applicable to maintainability rated with respect to displays and controls, external accessibility, covers, lubricants, tools, manuals, and test equipment as maintenance factors. The presence or absence of these features were then combined into consequence and factor scores and plotted as maintainability profiles for the equipment under evaluation. Obviously, such a weighted checklist method can be most usefully applied during the late stages of design, but, in the case of heavy industrial equipment, it can also be of value during early design phases.

In order to determine the maintainability design attributes that should be considered when compiling such a checklist, M.B. Kline (13) searched a number of maintainability design guides and documents for those primary factors that were most heavily stressed. These factors are ordered in Table 2. In addition, each of the factors for the various active downtime phases are shown on an ordinal ranking scale from 0 to 4. There is no ranking factor of 2. This is intended to indicate there is a greater difference in weight be-
between items ranked 3 and items ranked 1 than between those ranked 4 and 3 and items ranked 1 and 0. Although the 13 design factors chosen as most often mentioned represent the collective judgement and efforts of many investigators, it is not meant to imply that only these are important for any given system, nor necessarily in the order given.

Table 2. Most Often Mentioned Maintainability Design Factors and their Ordinal Rating (13).

<table>
<thead>
<tr>
<th>Times Mentioned</th>
<th>Design Factor</th>
<th>Recog</th>
<th>Loc</th>
<th>Corr</th>
<th>Checkout</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Accessibility</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>13</td>
<td>Test Points</td>
<td>3</td>
<td>4</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>13</td>
<td>Controls</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>Labeling and Coding</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>Displays</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>Manuals and Checklists</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>Test Equipment</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>Tools</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>Connectors</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>Cases, Covers, and Doors</td>
<td>0</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>Mounting and Fasteners</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Handles</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Safety</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

**Weighting Code**

0 not a factor  
1 not ordinarily important  
3 might be important  
4 necessity
CHAPTER IV

RELIABILITY OF A POWERED CHAIN SAW

To investigate the reliability characteristics of existing pulpwood harvesting equipment, failure data were recently obtained for the most frequently used machine in the industry: the gasoline powered chain saw. The test machine was a production model of one of the most popular brands. The chain was 5 feet in length and 1/4 inch wide.

Before any data were recorded, the saw was given a major tuneup and a new chain was installed. At this time, the saw had been used approximately 300 hours and its estimated remaining lifetime was 1400 hours. Data were collected for a period of 8 months during which the equipment operated a total of 917 hours. No special handling or treatment was afforded the machine but care was taken to insure that the manufacturer's servicing instructions were followed exactly.

The saw was operated in a tract of pine pulpwood. The forest and the saw were owned by one of the larger paper companies. Several different operators used the saw during the test. The foreman of the cutting crew recorded the dates of failure, operating hours since tuneup, cost of parts, and nature of repairs.

The recorded data from this test are presented in Table 3. Since the random variable was the number of failures experienced, the hypothesis was made that a Poisson distribution might be appropriate for analysis. (A general discussion of the exponential and Poisson distributions and their applications to reliability is presented in Appendix B). To validate this hypothesis, the data were plotted on semilogarithmic graph paper to see if a straight line resulted. This
plot is shown in Figure 6.

In addition to establishing the validity of the hypothesis graphically, a chi-square test was used to validate it analytically. This analysis is also shown in Appendix B.

Table 3. Chain Saw Failures

<table>
<thead>
<tr>
<th>Failure Number</th>
<th>Hours</th>
<th>Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>192</td>
<td>Side Cover</td>
</tr>
<tr>
<td>2</td>
<td>207</td>
<td>Dogs</td>
</tr>
<tr>
<td>3</td>
<td>237</td>
<td>Crank Pulley</td>
</tr>
<tr>
<td>4</td>
<td>272</td>
<td>Chain</td>
</tr>
<tr>
<td>5</td>
<td>322</td>
<td>Carburetor</td>
</tr>
<tr>
<td>6</td>
<td>417</td>
<td>Points, Plugs</td>
</tr>
<tr>
<td>7</td>
<td>432</td>
<td>Chain</td>
</tr>
<tr>
<td>8</td>
<td>542</td>
<td>Dogs</td>
</tr>
<tr>
<td>9</td>
<td>622</td>
<td>Cylinder</td>
</tr>
<tr>
<td>10</td>
<td>787</td>
<td>Spring</td>
</tr>
<tr>
<td>11</td>
<td>917</td>
<td>Ignition</td>
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</tbody>
</table>
Figure 6. Semilogarithmic Graph of Chain Saw Failures
CHAPTER V

MAINTAINABILITY STUDY OF A PULPWOOD HARVESTER

To investigate the maintainability of typical pulpwood harvesting equipment, performance and maintenance data were recorded for two identical harvesters. The data for both machines were combined and analyzed. These diesel-powered machines are widely used throughout the pulpwood industry and are especially popular in the Southeastern United States. They permit one operator to perform the following tasks:

(1) felling
(2) delimbing
(3) measuring
(4) bucking
(5) Bunching
(6) prehauling
(7) loading

The machines were operated by different harvesting crews over a variety of terrain and tree density conditions. Data were recorded for a one year period by the woodlands crew foreman of a large paper company. This method of operation and the complete cycle of seasons tended to remove any environmental bias.

The data applicable to a maintainability analysis is tabulated in Table 4. A histogram (Figure 7) which represents the number of instances in which various repair times were required to correct a failure suggests a possible lognormal distribution. (A general discussion of the lognormal function and its applicability to maintainability is presented in Appendix C.)
Table 4. Repair Times for Harvesters

<table>
<thead>
<tr>
<th>Time to Accomplish Repair</th>
<th>Number of Repairs Completed</th>
<th>Cumulative Number of Repairs Completed</th>
<th>Cumulative Percentage of Repairs Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>30</td>
<td>30</td>
<td>11.4</td>
</tr>
<tr>
<td>1.0</td>
<td>40</td>
<td>70</td>
<td>26.6</td>
</tr>
<tr>
<td>1.5</td>
<td>42</td>
<td>112</td>
<td>42.5</td>
</tr>
<tr>
<td>2.0</td>
<td>35</td>
<td>147</td>
<td>55.9</td>
</tr>
<tr>
<td>2.5</td>
<td>26</td>
<td>173</td>
<td>65.8</td>
</tr>
<tr>
<td>3.0</td>
<td>22</td>
<td>195</td>
<td>74.1</td>
</tr>
<tr>
<td>3.5</td>
<td>6</td>
<td>201</td>
<td>76.5</td>
</tr>
<tr>
<td>4.0</td>
<td>11</td>
<td>212</td>
<td>80.6</td>
</tr>
<tr>
<td>4.5</td>
<td>4</td>
<td>216</td>
<td>82.1</td>
</tr>
<tr>
<td>5.0</td>
<td>11</td>
<td>227</td>
<td>86.4</td>
</tr>
<tr>
<td>5.5</td>
<td>8</td>
<td>235</td>
<td>89.4</td>
</tr>
<tr>
<td>6.0</td>
<td>6</td>
<td>241</td>
<td>91.6</td>
</tr>
<tr>
<td>6.5</td>
<td>5</td>
<td>246</td>
<td>93.6</td>
</tr>
<tr>
<td>7.0</td>
<td>3</td>
<td>249</td>
<td>94.7</td>
</tr>
<tr>
<td>7.5</td>
<td>2</td>
<td>251</td>
<td>95.5</td>
</tr>
<tr>
<td>8.0</td>
<td>4</td>
<td>255</td>
<td>97.0</td>
</tr>
<tr>
<td>8.5</td>
<td>0</td>
<td>255</td>
<td>97.0</td>
</tr>
<tr>
<td>9.0</td>
<td>2</td>
<td>257</td>
<td>97.7</td>
</tr>
<tr>
<td>9.5</td>
<td>0</td>
<td>257</td>
<td>97.7</td>
</tr>
<tr>
<td>10.0</td>
<td>6</td>
<td>263</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Figure 7. Bar Graph of Pulpwood Harvester Repair Times

Total Number of Repair Actions = 263
$t = \text{time required to accomplish repair}$

$\text{CR} \% = \text{cumulative percentage of total number of repairs}$

Figure 8. Logarithmic Probability Graph for Pulpwood Harvester Repair Times
The straight line that results from plotting the data on logarithmic probability paper (Figure 8) graphically verifies the hypothesis that the lognormal distribution is applicable.

Several useful estimates can be made from this figure. First, a best fitting line is drawn. Since the median is equal to the geometric mean, the value of the median repair time can be read on the "t" scale opposite the point where the fitted line crosses the 50 percent gradation of the cumulative repairs. This gives an estimated median repair time of 1.7 hours and means simply that one-half of all repairs will be accomplished in that time or less. Similarly, 95 percent of all repairs will be accomplished in 7.3 hours or less and 28 percent of all repairs will be made within one hour.

Next, an estimate of the standard deviation, σ, may be made. To do this two or more points must be located on the graph. They are found by noting the points at which the fitted line crosses the 16 and 84 percent marks on the horizontal scale, and by then reading across to the vertical scale. The 16 and 84 percent choices correspond to one standard deviation on either side of the median and in the normal distribution. From the figure:

\[ t_{16} \approx 0.67 \text{ hrs.} \]
\[ t_{50} \approx 1.70 \text{ hrs.} \]
\[ t_{84} \approx 4.10 \text{ hrs.} \]

The value of \( \hat{\sigma} \) (estimate of \( \sigma \)) is then given by:
\[ \hat{\sigma} = \ln \left( \frac{1}{2} \left( \frac{t_{50}}{t_{16}} + \frac{t_{84}}{t_{50}} \right) \right) \]

\[ = \ln \left( \frac{1}{2} \left( \frac{1.70}{0.67} + \frac{4.10}{1.70} \right) \right) \]

\[ = \ln 2.48 \]

\[ = 0.91 \]

The estimated value of the mean is then calculated:

\[ \hat{MTTR} = (\text{median}) (e^{0.5\sigma^2}) \]

\[ = (1.70)(e^{0.412}) \]

\[ = (1.70)(1.51) \]

\[ = 2.6 \text{ hours} \]

The actual values of these characteristics were calculated (See Appendix C) and are compared to the graphically derived values in Table 5. It should be obvious that, in this case, the graphical method is accurate enough for simple design, specification or effectiveness evaluation.

Superficially, it may appear that the geometric mean has a distinct advantage over the arithmetic mean since it is so easy to locate and it divides the number of task times equally. However, an increased sample size is required to specify the geometric mean to the same accuracy as the arithmetic mean and the latter can be multiplied by task frequency to yield total maintenance time, a valuable relationship.
The geometric mean cannot be manipulated in this manner (19).

Table 5. Graphical and Calculated Harvester Repair Time Characteristics in Hours

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Graphical Value</th>
<th>Calculated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>1.7</td>
<td>1.78</td>
</tr>
<tr>
<td>MTTR</td>
<td>2.6</td>
<td>2.72</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.91</td>
<td>1.08</td>
</tr>
<tr>
<td>95th Percentile</td>
<td>7.3</td>
<td>7.4</td>
</tr>
</tbody>
</table>

A chi-square test of goodness of fit was performed to further verify the applicability of the lognormal distribution to the repair times recorded for the harvesters. The calculations for this test are presented in Appendix C. Whenever such a test is considered necessary, electronic data processing equipment should definitely be used if available. Manual computation requires a good deal of time. FORTRAN language is ideally suited for the test.
CHAPTER VI

AN EXAMPLE

General

In this chapter, a simple example of the usefulness of maintainability and reliability concepts is presented. Most of the data and events are typical of the environment experienced in the industry and the problem situation is based on an actual happening. Such factors as delay times, failure rates, costs, etc. closely approximate those observed at an actual pulpwood harvesting operation in central Georgia. No attempt to perform a complete systems analysis or effectiveness evaluation has been made.

The Basic Problem Situation

Two new rubber-tired chokerless skidders were purchased by an independent pulpwood harvesting contractor for 19,000 dollars each. The manufacturer's marketing agent represented the machines as having an "availability" of at least 95 per cent. Only ten machines of this particular model had been delivered to other cutters but the new model was simply an improved and more powerful version of a smaller machine that had been used successfully throughout the pulpwood harvesting industry.

The skidders were scheduled to operate 50 hours per week. The delivery rate of the two skidders equaled the loading rate of one hydraulic loader. Skidding began one-half hour earlier each shift than did the loading operation so that one skidder could be out of operation for one hour or both skidders for one-half hour without delaying loading
operations. If these downtimes were exceeded, the measuring, cutoff, and loading crews and equipment were interrupted and the truck fleet was partially idled.

A few failures occurred in the various subsystems during the first few days of use but these were promptly repaired by the manufacturer's technicians. After these initial failures, the skidders operated very well for about three months. Then an increasing number of hydraulic system failures began to occur. The data given in Table 6 are typical of data taken from maintenance records covering the first six months of operation of the two machines.

**Contractor Calculations**

Using the data of Table 6, the contractor made the following calculations pertaining to the hydraulic system.

\[
\text{MTBF} = \frac{\text{Total operating hours}}{\text{Number of failures}} = \frac{1400}{70} = 20 \text{ hours}
\]

The reliability for a ten hour shift was determined from Figure 6 using

\[
\frac{t}{\text{MTBF}} = \frac{10}{20} = 0.5
\]

\[\therefore R_t = 0.60\]

The MDT was:

\[
\text{MDT} = \frac{\text{Total Downtime}}{\text{No. of Repairs}} = \frac{457}{70} = 6.5 \text{ hours}
\]
Table 6. Maintenance Records for Skidder Hydraulic Systems

<table>
<thead>
<tr>
<th>Scheduled operating hours:</th>
<th>2500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual operating hours:</td>
<td>1400</td>
</tr>
<tr>
<td>Hours lost to causes other than hydraulic system failures:</td>
<td>643</td>
</tr>
<tr>
<td>Total no of hydraulic system repairs:</td>
<td>70</td>
</tr>
</tbody>
</table>

Downtimes in hours due to hydraulic system:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Active repair:</td>
<td>140</td>
</tr>
<tr>
<td>Servicing:</td>
<td>2</td>
</tr>
<tr>
<td>Awaiting parts:</td>
<td>300</td>
</tr>
<tr>
<td>Awaiting mechanic:</td>
<td>15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>457</strong></td>
</tr>
</tbody>
</table>

Hydraulic parts used and costs:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Filters:</td>
<td></td>
</tr>
<tr>
<td>5@ $6.00 ea</td>
<td>$30.00</td>
</tr>
<tr>
<td>Actuators:</td>
<td></td>
</tr>
<tr>
<td>20@ $62.00 ea</td>
<td>$1240.00</td>
</tr>
<tr>
<td>Pumps:</td>
<td></td>
</tr>
<tr>
<td>4@ $100.00 ea</td>
<td>$400.00</td>
</tr>
<tr>
<td>Lines:</td>
<td></td>
</tr>
<tr>
<td>16@ $5.00 ea</td>
<td>$80.00</td>
</tr>
<tr>
<td>Fluid, gaskets, and seals:</td>
<td>100.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$1850.00</strong></td>
</tr>
</tbody>
</table>

Other direct costs due to hydraulic system:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor, mechanic</td>
<td>$600.00</td>
</tr>
<tr>
<td>Telephone charges due to locating and ordering parts:</td>
<td>80.00</td>
</tr>
<tr>
<td>Transportation to pick up parts from 100 miles away (25 trips):</td>
<td>$600.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$1280.00</strong></td>
</tr>
</tbody>
</table>

Total direct cost of hydraulic system repairs: $3130.00

Total cords skidded: 3000

Direct cost per cord due to hydraulic system repairs: $1.04
Since servicing and preventive maintenance times consumed only two hours:

\[ \text{MTBM} \div \text{MTBF} = 20 \text{ hours} \]

Then, operational availability was determined from Figure 3:

\[ \frac{\text{MDT}}{\text{MTBM}} = \frac{6.5}{20} = 0.325 \]

\[ \therefore A_0 = 0.75 \]

When the individual repair times were plotted cumulatively on logarithmic probability paper, an approximately straight line graph similar to the one in Figure 8 was obtained indicating that the maintainability function was lognormally distributed. Since one skidder could be down for one hour without affecting other operations, the point where the line intersected the one hour gradation on the "t" scale was of interest. Reading the "CR %" scale opposite this point gave a reading of 30 per cent. This meant that the probability of repairing the hydraulic system within the one hour limit was only 0.30. Using,

\[ P_R = 0.30 \]
\[ R_t = 0.60 \]

job availability was determined from the nomograph in Figure 4:

\[ A_j = 0.72 \]
Obviously, the efficiency of the hydraulic system had to be improved, but there were some immediate changes that could be made in the contractor's operation to improve job availability.

For instance, if the lead time of the skidders was increased to one hour, then one of the skidders could be down for as long as two hours without affecting other operations. From Figure 8, with:

\[ t = 2 \text{ hours} \]

\[ \therefore P_R = 0.60 \]

and from Figure 4,

\[ A_j = 0.85 \]

an improvement of 12 per cent.

Another improvement would result from an increased stockage of spare parts. Originally, only lines, filters, fluid, seals, and gaskets were kept on hand as ready spares. By also stocking two actuators and a pump (total cost of $224) the direct costs of telephone charges and transportation for pickup could be drastically reduced and most resupply could be effected by mail service. Also, the total time spent awaiting parts would be reduced from 300 hours to approximately 100 hours and the total downtime would be reduced to approximately 257 hours. MDT would drop to approximately 3.9 hours resulting in (from Figure 3):

\[ \frac{MDT}{MTBM} = \frac{3.9}{20} = 0.195 \]

\[ A_o = 0.84 \]
If another logarithmic probability plot of cumulative maintenance times were made, a line with a lesser slope would result showing that approximately 50 per cent of all repairs could be made in one hour or less and 90 per cent could be made within two hours.

With a one hour lead time:

\[ P_R = 0.50 \]
\[ R_T = 0.60 \]

From Figure 4:

\[ A_j = 0.80 \]

With two hours lead time and the additional spares:

\[ P_R = 0.90 \]
\[ R_T = 0.60 \]
\[ \therefore A_j = 0.96 \]

**Manufacturer's Computations**

The contractor complained to the manufacturer about the low "availability" of the skidders due to failures of the hydraulic system. As shown earlier, he had computed an availability of only 75 per cent even if no other subsystems malfunctioned. The manufacturer then computed the availability from Figure 2:
MTTR = MADT = 2 hours

MTBF = 20 hours

"A" = 0.91

He, of course, computed intrinsic availability while the contractor had quoted operational availability. Nevertheless, either measure of availability was far too low and the data were fed back to the design engineer responsible for the hydraulic system.

Originally, the design engineer had calculated intrinsic availability based upon estimated failure and repair rates provided by subcontractors. These estimates are shown in Table 7.

Table 7. Predicted Reliability and Repair Factors for Hydraulic Components

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Part</th>
<th>MTTR in hours</th>
<th>MTBF in hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pump</td>
<td>2.0</td>
<td>2000</td>
</tr>
<tr>
<td>2</td>
<td>Actuator</td>
<td>1.0</td>
<td>1000</td>
</tr>
<tr>
<td>3</td>
<td>Reservoir</td>
<td>5.0</td>
<td>5000</td>
</tr>
<tr>
<td>4</td>
<td>Filter</td>
<td>0.25</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>Lines</td>
<td>0.25</td>
<td>500</td>
</tr>
</tbody>
</table>

The system MTBM was calculated (See Appendix D for all calculations for this chapter) to be 73 hours. System MTBF was computed to be 270 hours by excluding the times required to replace filters, since this was considered to be a preventive maintenance action. MTTR
for the system was predicted to be 0.946 hours. MADT was calculated to be 0.438 hours. Filter service times were included in this calculation.

Then, from Figure 2:

\[ A_1 = 0.996 \]

and

\[ A_2 = 0.994 \]

From the nomograph in Figure 10, the reliability for a ten hour shift was predicted:

\[ \frac{10}{270} = 0.037 \]

\[ \therefore R_t = 0.965 \]

**Problem Analysis**

Predicted MTBFs were compared with actual MTBFs as shown in Table 8.

**Table 8. Comparison of Predicted and Actual MTBFs for Hydraulic Components**

<table>
<thead>
<tr>
<th>Part</th>
<th>Predicted MTBF in hours</th>
<th>Actual MTBF in hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>2000</td>
<td>350</td>
</tr>
<tr>
<td>Actuator</td>
<td>1000</td>
<td>70</td>
</tr>
<tr>
<td>Reservoir</td>
<td>5000</td>
<td>-</td>
</tr>
<tr>
<td>Filter</td>
<td>100</td>
<td>280</td>
</tr>
<tr>
<td>Lines</td>
<td>500</td>
<td>78</td>
</tr>
</tbody>
</table>
Although three different parts were not meeting their predicted reliability rates, the biggest offender was obviously the actuator. When the subcontractor who manufactured it was contacted, he insisted that the unit had been tested thoroughly and that it had demonstrated the predicted MTBF on other equipment installations. A tear-down inspection of one of the failed units showed that its internal parts had been badly scored from dirt and foreign material in the hydraulic fluid.

It was noted that the servicing instructions provided to the contractor had called for checking the condition of the filters every 100 operating hours or every 50 hours under extremely dirty or dusty conditions. The filter was checked by feeling its surface to ascertain if any foreign material had accumulated there. The data showed that only five filters had been used in 1400 operating hours, giving an actual MTBF of 280 hours versus a predicted MTBF of 100 hours.

When queried about his neglecting to change filters as specified, the contractor explained that the unit was located at the bottom of the reservoir which was 40 inches from the access port on its top. In order to check the filter, the system had to be drained of hydraulic fluid and the reservoir removed from its mounting. Access to the filter was then gained through the bottom of the reservoir. Once the filter was checked or replaced, reassembly and remounting of the reservoir had to be accomplished. The system was then refilled with hydraulic fluid and air was bled at several points. The complete operation required approximately two hours instead of the one-quarter hour that had been used as a predicted MADT and MTTR. Spending two hours of
maintenance time just to check a filter seemed wasteful to the contractor, so the units simply were not inspected or changed frequently enough to prevent foreign material from damaging the other system components. In fact, the filters had been checked only when other maintenance on the hydraulic system was required and the time for inspection and replacement had been added to active repair time. This explained only two hours being recorded for servicing and preventive maintenance.

On the smaller skidder which had been used as a model for the larger machine, the depth of the reservoir was only 24 inches. This permitted a person to reach the filter surface easily and to replace the filter without any disassembly. The basic cause of the problem was, of course, that the design engineer had simply enlarged the capacity of the reservoir and had not recognized that in so doing, he had created a serious maintainability problem.

After the problem was recognized, the internal filter was removed and a series filter was installed in the line between the reservoir and the pump. The new type filter was somewhat more expensive and its reliability was only one-half of that claimed for the original type. A comparison of features were made in Table 9.

Table 9. Comparison of Hydraulic Filters

<table>
<thead>
<tr>
<th>Factor</th>
<th>Old</th>
<th>New</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>$6.00</td>
<td>$9.00</td>
</tr>
<tr>
<td>MTTR (hrs)</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>MTTR (hrs)</td>
<td>2.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>
The predicted MTBF of the system stayed at 270 hours and its MTTR remained at 0.946 hours since filter service times were considered as preventive maintenance times; therefore, intrinsic availability was unchanged from 0.996. The new MTBM was reduced to 42.2 hours. MADT was increased to 0.570 hours. From Figure 2, the new achieved availability was reduced to 0.986. The predicted reliability for a ten hour shift remained at 0.965.

Assuming that the newly predicted reliability and maintainability standards were realistic and that the 224 dollar package of additional spare parts was maintained, the contractor could then estimate the criteria that concerned him most. MDT was estimated as 0.8 hours; then, operational availability was calculated from Figure 3:

\[
\frac{\text{MDT}}{\text{MTBM}} = \frac{0.8}{42.2} = 0.019
\]

\[\therefore \lambda_0 = 0.98\]

The probability of repair within a one hour period rose to approximately 0.95. Then job availability became (Figure 4):

\[P_R = 0.95\]

\[R_T = 0.965\]

\[\therefore A_J = 0.9983\]
Table 10. Comparison of Hydraulic System Characteristics at Different Problem Stages

<table>
<thead>
<tr>
<th>Factor</th>
<th>Stage A</th>
<th>Stage B</th>
<th>Stage C</th>
<th>Stage D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$</td>
<td>0.996</td>
<td>0.91</td>
<td>0.996</td>
<td>-</td>
</tr>
<tr>
<td>$A_a$</td>
<td>0.994</td>
<td>0.91</td>
<td>0.986</td>
<td>-</td>
</tr>
<tr>
<td>$A_0$</td>
<td>-</td>
<td>0.75</td>
<td>-</td>
<td>0.98</td>
</tr>
<tr>
<td>$A_j$</td>
<td>-</td>
<td>0.72</td>
<td>-</td>
<td>0.9983</td>
</tr>
<tr>
<td>$R_t$ (for 10 hr)</td>
<td>0.965</td>
<td>0.60</td>
<td>0.965</td>
<td>0.965</td>
</tr>
<tr>
<td>$P_R$ (within 1 hr)</td>
<td>-</td>
<td>0.30</td>
<td>-</td>
<td>0.95</td>
</tr>
<tr>
<td>MTBF</td>
<td>270</td>
<td>20</td>
<td>270</td>
<td>-</td>
</tr>
<tr>
<td>MTBM</td>
<td>73</td>
<td>20</td>
<td>42.2</td>
<td>-</td>
</tr>
<tr>
<td>MAOT</td>
<td>0.438</td>
<td>2</td>
<td>0.57</td>
<td>-</td>
</tr>
<tr>
<td>MDT</td>
<td>-</td>
<td>6.5</td>
<td>-</td>
<td>0.8</td>
</tr>
<tr>
<td>Direct cost per cord of wood</td>
<td>-</td>
<td>$1.04</td>
<td>-</td>
<td>$0.17</td>
</tr>
</tbody>
</table>

Stage

A - original prediction by engineer

B - actual performance

C - engineer's prediction after modification

D - contractor's prediction after modification and an increase in spares
The cost per cord was calculated to be 17 cents even though the new filter cost 50 per cent more than the original one and had to be replaced every 50 hours. Table 10 compares the different factors as they were calculated or estimated under the various conditions of this example.

**Discussion of Example**

This example shows how easily a mistake can be made in maintainability design and just how expensive it can become. The basic mistake was made by the design engineer and then the resulting negligence on the part of the contractor removed most, if not all, of the profit that could be realized from the pulpwood harvesting operation.

Undoubtedly, the problem would have eventually been recognized and solved without employing the concepts of reliability, maintainability, and availability. However, these concepts permitted quantitative descriptions of the problem and of the costly effects that resulted from it. They also permitted a quantitative evaluation of the effects resulting from the change in design and proved that it was an effective solution.

After modification the frequency of maintenance actions increased; however, the reliability for a work shift remained the same. Operational availability showed a sizable increase but the most significant change was shown by the increase in job availability. Regardless of what changes the other factors undergo, unless this factor increases, the effectiveness of the operation will not improve
and the total costs per cord of wood will not decrease. As described previously, the increase in job availability was the result of improvements in maintainability design and also of a small increase in the number of spare parts that were kept readily available.

The failure to recognize the problem during design resulted in the manufacturer having to pay for redesign. It also cost him indirectly through adverse publicity. The biggest proportional cost, however, was borne by the contractor. Direct costs for the 3000 cords of pulpwood harvested were 2610 dollars more than they should have been. The indirect costs due to the reduced operation of the loading and hauling crews and equipment were not calculated in this example, but were at least as much as the direct costs. The contractor should now realize that maintainability and reliability can be quantified and specified just as easily as performance factors can. When purchasing expensive equipment in the future, he should insist that mutually defined specifications for all of these factors be included in the purchase contract. Faced with meeting such specifications, the manufacturer will demand a more thorough analysis of reliability and maintainability from his designers. Undoubtedly, with this increased motivation, the number of similar design mistakes will be reduced.
CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. Maintainability and reliability can and should be specified for pulpwood harvesting equipment.

2. An examination of applicable literature indicates that little attention has been given by the manufacturers of pulpwood harvesting equipment toward building machines that are easily, rapidly, and inexpensively maintained. On the other hand, the literature shows that emphasis has been placed on maintainability by producers of electronic and aerospace equipment. Many results and techniques derived from these two industries have applicability to heavy mechanical equipment.

3. The calculation of job availability in the example of Chapter VI indicates that it is an effective measure of performance that embraces the effects of both reliability and maintainability. This approach permits an evaluation of changes in operational effectiveness that result from different engineering designs or tradeoffs and from changes in operating procedures.

4. For the pulpwood harvester studied in this report, the empirical distribution of repair time data fitted the lognormal distribution. This permits accurate prediction of future maintainability requirements for this particular machine.

5. The empirical distribution of failure data for a common power saw fitted the exponential distribution. This permits prediction of future reliability traits for this particular machine.
6. Graphical aids presented in this report are accurate and easy to use for determining various reliability and maintainability characteristics. These graphs are especially useful for performing a quick tradeoff analysis.

Recommendations

1. Pulpwood harvesters should insist that equipment manufacturers achieve a higher level of maintainability in their machines. The best way to motivate the manufacturers toward such improvement is for the equipment purchasers to specify maintainability requirements in terms of downtime or availability. Most of the new complex harvesting equipment is purchased by the large pulp and paper companies. These companies should take the lead in securing the benefits that can be derived from improvements in equipment maintainability. It took almost twenty years for the benefits of reliability engineering to manifest themselves in industrial consumer machinery. Unless persistent and determined efforts are made by pulpwood harvesters to secure the benefits promised by maintainability engineering, another lengthy period of sub-optimum effectiveness will be experienced.

2. Because of the high costs of maintenance and because so little investigation has been performed on the maintainability of mechanical equipments, many opportunities for further research in this area can be found. Investigation of the reliability and maintainability characteristics of other equipment is recommended. Although the equipments that are studied in this report are representative of the most commonly used machines, generalizations cannot
be made until many more machines operating under different conditions are examined.

3. The other parameters of the systems effectiveness model described in Chapter I should be studied and the complete model should be investigated by simulation techniques.

4. The concept of maintainability should be included in the pulpwood harvesting models that are presently being used and built by industry groups, companies, and academic groups.
APPENDICES
APPENDIX A

ADDITIONAL LITERATURE OF INTEREST

**Maintainability: A Major Element of System Effectiveness** (10) is a 282 page book, in four parts, aimed at defining maintainability and relating it to system effectiveness, cost, and other characteristics of system design — principally availability and reliability. In addition, basic concepts, principles, and models of maintainability are presented as aids to maintainability design decisions.

The first part of the book reviews the history of quantitative definition of maintainability and describes steps for deriving maintainability requirements, for establishing what part of availability is to be contributed by maintainability versus reliability, and for use of simulation to define maintainability requirements. A conceptual relationship is shown among system job requirements, downtime requirements, design decisions, maintenance policies and technician requirements.

The second part of the book is concerned with the analysis of maintenance strategies. Basic concepts in dealing with maintenance scheduling are presented. Techniques and models to aid in the making of design decisions concerning repair versus discard of components and subassemblies are discussed.

Provisioning of spare parts is the major concern in the third part of the book. An approach based on addition of spares in such a way that each dollar spent results in greater shortage protection than would be obtained by spending the same dollar for any other
item optimizes a mix of spares subject to constraints such as cost, weight, or space.

The last part of the book is concerned with automation versus manual labor in maintainability. A discussion of automatic checkout equipment is followed by an overview of human factors that affect the performance of maintenance in the field and a brief discussion of the nature of the interface between technician and equipment.

The authors claim that the philosophies and techniques described in this book apply equally well to any type of system but most of the examples deal with electronic and aerospace systems. The importance of human factors is repeated in a number of places, but no techniques for even attempting quantification of human performance are offered. Despite these shortcomings, this is probably the best text available on the subject of maintainability today.

An Elementary Guide to Reliability (11) explains in simple, largely non-technical language what is meant by reliability, maintainability, and other similar concepts. This book deals with basic considerations which apply equally to electrical or mechanical designs but, as usual, examples are drawn mostly from electronics. It was written to provide an introduction to reliability and maintainability for those without any previous knowledge of the subjects. It is recommended for acquiring the basic concepts of the subjects on which more detailed and more technical knowledge can subsequently be based.

There are many different reliability/maintainability meetings held each year. For example, at least 283 different conferences were
conducted during 1963. Most of the papers presented at these meetings are concerned primarily with reliability but since the two parameters are so interdependent, various aspects of maintainability are covered also. The most useful conference, especially for the heavy equipment industry, is an annual conference cosponsored by the AIAA, SAE, and ASME. The proceedings and papers are presented in the *Annals of Reliability and Maintainability.*

So widespread has the need become in the Army to publish supplemental maintenance information about equipment after it has been issued to troops, that the Army publishes a monthly magazine of afterthoughts. The magazine is called "PS" (post scriptum). It presents illustrated information to mechanics and operators in a readable, interesting, and effective manner. Much of the equipment reported on is similar to that used for harvesting pulpwood. A very good checklist for design engineers could be compiled from this publication.

"The Military Engineer" is a bi-monthly publication of the Society of American Military Engineers. Articles covering design and performance requirements and techniques of both military and industrial equipments are presented.
APPENDIX B

THE EXPONENTIAL DISTRIBUTION AND RELIABILITY

General

An equation of the type:

\[ y = b^x \]

is called an exponential equation. In reliability studies, the exponential failure density that is commonly used is a direct consequence of the assumption that the probability of failure in a given time interval is directly proportional to the length of the interval and is independent of the age of the product. The exponential density derived from this basic assumption has the form:

\[ f(t) = \frac{1}{MTBF} e^{-\frac{t}{MTBF}} \]

where

\( MTBF \) = mean-time-between-failures

\( t \) = time period of interest

\( e \) = base of natural logarithms

The reliability at time \( t \) is:

\[ R_t = \int_{0}^{\infty} \frac{1}{MTBF} e^{-\frac{t}{MTBF}} dt = e^{-\frac{t}{MTBF}} \]

The instantaneous failure rate is denoted by \( \lambda \).
\[ \lambda = \frac{1}{MTBF} \]

thus:

\[ R_t = e^{-\lambda t} \]

Where MTBF is large relative to \( t \), the failure rate per \( t \) hours is usually approximated by:

\[ \frac{t}{MTBF} \text{ or } t\lambda \]

In design, if \( R_t \) can be estimated for a part or subassembly or can be calculated from previous experience records, then MTBF can be predicted by:

\[ MTBF = \frac{-t}{\ln R_t} \]

Numerical relationships between these quantities may be determined by use of the reliability graph in Figure 9 or the nomograph presented in Figure 10.

A very useful realization is that an exponential curve is simply a logarithmic curve with the axes interchanged. The basic equation:

\[ y = b^x \]

may be written in the form:

\[ x = \ln y \]
Figure 9. Exponential Reliability Function
<table>
<thead>
<tr>
<th>MTBF (hours)</th>
<th>$\lambda$</th>
<th>$R_t$</th>
<th>$t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000</td>
<td>.0001</td>
<td>.999999</td>
<td>.01</td>
</tr>
<tr>
<td>5,000</td>
<td>.005</td>
<td>.99995</td>
<td>.02</td>
</tr>
<tr>
<td>2,000</td>
<td>.001</td>
<td>.9999</td>
<td>.03</td>
</tr>
<tr>
<td>1,000</td>
<td>.005</td>
<td>.9995</td>
<td>.05</td>
</tr>
<tr>
<td>500</td>
<td>.01</td>
<td>.999</td>
<td>.1</td>
</tr>
<tr>
<td>100</td>
<td>.05</td>
<td>.995</td>
<td>.2</td>
</tr>
<tr>
<td>50</td>
<td>.1</td>
<td>.95</td>
<td>.3</td>
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<tr>
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<td>.5</td>
<td>.5</td>
<td>.5</td>
</tr>
<tr>
<td>5</td>
<td>.1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1.0</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 10. Reliability Nomograph
if e is used as a base. This means that if values of (x, y) are plotted using evenly spaced gradations to locate the x coordinate and logarithmically spaced gradations to locate the y coordinate, the resulting plot will be a straight line. This is a most convenient way to determine the validity of assuming an exponential failure distribution. Graph paper marked with such gradations is called semilogarithmic graph paper.

**Relationship of the Exponential to the Poisson Distribution**

The exponential and the Poisson distributions are equivalent except for the choice of the random variable. For the exponential, the random variable is the time-to-failure; for the Poisson, it is the number of failures per given time period where times to failure are exponentially distributed. The exponential variable is continuous; the Poisson variable is discrete.

The Poisson density of number of failures, N, is:

\[ f(N) = \frac{e^{-M_N}}{N!} \]

where \( N = 0, 1, 2, 3, \ldots \)

Letting

\[ M = \lambda t \]

the expected number of failures over the interval \((0, t)\) in a replacement situation, the density becomes:
\[ f(N) = \frac{e^{-\lambda t}(\lambda t)^N}{N!} \]

The probability of zero failures in the interval \((0, t)\) is therefore:

\[ f(0) = e^{-\lambda t} \]

which is the exponential reliability function.

As with the exponential function, the validity of an assumed Poisson distribution may be determined by the straightness of a plot of hours versus number of failures on semilogarithmic graph paper.

Chi-Square Validation of Poisson Distribution for Chain Saw Reliability

For the exponential and Poisson distribution:

\[ \chi^2 = -2 \sum_{n=1}^{N} \ln\left(\frac{t_N}{T}\right) \]

where

\(t_N = \text{total operating time at the Nth failure}\)

\(T = \text{total operating time at end of test}\)

\(N = \text{total number of failures}\)

The variate has \(2N\) degrees of freedom.
For the chain saw data of Chapter IV:

\[ \chi^2 = -2 \sum_{n=1}^{11} \ln \left( \frac{T_i}{T} \right) \]

\[ = -2 \left( \ln \frac{192}{917} + \ln \frac{207}{917} + \ln \frac{237}{917} + \ln \frac{272}{917} + \ln \frac{322}{917} + \ln \frac{417}{917} + \ln \frac{432}{917} + \ln \frac{542}{917} + \ln \frac{622}{917} + \ln \frac{787}{917} + \ln \frac{917}{917} \right) \]

\[ = -2 \left( \ln .2094 + \ln .2257 + \ln .2584 + \ln .2966 + \ln .3511 + \ln .4547 + \ln .4711 + \ln .4820 + \ln .6783 + \ln .8582 + \ln 1 \right) \]

\[ = -2(-1.564 -1.489 - 1.353 - 1.214 - 1.047 - .789 - .753 - .730 \]

\[ - .388 - .153 - 0) \]

\[ = -2(-9.480) \]

\[ \chi^2 = 18.960 \]

At the 95 per cent confidence level, the following values are found in chi-square statistical tables:

\[ \chi^2(0.025, 22) = 11.0 \]

\[ \chi^2(0.975, 22) = 36.8 \]

Since,

\[ 11.0 < 18.96 < 36.8 \]

the assumption of a Poisson distribution is validated.
APPENDIX C

THE LOGNORMAL DISTRIBUTION

General

Reliability engineers have found that the exponential distribution is a satisfactory approximation to the failure distribution of most components and equipments during their useful life period. These same engineers were the first to explore the concept of maintainability and they assumed that the same function was also a good approximation for downtime and repair time. However, actual measurements of these times have shown that this was not a valid assumption.

At the present stage of development of maintainability theory, it is not yet clear that any single distribution is sufficient for describing maintenance actions which would be performed during the period of time where chance failures occur. However, there is much evidence to indicate that the lognormal distribution is suitable in most cases and the exponential distribution is suitable in only a few (10,16). Still, some people concerned with maintainability insist that the exponential distribution is a good enough representation and that the lognormal is too complex to use. The theory describing the lognormal is indeed somewhat difficult but relationships that are both useful and easy to use can be derived from it.

The reasons why maintainability is best described by a lognormal distribution are largely speculative, however, this distribution is frequently observed in two general areas of phenomena. One of these is in connection with growing organisms; the other is
in connection with partitioning processes. Bovaird and Zagor (16) noted:

It has been known for a long time that response times of animals and humans to simple physical stimuli or perceptions are frequently lognormal. More recently, experimental studies of the reaction time of humans to more complicated perceptual patterns involving some degree of learning indicate that these reaction times are also frequently lognormal.

It has also been observed that when a large number of items is classified on some homogeneity principle, the variate defined as the number of items in a class is often approximately lognormal.

Horvath (17) has found that the service times at a tool crib and in a library can be fit very well by a lognormal distribution. The process of locating a demanded tool or book is a partition process characterized by logic, for some sort of coordinate system is used to find the tool or book. In both cases, a large number of items is classified on a homogeneity principle (location). Such observations suggest that the human partition process of placing objects in logical categories somehow leads to a lognormal distribution. Since location and correction of a fault in a system is to a large extent a logical process of placing things in categories, it is not surprising that actual maintenance task times tend to follow the lognormal distribution.

First considerations suggest that the distribution of downtimes and corrective action times for the same components or equipments should be normally distributed. Occasionally, however, an unfamiliar trouble occurs or an inexperienced mechanic performs the maintenance or a replacement part is not readily available. Such repairs require longer periods of time than most repairs. This tends to skew the distribution toward longer downtimes. As can be seen
Figure 11. General Shape of Lognormal Curves and the Negative Exponential Curve

from Figure 11, the lognormal curve describes the initial considerations, modified by the tendency just described, much better than does an exponential curve.

Whereas the exponential distribution makes use of the arithmetic mean of the variable, the lognormal makes use of the geometric mean of the variable or the arithmetic mean of the logarithm of the variable. Since the lognormal distribution, in its simplest form,
is a two-parameter distribution, it cannot be specified by the mean alone.

The lognormal distribution is a skewed distribution but it approaches the normal distribution as the standard deviation gets smaller. It is applicable when the geometric mean better describes the central tendency of the distribution rather than the arithmetic mean. It has been characterized by some as a model of the "law of proportionate effect." This law holds whenever the change in a variable at any step of a process is a random proportion of the previous value of the variable (16).

Quantitative maintainability criteria should be specified based on job requirements, not on statistical distributions. For the purposes of maintainability prediction, demonstration, and evaluation during a design or purchase decision, however, an assumption of a specific distribution is necessary, but not for the specification of requirements. For example, to specify a MTTR of 1 hour for a skidder only says that, on the average, the repair time will be 60 minutes. However, a substantial number of repairs may take a full shift time or more and still have a mean of 1 hour. If the skidder is feeding several trucks, then the long repair times become very costly. Woodlands managers are not interested in knowing that a system will be down a certain length of time "on the average," they want assurance that if a failure does occur, the equipment will be "fixed" and operating again in the least possible time.

On the other hand, specifying requirements in terms of a cumulative distribution (percentiles) is both proper and desirable.
If the skidder's average lead time over other operations is 1 hour, the specification might very well require that the downtime should not exceed one-half hour in 50 per cent of the cases, and that there should be a 95 per cent probability that it will not exceed 1 hour.

These, then, are job-related requirements and specify the 50 and 95 percentiles of the cumulative probability distribution. Such requirements serve as useful criteria for system maintainability design and are independent of what the actual distribution function might turn out to be. The assumption of a specific distribution, such as the lognormal, may then be used in order to facilitate maintainability prediction and to establish statistical sampling plans for demonstration as well as for use in availability calculations or reliability/maintainability allocations and tradeoffs.

**Summary of Lognormal Properties**

The following information summarizes the important mathematical properties of the basic two-parameter lognormal distribution. For a complete discussion of the theory and manipulations that lead to these results, it is suggested that a text such as that written by Aitchison and Brown (18) be consulted.

If a positive variable \( x \) is related to another variable \( y \) by the equation:

\[
y = \log_b x
\]

and the variable is normally distributed with mean \( \mu \) and variance \( \sigma^2 \), then \( x \) is said to be lognormally distributed. This distribution is completely specified by the two parameters \( \mu \) and \( \sigma^2 \). The lognormal
frequency function may be written as:

\[
f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}
\]

where

\[\mu = \text{mean of } \ln x\]

\[\sigma^2 = \text{variance of } x\]

Other characteristics are:

- Mode \(= e^{\mu-\sigma^2}\)
- Median \(= e^\mu\)
- Mean \(= e^{\mu+0.5\sigma^2}\)
- 75th percentile \(= e^{\mu+0.67\sigma}\)
- 90th percentile \(= e^{\mu+1.282\sigma}\)
- 95th percentile \(= e^{\mu+1.645\sigma}\)

A plot of the lognormal frequency function is shown in Figure 12.

For the lognormal distribution, the median is equal to the geometric mean. If the proportion of sample values that are less than or equal to \(x\) is plotted on a normal probability scale and \(x\) is plotted on a logarithmic scale, a very useful graphical relationship appears. If the distribution is lognormal the resulting plot will be a straight line. The use of such a plot was demonstrated in Chapter V.
Chi-Square Validation of Lognormal Distribution for Harvester Maintainability

To verify the correctness of assuming the lognormal distribution for the maintainability data of Chapter V, a chi-square goodness-of-fit determination was made. First, the data were arranged as shown in Table 11. Then:

\[ MTTR = \bar{M} + cd = \bar{M} + c \frac{\sum fd}{\Sigma f} \]

where

\[ \bar{M} = \text{trial mean} \]
\[ c = \text{class interval} = 0.5 \text{ hours} \]

Then:

\[ MTTR = 2.5 + 0.5 \left( \frac{116}{263} \right) = 2.5 + 0.22 \approx 2.72 \text{ hours} \]
Table 11. Harvester Downtimes Grouped for Calculation

<table>
<thead>
<tr>
<th>T</th>
<th>d</th>
<th>f</th>
<th>ln f</th>
<th>fd</th>
<th>d(ln f)</th>
<th>fd²</th>
<th>d²(ln f)</th>
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<td>3.74</td>
<td>- 84</td>
<td>- 7.48</td>
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<td>14.96</td>
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<td>3.56</td>
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<td>-</td>
</tr>
<tr>
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<td>6</td>
<td>1.79</td>
<td>90</td>
<td>26.85</td>
<td>1350</td>
<td>402.75</td>
</tr>
</tbody>
</table>

Totals 263 116 99.72 5044 1331.50

Next, the standard deviation is calculated:

\[
\sigma = c \sqrt{ \frac{\sum f d^2(ln f)}{\sum f} - \left( \frac{\sum f d(ln f)}{\sum f} \right)^2 }
\]

\[
= 0.5 \sqrt{ \frac{1331.5}{263} - \left( \frac{99.72}{263} \right)^2 }
\]

\[
= 1.0815 \text{ hours}
\]
A test value of $\chi^2$ is obtained from:

$$\chi^2 = \sum \frac{(E_i - O_i)^2}{E_i}$$

where

$E_i = \text{expected value of } ith \text{ observation}$

$O_i = \text{actual value of } ith \text{ observation}$

The expected values for a lognormal function applicable to maintainability may be obtained by the following procedure:

First, the mean of the distribution of the logarithms is computed from the median repair time. For the harvester repair time data presented in Chapter V:

$$e^\mu = 1.779$$

$$\therefore \mu = 0.577$$

Next the value of

$$\frac{\ln t_i - \mu}{\sigma}$$

is computed. For the harvester data, $t_i = 0.5, 1.0, 1.5... 10.0$

Using this calculated value, the expected fraction of the total number of observations for each value of $t_i$ can be determined from tables of the cumulative normal distribution. This fraction is then multiplied by the total number of observations to obtain $E_i$.

Table 12 shows the complete computation procedure.
Table 12. Chi-Square Goodness of Fit Calculation for the Lognormal Distribution

<table>
<thead>
<tr>
<th>$t_i$</th>
<th>$\ln t_i$</th>
<th>$\frac{\ln t_i - \mu}{\sigma}$</th>
<th>Expected Fraction of Total Observations</th>
<th>$E_i$</th>
<th>$O_i$</th>
<th>$\frac{(E_i - O_i)^2}{E_i}$</th>
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</thead>
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$\chi^2 = 10.48$
APPENDIX D

CALCULATIONS FOR CHAPTER VI

\[ MTBM = \frac{1}{\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5} \]

\[ = \frac{1}{0.0005 + 0.001 + 0.0002 + 0.01 + 0.002} \]

\[ = 73 \text{ hours} \]

\[ MTBF = \frac{1}{\lambda_1 + \lambda_2 + \lambda_3 + \lambda_5} \]

\[ = \frac{1}{0.0005 + 0.001 + 0.0002 + 0.002} \]

\[ = 270 \text{ hours} \]

\[ MTTR = \frac{\sum \lambda_i (MTTR)_i}{\sum \lambda_i} \]

where \( i = 1, 2, 3, 5 \)

\[ = \frac{(0.0005)(2) + (0.001)(1) + (0.0002)(5) + (0.002)(0.25)}{(0.0005) + (0.001) + (0.0002) + (0.002)} \]

\[ = 0.946 \text{ hours} \]
\[
\text{MADT} = \frac{\sum \lambda_i (MTTR)_i}{\sum \lambda_i} 
\]

where \( i = 1, 2, 3, 4, 5 \)

\[
= \frac{(0.005)(2) + (0.001)(1) + (0.0002)(5) + (0.01)(0.25) + (0.002)(0.25)}{(0.005) + (0.001) + (0.0002) + (0.01) + (0.002)}
\]

= 0.438 hours
LITERATURE CITED


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A Simulation Model
for the
Common Pulpwood Harvesting Systems
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Southern Pine Region

A SPECIAL RESEARCH REPORT

Submitted to
The Southern Executives Association

by
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Walter Wayne Cosby
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SUMMARY

The purpose of this report is to form the groundwork necessary for further research and study in the area of pulpwood harvesting and transportation, i.e., to study the basic systems commonly used at present by the majority of pulpwood producers. In order to achieve this objective the following specific goals were attained: (1) characteristics and constraints presently imposed on the common systems of pulpwood harvesting were defined and quantified, (2) three basic systems were defined, and (3) a General Simulation model was developed which is representative of the common 5'3" pulpwood harvesting methods.

The approach used in this study is that of system analysis. The system analysis methodology consists of eight distinct parts: (1) system definition, (2) reticulation, (3) abstraction, (4) identification, (5) measurement, (6) solution, (7) optimization, and (8) validation.

Two conclusions are drawn directly from the sample model. First, the model does represent the system, and second, quantitative insight into the real world system can be obtained from the model with respect to system limiting operations.
CHAPTER I

INTRODUCTION

Background

The record of the pulpwood industry in the South* has been one of exceptional growth over the past several decades. In 1920, there were 24 pulp mills operating in the South with an average mill production capacity of 41 tons of pulp per day (61). In 1966, 87 mills were in operation and average mill capacity had climbed to approximately 744 tons per day (52). In 1920 the South's share had been only six per cent of the nation's total pulp production, but by the end of 1966 the combined capacity of southern pulp mills represented fifty-eight per cent of the total national production (52). These statistics clearly indicate that the majority of the national pulpwood industry has shifted to the South.

While the number of pulp mills in the South and their capacity is known exactly, there are only rough approximations of the number of independent pulpwood producers in the entire Southeast. Today's partially mechanized, full-time producers can consistently produce 100 cords of pulpwood per week. If all producers could harvest just 4000 cords per year (worked 40 of 52 weeks) it would have only required 8,250 producers to supply the 33 million cords harvested in 1966. Yet one company paid nearly 10,000 different producers in the year 1966. This clearly shows

*Florida, Georgia, Alabama, Mississippi, Louisiana, South Carolina, North Carolina, Tennessee, Missouri, Arkansas, Virginia, Texas.
that even with present methods and machinery, the industry needs could easily be met with the available labor force if the present woods workers were full-time workers. Unfortunately, pulpwood harvesting is a seasonal or part-time occupation— the rural farmer. From the large number of producers paid and the small number of producers actually required, the small scale of operation of the typical supplier is apparent.

The objective sought by the pulp mills is an efficient, reliable, year-round pulpwood source. To obtain this objective, the industry seeks to grow more timber, harvest it more economically, and obtain better utilization from each tree (11). With respect to the harvesting goal, the industry is now seriously searching for feasible methods which will increase the productivity of the producers in order to cope with the increasing demand for pulpwood and the decline of the labor supply traditionally used in woods work (11, 22).

In conjunction with the above industry objective, Georgia Institute of Technology, School of Industrial Engineering is conducting research to study the "Systems Aspects of Harvesting and Transportation of Pulpwood". The objective of this research is to structure a systems model sufficient to validly represent the significant characteristics and constraints on present systems, and as the systems may appear up to the year 2000. This is one of the first reports produced from this research project and as such it endeavors to lay the basic foundation concerning common present day harvesting systems.

The specific objective of this report is to form the groundwork necessary for further research and study in the area of pulpwood harvesting and transportation, i.e., to study the basic systems commonly used by
the majority of pulpwood producers. In order to achieve this objective the following goals were attained: (1) characteristics and constraints presently imposed on the common systems of pulpwood harvesting were defined and quantified, (2) three basic systems were defined, and (3) a general simulation program was developed which is representative of the common 5'3" pulpwood harvesting methods.

Scope of Research

This research is directed toward the common, existing facilities now utilized in the production of 5'3" pulpwood. However, any organization concerned with pulpwood harvesting might find the approach and methodology useful. For example, in the study of long-wood pulpwood harvesting systems many of the same basic principles of operation are found and it is expected that these results would be useful in this area.

Approach

The approach used in this study is that of systems analysis. Courses in Systems Engineering, state that systems analysis methodology consists of eight distinct parts. The parts are: (1) system definition, (2) reticulation, (3) abstraction, (4) identification, (5) measurement, (6) solution, (7) optimization, and (8) validation. This basic methodology was adopted for this study for two reasons. First, the pulpwood harvesting procedure is amenable to this approach and second, the methodology allows for an orderly construction of the simulation model. The details of this method are outlined in Chapter IV--Procedure.
CHAPTER II

LITERATURE SURVEY

Pulpwood Harvesting Literature

Pressures on the Industry

Today the pulp and paper industry is expanding to meet the constantly increasing demand for pulp products (8, 39, 58). The increased number of pulp mills and mill capacity in the South is stated on page one of this report. However, the increasing demand for pulp products can most easily be seen from the rise in per capita consumption of ordinary paper. In 1920, the per capita consumption was 90 lbs. In 1965 this had increased to 495 lbs. (37) and the first estimates of 1967 per capita consumption of paper state that there is now over 500 lbs. of paper per year per person used in the United States. In 1961, a consumption of 550 lbs. per person was predicted for 1975 (44, 58).

Concurrent with the increased demand for pulp products is the well established decline in the rural, Southern, unskilled labor which has traditionally been used for pulpwood harvesting (11, 22). This declining labor pool is assumed to have reduced the number of part-time producers formerly relied on to meet demand. The declining labor supply, the booming economy of the sixties, and rising minimum wage are the major factors which have contributed to the pressure on the pulp-using industries* to find a consistent economical supply of pulpwood.

*Pulp-using industries are hereafter referred to as "the industry."
Industry Research Efforts

Faced with increasing demand and decreasing supply of labor for harvesting, the industry is now willing to pay for research—both basic and applied—from universities and private research institutes in areas which will be of benefit to the entire industry. At present here in the South, the industry is sponsoring research projects at Georgia Institute of Technology and at Auburn University in the area of pulpwood harvesting. Across the South, other universities* having forestry schools are working on research projects in other areas for the industry. The American Pulpwood Association has recently established a Pulpwood Harvesting Research Program in Atlanta, Georgia. The Association is presently concluding a three year survey of southern pulpwood producers. The survey was designed to gather data on all aspects of present pulpwood systems. In order to efficiently utilize this data, Honeywell Corporation is working on a computerized storage and retrieval system. The John Deere Company has been retained by the industry to do research on forestry machinery.

This willingness of the industry to sponsor research has not always existed. From 1960 to 1963 a coalition of companies sponsored a major research project by Battelle Memorial Institute (19, 20, 21). The results were a series of twelve reports utilizing various techniques to study pulpwood harvesting. These results were considered proprietary information until the middle of 1967. While Battelle's research did

*University of Georgia, North Carolina State, Louisiana State University, Clemson University, Florida State University, and Auburn University.
produce some recommendations which could be applied to the industry successfully, no direct change can be seen to have been brought about as a result of such research. However, indirectly, the fact that scientific research could be applied to pulpwood harvesting has perhaps assisted in the present willingness of the industry to sponsor research.

Pulpwood Harvesting Machinery

There has been a veritable flood of papers discussing concepts and aspects of the new ideas and new machinery being developed for pulpwood harvesting during the past six years. While this literature is relevant to the objectives of this study, it is also rather extensive and we are forced to briefly cite only a few representative papers (6, 24, 51, 59, 60). The literature on mechanical harvesters is almost exclusively from the United States, Canada, Sweden, and the Soviet Union. However, it has only been in the past two years that harvesting machines have emerged from prototype to production. The literature on harvesting machinery predominantly concerns long-length and whole-tree logging (33). This is to be expected, as machinery can more efficiently handle long-length wood. Virtually nothing is written concerning mechanical shortwood harvesting systems. The exception to this are the articles on the Busch Combine harvester, designed here in the South to be compatible with existing mill requirements for shortwood (44, 45).

From the literature on logging machines several generalizations can be made. First, the only standard piece of machinery here in the South (and generally world-wide since about 1965) (26, 38) is the chain saw used for felling. While the power saw is also used for limbing in the South, it has been shown that a hand bow-saw is more productive in
species and stands found in the northern central states region (14). Second, due to climate and terrain differences, no one piece of machinery will be applicable to all pulpwood harvesting (6, 50). This applies here in the South as there are three basic terrains found in this area alone: the coastal plains, the Appalachian uplands, and the Piedmont Plateau. Third, there is a tremendous potential market for harvesting machinery. The manufacturer who can produce an efficient machine, capable of operating under widely varying conditions, can expect to receive great financial reward. However, the amount of capital necessary to own and operate present harvesting machinery pretends a major change in pulpwood financial systems in the South.

While the major emphasis has been on the building of mechanical harvesters in the United States and Soviet Union, in Great Britain and Soviet Latvia the emphasis appears to be toward the development of a machine to economically harvest the thinnings from plantations. This area is treated lightly in American literature as the greater proportion of American pine plantations are not yet near enough to the stage for thinning. This is an area of research which cannot be put off too long for the pulpwood industry in the South.

New models of de-barking machines are being produced. Studies have been made on the commercially available machine regarding their economics and quality of work (28, 48, 54). Basic research has been started on measuring the bond strength between the bark and wood in Canada. Chemical barking of the standing tree has yielded very disappointing results in British research (34).
Chipping in the forest shows increasing interest in the United States, Soviet Union, Poland, Germany and Sweden. These papers (2, 29, 32) contain studies on chipping machinery, work organization, economics, etc. Canada has not yet released complete results of economic feasibility studies regarding chip pipelines, but there are several organizations studying this approach to transportation (33).

**Industrial Engineering Work Study**

In a 1967 world literature survey (38), there were 44 reports of research in the area of Work Study. Particular note was made that the recent literature shows a definite move away from stop-watch methods in favor of work-sampling or activity-sampling techniques. Of the papers cited in the survey, not one was of American origin. While the studies of skidder operations, such as (12), belong in this category of literature, there is a major deficiency in Southern pulpwood harvesting literature with respect to such areas as those dealing with comparisons of methodology and productivity for elements of operations and in such areas as psychological and physiological studies of human factors. Canada has produced a variety of methods to calculate payment for woods workers, with most methods using an incentive plan; however, similar research on Southern woods labor problems is nearly non-existent.

**Pulpwood Standards**

A basic lack of standards is also apparent in the industry. Previously the lack of standard machinery was cited. In addition to a variety of machines, there is a variety of methods of harvesting pulpwood, even among those systems using similar machines. This fact is demonstrated
in Figure 2 which shows the possible combinations of basic harvesting operations commonly found in the South.

Chapter III discusses the various pulpwood measures of weight and volume. An understanding of pulpwood measure is essential to read the literature satisfactorily. Canada uses a measure called the cunit or C-unit. In the South pulpwood is commonly measured by the cord. However, the term unit is also extensively used in the literature. Each of these terms is defined by volume and by weight measure with the inevitable result of variation as to exactly what is meant (3, 5, 42). Associated with this, there is a lack of standards regarding definition of acceptable "roundwood" (1, 14, 53). A list of general criteria commonly used in company wood specifications has been formulated in Chapter III.

Simulation Literature

History of Simulation

Simulation has a long and interesting history. This was the method employed to obtain the celestial navigation tables needed for world exploration and the establishment of international trade. For navigation, the value was so great that men spent their lifetime compiling by hand computation the future positions of the moon, planets, and stars (15). This laborious process was the only alternative because an analytical solution to the multi-body problem could not be found.

Until the electronic computer became available, the cost of simulation rendered it economically unfeasible, therefore, little was known of its power or potential. Because simulation techniques were unknown
it was not even attempted for those situations which might have been economically justifiable.

Analog and digital computers arrived as engineers became involved in systems of such complexity that they could not be simplified to obtain analytical solutions. The demand for simulation has risen since 1950 as the cost of the computer has decreased. Perhaps the largest single item contributing to the rapid rise of simulation was its use in post World War II in the solution of atomic energy problems (21, 47).

**Literature Partition**

The literature describing simulation experiments can be partitioned according to the kind of system measurement used. Military simulation experiments tend to measure systems response to a specific set of initial conditions (10, 36). There appears to be a definite lack of literature on measurement of response to system initial conditions. It is felt that this is an indication of its specialized nature, not its worth (13). In this study, a simulation program applied to the specialized topic of pulpwood harvesting, the concept of measurement of system response to initial conditions is expanded. The expansion is accomplished through the use of user designed distributions describing the initial conditions from which random samples are taken and tested for their effect on the system.

**Definition of Simulation**

In the past the term simulation has had many meanings. Everyone who has had some influence on its development has applied his own definition. This has resulted in a class of vague, often conflicting, ideas about must what simulation is and what it encompasses. C. W. Churchman
has set down two somewhat philosophical definitions. However, Thomas H. Naylor gives a definition that involves the common concepts of the simulation technique:

Simulation is a numerical technique for conducting experiments on a digital computer, which involves certain types of mathematical and logical models that describe the behavior of a business or economic system (or some component thereof) over extended periods of real time (35, p. 3).

The concept of model building is stressed by Dimitris M. Chorafas in his definition:

Simulation involves the construction of a working mathematical or physical model presenting similarity of properties of relationships with the natural or technological system under study (9, p. 9).

Martin Shubik gives the advantages and purposes of simulation in a concise form in his definition:

A simulation of a system or an organism is the operation of a model or simulator which is a representation of the system or organism. The model is amenable to manipulations which would be impossible, too expensive or impractical to perform on the entity it portrays. The operation of the model can be studied and, from it, properties concerning the behavior of the actual system or its subsystems can be inferred (49, p. 199).

P. J. Kiviat (27) simplifies the definition by stating that "Simulation is the use of a numerical model to study the behavior of a system as it operates over time."

Note the use of the word "study." When a simulation model is given a set of input parameters and an initial system state, it is "run" to
to deduce subsequent system states and estimate measures of system performance. Different parameter settings produce different system responses. These responses are studied to determine the set of parameter values that in some sense optimizes system performance. A simulation model programmed in GPSS-II computer language is designed in this research work in an experimental manner. It does not find or seek to find optimal system parameter settings by itself. This is the conceptual framework for simulation in this report.

Simulation Program Languages

For this research a computer was available, and, since the computation time by hand appeared to be excessive, it was decided to program the problem for machine solution. The programming time, even with a general purpose language, could not compare with the time required to solve even a very small portion of the experiments possible if they were done by hand.

The selection of a computer language for programming the simulation was dependent on the capabilities of available hardware. Several special purpose computer languages have been developed which make simulation programming easier and more comprehensive. Two of the most notable of these are: SIMSCRIPT, a product of the Rand Corporation, and General Purpose Systems Simulator (GPSS-II), developed by IBM Corporation. A number of other languages have been written but they are designed primarily to be used for particular types of problems and do not have the general applicability of SIMSCRIPT and GPSS-II.

GPSS and SIMSCRIPT facilitate the preparation of simulation programs in two ways:
1. They provide a convenient set of concepts for translating the model from an ordinary word description to a more rigorous and complete description from which it is easier to write a computer program. This set of concepts is termed the "world view" of the language.

2. They provide a language which is particularly suited for transforming the above description of the model into a computer program.

Both languages are predicated on the assumption that computer time is inexpensive relative to the cost of a programmer. As such, they substantially reduce the programming effort required by shifting much of the translating task to the computer (17, p. 3).

Both languages offer the advantage of shorter programming times when compared to a general purpose language such as FORTRAN or ALGOL. Since GPSS-II was available at the Rich Computer Center of Georgia Institute of Technology and the research personnel were trained in the language, GPSS-II was chosen to model the system.

The GPSS-II programmer requires only a Reference Manual which is written specifically for the U-1108 computer by Univac Data Processing Division. GPSS is comparable with other computer systems.

The program described herein is a general-purpose simulator designed to aid system study work. The system to be simulated must be described by the user in terms of special block diagrams. The program operates on the UNIVAC 1108. . . . and no knowledge of the computer operation is assumed. The user need only know the rules by which the block diagrams are constructed (57, p. 3).

The details of how GPSS-II was used in the model building process is covered in Chapter IV.
Technical Simulation Problems

Although simulation has many advantages, the difficulty involved in developing a model, programming the model, and utilizing the results should not be overlooked. Computer programming has proven to be the major stumbling block in many simulation attempts. This difficulty has been overcome in recent years to a large part through the development of specialized simulation languages (DYNAMO, SIMSCRIPT, SIMULA, GPSS-II, etc.).

Another problem area is that of the experimental design. Considerable effort can be expended with little result if the experimental design and the input data are poor. This was realized many years ago and popularized by the term GIGO (Garbage In—Garbage Out); however, this area is still a major pitfall (13).

One prime area of difficulty in simulation is that concerned with statistical questions. Simply because a problem is run on a computer does not mean it is either valid or statistically significant. Fishman and Kiviat (13) raise several statistical questions which are common to all problem analyses and to model structural verification and validation as well. One question relates to sampling intervals, or the choice of time periods between successive observations. Another question deals with methods to efficiently obtain results of a desired level of reliability. This question is often discussed under "variance reduction techniques" in the literature of statistics. However, reliability estimation itself poses a statistical problem with respect to the length of time required to run the simulation.
Finally, in any system, there are usually certain key characteristics which will contribute most of the information to be derived from the simulation (4). There are also a great number of minor factors than may feasibly be included in the program. Thus, the number and type of characteristics to be included should be carefully selected.

By discussing these four problem areas it is not to be inferred that this is the extent of simulation problems. These areas are mentioned because of the problems they posed to the authors.

Forestry Simulation Literature

George M. Furnival (16), in the 1966 Forestry Symposium at Louisiana State University, stated that there are three basic uses of the computer in forestry. These are (1) to compile statistics to describe the forest, (2) to predict change in a given forest, and (3) to aid in analysis of management alternatives. The technique of computer simulation as a forestry management tool belongs in this third class.

At present two forest simulators approach operational status. One is the Harvard Forest Simulator, developed by E. M. Gould and W. G. O'Regan in 1965 (18); the other is the University of Georgia program, POPS, prepared by J. L. Clutter and J. H. Bamping in 1967 (10). Both simulators employ yield tables and suffer from the weaknesses recognized as inherent in yield tables. Both require that the entire stand be used as the basic unit of record keeping. While this reduces the initial computer data problem, it creates additional work in remapping of stands and keeping track of the cut by stands. However, while several authors have enumerated these basic weaknesses, none have suggested a better method (16, 40).
These simulators are receiving attention because they offer at least a partial solution to an important problem. The most elaborate forest inventory, no matter how current and detailed, can only answer the question, "What is the present forest condition?" The reply of a computer to this question, while useful, tells management only present data. These forest simulators are designed to answer the more pointed question, "Given the present forest conditions, what will be the economic consequences of a particular management decision?" Thus, by asking the question for each possible decision, the simulator provides a means of answering the basic question, "What should be the management practices on a given forest property?" With 75 mills of the South, this question is of great economic interest.

Although pulpwood harvesting is also a multi-million dollar industry, there are no producers with adequate facilities or capital to study harvesting by computer simulation. To date, the only pulpwood harvesting study utilizing simulation is by R. M. Newnham (36). This study simulates the passage of a feller-buncher type of harvesting machine through a pulpwood stand. The input parameters for the model are the stand and machine characteristics; the output gives a breakdown of harvesting time (into machine travelling time, felling and bunching time, unloading and non-productive time), the position of each sweep and the number of trees felled and their volume. An optional computer map is produced to show the spatial pattern of the trees and the harvesting pattern.

Stand characteristics (spatial distribution, log diameter distribution, stand density, and tree volume) were artificially generated or kept constant for all tests in order to eliminate costly and time-consuming
field work to gather the necessary data. The model does have some response to the presence of cull trees; however, this does present a possible conflict with one of the basic assumptions of the model. The effects of slope and microtopography were not considered in this model. As a harvesting machine simulator, the model is flexible and has produced results close to those published by manufacturers of feller-buncher harvesters.

Row (46), in 1963, developed a FORTRAN program to compute rates-of-return for complex forest-investment alternatives. This program evaluates six investment alternatives simultaneously and performs the analyses repetitively for many cost and price situations.

Palley and O'Regan (41, 43) have published two studies utilizing a computer to compare forestry sampling techniques. Chappelle (7), a forest economist, has published a FORTRAN IV program for calculating allowable cut from a stand. The works of Hool (25) and Tse-Hao (56) are typical of the many M.S. and Ph.D. thesis and dissertations utilizing specific computer techniques to approach general forestry problems.

Thus, while the computer has been used in forestry, the particular technique of simulation and the use of a computer to aid harvesting studies is virtually non-existent. However, as research efforts increase, the use of simulation will increase. Simulation can cope with the multitude of factors involved in the harvesting or management of a large forest property with our present state of knowledge.
CHAPTER III

CHARACTERISTICS AND CONSTRAINTS

Pulpwood Specifications

The pulp mills which have entered the South in the past two decades have designed their plant equipment to handle the existing common form of the raw material. This has resulted in the placing of the largest single constraint on pulpwood harvesting, namely, the requirement for pulpwood to be in the form of a 5'3" bolt. Chips are the only other generally acceptable form of the raw material since all pulpwood is ultimately reduced to chip form.

Every mill has published a list of specifications for pulpwood which it will accept; however, the following seven specifications are representative of the industry requirements:

1. Bolts must be at least 3 to 4 inches in diameter inside the bark at the small end and cut to the specified length.

2. Bolts must not exceed 18 to 24 inches in diameter outside the bark at the large end.

3. Wood must be straight and sound.

4. Ends must be cut square and limbs trimmed flush.

5. No burned or rotten wood is accepted.

6. All nails and metal must be removed from bolts.

7. Mixed loads of softwood and hardwood will not be accepted.

(Square brackets indicate range of variation between mills.)
Reasons for the Shortwood Lengths

Pulpwood bolts of 4 or 5 feet were originally adopted for two very good reasons which have to do with the original location of pulp mills in the New England area. One was that each stick had to be moved by hand a number of times in the trip from woods to mill; and the traditional pulpwood species (spruce, fir, and aspen) could be easily handled by one man in these lengths. The other reason was that the chief method of transportation of wood was the river drive and the small streams of the area handled this length of wood best. Today, with mechanical handling facilities and the abandonment of the river drive in favor of year round trucking or rail transportation, these original reasons for shortwood are no longer necessarily valid.

The only valid remaining reason for cutting pulpwood into 4 or 5 foot lengths is that the handling facilities at the mills are designed specifically for this kind of wood. Flume radii, grab cranes, drum debarkers and pocket grinders are specific examples of high cost items which have very long useful lives. Thus, the high cost of converting mill wood handling systems to accept other than shortwood is the largest single reason for maintaining the present form of the raw material and therefore the present supply system.

Long-length wood forms and chip forms were predicted as the future form of pulpwood resource as far back as 1953 (31).

Volume Measure

The standard cord of wood is a rick (or stack) measuring 4 x 4 x 8 feet and containing 128 cubic feet. However, this is a measure of space
occupied as it contains wood, bark, and many voids. Short cords and long cords are common variations of the standard cord and are often referred to as "units." The short cord refers to an 8 foot rick which is 4 feet high but cut to firewood length, generally 2 to 3 feet long. Likewise a long cord is a 4 x 8 foot rick of bolts in excess of 4 feet and up to 8 feet long. Lumbermen also refer to 500 board feet as the equivalent of a standard cord of wood.

Today, United States pulpwood is cut in lengths of 2, 4, 5, 5.25, and 8.33 feet. The southern states pulp mills predominantly used wood 5'3" in length. While the United States has many lengths of pulpwood and many measures of it, Canada and Europe have almost totally adopted the cunit, C-unit, or cubic-unit. This refers to 100 cubic feet of solid wood, not stacked volume.

Solid wood is the preferred unit of measure from the pulp mills viewpoint. A major work on the measurement of the solid volume of wood was published by Taras (55) in 1956 and today is referenced as the authority in the field of measuring solid content of southern tree species.

The following table gives approximations of wood volume in various sized cords of ricks; however, these estimates of rick volume are admitted to have great variation (1).

<table>
<thead>
<tr>
<th>Rick Size</th>
<th>Cu. Space</th>
<th>Cu. Volume (Wood &amp; Bark)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 x 8 x 4</td>
<td>128</td>
<td>90</td>
</tr>
<tr>
<td>4 x 8 x 5</td>
<td>160</td>
<td>113</td>
</tr>
<tr>
<td>4 x 8 x 5.25</td>
<td>168</td>
<td>119</td>
</tr>
<tr>
<td>4 x 8 x 6</td>
<td>192</td>
<td>136</td>
</tr>
<tr>
<td>5 x 8 x 8.33</td>
<td>266.6</td>
<td>181</td>
</tr>
</tbody>
</table>
Variation in cubic volume is a function of the species, method of piling, diameter, stick length, straightness and freedom of knots. Values for variation due to these factors are given by Taras (55). Despite these variations there has never been a simpler or more convenient method found to measure wood. In the Lake states, a value of 79 cubic feet of solid wood is the estimate of a standard cord. The South produces only 72 cubic feet of wood per cord for pine and 79 cubic feet for hardwoods according to the U.S. Forest Service. Individual mills have traditionally computed their own values of solid wood per cord and weight of wood per cord based on the size and quality of wood which they purchase.

An ideal measure of volume would be absolute, unambiguous, accurate, simple and cheap. The method closest approaching these criteria utilizes the archimedes principle of water displacement. However, the xylometer is still in the experimental stage.

Weight Measure

Mine timber and pine stumps have been bought by weight for many years. Today we find there is a great increase in the appeal of buying by weight. This has been attributed to the change in the location of the measurement and purchasing functions—from the forest to the mill or concentration yard (1). Since 1955, a large segment of the pulp industry has adopted weight scaling instead of volume estimation. This has grown in the same manner as volume measure, that is, each company has studied the wood it procures and obtained values which it alone uses. This is shown in the values used today for weight measure. Prices are usually quoted on average weight per standard cord. Signi-
ficantly not in use are the former measures of ton and hundred weight.

Factors contributing to variation of weight within a given species and area are wood volume, moisture content and density. Wood volume variations are discussed in terms of wood volume measure. Moisture content varies for heartwood and sapwood. Density is affected by per cent of summer-wood, growth rate, and position in tree, i.e., density is lower at the top of the stem than at the base. This variation in weight is illustrated by the following tables from Taras (55).

<table>
<thead>
<tr>
<th>Species</th>
<th>Specific Gravity</th>
<th>Moisture Content (%)</th>
<th>Density #/cu.ft.</th>
<th>Solid Vol/cord</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loblolly</td>
<td>0.46</td>
<td>110</td>
<td>60.3</td>
<td>72</td>
</tr>
<tr>
<td>Longleaf</td>
<td>0.53</td>
<td>105</td>
<td>67.8</td>
<td>72</td>
</tr>
<tr>
<td>Shortleaf</td>
<td>0.44</td>
<td>120</td>
<td>60.4</td>
<td>72</td>
</tr>
<tr>
<td>Slash</td>
<td>0.52</td>
<td>120</td>
<td>71.4</td>
<td>72</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Species</th>
<th>Weight of Solid Wood/cord (lb.)</th>
<th>Estimated Bark (lb.)</th>
<th>Total Weight (lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loblolly</td>
<td>4,342</td>
<td>700</td>
<td>5042</td>
</tr>
<tr>
<td>Longleaf</td>
<td>4,882</td>
<td>650</td>
<td>5532</td>
</tr>
<tr>
<td>Shortleaf</td>
<td>4,349</td>
<td>500</td>
<td>4849</td>
</tr>
<tr>
<td>Slash</td>
<td>5,141</td>
<td>500</td>
<td>5641</td>
</tr>
</tbody>
</table>

While Taras has computed total weight very accurately, he has also shown the limitation which has yet to be overcome. "For each 0.02 change in specific gravity at 100% moisture, wood weight will change approximately 2.5 lb./cubic foot." Also, if moisture content varies five per cent the weight change will be 1 to 2 lb./cubic foot. Therefore, if a 72 cubic foot cord changed 0.02 specific gravity and five per cent in moisture the weight change could be as great as 280 lb.

Contrary to popular belief, it has not yet been proven that weight scaling is greatly superior to measuring stacked ricks from the standpoint of predicting actual amount of solid wood in a cord (1).
Reasons for Weight-Scaling Pulpwood

1. It encourages delivery of green wood to the mill. The mills prefer green wood as it will store longer and yields more useable fiber if pulped when green.

2. It is a fast method requiring no special handling, thereby saving time and money.

3. Weight scaling is more objective than cordwood scaling and positive records of all transactions are automatically provided by the weight tickets. Weight scaling eliminates human error or indifference in manual volume calculations.

4. Incentive is provided for better piling on trucks, thereby increasing volume handled.

5. Woodyard inventories are easier to maintain because of greater uniformity in record keeping. Thus it is a much more satisfactory way to do business with a bulk product.

Factors Favoring the Small Producer

There are several factors today which tend to sustain the existing pulpwood supply system. These factors are economic and environmental in nature.

Pulpwood harvesting in the South was originally a part-time job for the farmers after the crops had been planted and again after the harvest. It was ideally suited for the farmer as the forest was just too cold and wet in the winter and too hot and humid in the summer. The small amount of capital needed to be a part-time producer allowed nearly everyone to do some pulpwood cutting. The price of a chain saw
for felling and bucking efficiently, and the existence of an old truck for hauling the wood is all that is necessary to become a pulpwood producer even today.

The standard 5'3" bolt still needed by today's mill perpetuates the part-time producer. This situation stems directly from the original reason for shortwood--ease of manual handling. (The average pine bolt weighs approximately 65 lbs.)

Changes in land ownership patterns of the South in the past 50 years have reduced the size of privately owned timber tracts available for cutting. Thus small tract size (less than 100 acres) (22) has favored the small, part-time producer. The absence of large blocks of available timber retards the trend toward the mechanical harvesting of pulpwood. It is very expensive to constantly move heavy equipment between small stands. The desired size stand for optimal mechanical harvesting has been estimated to be approximately 650 acres (10).

Recent years have seen the emergence of the full-time producers. Their initial capital investment may not be much larger than that of a part-time producer (two saws and a two-ton truck, as opposed to a saw and any truck). However, in order to produce more than 30 cords per week, additional investment in machinery is needed. Some of the independent producers that harvest 80 to 100 cords a week, have an investment of $40,000 and more in machines. Yet a paradox exists when the profit of the small manual producer and the profit of the mechanized producer are generally comparable. Initial studies by the research group at Georgia Tech indicate that present mechanized harvesting systems offer very limited economic advantages over the manual systems
due to the mechanized equipment's high initial cost relative to its productive capability and the more competent labor required to operate mechanized systems.

Another factor which has played a part in limiting the size of the business of an independent producer is his inability to supervise and obtain steady employment for more than a single harvesting crew. Those men which have such ability are often lost to the factories where the work is steady, indoors and much less demanding physically and mentally (11, 30). However, there does exist a certain amount of prestige associated with owning and operating a pulpwood harvesting business. This prestige and independence of the operator are perhaps the biggest factors which have kept the supply of pulpwood equal to the demand.

These factors (small tracts, low capital needed to enter the business, independence, prestige, and cost to mill and producer for conversion to other harvesting methods) are still valid reasons for continuing with the existing system. However, in order to maintain the present price paid for pulpwood and insure that supply will not fall below demand, the system must change. An example of such a system can be seen in American farming. Farming has been changed during the past 50 years by the economics of scale, into highly specialized production of a crop by each farmer. Pulpwood producers can look toward similar high-volume specialization if the fight against pulpwood cost increases is to be waged successfully by the mills.

Further, it must be recognized that pulpwood harvesting is physically demanding. Coupled with the uncertainties of woods work
(weather, demand, and available forest), pulpwood production is not as attractive as many other jobs.

Rural out-migration can be seen clearly from the following statistics of the U.S. Census Bureau. The 12 Southeastern states had 3.24 million farm workers and 1.87 million farms in 1950. By 1959 these figures had decreased to 2.22 million workers on 1.15 million farms. Between 1959 and 1964 the number of farms across the entire South declined 16 per cent. This resulted in a loss of only slightly more than 11,000 acres as the size of the average farm climbed from 217 acres to 252 acres. The population shift in the South is also revealed in the 1950 and 1960 census figures. These figures show that the South had a loss of 2.5 per cent in rural population and a 42 per cent increase in urban population for a net increase of nearly 17 per cent. Thus, while Southern rural emigration and job-creating industrialization have not lead to pulpwood shortages so far, this possibility exists in the future (20). This, again, points toward mechanization and specialization in order for pulpwood harvestings to remain an economical and attractive means of livelihood.
CHAPTER IV

PROCEDURE

Introduction

The procedure used in this investigation was subdivided into two separate areas. The first was the area of systems analysis and concerns the extraction of the real world system from the environment and the preparation of certain models. The second area was the use of these models for the development of simulation programs.

System Analysis

Approach

In selecting an approach for modeling the system, the original choice was to try and describe each basic component by a mathematical equation and solve the system of equations by Laplace Transformations and Matrix Theory. As system research progressed and knowledge of the system variables increased there were obvious indications that a purely formal, rigorous mathematical approach would not necessarily yield satisfactory solutions. Further research into the methods of solution of complex system models indicated that simulation using Monte Carlo methods could be of use in this case.

Once simulation was selected, two problems arose:

1. Since simulation requires an enormous number of arithmetical calculations, a computer is necessary.

2. General purpose language programming for simulation of this type is most tedious, time-consuming, and not necessarily the most efficient method.
Figure 1. Environmental Factors In Pulpwood Harvesting
Figure 2. Interchangeable Blocks for Three Common Shortwood Harvesting Systems
Solution at Georgia Tech to these problems were found in the Fall of 1967 with the installation of a UNIVAC 1108, a high speed digital computer, equipped to handle the "General Purpose System Simulator II (GPSS-II)" language.

With the decision to use GPSS-II simulation language on the U-1108 computer, the method of approach could then be broken into eight phases. These phases are listed as follows: (1) system limit definition, (2) reticulation, (3) abstraction, (4) measurement, (5) identification, (6) solution, (7) optimization, (8) validation.

**System Definition**

The first step toward an analysis of a system through modeling is to define the system and its environment. The real world system under consideration in this report are those physical functions which are performed by the pulpwood producer's personnel and equipment. This means that the system will start with a stand of trees ready to be harvested and will terminate when the 5'3" pulpwood bolts have been brought to the concentration yard for rail shipment to the mill. The environment consists of all other factors which provide information for the input channels which the harvester uses to decide when and where to cut and how much to cut. These information inputs from the environment would correspond to the woodlot owner, the pulp mill procurement manager, the concentration yard operator, and the forestry agent of state or federal government.

This harvesting model summarizes the major environmental inputs considering that a stand of trees awaits harvesting. It is also assumed
that a market is available to accept the pulpwood. The system and its environment are now defined with these two simplifying assumptions.

Reticulation and Abstraction

Three common harvesting methods were outlined. The three systems were then reticulated into basic operation through product flow charting techniques. The sequence of operations of these systems is shown in Figure 2. The systems contain a total of 12 different operations.

There are many possible combinations of the 12 basic operations into workable systems. In order to establish all the combinations which were reasonable realistic, the technique used in the Critical Path Method of project management was utilized since the possible precedence relationships of each operation were known. The 28 possible realistic combinations are identified on figure 3.

Identification

This phase of the analysis resulted in a listing of those factors effecting each operations productivity. The operations are listed as follows, with factor explanations given as required:

(1) **Planning, Moving, and Felling of Tree** (Block 20)

(a) Type of harvesting operation

1. Seed Tree
2. Select Cut
3. Clear Cut
4. Multi-Product Harvesting

(b) Terrain

1. Slope
2. Soil Moisture
3. Obstacles
   a. Rivers and Creeks
   b. Rock and Crops
   c. Windfalls
4. Underbrush
(c) Stand Characteristics

1. Spatial Distribution
2. Diameter Distribution
3. Individual Tree Characteristics

(d) Species

1. Softwoods
2. Hardwoods

(e) Extra Work Required (Swamping, Pre-measuring, etc.)

(f) Crew Organization

(g) Method of Cut

1. Chain Saw
2. Hydraulic Shear
3. Handcut

(2) Bucking, Limbing and Topping (Block 30)

(a) Log Size

1. Diameter
2. Length

(b) Species

1. Softwood
2. Hardwood
3. Limbiness

(c) Felling Pattern

1. "Hang-ups"
2. "Cross-overs"
3. Obstacles

(d) Slash Disposal

(e) Measuring Method

(f) Method

1. Multi-Function Machine
2. Chain Saw
3. Hand Saw

(3) Skidding or Pre-haul (Blocks 40 and 52)

(a) Weight Considerations
1. Sufficient Logs for Optimum Load
2. Sufficient Chokers Available

(b) Terrain

1. Slope
2. Soil and Soil Moisture Content
3. Obstacles
4. Brush

(c) Distance Per Turn

(d) Non-Effective Time

1. Choking of Logs (grapple or cable)
2. Awaiting a Load
3. Unloading
4. Trail/Road Repairs
5. Machine Repairs

(4) **Stack or Load Pallet** (Blocks 50 or 51)

(a) Weight

(b) Height

(c) Distance (major factor)

(d) Number of Pieces per stack (the larger the required size stack, the longer the distance necessary to get the wood).

(5) **Loading or Transfer** (Blocks 60, 62, and 63)

(a) Manual (same factors as "stack" except that height is now the major factor and distance a minor factor).

(b) Mechanical

1. Number of Pieces Loaded Per Cycle
2. Effective Crew Loading Time
   a. Available wood
   b. Available truck

(6) **Transport** (Block 70)

(a) Size of Load

1. Trucking Limitations
2. Legal Road Limits

(b) Length of Haul
(c) Speed Limits
   1. Load Size
   2. Road Quality

(d) Effective Hauling Time
   1. Load and Unload Time
   2. Delays in Loading and Unloading
   3. Mechanical Failures

(7) Buck (Block 32)
   (a) Log Size
      1. Diameter
      2. Length
      3. Hardwood or Softwood

   (b) Site and Arrangement of Logs
      1. In the Woods
      2. On a Landing

   (c) Measuring

   (d) Method
      1. Chain Saw
      2. Slasher
      3. Handsaw

(8) Limb and Top (Block 31)
   (a) Log Length

   (b) Species
      1. Softwood
      2. Hardwood
      3. Limbiness

   (c) Site Obstacles

   (d) Slash Disposal

   (e) Method
      1. Manual
      2. Mechanical
| Sys. No. | 1. | 2. | 3. | 4. | 5. | 6. | 7. | 8. | 9. | 10. | 11. | 12. | 13. | 14. | 15. | 16. | 17. | 18. | 19. | 20. | 21. | 22. | 23. | 24. | 25. | 26. | 27. | 28. |
|---------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
|         | 20 | 31 | 32 | 51 | 52 | 62 | 70 | 20 | 40 | 31 | 32 | 51 | 52 | 62 | 70 | 20 | 40 | 31 | 32 | 51 | 52 | 62 | 70 | 20 | 31 | 40 | 32 | 51 | 52 | 62 | 70 |
| Harvesting Operation Number Sequence |

Figure 3: Possible Combinations of Harvesting Operations
Measurement

Measurement of the factors identified in each operation proved to be the hardest part of the work. Many factors are presently being researched by various institutions and published data is often non-existent. A list of all variables and parameters considered in the simulation program is given in the following section discussing the simulation program.

Solution

The solution phase of the analysis resulted in a generalized harvesting operation computer program built for simulation purposes. This type simulation program was designed to enable researchers to make (1) comparisons of alternatives, and (2) studies of system response to random variations in parameter values. Such experimental work is left for those who use this simulation program in the future.

Optimization

While normally a part of systems analysis such as this, optimization of the system models was not attempted. It was not an objective of this report. Basically, the models are designed for determining system effects due to random changes in system values. However, persons interested in a specific system could utilize these models and the simulation program for optimization studies.

Validation

The problem of validation is most critical for macroscopic models with relatively few variables. For microscopic models, such as are employed in this research, the problem is minimized through the use of detailed model structure corresponding to the real world system. Valida-
tion of the pulpwood harvesting models has been achieved through the isolation, identification, and representation of system component relationships and the correlation of the results with the real world system. Any model should accurately portray the real world, if it is to serve as a realistic point of departure for conceptual innovations.
CHAPTER V

THE COMPUTER PROGRAM

The Computer Programming Procedure

A general purpose computer model was developed in GPSS-II to simulate the 28 systems listed in Figure 3. Twelve major types of subprograms were developed to simulate the twelve operations depicted in Figure 2. The subprograms for the twelve basic operations are components used to make up any one of the 28 systems. The function and programming procedure of the subprograms in the general model are explained hereafter. Reference to the general model (Appendix I) will assist the reader to understand the discussions of each subprogram.

The Forest Generator

The Forest Generator is the common origin for all system models or variations. It consists of a GENERATE block, a COMPARE block, a series of ASSIGN blocks, a TABULATE block, and a QUEUE block. The GENERATE block initiates transactions into the system. Each transaction is analogous to a tree in the forest and therefore is a discrete entity. Values of variables needed to uniquely define the "tree" are assigned to parameters of the transaction as it passes through the series of ASSIGN blocks. Values used to describe each tree are randomly chosen from a distribution of values approximating the probability of occurrence in the real world. Specifically, the values assigned are:

1. Type cut factor (1), representing a clear cut operation, is assigned to parameter 1 at block 3.
2. Tree spacing as determined by function 16 is assigned to parameter 2 at block 4.

3. Diameter at breast height as determined by function 13 is assigned to parameter 3 at block 5.

4. Useable stem length as determined by function 11 is assigned to parameter 4 at block 6.

5. Bolts per stem as determined by variable 7 is assigned to parameter 5 at block 7.

6. Variable 11 is assigned to parameter 7 at block 9 to help compute tree volume at block 18.

7. Bush factor as determined by function 17 is assigned to parameter 8 at block 10.

8. Plan, move, and cut time as determined by variable 1 is assigned to parameter 9 at block 11.

9. Stem count of one per transaction is assigned to parameter 12 at block 12.

10. Volume of stem as determined by variable 9 is assigned to parameter 17 at block 18.

These values are permanently assigned to each transaction to describe the tree as the transaction simulates the tree being processed in the system. After the Assign block, the transactions pass through a TABULATE block to form a table of tree volumes used in the simulation. The transactions are now placed in the QUEUE block where they wait to be processed through the system. The COMPARE block following the QUEUE block regulates the flow of transactions into the system so there will always be trees available to harvest, but not too many for the computer capacity.
Plan, Move, and Fell (Block 20)

The felling operation consists of three major elements—moving to the tree, planning the fall of the tree, and actually severing the stem from the stump. The first and last elements are functionally the same in all harvesting operations. The planning of the fall is dependent upon several exogeneous variables: the microtopography, wind direction and velocity, tree growth irregularities (i.e., lean or uneven branch distribution), and the silviculture/forest management practices for the stand. Stand management may dictate (1) a clear-cut harvesting operation, or (2) harvesting of selected trees from storm damaged stands or plantation thinnings, or (3) harvesting of all but selected trees (to allow for natural stand regeneration). These are the major factors considered in some degree by the feller before the severing of the tree actually takes place.

Since clear-cut harvesting is common and can be reasonably assumed to minimize the moving, planning, and felling time, a constant factor of 1 has been used to signify clear-cut harvesting operations in the simulation program. Should research be able to quantify the effect that type of harvesting has on the felling operation, an appropriate value may be inserted in place of unity, (i.e., then place a value of 2 in the program parameter simulating the type of harvesting operation, if cutting all but selected trees takes the felling operator twice as long as in clear-cutting).

The operation time for any operation is determined by a function and a variable computer from another function or variable. The function
is required to convert a variable value to a hold time. The variable value is used to specify the number of specific operations in a system.

The operation time for the felling operation is determined by function 1 (FN1) (converts V25 to hold time) and variable 25 (V25) (specifies number of felling operations) computed from variable 1 (V1) (computes operation time for one feller):

\[
V1 = \left(\frac{(Distance \ to \ Tree + Brush \ Factor)}{5}\right) \times Type \ harvesting \ Operation \right) \\
+ \ Time \ to \ Sever \ Stem
\]

Values for distances between trees are randomly selected from a distribution described by function 16 (FN16). Underbrush factors are randomly selected from a distribution described by function 17 (FN17). As data for the underbrush factor originally came from a skidding operation study, a constant divisor of two was assigned to modify the data to allow for its use in this section. The type of harvesting operation is signified by the constant one. The time to sever a stem is dependent on the tree diameter. This distribution is described by function 10 (FN10).

The constant five, used as a divisor of distance to tree, is an arbitrary conversion factor used to convert distance into time. This is required because the basic unit of time in the program is 10 second intervals. The value of five was chosen as the pace of the average feller moving his equipment tree to tree as it allows some consideration for the variation in terrain, (i.e., a feller moves five feet per 10 second period). This also includes time for placement of the equipment.

The specific variables considered in the felling operation are:
(1) Tree spacing
(2) Stem diameter at breast height
(3) Rate and method of cut
(4) Underbrush Factor
(5) Terrain variables are indirectly accounted for in the factor converting tree spacing into time to move between trees.

Assumptions for this operation are:

(1) The cut is made with a portable chain saw.
(2) One man is used per felling operation.
(3) A clear cut harvesting operation is desired.

Assumptions (1) and (2) can be changed to allow for consideration of other methods of felling, (i.e., mechanical or hydraulic shear, hand saw, etc.). This would be accomplished by specifying the desired distribution for rates of cut in function \( f \) (F10) and changing the parameter constant (presently equal to five) to reflect the average rate of movement over the terrain between trees. A short discussion concerning assumption (3) may be found earlier in this section.

The entire operation is simulated by a single program HOLD block. The operation of the block allows for the consideration of one transaction at a time. The transactions are held in the block for the time specified for planning, moving and felling as determined by \( V_1 \); then it is released to a queue to await the next operation.

Buck, Limb, and Top (Block 30) (Not for use behind a skid operation)

This operation has four major elements, namely bucking, limbing, topping, and moving. The purpose of this operation is to remove the
top and limbs from the merchantable part of the tree, to divide it into
the desired product--a pulpwood bolt of 5'3", and to move to the next
tree. Since in many systems the bucking operation does not take place
concurrent with limbing and topping, the time allowed for bucking,
limbing, and topping is assumed to be equal to the sum of its parts.
The total operation time is determined by functions 2(FN2) and variable
26(V26) from variable 21(V21):

\[ V21 = V2 + V8 \]
\[ V2 = V3 + V4 \]

The equation for computing limbing and topping time is given by
variable 3(V3):

\[ V3 = \text{Limb-Top Time X Limb Factor} \]

Limb factors are randomly generated from a distribution described by
function 7 (FN7). Limb-top times are randomly generated from a distri-
bution described by function 8(FN8). The limb factor accounts for the
large variation in the number of limbs found on typical pulpwood species.
Loblolly Pine is an example of a typical specie which requires a mini-
mum amount of limbing. The other extreme is represented by Virginia
Pine. No attempt was made to relate tree height to number of limbs
or time to limb and top.

The equation for computing the bucking operation time is given
by variable 4(V4):

\[ V4 = \text{Time to Sever a Bolt X Number of Bolts} \]

Time to sever a bolt is dependent on stem diameters. Values are gen-
erated from a distribution described in function 27(FN27). The number
of bolts is obtained from variable 7(V7) which divides the merchantable
stem length (previously determined) into five foot units, discarding the remainder. (Note: The figure of five feet is used in place of 5'3" due to computer program restrictions.)

The moving time is computed by variable $V_8$:

$$V_8 = (P_2/K_5) + (P_8/K_2)$$

$P_2$ (distance to tree) is determined randomly from the distribution described by function $16(F_{N16})$. $P_8$ (brush factor) is determined randomly from the distribution described by function $17(F_{N17})$. Further discussion of these factors has been made heretofore in the section on Plan, Move, and Fell (Block 20).

The assumptions made with respect to this operation are:

1. There is no time chargeable to slash disposal.
2. One man with a chain saw is used per operation.
3. Time used to measure bolt length is included in the time allowed for the operation.

Assumption (1) is realistic as slash is left where it falls in most pulpwood harvesting operations. The second assumption could be changed to consider mechanization of limbing, topping, and bucking, provided the bucking time can be differentiated from limbing and topping, by redefining function 20 ($F_{N20}$) and function 8 ($F_{N8}$). To allow for a separate consideration of a variable for measuring would require additional reprogramming and field work to gather the necessary data.

The operation of bucking, limbing, topping, and moving is simulated by a single HOLD block in the same manner as the previous operation of Plan, Move, and Fell (Block 20).
Buck, Limb, and Top (Block 30) (For use behind a skid operation)

This operation has three major elements, namely, bucking, limbing, and topping. It is similar to Buck, Limb, and Top (Block 30) (Not for use behind a skid operation). The difference between the two operations is moving time is not necessary. The operation time is determined by function 44 (FN44) and variable 27 (V27) from variable 2 (V2):

\[ V2 = V3 + V4 \]

V3 and V4 have been discussed earlier.

The two operations are identical in all other aspects.

Limb and Top (Block 31) (Not to be used in a sequence behind a skid operation)

The operation is made up of the following elements: limbing, topping, and moving. The total operation time is determined by function 3 (FN3) and variable 28 (V28) from variable 22 (V22):

\[ V22 = V3 + V8 \]

Refer to Buck, Limb, and Top (Block 30) for discussions of V3 and V8.

The distributions are described for one man per operation.

The operation of limbing, topping, and moving is simulated by a single HOLD block in the same manner as the simulation for Plan, Move, and Fell (Block 20).

Limb and Top (Block 31) (To be used in a sequence behind a skid operation)

Since the skid operation delivers the trees to the limbing and topping site in this operation, there is no need to consider a moving
time. Therefore, the total operation time is determined by function $43(FN43)$ and variable $27(V27)$ from variable $3(V3)$. $V3$ has been discussed under Buck, Limb, and Top (Block 30).

In all other aspects the simulation of this operation is identical to Limb and Top (Block 31) (Not to be used in a sequence behind a skid operation).

**Buck (Block 32) (Not to be used with skid option)**

This operation is made up of two elements--bucking the tree into the desired lengths and moving to the next tree. The total operation time is determined by function $34(FN34)$ and variable $30(V30)$ from variable $23(V23)$:

$$V23 = V4 + V8$$

Refer to Buck, Limb, and top (Block 30) for a discussion of $V4$ and $V8$.

The operation of bucking and moving is simulated by a HOLD block in the same manner as the simulation for Plan, Move, and Fell (Block 20).

One man is required for each buck operation.

**Buck (Block 32) (To be used with skid option)**

This operation time is determined by function $4(FN4)$ and variable $31(V31)$ from variable $4(V4)$. $V4$ (bucking time) has been discussed earlier. A moving time was not considered for this operation because the skidder delivers the trees to the bucking operation. This operation is identical to Buck (Block 32) (Not to be used with skid option) in all aspects other than moving.

**Skid (Block 40)**

The skid subprogram is designed to simulate the forming of a skid
load and the skidding, drop, and return of the load to a landing. Each group of logs contain 50-65 cubic feet of wood. These load values were selected to represent the productive capability of the smallest commercial skidders. Other productivity rates could be selected if desired by altering the cubic volume of wood.

The skid operation is simulated by first routing transactions one at a time through a series of SIEZE, COMPARE, ENTER, RELEASE, and SPLIT blocks that are designed to cut off the flow of tree transactions after the most recent tree transaction has increased the load volume to or above 50 cubic feet. The SPLIT block forms a duplicate transaction that is routed to a series of ADVANCE, TERMINATE, HOLD, COMPARE, and TERMINATE blocks to record the total time required to form and skid a load. The original transaction continues from here through a series of ENTER, COMPARE, SPLIT, and QUEUE blocks. These blocks are designed to accept transactions that do not increase the load to or above 50 cubic feet and route them to a queue (Block 130) where they are held by a COMPARE block until the skid simulation is complete for the load. The transaction that increases the load volume to or above 50 cubic feet is routed to block 45. This transaction which represents the last tree in a load is used to simulate the skidding of the load by passing through a series of SPLIT, ASSIGN, PRINT, ASSIGN, SAVEX, HOLD, ADVANCE, and LEAVE blocks. In this series of blocks, a duplicate transaction is formed to be routed to a queue to represent the last tree in the load. Meanwhile the original transaction for this tree continues its work by printing out the load statistics, resetting the statistics
SAVEX's, simulating the time for the skid, drop, and return, and releasing the transactions in the queue to continue to another operation.

The time for the skid and return of the skidder is determined by function 23(FN23) and variable 32(V32) from variable 12(V12):

\[ V12 = P10 \times K35/K100 + P10 \]
\[ P16 = V10 \]
\[ V10 = FN21 + P8 \]
\[ P8 = FN17 \]

Function 21(FN21) computes the basic time for skidding a load. Function 17(FN17) accounts for the effect of underbrush. Both functions consider the following factors:

1. Distance
2. Productive and non-productive time
3. Loading
4. Soil conditions

The manpower requirement is one man per skid operation.

**Stack (Block 50) (Not to be used with skid option)**

The stacking operation is made up of two major operations—stacking the bolts of a tree and moving to the next tree. The total time for the operation is determined by function 36(FN36) and variable 34(V34) from variable 24(V24):

\[ V24 = FN12 + V8 \]

Variable 8 is the moving time between trees and is determined in the same manner as the moving time in Buck, Limb, and Top (Block 30).
Function 12 accounts for the time required for stacking the tree bolts. The time required to rough stack bolts from one tree increases directly with the number of bolts per stem due to the increasing distance to the farther bolts. This relationship of distance, time, and number of bolts is formulated in Function 12 so that, given the number of bolts per tree, the time to stack "n" bolts can be determined directly.

The stack may be either of two types--a rough and tumble pile, or a neat rick. Neat piles are built when bolts are to be loaded or forwarded mechanically. Rough stacks are generally made to facilitate manual loading to a truck or pallet at the stump.

The time necessary to build a neat, raised stack, backed up against a tree was observed and measured for a fork lift forwarder operation. Building this type stack was found to take nearly three times as long as making a rough pile of the same size. Much of this increased time was attributed to the specific working conditions under which the data was collected. It is assumed for simulation purposes that, if the time to form a rough and tumble pile is given in Function 12, then the time to form a neat stack of parallel bolts could be simulated by multiplying by a factor of two in the mean block position in the simulation program, thereby simply doubling the time required for the stacking operation.

The manpower requirement for this operation is one man per stacking operation.

Stack (Block 50) (To be used only with the skid option)

In this stacking operation, the skidder delivers the trees to the immediate stacking area where the wood is stacked after it has been
bucked. Therefore, the stacker does not have to move between trees.
The stacking time per tree is determined by function $45(FN45)$ and
variable $33(V33)$ from function $12(FN12)$. Function $12$ is the same for
both stack simulations. Both stack simulations are identical in all
aspects except for moving between trees.

**Pallet Load** *(Block 51)* *(Not to be used with the skid option)*

This operation consists of loading a pallet to a capacity of
109-140 cubic feet of solid wood per unit and moving to the next pallet.
Loading a pallet is similar to manually loading a truck. The major ad-
vantage to pallet loading is the decrease in the height that each bolt
is lifted before being placed on the load. This is reflected in the
loading time when it is compared to manual truck loading time. The
pallet is also capable of being positioned in areas that would be in-
accessible to a truck, thereby decreasing the distance the average bolt
is carried by manpower. However, decreasing hand loading distance will
lead to increases in the distance of the prehaul.

The pallet load operation is started by transactions passing one
at a time through a series of **SEIZE, COMPARE, ENTER, RELEASE, and SPLIT**
blocks that are designed to cut off the flow of transactions following
the loading of the bolt that increases the pallet volume to or above 109
cubic feet of solid wood. The **SPLIT** block forms a duplicate transaction
that is routed to a series of **ADVANCE, TERMINATE, HOLD, COMPARE, and TER-
MINATE** blocks to record the total time required while waiting for wood
to load, loading the pallet, and moving to a new pallet. Meanwhile, the
original transaction is routed through a series of **SAVEX** blocks to record
the volume, stems, and bolts loaded on each pallet. The time required
for loading each tree is simulated by a **HOLD** block *(Block 151)*. The
time required to load a tree is determined by function 29(FN29) and variable 35(V35) from variable 15(V15):

\[ V15 = FN18 \times P5 \]

\[ FN18 = \text{Load time per bolt} \]

\[ P5 = \text{Number of bolts per tree} \]

The average time used to simulate loading bolts of a given tree is randomly chosen from function 18(FN18). This value is then multiplied by the number of bolts in the tree (stored in parameter 5 of the transaction). In specifying the distribution of FN18, the range of distances a bolt is carried and the probability of encountering any given distance throughout that range is considered.

After simulating the loading of the tree, the transaction leaves the HOLD block and progresses through ENTER and COMPARE blocks. These blocks are programmed to route the tree transaction that increases the load to or above 109 cubic feet to block 58. All other transactions are routed to block 99 where they are terminated. The last tree transaction to each load (the transaction routed to block 58) is routed through a series of ASSIGN, PRINT SAVEX, HOLD ADVANCE, and LEAVE blocks. In this series, the pallet volume, number of bolts, and number of stems are assigned to parameters of the transaction to define it as a pallet transaction rather than a tree transaction. All other transactions representing trees in the pallet load are terminated because all subsequent operations are concerned with pallets rather than trees. This series also simulates the time for moving to the next pallet. The moving time between trees was used to compute moving time between pallets. One fourth of the moving time is determined by function 35(FN35) and variable 36(V36) from variable 8(V8). The quarter moving time is con-
verted to actual moving time by multiplying by a factor of four in block 350. A discussion of V8 is contained in the discussion of Back, Limb, and Top (Block 30).

The manpower requirement for stacking is one man per operation.

**Pallet Load (Block 51)** *(To be used with skid option)*

This operation is identical to Pallet Load (Block 51) *(Not to be used with skid option)* in all aspects with the exception of block 350 which simulates moving time between pallets. Since a skidder groups the wood at a landing, movement between pallets is not necessary. Therefore block 350 is omitted.

**Prehaul (Block 52)**

The pallets are usually prehauled from the stumpage site to a landing where they are transferred to trucks. The time for the one-way trip between stumpage site and landing is determined by function 30(FN30) and variable 38(V38) from variable 16(V16):

$$V16 = \frac{\text{Prehaul Distance}}{150} \times 6$$

Prehaul Distance = FN26

The constant 150 represents the prehauler's average speed in feet per minute. The constant six converts minutes into program time units of ten seconds. The prehaul distance is randomly selected from function 26(FN26). A factor of two is used in block 52 to convert one-way trip time (V16) to round trip time. Allowance for hook-up and unhook time is not made because of their small time in comparison to haul time.

The operation of prehaul is simulated by a single HOLD block in the same manner as the simulation for Plan, Move, and Fell (Block 20).

Manpower assignment is one man per prehaul operation.
Manual Load (Block 60) (To be used only in the stump to stump load option)

This operation simulates the truck being manually loaded as it moves from stump to stump. The truck load varies in capacity from 220 to 240 cubic feet of solid wood (approximately 3 cords).

The simulation starts by routing the transactions one at a time through a series of SEIZE, COMPARE, ENTER, and RELEASE blocks that are designed to cut off the flow of tree transactions following the one that increases the load volume to 220 cubic feet or more. A COMPARE block follows this series to delay the beginning of a new load until the last haul simulation is complete and the truck is available to be reloaded. The transaction then progresses through a SPLIT block to form a duplicate transaction for routing through a series of ADVANCE, TERMINATE, HOLD, COMPARE and TERMINATE blocks to record the total loading time for a load (including waiting time for wood). The original transaction leaves the SPLIT block and progresses through a series of SAVEX blocks where a record is maintained on the volume, bolts, and stems in each load. The next block is a HOLD block (block 67) where simulation is made of the time required to load a tree and move to the next tree. The time is determined by function 5(FN5) and variable 39(V39) from variable 5(V5):

\[ V5 = \text{Time to Load Bolts} + \text{Time to Move Truck} \]

\[ \text{Time to Load Tree} = FN19 \]

\[ \text{Time to Move Truck} = FN3 \]

The time to load a tree is dependent on the number of bolts per tree. This value is taken from the distribution described by function 19
(FN19) which is based on two men per loading operation. One man drives the truck and one man does the loading. The truck moving time considers the probability of having to move and the distance to move. The time for moving is determined randomly from the distribution described by function 9(FN9).

When the transaction completes the simulation at block 67, it passes through ENTER and COMPARE blocks. These blocks are programmed to route the tree transaction that increases the load to 220 cubic feet or above to block 162. All other transactions are routed to block 99 for termination. The tree transaction that was routed to block 162 becomes the transaction to simulate the truck load. It is routed through a series of ASSIGN, PRINT, SAVEX, ADVANCE, and LEAVE blocks where it's parameters are assigned volume, bolts, and stems in the load and the statistics SAVEX's are reset to zero. SAVEX 20 is set equal to 10 to delay forming a new load until this load has been transported. The transaction then releases the load simulation and enters the haul sub-program.

Manual Load (Block 60) [Not to be used in the stump to stump load option]

Since the skidder delivers the wood to a landing where it is bucked and loaded, there is not a requirement for moving time between trees in this operation. The loading time per tree is determined by function 46(FN46) and variable 37(V37) from function 19(FN19). Function 19 has been discussed in the earlier discussion of manual load. Since a truck is not moved, only one man per operation is required. Excluding moving requirements, both manual load simulations are identical.
Mechanical Load (Block 61) (To be used only in stump to stump load option)

This operation simulates the truck being loaded with a hydraulic grapple as it moves from stump to stump. The method of simulation is similar to that of Stump to Stump Manual Load (Block 60). The loading and moving time per tree is determined by function 31(FN31) and variable 41(V41) from variable 18(V18):

\[ V18 = FN9 + FN24 \times FN32 \]

Function 9(FN9) accounts for the truck moving time. The loader cycle time is randomly selected from function 24(FN24). The number of cycles per tree is determined by function 32(FN32) relative to the volume of the tree (10 cubic feet of solid wood is the maximum volume per loader cycle). The loading time per tree is the product of FN24 and FN32.

The manpower requirement per loading operation is two men (one man to operate the loader and one man to drive the truck).

Mechanical Load (Block 61) (Not to be used in the stump to stump load option)

This operation consists of loading the truck at a landing with a hydraulic grapple. There is not a need for moving the truck, because the trees are skidded to the landing where the loading is done. The truck loads vary from 220 to 240 cubic feet of solid wood (approximately 3 cords).

The simulation begins with a series of SEIZE, COMPARE, COMPARE, SAVEX, and RELEASE blocks that meter transactions through them one at a time. These blocks are programmed to cut off the flow of tree transactions following the one that increases the load volume to or above
220 cubic feet. They also delay the loading of a new load until the
haul simulation has been completed and a truck is available to be loaded.
Next, the transaction passes through a group of SAVEX blocks that record
volume, bolts, and stems in each load. After the SAVEX blocks, the
transaction is routed through a series of ADVANCE, HOLD, COMPARE
TERMINATE, and TERMINATE blocks that record the total time required for
loading (this includes waiting for trees if they are not available for
loading).

The actual simulation of the grapple loading the wood begins with
another flow of transactions that represent grapple loads of wood. The
flow of transactions discussed in the paragraph above are used to main-
tain records of the volume, bolts, and stems in a load and converts tree
volumes into volume available for grapple loading (this volume is main-
tained in SAVEX 33 - block 308). The grapple load transactions originate
in a GENERATE block and then pass one at a time through a series of
SEIZE, COMPARE, ASSIGN, and SAVEX blocks that are programmed to cut off
the flow of grapple loads following the one that increases the load
volume to or above 220 cubic feet. In addition, the ASSIGN block assigns
to parameter 1 the cubic feet per load cycle (9 to 11 cubic feet of
solid wood). This value is assigned randomly from the distribution
described by function 33(FN33). The next series of blocks is made up
of SAVEX, ADVANCE, COMPARE, SAVEX, SAVEX, and RELEASE blocks. In this
series, the grapple transaction first checks SAVEX 33 to determine if
the load assigned by FN33 is available for loading. If there is adequate
wood available, the transaction then subtracts the grapple load from
SAVEX 33 and adds it to the truck load. If adequate wood is not available but there is enough in SAVEX 33 to increase the truck load to or above 220 cubic feet, the transaction subtracts the grapple load from SAVEX 33 (making it negative) and adds it to the truck load. This causes an overage on this load but the next load is delayed due to the requirement to make up for the negative value in SAVEX 33. Therefore, the above error necessitated by the computer programming is compensated for by the next load. If there is inadequate wood in SAVEX 33 to make a complete grapple load or complete the truck load, the transaction is delayed until one of the above conditions are satisfied.

The loading time is now simulated in a HOLD block (Block 325). The loading time per grapple load is determined by function 47(FN47) and variable 40(V40) from function 24(FN24). Function 24 is a distribution of loader cycle time from which a specific cycle time is randomly chosen. At this point, a COMPARE block tests to determine if the load is 220 cubic feet or more. If the load is not complete, the transaction is terminated. If the load is complete, the transaction is routed through a series of ASSIGN, PRINT, SAVEX ADVANCE, and SAVEX blocks. In this series, the load statistics (volume, bolts, and stems) are printed and the statistic SAVEX locations are reset for the next load. In addition, the loading hold (SAVEX 20) is set to delay loading the next load until the truck has completed the haul and is available for reloading.

The manpower requirement is one man per operation.

Pallet Transfer (Block 62) (Not to be used with prehaul or/and skid options)

In this operation a truck moves through the woods picking up pallets
until a five pallet load (approximately 7.5 cords) has been formed. The
winch on and move time per pallet is determined by function 49(FN49) and
variable 42(V42) from function 48(FN48). Function 48 describes a dis-
tribution of winch on and move times from which the operation time for
a particular pallet is randomly selected.

The manpower requirement is one man per operation.

The method of simulation and programming is similar to Manual Load (Block 60).

**Pallet Transfer (Block 62)** *(To be used with prehaul or/and skid options)*

In this operation a truck is loaded with five pallets at a landing.
Movement to pick up pallets is not necessary. The winch on time for all
five pallets is determined by function 51(FN51) and variable 43(V43)
from function 50(FN50). Function 50 is a distribution of winch on times
from which the operation time is randomly selected.

One man is required per operation.

The method of simulation and programming is similar to Manual Load (Block 60).

**Transport (Block 70)**

The transport subprogram simulates the load being transported to
the mill or concentration yard, unloading of the wood, and return of the
truck to the loading site. The simulation begins with three ASSIGN blocks
where the paved road distance, dirt road distance, and half of the unload
time are assigned to parameters 14, 15, and 16 respectively. The time
between loads is then tabulated in table 5. A HOLD block then simulates
the time required for each load. Half the complete trip time is deter-
mined by function 6(FN6) and variable 44(V44) from variable 6(V6):

\[
V6 = \text{Woods Road Distance} \times 120 + \text{Paved Road Distance} \times 12 + ' Unloading Time
\]

The constant values of 120 and 12 are conversion factors for converting travel distance into time. The woods road distance and paved road distance are randomly selected from distributions described by functions 15 and 14 (FN15 and FN14) respectively. An average speed of 3 m.p.h. has been assumed for woods road travel and 30 m.p.h. for paved road travel. Unload time is randomly selected from a distribution described in function 28 (FN28). Function 28 is one half of the unloading time values which enables its use with V6 which is multiplied by a factor of 2 at block 74 to determine total trip time. After a HOLD in block 74, the transaction is routed through tables 3 and 4 to tabulate the paved road and dirt road distances. The half values of unload time are then printed out by the use of a SAVEX and PRINT block. Finally, the transaction passes through SAVEX 20 to set it equal to 5 to release the loading operation for the next load.

The manpower requirement is one man per haul operation.

The haul subprogram simulates the 3 cord trucks as well as the 7½ cord pallet trucks. The major difference is the loading time which is accounted for in the loading and pallet transfer operations.

Delay Subprograms

Certain operations are physically exerting, so rest periods are necessary. The operations assumed to require rest periods are:

1. Felling

2. Limbing and Topping or Limbing, Topping, and Bucking
3. Bucking
4. Pallet Loading
5. Stacking
6. Manual Loading - (Not for Stump to Stump Loading)

Each of these operations have a delay subprogram that is made up of generate, assign, hold, and tabulate blocks. The rest transactions are created by the generate blocks at intervals based on values specified for each rest program by FN20, FN38, FN39, FN40, FN41, and FN42 respective to the listing of operations above. As presently programmed, the rest periods occur 23 to 43 minutes apart and last for a mean time of approximately 4.3 minutes. The time between rest periods can be changed by changing the function that specifies the interval between periods. The functions that specify the length of the rest periods, respective to the above listing of operations, are: FN20, FN38, FN39, FN40, FN41, and FN42. These rest period values are assigned to parameter 9 of the rest transactions at the assign blocks. The length of the rest period is changed by changing the pertinent function distribution. The transactions are routed from the assign block in accordance with a probability equal to the utilization rate of the operation containing the specific rest period. The percentage of transactions equal to the idle time of the operation is then terminated. The transactions that are not terminated, continue to the hold block to delay the operation for the length of the rest period. The rest period is able to delay new tree transactions flowing into an operation because it is of higher priority than the tree transactions. After simulating the rest period,
the transaction progresses through a TABULATE block where the length of rest period is recorded in a table.

**Length of Simulation Run**

The start card is used to specify the length of run. The run can be terminated on the basis of complete truck loads or on a desired clock time basis.

**Procedures for Using the Model**

Several steps are necessary to form a simulation program for a particular system as listed in figure 3. These steps are:

1. **Assemble Model**
2. Determine Multiples of Operations
3. Adjust Rest Delays

Each of these steps are discussed below.

**Assemble Model**

All models have the following sections:

1. Function Section
2. Variable Section
3. Forest Simulator
4. Move, Plan, and Cut Simulation
5. Simulation of Operations Peculiar to a Particular System
6. Transport Simulation
7. Rest Delay Subprograms
8. Termination Section

Simulation models for all 28 systems are identical in all the above sections except section 5. The simulation subprograms pertinent to a
particular system are used to form section 5. These operation subprograms are joined together to form a complete program by QUEUE blocks which are programmed to route transactions from one subprogram to the next. A simulation model of system 14, Figure 3, is contained in Appendix II to provide an example of how the models are assembled from components of the general model (Appendix I).

Determine Multiples of Operations

Once the simulation model has been assembled from components of the general model, it is necessary to determine multiples of each operation. The near optimal combination can be determined by running the basic model of a system with the rest delay subprograms removed. This is done to determine the production rate of each operation in order to determine multiples of operations that are necessary to balance the flow through the system. The production rate is obtained from the utilization rate of the particular facility used for an operation, and from the transactions (tree type) that process through the operation.

The above method has been used to determine the production rates of all the operations. The production rates were then used to determine the number of multiples of an operation that are necessary to equal the production rate of one Move, Plan, and Cut operation. The values determined are listed as follows:
<table>
<thead>
<tr>
<th>Operation Name</th>
<th>Value (in parentheses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buck, Limb, and Top (Block 30) (Not to be used in a sequence behind a skid operation)</td>
<td>5 (4.9)</td>
</tr>
<tr>
<td>Buck, Limb, and Top (Block 30) (To be used only in a sequence behind a skid operation)</td>
<td>5 (4.4)</td>
</tr>
<tr>
<td>Limb and Top (Block 31) (Not to be used in a sequence behind a skid operation)</td>
<td>2 (1.75)</td>
</tr>
<tr>
<td>Limb and Top (Block 31) (To be used only in a sequence behind a skid operation)</td>
<td>2 (1.25)</td>
</tr>
<tr>
<td>Buck (Block 32) (Not to be used with skid option)</td>
<td>4 (3.7)</td>
</tr>
<tr>
<td>Buck (Block 32) (To be used with skid option)</td>
<td>4 (3.2)</td>
</tr>
<tr>
<td>Skid (Block 40)</td>
<td>2 (1.25)</td>
</tr>
<tr>
<td>Stack (Block 50) (Not to be used with skid option)</td>
<td>3 (3.0)</td>
</tr>
<tr>
<td>Stack (Block 50) (To be used only with skid option)</td>
<td>3 (2.5)</td>
</tr>
<tr>
<td>Pallet Load (Block 51) (Not to be used with skid option)</td>
<td>3 (2.25)</td>
</tr>
<tr>
<td>Pallet Load (Block 51) (To be used only with skid option)</td>
<td>3 (2.1)</td>
</tr>
<tr>
<td>Prehaul (Block 52)</td>
<td>1 (0.4)</td>
</tr>
<tr>
<td>Manual Load (Block 60) (To be used in stump to stump option)</td>
<td>3 (3.0)</td>
</tr>
<tr>
<td>Manual Load (Block 60) (Not to be used in stump to stump option)</td>
<td>3 (3.0)</td>
</tr>
<tr>
<td>Mechanical Load (Block 61) (To be used in stump to stump option)</td>
<td>1 (1.0)</td>
</tr>
<tr>
<td>Mechanical Load (Block 61) (Not to be used in stump to stump option)</td>
<td>1 (0.5)</td>
</tr>
</tbody>
</table>

The integer number of production operations necessary to equal the production rate of one Move, Plan, and Cut Operation. (The value in parenthesis is the fractional number for equal production.)
Pallet Transfer (Block 62) (To be used with Prehaul or/and Skid option) 1(0.3)
Haul (Block 70) (3 cord Truck) 3(3.0)
Haul (Block 70) (7.5 cord Pallet truck) 2(1.5)

The above figures are correct for the particular systems parameters (tree size, spacing, haul distance, operation time, distributions, etc.) described and used for illustrative purposes in the general model. If any of the parameters are changed, new production rates will have to be determined in order to determine the number of operation multiples necessary.

Based on the above information, the operation multiples for system 14 would be as follows:

<table>
<thead>
<tr>
<th>Operation</th>
<th>Multiples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan, Move, and Cut</td>
<td>1</td>
</tr>
<tr>
<td>Buck, Limb, and Top</td>
<td>5</td>
</tr>
<tr>
<td>Stack</td>
<td>3</td>
</tr>
<tr>
<td>Mechanical Load</td>
<td>1</td>
</tr>
<tr>
<td>Haul</td>
<td>3</td>
</tr>
</tbody>
</table>

It then becomes necessary to assign manpower to the various operations and adjust the number of operations to utilize the selected manpower. The only problem encountered with manpower in the operations combined above, is found in the mechanical load function. Mechanical loading requires two men, one being the truck driver. Therefore the loading operations and hauling operations must share manpower. Since it is necessary
with this concept to have a loading operation for each haul operation, the haul operations will be increased to 4 to provide half the extra manpower for loading and the loading operation will be increased to 4 to match the hauling operations. Now only half the necessary manpower is available for loading, so it has been decided to increase the stack operations to 4 to provide the remaining manpower for loading.

In the actual operation the stackers and drivers would spend 75% of their time stacking and hauling respectively with the remaining 25% of their time loading.

The resulting manpower when assigned to a combination of tasks is as follows:

- Plan, Move, and Cut \(1 \times 100\% = 1\)
- Buck, Limb, and Top \(5 \times 100\% = 5\)
- Stack \(4 \times 75\% = 3\)
- Mechanical Load \(4 \times 50\% = 2\)
- Haul \(4 \times 75\% = 3\)

The total manpower is 14 men.

If it is desired to simulate an actual system that is not balanced, then one may assign the number of operations that actually exist. The simulation will then indicate where the bottleneck exists in the system.

The number of operations is assigned to the simulation model by a multiplication variable for each operation. Each operation subprogram has a comment at its beginning specifying which multiplication variables dictate the number of operations. Each of these multiplication variables referred to is ended by K10/K10 in the general model (Appendix I). The
number of operations are specified by changing this term to equal the inverse of the number of operations, i.e., 5 operations would be specified by K10/K50 or K1/K5; 1/3 operation would be specified by K10/K5.

**Adjust Rest Delays**

After adjustments have been made for multiples of operations, the Rest Delay Subprograms must be put back in the model and adjusted for utilization rates. It is necessary to adjust rest delays relative to utilization rates to make the rest time appropriate for work time. Rest delay adjustments are determined by making a simulation run with the model to determine the utilization rate of operations that have rest delays. The subprogram of each operation specifies what block of the Rest Delay Subprogram must be adjusted for utilization. The adjustment is made in the selection mode of the ASSIGN block of each Rest Delay Program. The selection mode is assigned .999 (representing 100% utilization) in all delay subprogram ASSIGN blocks of the general model in Appendix I. If a facility representing an operation is utilized only 75% of the time then the value in the appropriate ASSIGN block of the Rest Delay Subprogram should be .750. This would cause only 75% of the number of rest delays to be used by the facility.

Several trial runs may be necessary to adjust the rest delays according to utilization rates.

The simulation program is now ready to simulate a system. Appendix II contains a simulation model for system 14, Figure 3, as an example of a complete model ready for system simulation.
Model Output

In order to determine the performance of a particular system, it is necessary to analyze and interpret the simulation output. In order to explain a typical output, the output of system 14, figure 3 will be discussed. The output itself is shown in Appendix III. The important sections of output are as follows:

1. Load Statistics
2. Simulation Time
3. Transaction Counts
4. Load Statistics of Loads in Process at Termination
5. Utilization Statistics
6. Queue Statistics
7. Feller Delay Statistics Table
8. Buck, Limb, and Top Delay Statistics Table
9. Paved Road Statistics Table
10. Dirt Road Statistics Table
11. Time Between Loads Statistics Table
12. Stack Delay Statistics Table
13. Tree Volume Statistics Table.

Each of these sections will now be briefly discussed.

Load Statistics

In this section, the volume (cubic feet of solid wood), number of bolts, number of stems, and half the unload time are printed for each load. Additional information is also included for simulations of other systems (i.e., pallet load statistics, skid statistics, etc.).
Simulation Time

The simulation time for the complete run is printed in 10 second clock units.

Transaction Counts

This section prints out a record of the number of transactions that have entered or are presently in the blocks of the model during the complete simulation. This data assists in determining production rates.

Load Statistics of Loads Currently being Processed by Simulation at Program Termination

This section prints current load statistics at the instant the simulation was terminated. It is useful in determining operation status at program termination.

Utilization Statistics

This is one of the most valuable output sections. It gives the utilization of all operations in the program. The output for system 14 is as follows:

<table>
<thead>
<tr>
<th>Facility</th>
<th>Average Utilization</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.9998</td>
<td>Felling</td>
</tr>
<tr>
<td>2</td>
<td>.8865</td>
<td>Buck, Limb, and Top</td>
</tr>
<tr>
<td>4</td>
<td>.1634</td>
<td>Loading (actual time)</td>
</tr>
<tr>
<td>14</td>
<td>.2520</td>
<td>Loading (actual time plus waiting time for wood)</td>
</tr>
<tr>
<td>20</td>
<td>.7430</td>
<td>Hauling</td>
</tr>
<tr>
<td>43</td>
<td>.6989</td>
<td>Stacking</td>
</tr>
</tbody>
</table>
The feller operation was utilized approximately 100% of its capability. The Buck, Limb and Top operation was utilized 89% of its capability. The truck drivers and stackers were utilized 25% of the time loading and waiting for wood to load while only 16% of their time which means they were used 94% of the time for stacking and loading. The truck drivers were used 74% of the time for hauling which means they were utilized 99% of the time for loading and hauling.

The simulation time for this run was 14925 clock units for 60 loads (3 cords each) with 14 men. This results indicates that the system requires 3.24 manhours per cord. The utilization information can be used to determine where there is excess manpower so it can be shifted to improve the production per manhour. Since the labor utilization in system 14 is 89 to 100 per cent for all operations, the manpower assignment is considered adequate and 3.24 manhours per cord is near the optimal production rate of this system.

Queue Statistics

This section prints out the number of transactions in the queues at program termination time.

Feller Delay Statistics Table

This table records the mean time and the standard deviation of feller rest periods. It also prints out a distribution of the time of the rest periods.

Buck, Limb, and Top Delay Statistics Table

This table has the same type information as Feller Delay Statistics Table, but relative to Buck, Limb, and Top rest periods.
**Paved Road Statistics Table**

This table records the mean distance and the standard deviation of the paved road distances. A distribution of the distances is also included.

**Dirt Road Statistics Table**

This table contains statistics on the dirt road distances in the same form as Paved Road Statistics Table.

**Time Between Load Statistics Table**

This section records the distribution, mean time and standard deviation of time between truck loads.

**Stack Delay Statistics Table**

This table has the same type information as Feller Delay Statistics Table but relative to stacker rest periods.

**Tree Volume Statistics Table**

The section records the distribution, mean, and standard deviation of the volume (cubic feet) of trees processed in the system.
CHAPTER VI

RESULTS AND CONCLUSIONS

Discussion of Results

This research has resulted in the formulation of a General Simulation Pulpwood Harvesting Model that can be used to simulate 28 different harvesting systems.

A sample model is contained in Appendix II. This model is system 14, Figure 3. This system simulates felling; bucking, limbing and topping; stacking; mechanical loading; and hauling. The production rate of this system produces one cord per 3.24 manhours of work (2.47 cords per 8 hr. man day). This production rate seems realistic when compared to actual harvesting systems.

The use of distributions to describe initial system conditions provides the model with a major advantage when compared to more conventional simulation models which use specific sets of initial conditions for each simulation. The distributions may be readily altered or redesigned by the user to allow for positive control of simulation experiments. Specific values for parameters are also used in the model's initial conditions. Thus, the program responds to both constant and variable initial conditions during each run. The Monte Carlo technique of allowing random numbers to select values of variables from the variable cumulative probability distribution was used to minimize unintentional bias in value selection.
Conclusions

Two conclusions can be directly drawn from the sample program. First, the model does, in truth, represent the actual system, and second, quantitative insight into the real world system can be obtained from the model with respect to the limiting operations of the system.

At this point, statistically designed experiments should be carried out to study the effects of combinations of parameters and variables of harvesting operations. Newham reported that the cybernetic solutions of problems tested with his harvesting simulation program differed by 40 per cent from calculated solutions suggested by others. However, a preliminary test simulating another type machine yielded "remarkably accurate estimates." This is expected to be the case with this model due to its scope.

It is anticipated that the main use of this model will be to allow comparisons between harvesting systems. With data such as that expected from the American Pulpwood Association Producer Survey, greater accuracy should be possible in system comparisons. System balancing and optimizing studies can also be aided with this model.

Recommendations

This report is not considered a complete research study. It is however, a basis for further specific studies. Statistical experimentation with the model is definitely needed: first, to obtain comparative data between systems, and second, to obtain data on the differences in system output from actual and hypothesized data. Systems tested with actual and hypothesized data could be sued to compare present and future systems.
APPENDIX I

COMPONENTS OF THE

GENERAL HARVESTING SIMULATION MODEL
END OF CONTROL DECK
A SIMULATION OF SHORTWOOD PULPWOOD HARVESTING SYSTEMS

DATA FUNCTIONS AND SYSTEM VARIABLE DEFINITIONS

<table>
<thead>
<tr>
<th>FUNCTION</th>
<th>V25</th>
<th>C2</th>
<th>TIME FOR PLAN MOVE AND CUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>FUNCTION V26 C2</td>
<td>TIME TO BUCK, LIMB, TOP, AND MOVE</td>
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<tr>
<td>0</td>
<td>0</td>
<td>200</td>
<td>200</td>
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<td>3</td>
<td>FUNCTION V28 C2</td>
<td>TIME TO LIMB, TOP, AND MOVE</td>
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<td>0</td>
<td>0</td>
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<td>500</td>
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<td>FUNCTION V31 C2</td>
<td>TIME TO BUCK</td>
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<td>0</td>
<td>0</td>
<td>500</td>
<td>500</td>
</tr>
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<td>5</td>
<td>FUNCTION V39 C2</td>
<td>TIME TO HAND LOAD A TREE ON TRUCK AND MOVE</td>
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</tr>
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<td>0</td>
<td>0</td>
<td>500</td>
<td>500</td>
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<td>6</td>
<td>FUNCTION V44 C2</td>
<td>TIME FOR ONE WAY HAUL (TRUCK)</td>
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</tr>
<tr>
<td>0</td>
<td>0</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>7</td>
<td>FUNCTION RN1 D3</td>
<td>LIMB FACTOR</td>
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<tr>
<td>0.60</td>
<td>1.0</td>
<td>0.80</td>
<td>1.6</td>
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<tr>
<td>8</td>
<td>FUNCTION RN1 C2</td>
<td>NORM TIME TO LIMB AND TOP</td>
<td></td>
</tr>
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<td>0.6</td>
<td>3.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>9</td>
<td>FUNCTION RN1 C6</td>
<td>TIME TO MOVE TRUCK STUMP TO STUMP</td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.700</td>
<td>0.0</td>
</tr>
<tr>
<td>10</td>
<td>FUNCTION P3 D5</td>
<td>TIME TO CUT (FELL OR BUCK) CHAIN SHW</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>FUNCTION P3 C7</td>
<td>LENGTH OF MERCHANTEL STEM</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>13</td>
<td>FUNCTION RN1 C7</td>
<td>DBH DISTRIBUTION</td>
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<td>0.1</td>
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<td>14</td>
<td>FUNCTION RN1 C10</td>
<td>PAVED ROAD DISTANCE</td>
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<tr>
<td>0.0</td>
<td>2.0</td>
<td>0.1</td>
<td>10</td>
</tr>
<tr>
<td>0.88</td>
<td>35</td>
<td>0.92</td>
<td>40</td>
</tr>
<tr>
<td>15</td>
<td>FUNCTION RN1 C6</td>
<td>DIRT ROAD DISTANCE</td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>0.25</td>
<td>0.10</td>
<td>3</td>
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<tr>
<td>16</td>
<td>FUNCTION RN1 D3</td>
<td>DISTANCE BETWEEN TREES</td>
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</tr>
<tr>
<td>0.4</td>
<td>6.0</td>
<td>0.8</td>
<td>10.0</td>
</tr>
<tr>
<td>17</td>
<td>FUNCTION RN1 D3</td>
<td>UNDERBRUSH FACTOR</td>
<td></td>
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<tr>
<td>0.10</td>
<td>0.00</td>
<td>0.80</td>
<td>3.0</td>
</tr>
<tr>
<td>18</td>
<td>FUNCTION RN1 D4</td>
<td>TIME TAKEN TO LOAD ONE BOLT ON A PILLET</td>
<td></td>
</tr>
<tr>
<td>0.60</td>
<td>1.0</td>
<td>0.80</td>
<td>2.0</td>
</tr>
<tr>
<td>19</td>
<td>FUNCTION P5 C4</td>
<td>TIME TO LOAD BOLTS ON TRUCK MANUALLY</td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>4.0</td>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td>20</td>
<td>FUNCTION RN1 C5</td>
<td>DELAY FUNCTION (FELLER)</td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>10.0</td>
<td>0.3</td>
<td>20</td>
</tr>
<tr>
<td>21</td>
<td>FUNCTION RN22 C7</td>
<td>TIME FOR SKIDING ONE TURN DRY SOIL</td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>200</td>
<td>1000</td>
<td>60</td>
</tr>
<tr>
<td>22</td>
<td>FUNCTION RN1 C7</td>
<td>ONE WAY SKID DISTANCE IN FEET</td>
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</tr>
<tr>
<td>0.0</td>
<td>200</td>
<td>1.0</td>
<td>900</td>
</tr>
<tr>
<td>23</td>
<td>FUNCTION V32 C2</td>
<td>TOTAL SKID TIME</td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>500</td>
<td>500</td>
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<tr>
<td>24</td>
<td>FUNCTION RN1 C3</td>
<td>MACHINE LOADER CYCLE TIME</td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>2.0</td>
<td>0.85</td>
<td>5</td>
</tr>
</tbody>
</table>
FUNCTION RN1 C6 PRE-HAUL ONE WAY DISTANCE IN FEET
0 0 200 0.15 500 0.40 750 0.80 875 0.96 1050 1.0 1300
FUNCTION RN1 C6 UNLOAD TIME AT MECHANIZED YARD (HALF TIME VALUES)
0 0 21 0.60 45 0.601 66 0.900 90 0.901 108 1.0 135
FUNCTION V35 C2 TIME TO LOAD A TREE ON PALLET
0 0 0 500 500
FUNCTION V39 C2 TIME FOR PREHAUL A PALLET
0 0 0 100 100
FUNCTION V41 C2 TIME FOR MACHINE LOAD CYCLE (STUMP TO STUMP)
0 0 0 500 500
FUNCTION P17 D3 LOADER CYCLES PER TREE IN STUMP TO STUMP MECH LOAD CYCLE
0 0 1 20 2 10 3
FUNCTION RN1 D3 SOLID WOOD VOLUME PER MECHANICAL LOAD CYCLE
0 0 9 0.66 10 1.0 11
FUNCTION V40 C2 TIME TO BUCK AND MOVE
0 0 0 1000 1000
FUNCTION V36 C2 ONE QUARTER OF TIME TO MOVE TO NEW PALLET
0 0 0 500 500
FUNCTION V34 C2 TIME TO STACK AND MOVE
0 0 0 500 500
FUNCTION P9 C2 DELAY TIME
0 0 0 100 100
FUNCTION RN1 C5 DELAY FUNCTION (LIMB, TOP, AND BUCK)
0 0 10 0.3 20 0.7 30 0.96 50 1.0 70
FUNCTION RN1 C5 DELAY FUNCTION (BUCKER)
0 0 10 0.3 20 0.7 30 0.96 50 1.0 70
FUNCTION RN1 C5 DELAY FUNCTION (PALETTE LOADER)
0 0 10 0.3 20 0.7 30 0.96 50 1.0 70
FUNCTION RN1 C5 DELAY FUNCTION (STACKER)
0 0 10 0.3 20 0.7 30 0.96 50 1.0 70
FUNCTION RN1 C5 DELAY FUNCTION (LOADER)
0 0 10 0.3 20 0.7 30 0.96 50 1.0 70
FUNCTION V29 C2 TIME TO LIMB AND TOP
0 0 0 500 500
FUNCTION V27 C2 TIME TO BUCK, LIMB, AND TOP
0 0 0 500 500
FUNCTION V23 C2 TIME TO STACK BOLTS
0 0 0 500 500
FUNCTION V37 C2 TIME TO HAND LOAD A TREE (NOT STUMP TO STUMP)
0 0 0 1000 1000
FUNCTION V40 C2 TIME FOR MACHINE LOAD CYCLE (NOT STUMP TO STUMP)
0 0 0 100 100
FUNCTION RN1 C2 TIME FOR WINCHING RACKS ON TRUCK AND MOVING
0 0 30 1.0 70
FUNCTION V42 C2 HELPS FN44A DETERMINE WINCH TIME
0 0 0 500 500
FUNCTION RN1 C2 TIME FOR WINCHING RACKS ON TRUCK
0 0 120 1.0 240
FUNCTION V43 C2 HELPS FN50 DETERMINE WINCH TIME
0 0 0 1000 1000
FUNCTION RN1 C2 CYCLE TIME OF FELLER REST PERIOD
0 0 140 1.0 260
FUNCTION RN1 C2 CYCLE TIME OF LIMBER AND TOPPER REST PERIOD OR LIMBER, TOPPER, AND BUCKER REST PERIOD
0 0 140 1.0 260
FUNCTION RN1 C2 CYCLE TIME OF BUCKER REST PERIOD
0 0 140 1.0 260
FUNCTION RN1 C2 CYCLE TIME OF PALLET LOADER REST PERIOD
0 0 140 1.0 260
FUNCTION RN1 C2 CYCLE TIME OF STACKER REST PERIOD
0 0 140 1.0 260
FUNCTION RN1 C2 CYCLE TIME OF TRUCK LOADER REST PERIOD
0:0 140 140 260
1 VARIABLE V&P1+FN10 TIME FOR PLAN MOVE CUT BLOCK
2 VARIABLE V#4+V# TIME FOR RUCK, LIMB, AND TOP
3 VARIABLE FN#FN7 TIME FOR LIMB AND TOP
4 VARIABLE FN10+P5 TIME TO RUCK A TREE
5 VARIABLE FN10+FN9 TOTAL TIME TO MANUAL LOAD A TREE AND MOVE
6 VARIABLE P15#K10+P14#K12+P16 TRANSPORT AND UNLOAD TIME
7 VARIABLE P4#K5 BOLTS PER STEM
8 VARIABLE P2#K5+P8/K2 HELP V1 COMPUTE
9 VARIABLE P7#P7#P4#K1#K64/V17 COMPUTES TREE VOLUME
10 VARIABLE FN21+P8 TIME FOR ONE SKIDDER TURN (PRODUCTIVE TIME)
11 VARIABLE P35+K5 HELPS V9
12 VARIABLE P10#K35#K100+P10 TOTAL TIME FOR SKIDDER OPERATION
13 VARIABLE FN2+Y+FN7 PALLETT LOAD TIME PER TREE
14 VARIABLE FN26#K150#K6 ONE WAY PREHAUL TIME
15 VARIABLE K1002#K100 HELPS V9
16 VARIABLE FN9+FN24+FN32
* V18 USED TO COMPUTE MECHANICAL LOAD TIME IN STUMP TO STUMP OPTIONS
19 VARIABLE G1+G2+G3+G4 G5+G6 G7+G8+G9+G10 CONTROL NP. TREES IN SYSTEM
20 VARIABLE V2+V8 TIME TO BOLT, LIMB, TOP, AND MOVE
21 VARIABLE V2+V8 TIME TO LIMB, TOP, AND MOVE
22 VARIABLE V4+V8 TIME TO RUCK AND MOVE
23 VARIABLE FN12+V8 TIME TO STACK AND MOVE
24 VARIABLE FN12+V8 TIME TO STACK AND MOVE
25 VARIABLE P9#K10/K10 CONTROL FOR NUMBER OF FELLING OPERATIONS
26 VARIABLE V21#K10/K10 CONTROL FOR NUMBER OF RUCK, LIMB, AND TOP
* OPERATIONS (NOT USED IN A SEQUENCE BEHIND A SKID OPERATION)
27 VARIABLE V2#K10/K10 CONTROL FOR NUMBER OF RUCK, LIMB, AND TOP
* OPERATIONS (USED IN A SEQUENCE BEHIND A SKID OPERATION)
28 VARIABLE V22#K10/K10 CONTROL FOR NUMBER OF LIMB AND TOP
* OPERATIONS (NOT USED IN A SEQUENCE BEHIND A SKID OPERATION)
29 VARIABLE V5#K10/K10 CONTROL FOR NUMBER OF LIMB AND TOP
* OPERATIONS (USED IN A SEQUENCE BEHIND A SKID OPERATION)
30 VARIABLE V23#K10/K10 CONTROL FOR NUMBER OF RUCK OPERATIONS (NOT
* USED IN A SEQUENCE WITH SKID OPERATIONS)
31 VARIABLE V4#K10/K10 CONTROL FOR NUMBER OF RUCK OPERATIONS (USED
* IN A SEQUENCE WITH SKID OPERATIONS)
32 VARIABLE V1]*K10/K10 CONTROL FOR NUMBER OF SKIDDERS
33 VARIABLE FN12#K10/K10 CONTROL FOR NUMBER OF STACK OPERATIONS (USED
* WITH SKID operation)
34 VARIABLE V24#K10/K10 CONTROL FOR NUMBER OF SKIDDER OPERATIONS (NOT
* USED WITH SKID OPERATIONS)
35 VARIABLE V15#K10/K10 CONTROL FOR NUMBER OF PALLETT LOAD OPS. (IF
* USED IN SEQUENCE WITH SKID OPERATION) (IF NOT USED IN A SEQUENCE WITH A
* SKID OPERATION, V36 IS ALSO REQUIRED TO AGREE IN NUMBER OF PALLETT LOAD OPS.)
36 VARIABLE V8#K10/K10 CONTROL FOR NUMBER OF PALLETT LOAD OPS. (NOT
* USED IN A SEQUENCE WITH A SKID OPERATION)
37 VARIABLE FN19#K10/K10 CONTROL FOR NUMBER OF MANUAL LOAD OPERATIONS
* (NOT FOR STUMP TO STUMP LOADING OPERATIONS)
38 VARIABLE V16#K10/K10 CONTROL FOR NUMBER OF PREHAUL OPERATIONS
39 VARIABLE V5#K10/K10 CONTROL FOR NUMBER OF MANIUAL LOAD OPERATIONS
* (FOR STUMP TO STUMP LOADING OPERATIONS)
40 VARIABLE FN24#K10/K10 CONTROL FOR NUMBER OF MACHINE LOAD
* OPERATIONS (NOT FOR STUMP TO STUMP LOADING OPERATIONS)
41 VARIABLE V13#K10/K10 CONTROL FOR NUMBER OF MACHINE LOAD
* OPERATIONS (FOR STUMP TO STUMP LOADING OPERATIONS)
42 VARIABLE FN48#K10/K10 CONTROL FOR NUMBER OF TRUCKS HAULING (NOT
* USED WITH PREHAUL AND/OR SKID OPERATION)
43 VARIABLE FN90#K10/K10 CONTROL FOR NUMBER OF TRUCKS HAULING (USED
* WITH PREHAUL AND/OR SKID OPERATION)
44 VARIABLE V8#K10/K10 CONTROL FOR NUMBER OF TRUCKS HAULING
* *
* FOREST SIMULATION START OF SIMULATION PROGRAM
* GENERATE 4
  2 3  CONTROL FLOW
  4  K150  3  CLEAR CUT OPER.
  5  K1  4  TREE SPACING.
  6  FN16  5  D.B.H.
  7  FN13  6  USABLE STEM
  8  FN11  7  BOLTS PER STEM
  9  V7  8  TREE TRANSACT.
  10  K4  9  HELP V9
  11  V11  10  BRUSH FACTOR
  12  FN17  11  PMC TIME PK 20
  13  V1  12  TRANSACT = LOG
  14  V9  13  VOLUME OF STEM
  15  STATISTICS ON VOM PER TREE
  16  50
  17  P17  1
  18  1 2  AWAITING FELL
  19 ずに
  20  END OF FOREST GENERATOR

* START OF MOVE PLAN, AND CUT SIMULATION (BLOCK 20)
* VARIABLE 25 MUST BE ADJUSTED FOR CORRECT NUMBER OF FELLING OPERATIONS
* BLOCK 103 OF FELLER DELAY SUBPROGRAM MUST BE ADJUSTED FOR UTILIZATION
  20  HOLD 1 80 1 FN1 PLAN MOVE FELL
* END OF MOVE PLAN, AND CUT SIMULATION

* START OF BUCK, LIMB, AND TOP SIMULATION (BLOCK 30)
* NOT TO BE USED IN A SEQUENCE BEHIND A SKID OPERATION
* VARIABLE 26 MUST BE ADJUSTED FOR CORRECT NUMBER OF BUCK, LIMB, AND TOP OPS.
* BLOCK 108 OF BUCK, LIMB, AND TOP DELAY SUBPROGRAM MUST BE ADJUSTED FOR UTILIZATION
  30  HOLD 2 81 2 FN7 R L T
* END OF BUCK, LIMB, AND TOP SIMULATION

* START OF BUCK, LIMB, AND TOP SIMULATION (BLOCK 30)
* TO BE USED ONLY IN A SEQUENCE BEHIND A SKID OPERATION
* VARIABLE 27 MUST BE ADJUSTED FOR CORRECT NUMBER OF BUCK, LIMB, AND TOP OPS.
* BLOCK 108 OF BUCK, LIMB, AND TOP DELAY SUBPROGRAM MUST BE ADJUSTED FOR UTILIZATION
  30  HOLD 2 81 1 FN44 R L T
* END OF BUCK, LIMB, AND TOP SIMULATION

* START OF LIMB AND TOP SIMULATION (BLOCK 31)
* NOT TO BE USED IN A SEQUENCE BEHIND A SKID OPERATION
* VARIABLE 28 MUST BE ADJUSTED FOR CORRECT NUMBER OF LIMB AND TOP OPERATIONS
* BLOCK 108 OF LIMB AND TOP DELAY SUBPROGRAM MUST BE ADJUSTED FOR UTILIZATION
  31  HOLD 2 83 1 FN3 LIMB AND TOP
* END OF LIMB AND TOP SIMULATION
* START OF LIMP AND TOP SIMULATION (BLOCK 31)
* TO BE USED ONLY IN A SEQUENCE BEHIND A SKID OPERATION
* VARIABLE 29 MUST BE ADJUSTED FOR CORRECT NUMBER OF LIMP AND TOP OPERATIONS
* BLOCK 108 OF LIMP AND TOP DELAY SUBPROGRAM MUST BE ADJUSTED FOR UTILIZATION
* HOLD 2 83 1 FN43 LIMP AND TOP
* END OF LIMP AND TOP SIMULATION
*
* START OF BUCK FUNCTION SIMULATION (BLOCK 32)
* NOT TO BE USED WITH SKID OPTION
* VARIABLE 30 MUST BE ADJUSTED FOR CORRECT NUMBER OF BUCK OPERATIONS
* BLOCK 401 OF BUCK DELAY SUBPROGRAM MUST BE ADJUSTED FOR UTILIZATION
* HOLD 6 85 1 FN34 BUCK FUNCTION
* END OF BUCK SIMULATION
*
* START OF SKID SIMULATION (BLOCK 40)
* VARIABLE 32 MUST BE ADJUSTED FOR CORRECT NUMBER OF SKIDDERS
* ASSIGN 32 R17 L K50 METER FLOW
* 27 COMPARE 52 L K50 139 15 LOAD COMPL
* 126 CAPACITY 65 MAX SKID LOAD OF SOLID WOOD
* 130 MAX RELEASE 23 603 START OF SKID
* 139 SPLIT 23 139 METER FLOW
* 41 SAVEX 1+ P5 41 LOAD HOLD
* 42 SAVFX 2+ P17 43 ADD TREE POLTS
* 43 SAVEX 3+ P12 44 ADD TREE VOL
* 12 CAPACITY 65 MAX SKID LOAD OF SOLID WOOD
* 220 ENTER 12 P17 44 129 ROUTING
* 24 COMPARE 512 L K50 130 YES SKID LOAD
* 129 SPLIT 512 L K50 130 LOAD HOLD
* 45 ASSIGN 7 X2 48 VOL OF TURN
* 48 PRINT 1 3 21 SKIDDER OUTPUT
* 21 ASSIGN 10 V10 22 TURN TIME
* 22 SAVEX 1 K0 23 RESET BOLTS
* 23 SAVEX 2 K0 24 RESET VOLMF
* 24 SAVEX 3 K0 25 RESET LOGS
* 25 HOLD 12 115 1 FN23 SKIDDING TIME
* 135 ADVANCE 221 1 LOAD RELEASE
* 221 LEAVE 12 P7 49 SKID COMPLET
* 49 LEAVE 12 P7 136 SKID COMPLET
* 130 QUF 12 131 LOAD HOLD
* 131 COMPARE W195 G K0 84 LOAD RELEASE
* 136 TERMINATE BOTH 144 143 ROUTING
* 142 ADVANCE 1 LOAD RELEASE
* 143 TERMINATE
* 144 HOLD 13 145 SKID TURN
* 145 COMPARE W195 G K0 146
* END OF SKID SIMULATION

* START OF STACK SIMULATION (BLOCK 50)
* NOT TO BE USED WITH THE SKID OPTION
* VARIABLE 74 MUST BE ADJUSTED FOR CORRECT NUMBER OF STACK OPERATIONS
* BLOCK 411 OF STACKER DELAY SUBPROGRAM MUST BE ADJUSTED FOR UTILIZATION
50  HOLD  42  82  1  FN36  STACK ROUGH
* END OF STACK SIMULATION

* START OF STACK SIMULATION (BLOCK 50)
* TO BE USED ONLY WITH THE SKID OPTION
* VARIABLE 73 MUST BE ADJUSTED FOR CORRECT NUMBER OF STACK OPERATIONS
* BLOCK 411 OF STACKER DELAY SUBPROGRAM MUST BE ADJUSTED FOR UTILIZATION
50  HOLD  42  82  1  FN40  STACK ROUGH
* END OF STACK SIMULATION

* START OF PALLET LOADING SIMULATION (BLOCK 51)
* NOT TO BE USED WITH SKID OPTION
* VARIABLES 34 AND 36 MUST BE ADJUSTED FOR CORRECT NUMBER OF PALLET LOAD OPS
* BLOCK 406 OF PALLET LOAD DELAY SUBPROGRAM MUST BE ADJUSTED FOR UTILIZATION
51  SEIF  27  157  METER FLOW
157  COMPARE  53  L  K109  53  IS THERE ROOM
3  CAPACITY  140  MAX PAILLET VOLUME OF SOLID WOOD
53  ENTER  3  P17  602  OCCUPY SPACE
602  RELEASE  22  150  METER FLOW
602  LOAD HOLD  54  152
54  SAVEX  4+  P17  55  VOL OF STEM
55  SAVEX  7+  P12  56  NO OF STEM
56  SAVEX  8+  P5  151  NO OF BOLTS
151  HOLD  8  230  1  FN20  LOAD PALLET
13  CAPACITY  140  MAX PAILLET VOLUME OF SOLID WOOD
230  ENTER  13  P17  BOTH  57  58  ROUTING
57  COMPARE  513  L  K109  99  YES FULL LOAD
58  ASSIGN  6  X8  59  NO OF BOLTS
59  ASSIGN  7  X6  34  VOL LOADED
34  ASSIGN  12  X7  35  NO OF TREE CUT
35  PRINT  6  B  36  STAT PRINT OUT
36  SAVEX  6  K0  37  RESET VOL
37  SAVEX  7  K0  38  RESET STEM
38  SAVEX  8  K0  350  RESET BOLTS
150  HOLD  3  39  4  FN36  MOVE TO NEXT P
39  ADVANCE  231  1  LOAD RELEASE
231  LEAVE  13  P7  149  LOAD COMPLETE
149  LEAVE  3  P7  87  END PALLET SIM
152  ADVANCE  BOTH  154  159  ROUTING
153  TERMINATE
154  HOLD  14  155  LOAD TIME
155  COMPARE  W19  G  K0  156  RELEASE PALLET
156  TERMINATE
* END OF PALLET LOADING SIMULATION
* START OF PALLETS LOADING SIMULATION (BLOCK 51)
* TO BE USED ONLY WITH SKID OPTIONS
* VARIABLE 35 MUST BE ADJUSTED FOR CORRECT NUMBER OF PALLETS LOAD UTILIZATION
* BLOCK 406 OF PALLET LOAD DELAY SUBPROGRAM MUST BE ADJUSTED FOR UTILIZATION

51 SEIZE 22 157 METER FLOW
157 COMPARE 53 L K109 53 IS THERE ROOM
3 CAPACITY 140 MAX PALLETS VOLUME OF SOLID WOOD
53 ENTER 3 P17 602 OCCUPY SPACE
602 RELEASE 22 150 METER FLOW
150 SPLIT 54 152 LOAD HOLD
54 SAVEX 6+ P17 55 VOL OF STFM
55 SAVEX 7+ P12 56 NO OF STFM
56 SAVEX 8+ P5 151 NO OF BOLTS
151 HOLD 3 230 1 FN29 LOAD PALLET
13 CAPACITY 140 MAX PALLETS VOLUME OF SOLID WOOD
230 ENTER 13 P17 BOTH 57 58 ROUTING
57 COMPARE 513 L K109 99 YES FULL LOAD
58 ASSIGN 5 X8 59 NO OF BOLTS
59 ASSIGN 7 X6 34 VOL LOADED
34 ASSIGN 12 X7 35 NO OF TREE CUT
35 PRINT 6 8 36 STAT PRINT OUT
36 SAVEX 6 K0 37 RESET VOL
37 SAVEX 7 K0 38 RESET STFM
38 SAVEX 8 K0 39 RESET BOLTS
39 ADVANCE 231 1 LOAD RELFASF
231 LEAVE 13 P7 149 LOAD COMPLETE
149 LEAVE 3 P7 87 FIND PALLETS SIM
152 ADVANCE BOTH 154 153 ROUTING
153 TERMINATE
144 HOLD 14 154 LOAD TIME
155 COMPARE W39 G K0 156 RELEASE PALLET
156 TERMINATE

* END OF PALLETS LOADING SIMULATION

* START PRE-RAIL SIMULATION (BLOCK 52)
* VARIABLE 38 MUST BE ADJUSTED FOR CORRECT NUMBER OF PRE-RAIL OPERATIONS

52 HOLD 7 88 2 FN30 PRE-RAIL PALLET

* END OF PRE-RAIL SIMULATION

* START OF MANUAL LOAD SIMULATION (BLOCK 60)
* TO BE USED ONLY IN THE STUMP TO STUMP MANUAL LOAD OPTION
* VARIABLE 39 MUST BE ADJUSTED FOR CORRECT NUMBER OF MANUAL LOAD OPERATIONS

60 SEIZE 21 175 METER FLOW
175 COMPARE S1 L K220 63 IS THERE ROOM
1 CAPACITY 260 MAX TRUCK LOAD (VOLUME OF SOLID WOOD)
63 ENTER 1 P17 600 TAKE UP SPACE
600 RELEASE 21 64 METER FLOW
64 COMPARE X20 L K8 66 HOLD FOR HAIL
66 SPLIT 68 170 LOAD HOLD
68 SAVEX 4+ P12 69 COUNT TREE
69 SAVEX 5+ P4 160 COUNT BOLTS
160 SAVEX 6+ P17 67 ADD VOL
67 HOLD 4 203 1 FN5 LOAD MANUALLY
11 CAPACITY 260 MAX TRUCK LOAD (VOLUME OF SOLID WOOD)
203 ENTER 11 P17 BOTH 161 162 ROUTING
161 COMPARE S11 L K220 99 IS LOAD READY
162 ASSIGN 1 S1 163 RECORD VOL
163 PRINT 4 6 16A  PRINT STAT
164 SAVEK 4 K0 165  SET TREE COUNT
165 SAVEK 5 K0 166  SET PLOT COUNT
166 SAVEK 6 K0 167  SET VOL
167 SAVEK 20 K10 168  HOLD LOADING
168 ADVANCE 204 1  LOAD RELEASE
204 LEAVE 11 P1 169  LOAD COMPLETE
169 LEAVE 1 P1 70  LOAD COMPLETE
170 ADVANCE BOTH 172 171  ROUTING
171 TERMINATE
172 HOLD 14 173  LOADING TIME
173 COMPARE W168 G K0 174  RELEASE LOAD
174 TERMINATE

* END OF MANUAL LOAD SIMULATION
*
*
*
*

* START OF MANUAL LOAD SIMULATION (BLOCK 60)
* NOT TO BE USED IN THE STUMP TO STUMP MANUAL LOAD OPTION
* VARIABLE 37 MUST BE ADJUSTED FOR CORRECT NUMBER OF MANUAL LOAD OPERATIONS
* BLOCK 416 OF MANUAL LOAD DELAY SUBPROGRAM MUST BE ADJUSTED FOR UTILIZATION
60 SEIZE 21 175  METER FLOW
175 COMPARE S1 L K220 63  IS THERE ROOM
1 CAPACITY 260 MAX TRUCK LOAD (VOLUME OF SOLID WOOD)
63 ENTER 1 P17 600  TAKE UP-space
600 RELEASE 21 64  METER FLOW
64 COMPARE X20 L K8 66  HOLD FOR HAUL
66 SPLIT 68 170  LOAD HOLD
68 SAVEK 4+ P12 69  COUNT TREES
69 SAVEK 5+ P5 160  COUNT BOLTS
160 SAVEK 6+ P17 67  ADD VOL
67 HOLD 40 203 1 FN46  LOAD MANUAL
11 CAPACITY 260 MAX TRUCK LOAD (VOLUME OF SOLID WOOD)
204 ENTER 11 P17 BOTH 161 162  ROUTING
161 COMPARE 511 L K220 99  IS LOAD READY
162 ASSIGN 1 S1 163  RECORD VOL
163 PRINT 4 6 164  PRINT STAT
164 SAVEK 4 K0 165  SET TREE COUNT
165 SAVEK 5 K0 166  SET PLOT COUNT
166 SAVEK 6 K0 167  SET VOL
167 SAVEK 20 K10 168  HOLD LOADING
168 ADVANCE 204 1  LOAD RELEASE
169 LEAVE 11 P1 169  LOAD COMPLETE
169 LEAVE 1 P1 70  LOAD COMPLETE
170 ADVANCE BOTH 172 171  ROUTING
171 TERMINATE
172 HOLD 14 173  LOADING TIME
173 COMPARE W168 G K0 174  RELEASE LOAD
174 TERMINATE

* END OF MANUAL LOAD SIMULATION
*
*
*
*

* START OF MECH LOAD SIMULATION (BLOCK 61)
* TO BE USED ONLY IN THE STUMP TO STUMP MECH. LOAD OPTION
* VARIABLE 41 MUST BE ADJUSTED FOR CORRECT NUMBER OF MECHANICAL LOAD OPERATIONS
61 SEIZE 21 175  METER FLOW
175 COMPARE S1 L K220 63  IS THERE ROOM
1 CAPACITY 260 MAX TRUCK LOAD (VOLUME OF SOLID WOOD)
63 ENTER 1 P17 600  TAKE UP SPACE
600 RELEASE 21 64  METER FLOW
64 COMARE X20 L KB 66 HOLD FOR HAUL
66 SPLIT 68 170 LOAD HOLD
68 SAVEK 4+ P12 69 COUNT TREES
69 SAVEK 5+ P5 160 COUNT BOLTS
160 SAVEK 6+ P17 67 ADD VOLT
167 SAVEK 20 K10 168 HOLD LOADING
168 ADVANCE 204 I LOAD RELEASE
204 LEAVE 11 P1 169 LOAD COMPLETE
169 LEAVE 1 P1 70 LOAD COMPLETE
170 ADVANCE ROTH 172 171 ROUTING
171 TERMINATE
172 HOLD 14 173 LOADING TIME
173 COMARE W168 G K0 174 RELEASE LOAD
174 TERMINATE

* END OF MECH. LOAD SIMULATION

* START OF MECH LOAD SIMULATION (BLOCK 61)
* NOT TO BE USED IN THE STUMP TO STUMP MECH LOAD OPTION
* VARIABLE 40 MUST BE ADJUSTED FOR CORRECT NUMBER OF MECHANICAL LOAD OPERATIONS

61 SEIZE 30 302 METER FLOW
302 COMARE X30 L K220 303 IS THERE ROOM
303 COMARE X20 L KB 305 HOLD FOR HAUL
305 SAVEK 31+ P17 309 ADD VOLUME
309 RELEASE 30 306 METER FLOW
306 SAVEK 31+ P5 307 COUNT BOLTS
307 SAVEK 32+ P12 308 COUNT TREES
308 SAVEK 33+ P17 99 LOADRELEASE CONTROL
310 ADVANCE ROTH 311 314 ROUTING
311 HOLD 31 312 LOADING TIME
312 COMARE W331 G K0 313 RELEASE LOAD
313 TERMINATE
314 TERMINATE
315 GENERATE 316 1 GRAPPLE LOADS
316 SEIZE 33 316 CONTROL FLOW
316 COMARE X35 L K220 317 CONTROL FLOW
317 ASSIGN 1 FN33 318 CYCLE VOL.
318 SAVEK 34 P1 319 START P1
319 ADVANCE ROTH 320 322 ROUTING
320 COMARE X33 GE X34 321 CYCLE LOAD
321 SAVEK 33+ P1 324 CORRECT X33
322 COMARE X30 GF K220 323 LOADING COMPLETE
323 SAVEK 33+ P1 324 CORRECT X33
324 SAVEK 33+ P1 326 ADD VOL
325 RELEASE 33 325 CONTROL FLOW
325 HOLD 32 ROTH 326 327 1 UNIT LOAD
326 COMARE X35 L K220 335 IS LOAD READY
335 TERMINATE
336 TERMINATE
337 ASSIGN 2 X35 328 VOL OF LOAD
328 PRINT 30 34 339 PRINT STAT
339 PRINT 35 35 329 PRINT STAT
329 SAVEK 31 K0 330 RESET BOLTS
* START Pallet Transfer Operation (BLOCK 62) *
* NOT TO BE USED WITH PREHAUL OR/AND SKID OPTION *
* VARIABLE 42 MUST BE ADJUSTED FOR CORRECT NUMBER OF TRUCKS

62 SEIZE 21 175
175 COMPARE S4 L K5 63
4 CAPACITY 5 MAX NUMBER OF PALLETS TO LOAD ON TRUCK
53 ENTER 4 K1 600
600 RELEASE 21 64
64 COMPARE X20 L KB 66
66 SPLIT 67 170
67 SAVEK 4+ P7 68
68 SAVEK 5+ P12 164
164 HOLD 4 240 1 FN49
14 CAPACITY 5 MAX NO OF PALLETS TO LOAD ON TRUCK
240 ENTER 14 K1 ROTH 69 160
69 COMPARE S14 L K5 95
160 PRINT 4 5 161
161 SAVEK 4 K0 162
162 SAVEK 5 K0 163
163 SAVEK 20 K10 165
165 ADVANCE 241 1 FN49
241 LEAVE 14 K5 166
166 LEAVE 4 K5 70
170 ADVANCE ROTH 172 171
171 TERMINATE
172 HOLD 15 173
173 COMPARE W165 G K0 174
174 TERMINATE
* END OF Pallet Transfer Operation

* START Pallet Transfer Operation (BLOCK 62) *
* TO BE USED WITH PREHAUL OR/AND SKID OPTION *
* VARIABLE 42 MUST BE ADJUSTED FOR CORRECT NUMBER OF TRUCKS

62 SEIZE 21 175
175 COMPARE S4 L K5 63
4 CAPACITY 5 MAX NUMBER OF PALLETS TO LOAD ON TRUCK
53 ENTER 4 K1 600
600 RELEASE 21 64
64 COMPARE X20 L KB 66
66 SPLIT 67 170
67 SAVEK 4+ P7 68
68 SAVEK 5+ P12 240
14 CAPACITY 5 MAX NO OF PALLETS TO LOAD ON TRUCK
240 ENTER 14 K1 ROTH 69 160
69 COMPARE S14 L K5 95
160 PRINT 4 5 161
161 SAVEK 4 K0 162
162 SAVEK 5 K0 163
163 SAVEK 20 K10 164
164 HOLD 4 165 1 FN51 Winch On Time
165 ADVANCE

241 LEAVE 14 K5 165 1 LOAD RELEASE

166 LEAVE 4 K5 166 1 LOAD COMPLETE

170 ADVANCE BOTH 172 171 ROUTING

171 TERMINATE

172 HOLD 15 173 LOADING TIME

173 COMPARE W165 G KD 174 RELEASE LOAD

174 TERMINATE

*END OF PALLET TRANSFER OPERATION

* * *

* START OF HAULING SIMULATION (BLOCK 70)*

* VARIABLE 44 MUST BE ADJUSTED FOR CORRECT NUMBER OF TRUCKS

70 ASSIGN 14 FN14 71 PAVED ROAD DIST

71 ASSIGN 16 FN15 72 DIRT ROAD DIST

72 ASSIGN 16 FN28 73 UNLOAD TIME

5 TABLE IA 0 180 20 74 TIME IN BETWEEN LOADS

73 TABULATE 4 74

74 HOLD 20 75 2 FN6 TRANSPORT

3 TABLE P14 1 1 60 STATISTICS ON PAVED ROAD DISTANCE

4 TABLE P15 1 1 150 STATISTICS ON DIRT ROAD DISTANCE

75 TABULATE 3 76

76 TABULATE 4 77

351 SAVFX 40 P16 352 UNLOAD TIME

352 PRINT 40 40 77 PRINT STAT

77 SAVEX 20 K5 100 LOADING OK

* END OF HAULING SIMULATION

* * *

* BEGINNING OF DELAY SUBPROGRAMS*

* DELAY SUBPROGRAMS SHOULD BE REMOVED FROM THE MAIN PROGRAM WHEN*

* THE FIRST RUN IS MADE TO DETERMINE MULTIPLES OF EACH OPERATION *

* REQUIRED TO PRODUCE A BALANCED SYSTEM. THE DELAY SUBPROGRAMS SHOULD *

* BE INCLUDED WITH THE MAIN PROGRAM WHEN A SIMULATION RUN IS MADE *

* OF AN APPROXIMATELY BALANCED SYSTEM

* * *

* START OF FELLER DELAY SUBPROGRAM*

101 GENERATE 100 5 103 1 FN52 FELLER DELAY

103 ASSIGN 9 FN20 .999 99 104 1 LENGTH OF REST

104 HOLD 1 105 1 FN37 NON OR TIME

1 TABLE P9 1 1 60 NON PRODUCTIVE TIME OF FELLER

105 TABULATE 1 98

* * *

* START OF LIMB AND TOP DELAY SUBPROGRAM OR BUCK, LIMB, AND TOP DELAY SUBPROGRAM*

106 GENERATE 100 5 108 1 FN53 LIMBER DELAY

108 ASSIGN 9 FN38 .999 99 109 1 LENGTH OF REST

109 HOLD 2 110 1 FN37 NON OR TIME

2 TABLE P9 1 1 60 NONPRODUCTIVE TIME OF LIMBER

110 TABULATE 2 97

* * *

* START OF BUCK DELAY SUBPROGRAM*

400 GENERATE 100 5 401 1 FN54 BUCKER DELAY

401 ASSIGN 9 FN39 .999 99 402 1 LENGTH OR REST
402 HOLD  6  403  1  FN37  NON OP, TIME
10 TABLE  P9  1  1  60  NONPRODUCTIVE TIME OF BUCKER  
403 TABULATE  10  99
*                             99
*                          *
* START OF PALLETF LOAD DELAY SUBPROGRAM                          *
405 GENERATE  100  5  406  1  FN55  PLT LOAD DELAY  
406 ASSIGN  9  FN40  .999  99  407  LENGTH OF REST  
407 HOLD  3  408  1  FN37  NON OP, TIME  
11 TABLE  P9  1  1  60  NONPRODUCTIVE TIME OF PALLETF LOADER  
408 TABULATE  11  99
*                             99
*                          *
* START OF STACK DELAY SUBPROGRAM                                *
410 GENERATE  100  5  411  1  FN56  STACKER DELAY  
411 ASSIGN  9  FN41  .999  99  412  LENGTH OF REST  
412 HOLD  43  413  1  FN37  NON OP, TIME  
12 TABLE  P9  1  1  60  NONPRODUCTIVE TIME OF STACKER  
413 TABULATE  12  99
*                             99
*                          *
* START OF MANUAL LOAD DELAY SUBPROGRAM (NOT FOR STUMP TO STUMP) *
415 GENERATE  100  5  416  1  FN57  LOADER DELAY  
416 ASSIGN  9  FN42  .999  99  418  LENGTH OF REST  
417 HOLD  40  418  1  FN37  NON OP, TIME  
13 TABLE  P9  1  1  60  NONPRODUCTIVE TIME OF LOADER  
418 TABULATE  13  99
*                             99
*                          *
* END OF DELAY SUBPROGRAMS                                      *
*                             *
* BEGINNING OF TERMINATION SECTION                              *
97 TERMINATE  
98 TERMINATE  
100 TERMINATE  R  
START  20  
END
*                             *
* QUEUE BLOCKS USED TO ASSEMBLE A PROGRAM                        *
80 QUEUE  2  40  BLOCK 20 TO 40  
80 QUEUE  2  31  BLOCK 20 TO 31  
80 QUEUE  2  30  BLOCK 20 TO 30  
81 QUEUE  3  50  BLOCK 30 TO 50  
81 QUEUE  3  60  BLOCK 30 TO 60  
81 QUEUE  3  51  BLOCK 30 TO 51  
82 QUEUE  4  60  BLOCK 50 TO 60  
82 QUEUE  4  61  BLOCK 50 TO 61  
83 QUEUE  5  32  BLOCK 31 TO 32  
83 QUEUE  5  40  BLOCK 31 TO 40  
84 QUEUE  6  31  BLOCK 40 TO 31  
84 QUEUE  6  30  BLOCK 40 TO 30  
84 QUEUE  6  32  BLOCK 40 TO 32  
85 QUEUE  7  51  BLOCK 32 TO 51  
85 QUEUE  7  50  BLOCK 32 TO 50  
85 QUEUE  8  60  BLOCK 32 TO 60  
85 QUEUE  8  61  BLOCK 32 TO 61
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APPENDIX II

THE SAMPLE SYSTEM MODEL

System 14
# DATA FUNCTIONS AND SYSTEM VARIABLE DEFINITIONS

<table>
<thead>
<tr>
<th>No.</th>
<th>Function</th>
<th>Definition</th>
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<tbody>
<tr>
<td>1</td>
<td><code>VF25</code></td>
<td><code>C2</code> TIME FOR PLAN MOVE AND CUT</td>
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<td>2</td>
<td><code>VF26</code></td>
<td><code>C2</code> TIME TO BUCK, LIMB, TOP, AND MOVE</td>
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<td>3</td>
<td><code>VF28</code></td>
<td><code>C2</code> TIME TO LIMB, TOP, AND MOVE</td>
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<td><code>VF31</code></td>
<td><code>C2</code> TIME TO BUCK</td>
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<td>5</td>
<td><code>VF39</code></td>
<td><code>C2</code> TIME TO HAND LOAD A TREE ON TRUCK AND MOVE</td>
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<td>6</td>
<td><code>VF44</code></td>
<td><code>C2</code> TIME FOR ONE WAY HAUL (TRUCK)</td>
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<td>7</td>
<td><code>KN1</code></td>
<td><code>D3</code> LIMB FACTOR</td>
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<td>8</td>
<td><code>KN1</code></td>
<td><code>C2</code> NORM TIME TO LIMB AND TOP</td>
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<td>9</td>
<td><code>KN1</code></td>
<td><code>C2</code> TIME TO MOVE TRUCK STUMP TO STUMP</td>
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<td>10</td>
<td><code>P3</code></td>
<td><code>D5</code> TIME TO CUT (FELL OR BUCK) CHAIN SAW</td>
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<td>11</td>
<td><code>P3</code></td>
<td><code>C7</code> LENGTH OF MERCHANTABLE STEM</td>
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FUNCTION R1 C2

* FUNCTION R1 C2 CYCLE TIME OF BUCKER REST PERIOD

FUNCTION R1 C2 CYCLE TIME OF PAILLET LOADER REST PERIOD

FUNCTION R1 C2 CYCLE TIME OF STACKER REST PERIOD

FUNCTION R1 C2 CYCLE TIME OF TRUCK LOADER REST PERIOD

VAR 1  V84P1+M1
    TIME FOR PLAN MOVE CUT BLOCK

VAR 2  V34V4
    TIME FOR BUCK, LIMB, AND TOP

VAR 3  F84M7
    TIME FOR LIMB AND TOP

VAR 4  F104P5
    TIME TO BUCK A TREE

VAR 5  F104M9
    TOTAL TIME TO MANUAL LOAD A TREE AND MOVE

VAR 6  P104K10+P14K12+P16
    TRANSPORT AND UNLOAD TIME

VAR 7  P14K8
    BOLTS PER STEM

VAR 8  P24K5+P24K12+P16
    HELP V1 COMPUTE

VAR 9  P74K7+P44K1364/V17
    COMPUTES TREE VOLUME

VAR 10  F102P5
    TIME FOR ONE SKIDDER TURN (PRODUCTIVE TIME)

VAR 11  P34K5
    HELPS V9

VAR 12  P104K35+K104P10
    TOTAL TIME FOR SKIDDER OPERATION

VAR 13  F108P5
    PALLET LOAD TIME PER TREE

VAR 14  F109K20+K56
    ONE WAY PREHUAL TIME

VAR 15  F109K10+K14
    HELPS V9

VAR 16  F109F4+M24F4
    V10 USED TO COMPUTE MECHANICAL LOADING TIME IN STUMP TO STUMP OPTION

VAR 17  W14Q2+Q3+Q4+Q5+Q6+Q7+Q8+Q9+Q10
    CONTROL NO. TREES IN SYSTEM

VAR 18  V24V8
    TIME TO BOLT, LIMB, TOP, AND MOVE

VAR 19  V34V8
    TIME TO LIMB, TOP, AND MOVE

VAR 20  V44V8
    TIME TO BUCK AND MOVE

VAR 21  F104V5
    TIME TO STACK AND MOVE

VAR 22  P94K10+K10
    CONTROL FOR NUMBER OF FELLING OPERATIONS

VAR 23  V24K10+K10
    CONTROL FOR NUMBER OF BUCK, LIMB, AND TOP

* OPERATIONS (NOT USED IN A SEQUENCE BEHIND A SKID OPERATION)

VAR 24  V24K10+K10
    CONTROL FOR NUMBER OF BUCK, LIMB, AND TOP

* OPERATIONS (NOT USED IN A SEQUENCE BEHIND A SKID OPERATION)

VAR 25  V34K10+K10
    CONTROL FOR NUMBER OF LIMB AND TOP

* OPERATIONS (NOT USED IN A SEQUENCE BEHIND A SKID OPERATION)

VAR 26  V24K10+K10
    CONTROL FOR NUMBER OF BUCK OPERATIONS (NOT

* USED IN A SEQUENCE WITH SKID OPERATIONS)

VAR 27  V44K10+K10
    CONTROL FOR NUMBER OF BUCK OPERATIONS (USED

* IN A SEQUENCE WITH SKID OPERATION)

VAR 28  V14K10+K10
    CONTROL FOR NUMBER OF SKIDERS

VAR 29  V12K10+K10
    CONTROL FOR NUMBER OF STACK OPERATIONS (USED

* WITH SKID OPERATION)

VAR 30  V24K10+K10
    CONTROL FOR NUMBER OF STACK OPERATIONS (NOT

* USED WITH SKID OPERATIONS)

VAR 31  V15K10+K10
    CONTROL FOR NUMBER OF PALLET LOAD OPS. (IF

* USED IN SEQUENCE WITH SKID OPERATION) (IF NOT USED IN A SEQUENCE WITH A

* SKID OPERATION, V36 IS ALSO REQUIRED TO AGREE IN NUMBER OF PALLET LOAD OPS.)

VAR 32  V8K10+K10
    CONTROL FOR NUMBER OF PALLET LOAD OPS. (NOT

* USED IN A SEQUENCE WITH A SKID OPERATION)
37 VARIABLE FN19*K10/K10 CONTROL FOR NUMBER OF MANUAL LOAD OPERATIONS * (NOT FOR STUMP TO STUMP LOADING OPERATIONS)
38 VARIABLE V16*K10/K10 CONTROL FOR NUMBER OF PREHAUL OPERATIONS * (FOR STUMP TO STUMP LOADING OPERATIONS)
39 VARIABLE V5*K10/K10 CONTROL FOR NUMBER OF MANUAL LOAD OPERATIONS * (FOR STUMP TO STUMP LOADING OPERATIONS)
40 VARIABLE FN24*K10/K10 CONTROL FOR NUMBER OF MACHINE LOAD OPERATIONS (NOT FOR STUMP TO STUMP LOADING OPERATIONS)
41 VARIABLE V18*K10/K40 CONTROL FOR NUMBER OF MACHINE LOAD OPERATIONS (FOR STUMP TO STUMP LOADING OPERATIONS)
42 VARIABLE FN48*K10/K10 CONTROL FOR NUMBER OF TRUCKS HAULING (NOT * USED WITH PREHAUL AND/OR SKID OPERATION)
43 VARIABLE FN50*K10/K10 CONTROL FOR NUMBER OF TRUCKS HAULING (USED * WITH PREHAUL AND/OR SKID OPERATION)
44 VARIABLE V6*K10/K40 CONTROL FOR NUMBER OF TRUCKS HAULING

* Forest Simulation -- Start of Simulation Program

1 GENERATE 2 COMPAR 4 V19 LE 5 K150
2 ASSIGN 3
3 ASSIGN 1 K1
4 ASSIGN 2 FN16
5 ASSIGN 3 FN13
6 ASSIGN 4 FN11
7 ASSIGN 5 V7
8 ASSIGN 6 K4
9 ASSIGN 7 V11
10 ASSIGN 8 FN17
11 ASSIGN 9 V1
12 ASSIGN 12 K1
13 ASSIGN 17 V9
14 TABLE P17 1 1 150 50 STATISTICS ON VOL PER TREE
15 TABLE P18 1 1 1
16 TABLE 15 1 19
17 TABLE 1 20 WAITING FELL
18 ENDFOR FOREST GENERATOR

* Start of Move, Plan, and Cut Simulation (Block 20)
* Variable 28 must be adjusted for correct number of felling operations
* Clock 100 of feller delay subprogram must be adjusted for utilization
28 HOLD 1 80 1 FN1 PLAN MOVE FELL
29 END OF MOVE, PLAN, AND CUT SIMULATION

30 WUELE 2 30 BLOCK 20 TO 30

* Start of Buck, Limb, and Top Simulation (Block 30)
* Variable 20 must be adjusted for correct number of buck, limb, and top ope.
* Clock 100 of buck, limb, and top delay subprogram must be adjusted for
* Utilization
30 HOLD 2 81 1 FN2 B L T
31 END OF BUCK, LIMB, AND TOP SIMULATION
* START OF STACK SIMULATION (BLOCK 50)
* NOT TO BE USED WITH THE SKU OPTION
* VARIABLE 34 MUST BE ADJUSTED FOR CORRECT NUMBER OF STACK OPERATIONS
* BLOCK 411 OF STACKER DELAY SUBPROGRAM MUST BE ADJUSTED FOR UTILIZATION
* HOLD 43 FN38 STACK HROUGH
* END OF STACK SIMULATION

* START OF MECH LOAD SIMULATION (BLOCK 61)
* TO BE USED ONLY IN THE STUMP TO STUMP MECH LOAD OPTION
* VARIABLE 44 MUST BE ADJUSTED FOR CORRECT NUMBER OF MECHANICAL LOAD OPERATIONS
  01 SIZE 21 175 METER FLOW
  175 COMPAR 51 L K220 63 IS THERE ROOM
  03 ENTER 1 P17 600 TAKE UP SPACE
  04 COMPAR E X20 L KB 60 METER FLOW
  06 SPLIT 69 170 HOLD FOR HAUL
  09 SAVEX 4 P12 9 COUNT TREES
  09 SAVEX 5 P5 160 COUNT BOLTS
  160 SAVEX 6 P17 7 ADD VOL
  07 HOLD 4 203 1 FN31 LOAD MECH
  11 CAPACITY 260 MAX TRUCK LOAD (VOLUME OF SOLID WOOD)
  103 ENTER 11 P17 BOTH 161 162 ROUTING
  161 COMPAR E S11 L K220 99 IS LOAD READY
  162 ASIGN 1 S1 163 RECORD VOL
  163 PRINT 4 6 164 PRINT STAT
  164 SAVEX 4 K0 165 SET THEE COUNT
  165 SAVEX 5 K0 166 SET BOLT COUNT
  166 SAVEX 6 K0 167 SET VOL
  167 SAVEX 20 K10 168 HOLD LOADING
  168 ADVANCE 204 1 LOAD RELEASE
  169 LEAVE 11 P1 169 LOAD COMPLETE
  169 LEAVE 1 P1 70 LOAD COMPLETE
  170 ADVANCE BOTH 172 171 ROUTING
  171 TERMINATE 173 LOADING TIME
  173 COMPAR E 1106 6 K0 174 RELEASE LOAD
  174 TERMINATE
* END OF MECH LOAD SIMULATION

* START OF HAULING SIMULATION (BLOCK 74)
* VARIABLE 44 MUST BE ADJUSTED FOR CORRECT NUMBER OF TRUCKS
  01 ASSING 14 FN14 71 PAVED ROAD DIST
  01 ASSING 15 FN15 72 DIRT ROAD DIST
  01 ASSING 16 FN28 73 UNLOAD TIME
  05 HADIL 1A 0 180 20 74 TIME IN BETWEEN LOADS
  74 HUL 20 75 2 FN6 TRANSPORT
3 TABLE P14 1 1 60 STATISTICS ON PAVED ROAD DISTANCE
4 TABLE P15 1 1 150 STATISTICS ON DIRT ROAD DISTANCE
75 TABULATE 3 76
76 TABULATE 4 351
351 SAVEX 40 P16 352 UNLOAD TIME
392 PRINT 40 40 77 PRINT STAT
77 SAVEX 20 KB 100 LOADING OK
* END OF HAULING SIMULATION

* BEGINNING OF DELAY SUBPROGRAMS
* DELAY SUBPROGRAMS SHOULD BE REMOVED FROM THE MAIN PROGRAM WHEN
* THE FIRST RUN IS MADE TO DETERMINE MULTIPLES OF EACH OPERATION
* REQUIRED TO PRODUCE A BALANCED SYSTEM, THE DELAY SUBPROGRAMS SHOULD
* BE INCLUDED WITH THE MAIN PROGRAM WHEN A SIMULATION RUN IS MADE
* OF AN APPROXIMATELY BALANCED SYSTEM

* START OF FELLER DELAY SUBPROGRAM
101 GENERATE 100 5 103 1 FN52 FELLER DELAY
103 ASSIGN 9 FN20 .978 99 104 LENGTH OF REST
104 HOLD 1 105 1 FN37 NON OP TIME
1 TABLE P9 1 1 60 NON PRODUCTIVE TIME OF FELLER
105 TABULATE 1 98

* START OF LIMB AND TOP DELAY SUBPROGRAM OR BUCK, LIMB, AND TOP DELAY SUBPROGRAM
100 GENERATE 100 5 108 1 FN53 LIMBER DELAY
108 ASSIGN 9 FN38 .890 99 109 LENGTH OF REST
109 HOLD 2 110 1 FN37 NON OP TIME
2 TABLE P9 1 1 60 NONPRODUCTIVE TIME OF LIMBER
110 TABULATE 2 97

* START OF BUCK DELAY SUBPROGRAM
400 GENERATE 100 5 401 1 FN54 BUCKER DELAY
401 ASSIGN 9 FN39 .999 99 402 LENGTH OR REST
402 HOLD 6 403 1 FN37 NON OP TIME
1 TABLE P9 1 1 60 NONPRODUCTIVE TIME OF BUCKER
403 TABULATE 10 99

* START OF PALLET LOAD DELAY SUBPROGRAM
405 GENERATE 100 5 406 1 FN55 PLT LOAD DELAY
405 ASSIGN 9 FN40 .999 99 407 LENGTH OF REST
407 HOLD 3 408 1 FN37 NON OP TIME
11 TABLE P9 1 1 60 NONPRODUCTIVE TIME OF PALLET LOADER
408 TABULATE 11 99

* START OF STACK DELAY SUBPROGRAM
410 GENERATE 100 5 411 1 FN56 STACKER DELAY
411 ASSIGN 9 FN41 .720 99 412 LENGTH OF REST
412 HOLD 43 413 1 FN37 NON OP. TIME
12 TABLE P9 1 1 60 NONPRODUCTIVE TIME OF STACKER
413 TABULATE 12 99

* * *

* START OF MANUAL LOAD DELAY SUBPROGRAM (NOT FOR STUMP TO STUMP)
415 GENERATE 100 5 416 1 FN57 LOADER DELAY
415 ASSIGN 9 FN42 .999 99 418 LENGTH OF REST
417 HOLD 40 418 1 FN37 NON OP. TIME
13 TABLE P9 1 1 60 NONPRODUCTIVE TIME OF LOADER
418 TABULATE 13 99

* * *

* END OF DELAY SUBPROGRAMS
* * *

* BEGINNING OF TERMINATION SECTION
97 TERMINATE
98 TERMINATE
99 TERMINATE
100 TERMINATE R
START 60
APPENDIX III

THE SAMPLE MODEL OUTPUT

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A GPSS II Simulation Model
to Evaluate
Terrain Capabilities of Typical
Pulpwood Harvesting Vehicles

A SPECIAL RESEARCH REPORT

Submitted to
The Southern Executives Association

by
Bertel Randolph Bertils

Georgia Institute of Technology
Fall, 1969
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ACKNOWLEDGMENTS

The author wishes to express his deepest appreciation to Mr. Nelson K. Rogers for the timely and valuable guidance and encouragement given by him while acting as thesis advisor.

Thanks are also due to the members of the Reading Committee, Col. Wayne W. Bridges and Dr. Douglas C. Montgomery, for their very constructive comments and support during this study.
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SUMMARY

A major problem facing the pulpwood producer is the purchasing of harvesting equipment with appropriate operating options. In view of increasing equipment costs the producer cannot afford mistakes in equipment selection.

The objective of this thesis is to provide the pulpwood producer with a means to evaluate typical pulpwood harvesting vehicles prior to purchase, in relation to their performance in various different terrain conditions.

To accomplish this objective a digital computer simulation model is used to simulate the movement of a typical pulpwood harvesting vehicle across the terrain to be encountered in five pulpwood resource areas within Georgia. General Purpose Systems Simulator II is the simulation language employed in order that the model may be as clear as possible to those individuals unfamiliar with simulation techniques.

In order to construct the computer simulation model, it is necessary to conduct a thorough literature search to determine vehicle mobility characteristics which define a vehicle's ability to negotiate terrain. Likewise the qualities of terrain must be defined in quantitative terms so that interaction between the vehicle and the terrain can be described. It was determined that no widely acknowledged method exists to accomplish the above. The researcher selected the U. S. Army Corps of Engineers Waterways Experiment Station's method of defining terrain and vehicle mobility and added refinements.
The results of the computer simulation show the percentage of the resource areas that the vehicle can negotiate prior to being halted. An analysis of variance is conducted to determine if there is a significant difference in trafficability among the five resource areas and if changing the tire size of the vehicle modelled results in a significant difference in vehicle performance.

The conclusions reached by the researcher are primarily that the simulation model does evaluate a vehicle, that differences do exist between the areas modelled and also that vehicle performance does vary with different tire sizes.

Further research is proposed to provide additional analysis of areas other than those modelled.
CHAPTER I

INTRODUCTION

Purpose

The rapidly rising costs of producing pulpwood harvesting equipment have reached the point where neither the pulpwood producer nor the equipment manufacturer can afford mistakes in equipment capabilities. The Malroe Bobcat 500 Loader costs $5,200 (1) and is a very small and basic vehicle. A major item of equipment, such as the 21-inch Nicholson Utilizer, costs $198,000 (2). As labor cost increases, the present trend is towards more productive and more efficient harvesting machines.

The high costs involved in these major items of equipment demand that the vehicle be objectively evaluated before purchase by the harvester and before tooling and production by the manufacturer. Part of this evaluation requires determination of the ability of the equipment to perform its task across the varying types of terrain to be encountered in pulpwood resource areas. In an ideal situation, the prospective purchaser would like to know that a specific machine has a probability X of operating over Y percentage of his total resource areas.

It is the purpose of this thesis to develop a valid vehicular model that will enable the vehicle to be evaluated on its ability to negotiate terrain. This evaluation is to be based primarily on assumed
statistical distributions of the ability of the ground to withstand vehicular movement, variations in slope and ground roughness, and the vegetation that restricts vehicular movement. The mobility model illustrates those critical vehicle characteristics which determine mobility and how slight changes in vehicle design can bring significant changes in performance.

It is expected that this approach will provide the pulpwood harvester with a means whereby he can select the item of equipment most suitable to the terrain to be encountered in his particular pulpwood resource areas. It is further expected that the producer will through use of this analytical technique, be able to project a dollar value on the benefits to be derived from equipment modification.

**Background**

The problem of ground mobility has existed since animals first walked on the face of the earth. As man learned that he was not totally committed to walking and carrying loads on his back, he began to devise substitutes for the rather exhausting process of do-it-yourself transportation. The stories of the development of the wheel and the ship are well known. When man began designing ships, he discovered that building a ship is a rather lengthy process at best. Mistakes in design did not result in a mere inconvenience but wasted considerable time and money. To avoid this waste, man began to apply scientific methods to ship design. The result was that the major factors constituting a ship's performance could be basically determined prior to actual construction.
The advent of aircraft carried with it the element of considerable risk to life in addition to money. Hence, aircraft design principles were also based on scientific methods. As aircraft became larger and carried increased loads, additional demands were made upon the scientist to determine aircraft performance prior to actual construction. A classic case of these scientific methods being applied to aircraft was the 1941 development of the North American P-51 Mustang (3). This aircraft's performance was fully predicted prior to manufacture. The time from beginning of design to production was minimal due to the ability to predict what the design would do before it was constructed. Today even that prediction of performance is not sufficient and modern aircraft are thoroughly "war-gamed" to determine their "cost-effectiveness" prior to production.

Because of the limited costs involved in producing ground vehicles in the past, it has been possible to design ground vehicles on a trial and error basis. As Dr. M. G. Bekker stated:

Unfortunately, the modern development of off-the-road vehicles has been somewhat overshadowed by other undoubtedly more spectacular means of transportation; in general, existing equipment has been modified empirically and there has been no attempt to develop basic principles of the mechanics of land locomotion (4).

Likewise, in evaluating possible vehicle designs, the art of determining "cost-effectiveness" is still in its infancy. A Rand Corporation Study has indicated that the majority of cost-effectiveness determinations are, at present, subjective type judgements (5).

World War II demonstrated the need for the ability to predict vehicle performance. The British Army enjoyed a high degree of success
in North Africa as regards the mobility of their vehicles. They received a considerable shock in the invasion of Europe when the same vehicles could not perform with an equal degree of efficiency (6). To prevent further occurrences of such surprises, the United States, Great Britain, and Canada began to appreciate the need to define the terrain-vehicle relationship.

Within the United States, the task initially fell to the United States Army Corps of Engineers Waterways Experiment Station. Their initial task was to develop a method whereby the supportive capacity of terrain could be determined. In 1956, the Waterways Experiment Station published a technique which was based on empirical data obtained from cone penetrometer readings and vehicle tests. The Waterways Experiment Station further attempted to quantitatively define terrain for mobility purposes and published this method in a series of papers in 1968 (7). The method itself is concisely explained by Shamburger in "A Quantitative Method for Describing Terrain for Ground Mobility" (8). Other areas that have concerned the Waterways Experiment Station include experimentation with other methods of quantifying mobility and terrain.

The Land Locomotion Laboratory of the United States Army Tank Automotive Center has also been working on the problems of ground mobility since World War II. The approach used by the Land Locomotion Laboratory was somewhat different from that used by the Waterways Experiment Station. The studies conducted by the Land Locomotion Laboratory were more theoretical and were primarily concerned with the relationship between the vehicle and the soil in which it operates.
*Theory of Land Locomotion*, written by Bekker (9) in 1956, examines this relationship in depth. The basis of this approach was the amount of sinkage of a wheel or track into soil. From this sinkage, rolling resistance and tractive effort were determined. The work of the Land Locomotion Laboratory through 1966 is summarized in its Research Report No. 6 (10).

In Canada, the problem of ground mobility has been primarily the responsibility of the Canadian Armament Research and Development Establishment although considerable work has also been performed by the Muskeg Research Council presently operating under the National Research Council. Canada, with its vast acreages of marginal terrain, is vitally interested in ground mobility. The Canadians have resorted to a semi-empirical approach which was published as "A Rational Empirical Approach to Muskeg Vehicle Research" (11). The Canadians, with whom Bekker began work following World War II, used certain aspects of the load sinkage equation to develop their drawbar-pull/weight ratio as a measure of mobility. They recognized that maximum drawbar-pull may occur at 100 per cent slippage of the driving wheels and thus resorted to dimensional analysis of physical models to further define the relationship (12). One of the contributions of the Muskeg Research Council is the hypothesis of considerable random factors in the determination of mobility.

The areas of disagreement among the preceding agencies are numerous. No agreement presently exists regarding the determination of ground mobility. There are several flaws in each theory and these further contribute to the disagreement among agencies.
The Land Locomotion Laboratory conducted a series of experiments whereby the drawbar-pull/weight was used as the index of performance. These experiments indicated that the drawbar-pull/weight ratio was a rather insensitive measure of off-the-road vehicle performance. The dominant factors were the man-machine factors and included such things as the transmission, visibility, ride, comfort, and driver ability (13). The importance of the man-machine relationship was also indicated by the Muskeg Research Council in their work in addition to such qualitative items as visibility and ease of operation (14).

The inferences to be drawn from this background are as follows:

(1) that there is, at present, no widely acknowledged measure of vehicle mobility;

(2) that the man-machine relationship, unquantified at present, plays a major role in ground mobility; and

(3) that the terrain factors which determine ground mobility are not quantified in a manner acceptable to all concerned.

The Muskeg Research Council stated that "... the problem is enormously difficult because of the large number of significant variables of a stochastic nature and the very many variables" (15). In such a situation digital computer simulation offers a method of approach that might provide a much more realistic evaluation than has heretofore been experienced.
General Nature of the Problem

In order to clarify the following chapters for the reader, a general description of the nature of operations of pulpwood harvesting vehicles in their assigned tasks is in order.

A typical pulpwood harvesting vehicle is expected to perform assigned tasks within a particular pulpwood resource area. In this paper such area is described by samples of specific resource areas scattered throughout the state of Georgia. In practical application, the producer expects to operate within a reasonable radius from his base of operations. This base of operations may be a place where he does his hiring, where he stores and maintains his equipment, or merely where he lives. The harvester requires his equipment to be transportable within his area and capable of coping with the terrain conditions within the resource areas available to him.

The vehicle, within the resource area, is expected to be able to move to all harvestable trees. This requirement necessitates the ability to traverse soil, overcome obstacles, negotiate slopes, maneuver through existing vegetation, and traverse minor terrain obstacles, such as streams of the resource area.

Each vehicle has options provided by the manufacturer. The harvester, in purchasing his equipment, must determine which vehicle option combination will best fit his requirements. He relies upon his experience, knowledge, and the knowledge and reputation of the manufacturer in making his decision.
Study Objectives

From the description of the background and general nature of the problem, it can be seen that the number of parameters acting upon a design are considerable and the combinations thereof are of a magnitude sufficient to rule out the possibility of exploring every one. Likewise, the total number of possible combinations of terrain classifications is sufficiently large to preclude examination of all types. However, the alternatives open to the pulpwood harvester are limited to ordering slight options in equipment design or in selecting completely different equipment produced by another manufacturer. This equipment selection is based upon a knowledge of the area in which the harvester operates. The overall objective of this study is to determine which design best suits the harvester’s area and what options affecting mobility are most desirable.

The specific objectives of this study in the order of their investigation are:

1. Select or formulate a system that adequately describes quantitatively the terrain-vehicle relationship within the limitations imposed hereafter.

2. Construct a digital computer simulation model of the system using a GPSS II simulation language.

3. Utilize the computer model to simulate a typical pulpwood harvesting vehicle and the terrain it is expected to traverse.

4. From the resultant data, specify the percentage of selected pulpwood resource areas which the vehicle can be expected to harvest with a high probability of success.
5. Indicate if the terrain is too difficult for the harvesting vehicle selected regardless of tire size.

These objectives will be accomplished by testing the following hypothesis:

(1) that there are no significant differences in the pulpwood resource areas under examination;

(2) that there is no significant difference in vehicle performance when equipped with two different tire sizes.

**Scope and Limitations**

In view of the large number of parameters, using all combinations of them would be a lengthy, if not impossible, task. Hence, the computer simulation model contained herein must be limited in scope. The approach, however, should be expandable, with minor modifications, to larger land areas and many vehicle designs with a wide variety of options. For the purposes of this study, it is sufficient to demonstrate the validity of a new approach to mobility evaluation, namely that of digital computer simulation. The vehicles' options are limited, but they are easily expandable to include the full range normally provided by a manufacturer. The varieties of terrain are also limited to a small area. Again, they are easily expandable to larger areas. The entire model is limited only by the computer programming time available and the ability of the experimenter to acquire the required data. Certain restrictions in the size of the model are imposed by the simulation language used. These restrictions are surmountable by utilization of additional programming techniques.
The terrain-vehicle relationship model is primarily restricted in this study to conventional rubber-tired vehicles. Additional assumptions and limitations are covered in detail within the following chapters. The primary terrain restriction in this model is that only soft soil conditions are covered. Coarse soils, snow, and organic soils are not considered within this study. Certain assumptions are further made concerning terrain limitations which will be covered in the following chapters.

The assumptions made for vehicle model construction are that:

1. The vehicle moves at a constant speed while traversing terrain except when it is halted by the terrain.

2. The vehicle has sufficient horsepower to overcome rolling resistance and maintain such constant speed.

3. The driver-vehicle and driver-terrain relationships are, for the purpose of this study, considered to be constant as the vehicle is moving at a constant speed.

4. The vehicle attempts to traverse slopes at the vehicle's most vulnerable angle to tipping.

The assumptions made for terrain model construction are that:

1. Terrain properties follow insofar as possible distributions available from prior research efforts, unless otherwise specified.

2. Soil analogues are correct.

A constant speed is obviously the most unrealistic assumption. However, speed variation, not only with the vehicle-terrain relationships but also those with the driver, rolling resistance, and negotiation of obstacles are all intertwined. The resultant model including
all such factors would require a massive research effort. Such research would be a worthwhile expansion of the technique.
CHAPTER II

LITERATURE SEARCH

Simulation problems are characterized by being mathematically intractable and having resisted solution by analytical methods. The problems usually involve many variables, many parameters, functions which are not well behaved mathematically, and random variables. Thus simulation is a technique of last resort. Yet, much effort is now being devoted to computer simulation because it is a technique that gives answers [italics supplied by author] in spite of its difficulties, costs, and time required (16).

The truth of this quotation becomes very evident when one begins to examine the complexities of the terrain-vehicle relationship. In searching the literature of this field, it becomes readily apparent to the investigator that a Pandora's box of disagreement and gaps in knowledge is being opened. Whereas in naval architecture or aeronautical engineering, definite mathematical relationships exist between the vehicle and the medium in which it moves, such is not the case with the automotive engineer.

Although Coulomb (17) first proposed in 1776 a relationship between a wheel and soil based on the sinkage of plates in soil, the relationship is not fully explained today. Bekker (18) proposed in 1956 a relationship that somewhat followed Coulomb’s work. This was that:

\[ p_n = \left( k + \frac{k_c}{b} \right)^n \]
where

\[ p_n = \text{nominal ground pressure} \]
\[ k_\phi = \text{modulus of soil deformation of frictional soils} \]
\[ k_c = \text{modulus of soil deformation on cohesive soils} \]
\[ b = \text{width of loaded area} \]
\[ z = \text{sinkage} \]
\[ n = \text{exponent of deformation} \]

where \( k_\phi \), \( k_c \), and \( n \) are determined experimentally. Bekker's equation is reproduced here because it forms the basis for much of the research that has since been performed. The Land Locomotion Laboratory followed Bekker's approach and has attempted refinements of his basic equation. In 1961, Janosi and Hanamoto (19) were dissatisfied with the limitations of the Bekker equation and worked to achieve a more comprehensive relationship. Sela (20) likewise in 1964 considered the Bekker equation to be limited and proposed a further refinement. Reece (21) challenged the equation as being valid for sand but inadequate for cohesive soils. The Bekker equation is still the basis for work done today even though it is constantly criticized. Hoop (22) in 1966 felt that the equation had failings but continued to use it.

The assumptions upon which the Bekker equation is based lead to much of the disagreement. One of these assumptions is a rigid wheel. Obviously, the majority of wheeled vehicles operating today use pneumatic tires. To seek the proper relationship, Haley (23) in 1964 began an initial search into the subject. He was unsuccessful because his apparatus was unsatisfactory and he felt a complete redesign was required. Dimensional analysis was attempted by Freitag (24) of the
Waterways Experiment Station in 1965. Although not completely satisfactory, Freitag felt that it could be employed to explain the pneumatic tire-soil relationship. In 1966, however, while recognizing certain possibilities of dimensional analysis, Liston (25) felt that dimensional analysis was not the proper approach and ruled out further efforts by the Land Locomotion Laboratory in dimensional analysis. Thus, the relationship of the pneumatic tire-soil interaction has not yet been fully explored although it plays a vital role in ground mobility.

The foregoing paragraphs have indicated some of the magnitude of the theoretical research being performed to uncover the true terrain-vehicle relationship. Paralleling this theoretical work is much empirical work. Following World War II, the Mobility Research Branch, Waterways Experiment Station, was given the task of discovering a means whereby ground trafficability could be determined for vehicles in military operations. This task was accomplished and the system was adopted. A detailed description of the system is given in TB Eng 37, "Soils Trafficability," dated 1959 (26). Basically two soil values, a cone index and a remolding index, are determined empirically by a simple device. The product of these two indexes is correlated to a Mobility Index which is determined through a formula (obtained by empirical means) which employs vehicle characteristics.

In 1961 Kennedy (27) performed numerous experiments to further refine the existing mobility index equation. The resulting revised mobility index accomplished trafficability prediction with better than 90 per cent accuracy.
Siddell et al. (28) of the Canadian Muskeg Research Council proposed a system based on dimensional analysis. He was concerned with muskeg and felt that neither the theoretical approach of the Land Locomotion Laboratory nor the empirical approach of the Waterways Experiment Station could be applied to the specific muskeg type environment.

The Canadian Armament Research and Development Establishment developed a semi-empirical approach based on dimensional analysis which uses the drawbar-pull/weight ratio to determine an index of the vehicle's mobility. (Drawbar-pull is that pulling force exerted by a vehicle after accomplishing its own movement) (29). The obvious fallacy of the system is that maximum force may be exerted at 100 per cent wheel slippage. Dickson (30) proposed a revision which included the velocity of the vehicle. Tests conducted by Liston (31) in 1966 indicated that drawbar-pull measures the ability of vehicles to operate in weak soils but there were many other factors which dominated the drawbar-pull/weight ratio.

Along with their work to measure soil trafficability, the Waterways Experiment Station strived to achieve a system whereby terrain could be quantified. The results of the initial efforts of the Waterways Experiment Station were presented to the 1st International Conference on the Mechanics of Soil-Vehicle Systems in 1961. The paper presented was prepared by Van Lopik and Compton (32) and represented the direction of the Waterways Experiment Station's efforts. The method was refined in tests conducted both in the United States and overseas. The method evolved through the formulation of an analytical model for
predicting the cross country performance of ground-contact military vehicles (33).

Considerable experimentation was performed by the Waterways Experiment Station with actual vehicles in the early sixties. A multitude of reports came out relating the ability of various vehicles to negotiate different trafficability conditions. Typical of these reports was "Trafficability Tests with a 5 Ton GOER (XM520) on Fine and Coarse Grain Soils" written by Rush (34) in 1962.

The Waterways Experiment Station applied their quantitative approach to selected areas in Thailand in 1965 and quantitatively mapped areas of the country. They recognized that the magnitude of the area required that much work be done through interpretation of aerial photographs. Through proper sampling and ground control, this interpretation was accomplished and a final report prepared and published (35). This application of the quantitative method has continued and the Waterways Experiment Station published in 1968 the results of a study in Puerto Rico (36).

One of the major trouble areas encountered by the Waterways Experiment Station in developing their quantitative approach was the necessity for a comprehensive soil classification system. The Waterways Experiment Station desired to use the United States Department of Agriculture Soil Classification due to the extensive areas of the world already mapped under the system. Two major stumbling blocks were encountered in applying the system used by the Department of Agriculture. First, there was the problem of the many different types of soils indexed qualitatively under the system and second, certain
countries of the world would not be particularly interested in permitting representatives from the United States to prowl around the countryside gathering soil trafficability parameters.

To alleviate the problem of the numerous soil types encountered under the United States Department of Agriculture Soil Classification System, the Waterways Experiment Station conducted tests to determine the level at which further subclassification would be unnecessary. In 1966, Bassett et al. (37) published the results of their work with soils encountered in Louisiana and Arkansas. They concluded that prediction at the soil series level was adequate for trafficability analysis of the four loess soil series studied. Any additional accuracy obtained through further subclassification was lost through the inaccuracies of the trafficability prediction system. Bassett et al. (38) recommended that further experiments be conducted on other similarly related soil series to determine the feasibility of grouping for trafficability purposes. Carlson et al. (39) issued another report in 1967 relating the variation of physical properties of loess soils.

The second problem faced by the Waterways Experiment Station was approached through the use of soil analogues. In this research, considerable assistance was rendered to the Waterways Experiment Station by the Land Locomotion Laboratory. Lassaline and Harrison (40) concluded that soil analogues were reasonable and practical for predicting soil strength parameters. A continuation of the study of soil analogues was conducted by Harrison and Chang (41) in the following year. Again it was concluded that prediction of soil strength parameters at the Series Level would be sufficient. Numerous experiments were conducted
throughout the Northeast and Northcentral United States to support their findings.

It must be noted here that the Land Locomotion Laboratory system of describing soil strength is not the same as the system used by the Waterways Experiment Station. However, in 1964 the Waterways Experiment Station conducted a series of experiments to determine the strength-moisture-density relations of fine-grained soils and concluded that the system used by the Waterways Experiment Station can be correlated to the Land Locomotion Laboratory system (42).

Another effort of the Waterways Experiment Station has been to determine the statistical nature of terrain. Siddell et al. (43) of the Muskeg Research Council mentions the large number of significant terrain variables of a stochastic nature as being a major stumbling block to the development of a mathematical model. Although speaking specifically of muskeg, Siddell goes on to state that a statistical approach is essential in any treatment of terrain. Under the auspices of the Waterways Experiment Station, the Department of Civil Engineering, The University of Tennessee (44), conducted an environmental survey of Ranger training areas. These Ranger training areas are located at Fort Benning, Georgia; Dahlonega, Georgia; and Eglin Air Force Base, Florida. Geology, hydrology, macrogeometry, and vegetation were considered and examined. The study is particularly informative in its treatment of slope variations and vegetation. Bassett et al. (45) conducted a statistical treatment of variations in trafficability indexes in the four loess soils studied. The majority of statistical work, however, has been done in determining ground roughness.
Perhaps because the soil-vehicle relationship is not fully understood, there has been much work done considering the effect of vehicle vibration caused by ground roughness. Since vehicle vibrations do play a large role in the human factor, the area receives much attention. Stone and Dugundji (46) propose ground roughness to be a Fourier Series. While not mentioning the mathematical properties of ground roughness, Liston (47) lists the vibration caused by it as a significant factor overriding the drawbar-pull/weight ratio as a determination of vehicle mobility. The Waterways Experiment Station published an instruction report on the collection of microgeometry (48). Stollmack (49) in his report on the tank weapon system devoted one full sub-report to the nature of ground roughness and means of generating it. The power spectral density is discussed fully by Bogdanoff et al. (50) and the statistical data upon which their work is based is presented.

Vehicle computer simulation techniques are relatively new. While terrain profiles have been simulated for some time in military war gaming, it was the response of military tactical units to terrain that interested the investigator rather than specific vehicles. Both Meyer (51) and Davis (52) discuss in detail the various military war games that consider terrain; however, in the field of vehicle computer simulation, little has been done. Perloff (53) as part of his role in determining tank mobility, wrote a special purpose program to be used in determining tank mobility. Perloff's model was based on Bekker's 1960 approach with refinements. The model is concerned only with soil sinkage as it relates to the ability of the tank to overcome soil resistance. Slope is thus seen as influencing the ability of the tank
to overcome soil resistance which has been increased through the shifting of forces. The ability of the track to maintain its grip without slippage is also considered.

Perloff's model was a submodel to the entire tank weapon system (54). While interesting, the other portions of the model dealt with military applications and would be inappropriate here. Perloff unfortunately had no means to validate his model. While he felt that his results looked reasonable, there was not any experimental verification of its predictive ability.

Another computer simulation model was developed by McKenzie et al. (55) of General Motors Corporation. They developed two models for "Computerized Evaluation of Driver-Vehicle-Terrain Systems." An analog computer model was developed for a 4 × 4 rigid framed, wheeled vehicle and a digital computer model was developed for a single-frame tracked vehicle. Both models were based on work by Bekker who was at General Motors Corporation at this time. These models considered terrain roughness, soil traction slip characteristics, and vehicle power and the interaction thereof. The effect of terrain roughness was concerned with the vibratory accelerations to which the driver of a vehicle is subjected. Sinkage and slippage were considered as forces acting in opposition to vehicle power. The simulation did not evaluate the vehicle against terrain but rather the reaction of the driver to terrain and the resultant effect upon the vehicle.

The foregoing paragraphs have indicated some of the diversity of effort that is being expended in the field of determining ground mobility, but when this effort is considered relative to other fields
of endeavor it is very small. At the Advanced Research Projects Agency workshop on improvement of off-the-road mobility, one of the major complaints heard was that, while the army was spending approximately equal amounts on ground vehicles and aircraft, the research funds for the latter were approximately 100 times as great as for the former (56).

Today, while many are working on the problem, there is still no definite way of describing ground mobility. While Bekker's technique appears to afford a theoretical approach, it is subject to many errors. The empirical approach is not satisfying from an aesthetic viewpoint but it does appear to give results.

The lack of extensive previous work in vehicle mobility simulation precludes a definite approach to be taken. No significantly useful means of evaluation have been discussed by earlier workers in this area. While the authors felt their work to be reasonable, they could not verify it.

Mobility simulation is a highly subjective field at this time. It offers to the participating individual full opportunity to make a significant contribution to vehicular design practices. The random variables which have created much of the confusion are tailored for computer simulation techniques.
CHAPTER III

PROCEDURE

Approach to the Problem

To accomplish the objective of this study, the terrain-vehicle system must be quantitatively described and modeled. Specifically, a typical pulpwood harvesting vehicle must be evaluated for its ability to traverse the terrain which comprises the pulpwood resource areas in which it may be expected to operate. A computer simulation model is required to simulate the movement of a vehicle across a specified piece of terrain. During this movement, the characteristics of the vehicle must be quantitatively compared against the characteristics of the terrain. The simulation of the terrain over which the vehicle passes must demonstrate the stochastic nature of that terrain. The method of evaluation is simply the ratio of successful passes over total attempts. If a sufficiently large number of trials are conducted, this ratio will reflect the probability that a pulpwood harvesting vehicle will successfully harvest a given acreage of land that has specified variables.

The quantitative description of the terrain-vehicle system uses the Waterways Experiment Station's method of quantifying terrain and determining vehicle soft soil mobility. Shamburger (57) provides a detailed description of the terrain classification system. Under the Waterways Experiment Station system, there are four factor families within terrain. These factor families are: surface composition
(which is soil trafficability), surface geometry, vegetation, and hydrology. The trafficability of surface composition is computed by a rating cone index. This rating cone index correlates to a vehicle mobility index. The result is a go-no go relationship. Surface geometry is the slope and microgeometry of the terrain. This surface geometry correlates to the center of gravity of the vehicle and its ground clearance. Vegetation correlates to the force available to the vehicle to overcome the resistance of the vegetation and the ability of the vehicle to negotiate among the larger vegetation such as trees. Hydrology correlates to the fording capability of the vehicle as well as its ability to negotiate stream banks and stream bottoms. The Waterways Experiment Station system is thus quantifiable and adaptable to computer simulation.

Having defined the quantitative relationships of the terrain-vehicle system, it was then necessary to describe the system for translation into a computer simulation language. The system was defined as a vehicle moving across terrain in the manner described in the first paragraph of this chapter. To portray this passage, the vehicle was evaluated against the terrain once for each movement of one vehicle length. The total distance to be traversed was set at 1,000 yards. As the vehicle proceeded over the terrain, it might be halted through inability to negotiate the soil, it might tip over, the power could be lacking to overcome vegetation, or terrain obstacles would be insurmountable. Vehicle speed was not considered and the model was strictly "go" or "no go" on each evaluation.
Following the description and formulation of the model, a computer simulation model was constructed. General Purpose Systems Simulator II was chosen as the computer simulation language. The computer model was validated by using available data to check each factor family. The program was designed so that the values of variables were printed out as well as the values contained within the transactions themselves. These printouts permitted the full analysis of the program.

The completed simulation model was used to predict the probability of a typical pulpwood harvesting vehicle, as described by Freitag (58), negotiating typical pulpwood resource areas as might be encountered in the state of Georgia. Several different sites were used to test at what point vehicle failure occurred. To increase the accuracy of the simulation, replications were performed at each level using different random number seeds.

All variables represent actual vehicle characteristics and terrain characteristics. Where actual data were available, it was used in the system. When data were not available, every attempt was made to assume values which appeared to be reasonable and consistent with other prior research.

**Simulation Language Employed**

This model could have been constructed in any general purpose language such as ALGOL or FORTRAN. Likewise, any one of several special purpose languages could have been used. The advantages of using GPSS II are several. The primary problem with selling the
results of simulation is convincing the individual concerned that the results are valid. With GPSS II, the flow chart is understandable by most people with a moderate education. In this particular simulation model, the program would generate a transaction (vehicle) which would pass through a gate and enter the test track. The program evaluated the vehicle characteristics against all four factor families on each loop. A loop was one vehicle wheel-base length. The program performed loops until the 1,000 yards of the terrain were completed or the vehicle was halted. A record was made of where the vehicle stopped and why it was stopped. The gate then opened and another transaction was permitted to enter the test track. This continued until the appropriate number of vehicles had attempted the test track. GPSS II lends itself particularly well to a situation such as this where a queing analogy can be drawn and a gathering of statistics is required.

General Language Description

To assist the reader, a brief description of some of the GPSS II language characteristics will be given here. By no means complete, the listing covers only those principle language characteristics employed in this simulation model. A complete description of the language may be found in the UNIVAC 1108 General Purpose Systems Simulator II Reference Manual (59).

The GENERATE block performs as the name implies. The block generates a transaction which enters the system. Once the transaction has entered the system, a new transaction is created.
The GATE block acts as a gate to prevent transactions from entering the system until desired.

The SPLIT block creates a duplication of the transaction to include duplicating any characteristics that may be assigned as the transaction's parameters.

The ASSIGN block assigns specified values to the transaction's parameters.

The LOGIC block sets to 1 or resets to 0 a specified LOGIC switch that accompanies the transaction through the system. LOGIC switches survive the reassembly of duplicate transactions, whereas the duplicate's parameters do not.

The ADVANCE block permits the selection of a number of exits. In this model, if the COMPARE block refuses entry to a transaction then the transaction looks to the preceding ADVANCE block for another exit to take.

The COMPARE block refuses entry to a transaction unless the relationship specified is satisfied.

The SEIZE block specifies the entrance to a facility. No other transaction can occupy or use the facility until the using transaction passes through the RELEASE block which releases the facility for use by another transaction.

The SAVEX block permits the storing of values within the model. Parameter or variable values may be stored at any point in the program to be printed out as directed by a corresponding PRINT block.

The LOOP block permits any portion of the program preceding the LOOP block to be repeated a specified number of times. The
transaction encounters the LOOP block and, if it has the required number of repetitions, may proceed to the next block in the program.

The ASSEMBLE block reassembles the transactions that had been duplicated in the SPLIT. In the process, the ASSEMBLE block destroys the duplicate transaction and any parameter values the duplicate may have had.

The TERMINATE block performs as the name implies. It terminates the life of the transactions.

These listed blocks comprise only a small portion of the total capability of GPSS II. However, with them, it is possible to construct a highly realistic model that portrays the terrain-vehicle relationship.
CHAPTER IV

DESCRIPTION OF THE MODEL

General Description

While detailed knowledge of GPSS II is not required to understand the computer simulation model presented here, the reader is presumed to have familiarity with the language. This familiarity should be sufficient to understand the modified flow charts contained within this chapter. For the programmer having complete knowledge of GPSS II, the complete computer program is listed in Appendix B. Most readers desiring only familiarity with the approach should find this chapter sufficient.

As shown in Figure 1, the model consists basically of three major sections: a vehicle characteristics assignment section, a vehicle evaluation section, and a data collection section. Within each section are several sub-sections. By its nature, the data collection section has sub-sections spread throughout the vehicle evaluation section which permit the collection of the necessary data. The vehicle characteristic assignment section and the vehicle evaluation section are subject to changes between experiments.

The vehicle characteristic section generates the vehicle and then assigns the characteristics to the vehicle as parameters where necessary. The mobility index of the vehicle must be computed as shown in Figure 2. The mobility index is then correlated to a vehicle cone
index (Figure 3) by the vehicle characteristic section. The section also holds the vehicle until the vehicle evaluation section is clear of the old vehicle. The new vehicle is then permitted to enter the vehicle evaluation section.

The vehicle evaluation section performs the function of evaluating the vehicle characteristics against the terrain characteristics once for every vehicle wheelbase length. It performs this evaluation repetitiously until the vehicle traverses the test course length of 1,000 yards. If for any reason, the vehicle is halted by a terrain characteristic and can progress no further, then the vehicle evaluation section releases the vehicle and permits the vehicle to enter the data collection section. The vehicle evaluation section is then clear to accept a new vehicle.

The data collection section has sub-sections spread throughout the programs. The section records the number of vehicles that are
$MI = \left\{ \begin{array}{c}
\frac{\text{Contact Pressure} \times \text{Weight Factor}}{\text{Tire Factor}} + \frac{\text{Wheel Load Factor} - \text{Clearance Factor}}{\text{EngineFactor}} \times \text{Transmission Factor} \\
\end{array} \right\}$

Contact Pressure = $\frac{\text{Gross Weight, Lbs.}}{\text{Outside Diameter}}$

Nom. Tire Width, In. $\times \frac{\text{Tire, In.}}{2} \times \text{No. of Tires}$

Weight Factor: $\begin{array}{ccc}
\text{Weight Range (Lb)} & \text{Weight Factor Equation} \\
< 2,000 & Y = 0.553X \\
2,000 \text{ to } 13,500 & Y = 0.033X + 1.050 \\
13,501 \text{ to } 20,000 & Y = 0.142X - 0.420 \\
> 20,000 & Y = 0.278X - 3.115 \\
\end{array}$

Tire Factor: $\frac{10 + \text{Tire Width, In.}}{100}$

Wheel Load Factor: $\frac{\text{Gross Weight (Kips)}}{\text{No. of Wheels}}$

Clearance Factor: $\frac{\text{Clearance, In.}}{10}$

Engine Factor: $\begin{array}{c}
> 10 \text{ hp/ton} = 1.00 \\
< 10 \text{ hp/ton} = 1.05 \\
\end{array}$

Transmission Factor: $\begin{array}{c}
\text{Hydraulic} = 1.00 \\
\text{Mechanical} = 1.05 \\
\end{array}$

Figure 2. Mobility Index Computation
[Kennedy et al., Revised Mobility Index]

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\[ Y = \text{Weight Factor} \]

\[ X = \frac{\text{Gross Weight (Kips)}}{\text{No. of Axles}} \]
Figure 3. Mobility Index Versus Vehicle Cone Index
[Kennedy et al., Revised Mobility Index]
Figure 4. Vehicle Characteristic Assignment
Section Flow Chart
successful in negotiating the vehicle evaluation section in all experiments. If the vehicle does not successfully negotiate the vehicle evaluation section, then the data collection section records which terrain characteristic halted the vehicle and at what point in distance the vehicle was stopped. After the data are collected, the data collection section releases the vehicle to a termination block where the vehicle's existence is terminated.

FUNCTION and VARIABLE statements are used throughout the specific sections. These statements are explained in the order in which they occur in the program. A recapitulation is included in the program listing.

Specific Sections
Vehicle Characteristic Assignment Section

In the vehicle characteristic assignment section, the necessary task of describing the vehicle and rendering its characteristics into usable form is performed. Because the Waterways Experiment Station's method of computing soft soil mobility is used, the mobility index of the vehicle must be computed. This computation is then correlated to a vehicle cone index within the vehicle characteristic assignment section. Another task that occurs within this section is the setting of LOGIC switches which permit necessary data to be retained later in the program. These steps plus the generation of vehicles and their retention prior to entering the test track are all performed within the vehicle characteristic assignment section.
Figure 5. Approach, Break, and Departure Angles
The initial VARIABLE statements which define the vehicle characteristics for the simulation model are listed in Figure 6. All of these statements are constants and their values are prefixed by a K to designate them as such. The manner in which these variables are obtained is self-evident except for approach angle, departure angle, and break angle. A diagram is shown as Figure 5 which demonstrates the angles as well as the various other vehicle dimensions.

V1  Wheelbase
V2  Horsepower
V3  Outside Tire Diameter
V4  Overall Vehicle Length
V5  Vehicle Ground Clearance
V6  Height to Center of Gravity
V7  Vehicle Track
V8  Approach Angle
V9  Departure Angle
V10 Break Angle
V11 Value for Vehicle Suspension
V12 Value for Vehicle Flotation
V13 Turning Radius
V14 Tire Width
V15 Vehicle Weight
V16 Number of Tires
V22 Number of Axles
V28 Transmission Factor
V30 V30 Mobility Index
V41 Maximum Drawbar Pull

**Figure 6. List of Variables Assigning Values for Vehicle Characteristics**

Block 100 is a GENERATE block which generates the vehicle as required. After the vehicle is generated, it waits until GATE, block 111, permits the vehicle to pass through on the basis of whether or not the test track, facility 1 is in use. If facility 1 is not in use, NUL, then the vehicle is allowed to proceed.
ASSIGN block 115 calls for VARIABLE 31, the computed value of the total track length, 36,000 inches, divided by the vehicle's wheelbase, to be assigned to parameter 3. This value will later tell the program how many times each vehicle is to be evaluated against test track conditions.

Blocks 120, 121, 122, and 123 are LOGIC blocks which set logic switches 1, 2, 3 and 4, respectively, to 1. Later in the program, if the vehicle is stopped by any terrain obstacle, these logic switches are reset to 0 and the vehicle immediately exits the test track recording which terrain obstacle stopped it. The LOGIC switches set here make the operation possible.

Block 124 is an ASSIGN block which assigns a constant of 1 to parameter 8 of the vehicle. Parameter 8 is the counter for the number of times the vehicle has been evaluated against the various terrain factor families.

The vehicles characteristics have now been defined and assigned as parameters where necessary. The vehicle now enters the next section of the program, the vehicle evaluation section.

Vehicle Evaluation Section

General. The vehicle evaluation section has four major sub-sections. These sub-sections are Factor Family 1, Factor Family 2, Factor Family 3, and Factor Family 4. As seen in Figure 7, the section seizes the vehicle, splits the vehicle into an original and three duplicates, evaluates the vehicle, and loops it the necessary number of times. Since the factor families have sub-sections within themselves,
Figure 7. General Flow Chart for Vehicle Evaluation Section
Figure 7. General Flow Chart for Vehicle Evaluation Section (Continued)
only the general concept of the entire section will be covered here and each factor family will be explained in detail within a sub-section under this heading.

The initial blocks in this sector cause the section to be seized by the vehicle entering it. This is accomplished by SEIZE block 180. SPLIT blocks 182, 183, and 184 then create three duplicates of the original for a total of four vehicles, one of each of which will go through each evaluation sub-section. Blocks 600, 605, and 610 are REASSEMBLE blocks which cause the program to revert to one vehicle. The vehicle then passes through a series of GATE blocks--612, 614, 616, and 618 which check to see if any logic switches have been reset. If a logic switch has been reset, then ADVANCE blocks 611, 613, 615, and 167 using the BOTH selection made will send the vehicle to ASSIGN block 620 where a value of 0 is assigned to parameter 3. Since LOOP block 650 looks to parameter 3 for the number of loops remaining to be performed, when a zero is encountered the vehicle exits the vehicle evaluation section to enter the data collection section.

The vehicle is considered not to be immobilized until three successive vehicle lengths of soil fail to have the necessary supportive rating lane index. This indicates the effect of vehicle momentum which would enable the vehicle to cross short soft spots.

**Factor Family 1 Sub-section**

After seizure by block 200, the vehicle goes through a series of SAVEX blocks, 205, 206, 207, which store the values of the soil over which the vehicle is passing. A moving average is maintained of
the three most current soil index values. The current value is obtained from FUNCTION 2 which was shown as Figure 3. A random number is generated which permits the readout of the soil cone index for each loop of the program. SAVEX block 208 and PRINT block 209 record and print the averaged soil index value. If the average of the three soil readings is greater than the vehicle cone index rating, FUNCTION 1 which correlates the mobility index to a vehicle cone index rating, COMPARE block 220 passes the vehicle through ASSIGN block 221 and SAVEX block 222 which counts and saves the number of times the vehicle has been evaluated for soft soil mobility. If COMPARE block 221 refuses passage to the vehicle then the vehicle goes to LOGIC block 225 where logic switch 1 is reset to 0. Release block 230 terminates Factor Family 1 evaluation.

**Factor Family 2 Sub-Section**

The slope and microgeometry evaluation sub-section evaluates the vehicle on its stability. To accomplish this requires that the ground slope, which varies within certain limits, be evaluated and the effect of the microgeometry be evaluated. Since both ground slope and microgeometry are random factors, their values are determined through FUNCTION 4 and FUNCTION 5, respectively. Figure 12 describes the general nature of these two functions. The vehicle is evaluated for its stability when being acted upon by these factors. Figure 10 illustrates the relationships involved. The determination of stability is made by the location of the center of gravity for the vehicle. If the center of gravity lies outside of the vehicle track, then the vehicle is unstable or in Figure 12, a is greater than b.
Figure 8. General Nature of Determining Function Values
[Illustrative Data]

This series of events is accomplished through VARIABLE statements and FUNCTION statements while all functions are listed in Chapter V as part of the experiments conducted, only the function's purpose will be described here. FUNCTION 6 calls on VARIABLE 37 for the angle of slope and gives the sine of that angle. FUNCTION 7 also calls on VARIABLE 37 and provides the cosine of that angle. FUNCTION 8 calls upon parameter 4 to go from sin W to cos W directly. Parameter 4 has stored the value of VARIABLE 46 which is sin W.

SEIZE block 300 causes the slope and microgeometry sub-section to be seized by the vehicle coming through the facility. ASSIGN block 301 places the value of VARIABLE 46 in parameter 4 of the transaction. The value of VARIABLE 47, the distance that the center of gravity is to the outside, is compared with VARIABLE 49, the distance provided by the wheel track for stability, by COMPARE block 310. If the vehicle is
Figure 9. Factor Family 1 Evaluation Sub-Section Flow Chart
Figure 10. Factor Family 2 Evaluation Sub-Section Flow Chart
V37  Ground Slope in Degrees
V46  Sin W
V47  h Sin W
V49  1/2 to Cos W

Figure 11. List of Variables Used to Determine if the Vehicle is Stable

stable, then the vehicle proceeds to ASSIGN block 311 and SAVEX block 312 which counts and stores, respectively, the number of successful completions by the vehicle. If the COMPARE refuses passage by the vehicle, ADVANCE block 305 causes the vehicle to enter LOGIC block 315 where logic switch 2 is reset to 0. The vehicle then exits through RELEASE block 390 to enter the data collection section.

Factor Family 3 Sub-Section

This sub-section evaluates the ability of the vehicle to overcome the vegetation of an area. The resistance of the vegetation is measured against the drawbar pull of the vehicle. If the vehicle lacks the power to overcome the resistance of the vegetation, then the driver is assumed to attempt twice more in an effort to maneuver around the vegetation. The resistance of the vegetation is given by the sum of FUNCTION 9, FUNCTION 10, and FUNCTION 11, Figure 10, which represent light, medium, and heavy vegetation, respectively. The resistance represented by the three functions is for a square 10 yards on a side. The vehicle's area is represented by the vehicle track times its length. This vehicle area figured as a percentage of the 30-foot square times the area resistance gives the resistance facing the vehicle.
\[ \theta = \text{Ground Slope} = V37 \]
\[ \lambda = \text{Microgeometry} = FN5 \]
\[ t = \text{Vehicle Track} = V7 \]
\[ h = \text{Height to Center of Gravity} = V6 \]
\[ \omega = \text{Combined Slope and Microgeometry} \]
\[ c = (h + t)\sin \theta \]
\[ d = h \sin \theta \]

\[ \omega = \arcsin \left( \frac{h \sin \theta + t \sin \theta - h \sin \theta}{t + h} \right) = \arcsin \left( \frac{t \sin \theta}{t + h} \right) \]

\[ a = h \sin W \]
\[ b = \frac{1}{st \cos W} \]

**Figure 12. Vehicle-Slope and Microgeometry Relationship**
Figure 13. Factor Family 3 Evaluation Sub-Section Flow Chart
The above sequence of events begins with SEIZE block 400 which
seizes the facility for the vehicle. VARIABLES 40, 41, 42, and 50
determine the resistance of the vegetation which is measured against
vehicle drawbar pull in COMPARE block 411. ASSIGN block 405 has
already assigned a constant of 3 to parameter 5; if the COMPARE block
refuses entry LOOP block 420 looks to parameter 5 and recycles
the vehicle for another try until a 0 exists in parameter 5. ASSIGN block 412 and SAVEX block 413 store and print, respectively, the number of times the vehicle has passed through successfully, the Factor Family 3 Evaluation Sub-Section. If the vehicle is not successful after 3 attempts to enter the COMPARE block, then the vehicle moves to LOGIC block 425 where logic switch 3 is reset to 0. The vehicle then exists through RELEASE block 430 to move to the data collection section.

**Factor Family 4 Evaluation Sub-Section**

This sub-section evaluates the ability of the vehicle to overcome terrain obstacles of, or caused by, hydrology. Figure 15 illustrates the general nature of the problem. The vehicle moves towards the hydrology type obstacle. The initial phase is as the vehicle's wheels drop down over the step. The break angle of the vehicle must be less than the break angle of the bank. The vehicle must have stability on the slope of the bank and the approach angle of the vehicle must be great enough to preclude the nose of the vehicle from burrowing into the stream bed. The vehicle must have a fording capability great enough to permit it to overcome the water depth. The final obstacle to overcome is the step height which must be less than the radius of the vehicle tires.

Streams are random factors and occur only upon occasion. Likewise, the obstacles created by streams are random and must be determined through statistical analysis. For the purposes of this study, a stream or hydrology type obstacle occurs once in every 200 vehicle lengths. The actual frequency within a given area may be less or it may be greater. For the purpose of this study, the above frequency is used.
Figure 15. General Nature of Hydrology Factors Influencing Vehicular Passage

s = step height
ω = break angle
θ = approach angle
d = water depth
To accomplish the above sequence of events, the flow chart for this sub-section is represented by Figure 16.

The facility is seized by the vehicle entering SEIZE block 500. Since only .005 of the vehicles are evaluated against hydrology .005 is the selection made for ADVANCE block 501. COMPARE blocks 506, 508, 510 and 512 evaluate the vehicle for break angle, approach angle, water depth, and step height, respectively. If the vehicle fails to negotiate any one of the COMPARE blocks, it returns to preceding ADVANCE which sends the vehicle to one of the ASSIGN blocks 525, 530, 535, or 540. These ASSIGN blocks place a 1, 2, 3, or 4, respectively, in parameter 4 to indicate which type of obstacle halted the vehicle. SAVEX block 548 stores the information for later use. The vehicle then moves to LOGIC block 560 where logic switch 4 is reset to 0. If the vehicle successfully passes through all COMPARE blocks it enters ASSIGN block 550 which counts success completions of Factor Family 4 Evaluation Sub-Section. This information is stored by SAVEX block 555 and the vehicle is released by RELEASE block 590.

Data Collection Section

The data collection section is represented in each evaluation sub-section by the ASSIGN and SAVEX blocks which store the successful number of passes by each vehicle in parameter 8. The data collection causes these values to be printed out for each vehicle by PRINT block 700, which is the value for Factor Family 2; PRINT block 701, which is the value for Factor Family 3; PRINT block 702, which is the value for Factor Family 4; and PRINT block 703, which is the value for Factor
Figure 16. Factor Family 4 Evaluation Sub-Section Flow Chart
Family 1. PRINT block 704 prints out the type of obstacle, if any, that halted the vehicle in Factor Family 4.
CHAPTER V

DESIGN OF EXPERIMENTS

Introduction

The overall objective of this study was to provide the pulpwood producer with a means whereby a typical pulpwood harvesting vehicle could be evaluated. The accomplishment of this objective required initially the selection and design of a model to perform this evaluation. Previous chapters have served to present this result. This chapter deals with the design of the experiments performed using the computer simulation model which provides the pulpwood producer with the necessary information upon which to base his evaluation.

The most promising avenue of approach for the attainment of usable data appeared to be evaluation of an actual vehicle against actual terrain. Data were available for five pulpwood resource areas in the State of Georgia located in Gwinnett County, Chatham County, McIntosh County, Haralson County, and Telfair County (60). These data included the general nature of the terrain in sufficient detail that a reasonable facsimile could be constructed. The design specifications for the Taylor S-112 logging skidder were also obtained. This vehicle was used earlier in an actual experiment by Freitag and Richardson (61). The resulting empirical data permitted validation of the model. The Taylor S-112 has several options, one of which is tire size. This option of tire sizes permitted the vehicle to be evaluated at two levels.
The Experiment

Two experimental designs evolved from the requirements of the producer. The first requirement was to determine with a probability, the percentage of resource areas that the producer could harvest prior to his vehicle being overcome by terrain obstacles. Five pulpwood resource areas were considered as a selective sample of a total of 35 pulpwood resource areas that the pulpwood producer expected to harvest over the next year. This experiment consisted of estimating the mean and variance of the distance the vehicle travelled until halted by an obstacle for each of the five resource areas considered.

By using the Student's t-distribution in the manner suggested by Hicks (62), the mean and variance of each area were determined. In this method, variance is determined by using the mean square for error of the analysis of variance divided by the number of replications performed. The square root of this value is multiplied by a t value which is gotten out of a standardized table. The resulting value is the deviation which, in this experiment, is subtracted from the average distance travelled to provide a lower limit that the producer may expect his vehicle to travel within the specified area prior to being overcome by terrain obstacles. The values obtained in this experiment are listed in Chapter VI by each area.

The second requirement was to determine if a difference existed in the performance of the pulpwood harvesting vehicle caused by selection of optional tire sizes. The experimental design employed to test this hypothesis was a two-factor design with two levels of vehicle effects and five levels of terrain effects. The analysis of variance
was utilized to formally test two hypotheses: (1) that there was no effect caused by terrain, and (2) that there was no difference in performance caused by changing the tire size. An analysis of variance table with illustrative data is shown as Table 1.

Table 1. ANOVA Table with Illustrative Values

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>ss</th>
<th>ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Areas</td>
<td>4</td>
<td>400</td>
<td>100</td>
</tr>
<tr>
<td>Tires</td>
<td>1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Interaction</td>
<td>4</td>
<td>400</td>
<td>100</td>
</tr>
<tr>
<td>Error</td>
<td>240</td>
<td>2400</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>249</td>
<td>3300</td>
<td></td>
</tr>
</tbody>
</table>

The number of replications to be performed in the experiments was determined through the method demonstrated by Bowker and Lieberman (63). Here, a level of significance for rejecting a true hypothesis is chosen, in this case, the value was .05. The appropriate figure is chosen from several possible on the basis of this level of significance. Two other values are then required to read from the figure. These values are the acceptable risk of failing to reject a hypothesis and the deviation from the true mean that is to be detected. Since no knowledge of the true standard deviation existed a value of 50 was chosen. It was desired to detect a 10 per cent shift in the true means with a .95 probability. A risk of .10 was considered acceptable in
failing to reject a false hypothesis. All of these values combined on
the figure to give a result of about 25 replications.

**Derivation of Data**

The five terrain areas were assumed to be representative of the
35 areas to be harvested. Each area's terrain characteristics were
placed into functions for evaluation against the test vehicle's
characteristics. For each area, there were ten functions to be
described. These functions are described for each area in Figures 17
to 21, respectively. Because the terrain was almost identical in
area 4 and area 5, it was assumed that the hydrology obstacles in area
5 were bridged. The same assumption was also made for area 1 and area
3 due to their similarity. Functions exactly duplicated in Figures 17
to 21 are not repeated for the respective following terrain areas.

The determination of the function values for area 1 is discussed
in detail. Where significantly different, the values of functions for
the other areas will be discussed. Because no real distributions were
available the values were, in the main, selected as being reasonable.

**FUNCTION 2** is the distribution of the soil cone indexes. The
values used in this function were approximations for sandy loam.
Bassett *et al.* (64) obtained values for a loess soil which gave a
general idea as to the nature of the soil distribution.

**FUNCTION 4** is the slope of the area. The available data pro-
vided either the exact slope of the area or a grouping of values within
5 per cent tolerances.
SOIL CONE INDEX
FUNCTION 2

SLOPE
FUNCTION 4

MICROGEOMETRY AND
SOIL SINKAGE
FUNCTION 5

RESISTANCE OF SMALL SIZE
VEGETATION
FUNCTION 9

RESISTANCE OF MEDIUM
SIZE VEGETATION
FUNCTION 10

Figure 17. FUNCTION Values for Area 1
[Data Provided by American Pulpwood Association]
RESISTANCE OF LARGE SIZE VEGETATION
FUNCTION 11

GROUND BREAK ANGLE
FUNCTION 15

APPROACH ANGLE
FUNCTION 16

WATER DEPTH
FUNCTION 17

STEP HEIGHT
FUNCTION 18

Figure 17. FUNCTION Values for Area 1 (Continued)
[Data provided by American Pulpwood Association]
Figure 18. FUNCTION Values for Area 2 (Continued)
[Data Provided by American Pulpwood Assn.]
Figure 19. FUNCTION Values for Area 3 [Data Provided by American Pulpwood Association]
FUNCTION 5 is microgeometry and soil sinkage. These values were taken from data on the five resource areas. The data gave the stoniness of the ground in terms of rocks greater than 12 inches high covering a percentage of the total ground. Ground roughness was given in qualitative terms. From the percentage figure on stoniness and the qualitative description of ground roughness, a reasonable distribution was assumed for each area.

The available data provided the number of trees per acre and a qualitative description of the brush. The data were not available to determine the bending moment for trees and brush. Values were again assumed for FUNCTIONS 9, 10, and 11. These values are relative to one another only for illustrative purposes.

The values for FUNCTIONS 15, 16, 17, and 18 came from the work performed on the Ranger training areas by the University of Tennessee (65). The assumption made here was that hydrology type obstacles would be similar within each broad area classification.
Figure 20. FUNCTION Values for Area 4 [Data Provided by American Pulpwood Association]
These classifications were Piedmont, Upper Coastal Plain, and Lower Coastal Plain. The distribution chosen was a straight line from the smallest value to the greatest value.

The disadvantage of this particular experimental input was that it immediately became apparent that the five areas were generally similar. For this reason it was decided to conduct one experiment containing significant differences in one factor family for each area.
The new functions and the areas in which they were placed are shown as Figures 22 to 26. While not totally related to the actual areas, this new experiment would give an indication of the sensitivity of the computer simulation model.
Figure 22. Sensitivity Values for Area 1

[Assumed Data]
Figure 23. Sensitivity Values for Area 2
[Assumed Data]
RESISTANCE OF LARGE SIZE VEGETATION FUNCTION 11

BREAK ANGLE FUNCTION 15

APPROACH ANGLE FUNCTION 16

WATER DEPTH FUNCTION 17

STEP HEIGHT FUNCTION 18

Figure 23. Sensitivity Values for Area 2 (Continued) [Assumed Data]
Figure 24. Sensitivity Values for Area 5 [Assumed Data]
Figure 25. Sensitivity Values for Area 3 [Assumed Data]
SOIL CONE INDEX
FUNCTION 2

SLOPE
FUNCTION 4

MICROGEOMETRY AND
SOIL SINKAGE
FUNCTION 5

RESISTANCE OF SMALL
SIZE VEGETATION

Figure 26. Sensitivity Values for Area 4
[Assumed Data]
RESISTANCE OF MEDIUM SIZE VEGETATION
FUNCTION 10

RESISTANCE OF LARGE SIZE VEGETATION
FUNCTION 11

BREAK ANGLE
FUNCTION 15

APPROACH ANGLE
FUNCTION 16

WATER DEPTH
FUNCTION 17

Figure 26. Sensitivity Values for Area 4 (Continued)
[Assumed Data]
CHAPTER VI

RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

General

The nature of the results indicated that the computer simulation model performed as expected and provided data in a usable form. The analysis of variance indicated that the effects tested were statistically significant. A statistically significant difference in vehicle performance attributable to optional equipment was also detected.

Results

Experiment 1 used models of actual pulpwood resource areas as the terrain values against which the vehicle was to be evaluated for a measure of effectiveness. Following the computer simulation runs, an analysis of variance was conducted to determine if there was a significant difference in vehicle performance. The ANOVA table is shown as Table 2.

Table 2. ANOVA Table for Experiment 1

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>ss</th>
<th>ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Areas</td>
<td>4</td>
<td>80962</td>
<td>20240</td>
</tr>
<tr>
<td>Tires</td>
<td>1</td>
<td>27521</td>
<td>27521</td>
</tr>
<tr>
<td>Interaction</td>
<td>4</td>
<td>22535</td>
<td>5634</td>
</tr>
<tr>
<td>Error</td>
<td>240</td>
<td>991651</td>
<td>4132</td>
</tr>
<tr>
<td>Totals</td>
<td>249</td>
<td>1122669</td>
<td></td>
</tr>
</tbody>
</table>
Using as the initial hypothesis, that there was no difference between the areas, the appropriate F ratio was $F_{4,240} = 4.898$ which was highly significant and the hypothesis was rejected. The second hypothesis was that there was no effect caused by the tire size. Here the corresponding F ratio was $F_{1,240} = 6.66$ which was highly significant and this hypothesis was also rejected. Thus the results of Experiment 1 lead us to conclude that there was a significant difference in the performance of the vehicle attributable to the areas to be harvested and the tire sizes.

To provide the producer with the information he requires, the method suggested by Hicks (66) as described in Chapter V was used. Here it was desired to state that the vehicle could negotiate x percentage of the terrain before being overcome by a terrain obstacle. The lower confidence level for this one-sided test was set at .95. This confidence level resulted in the following percentages:

Table 3. Lower Confidence Limits of Percent of Terrain Vehicle Can Negotiate

<table>
<thead>
<tr>
<th>18.1 x 26 Tire Size</th>
<th>23.4 x 34 Tire Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area 1  75%</td>
<td>Area 1  89%</td>
</tr>
<tr>
<td>Area 2  78%</td>
<td>Area 2  90%</td>
</tr>
<tr>
<td>Area 3  81%</td>
<td>Area 3  86%</td>
</tr>
<tr>
<td>Area 4  94%</td>
<td>Area 4  94%</td>
</tr>
<tr>
<td>Area 5  94%</td>
<td>Area 5  94%</td>
</tr>
</tbody>
</table>

Stated in terms of the total of all five areas, the larger size tire would permit the vehicle to cover 91 per cent of each area without
failure whereas the smaller size tire would only permit 85 per cent coverage. The individual producer could also see that no advantage existed for the larger tire in areas 4 and 5 and that the smaller tire (cheaper in price) would be entirely satisfactory.

The results of Experiment 2 were analyzed using the analysis of variance treatment as applied to the results of Experiment 1. The ANOVA table for Experiment 2 is shown below as Table 4.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>ss</th>
<th>ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Areas</td>
<td>4</td>
<td>5821642</td>
<td>1455410</td>
</tr>
<tr>
<td>Tires</td>
<td>1</td>
<td>107</td>
<td>107</td>
</tr>
<tr>
<td>Interaction</td>
<td>4</td>
<td>347</td>
<td>87</td>
</tr>
<tr>
<td>Error</td>
<td>240</td>
<td>287128</td>
<td>1196</td>
</tr>
<tr>
<td>Total</td>
<td>249</td>
<td>6109224</td>
<td></td>
</tr>
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</table>

Again proposing the hypothesis of no area effect, the F ratio is 12.17 which is highly significant. The hypothesis of no tire effect provides a ratio of less than 1 which is not significant. The first hypothesis is thus rejected and the second accepted. These results were not surprising when it is considered that the terrain portrayed was difficult to a degree that neither vehicle possessed the ability to overcome the obstacles. Hence, in order to harvest these areas, the producer would have to either extensively modify the terrain or use an entirely different vehicle. In extreme cases both actions might be required.
The results of the experiments conducted demonstrated the feasibility of a computer simulation model to predict the ability of a vehicle to negotiate terrain. From these results certain conclusions can be drawn.

**Conclusions**

It became obvious early in the conduct of the experiments that hydrology type obstacles dominated the relationship between the pulpwood harvesting vehicle and the terrain over which it passed. This domination could be significantly reduced by modification of the obstacle prior to the pulpwood harvesting vehicle encountering it.

The actual pulpwood resource areas presented in this digital computer simulation model did not present difficult obstacles to the pulpwood harvesting vehicle modeled. With the elimination of hydrology type obstacles, the pulpwood harvesting vehicle had almost complete freedom of movement within the resource areas.

The Upper Coastal Plain areas, such as Telfair County, presented no obstacles to the pulpwood harvesting vehicle. While the effect of moisture was not considered in this model, it is possible that the soil cone index in this area would not be adversely affected to a significant degree due to the somewhat sandy nature of the soil.

The pulpwood harvesting vehicle, presently in use, is more than adequate for the five listed areas in Georgia.

The model, as constructed, provides the individual pulpwood producer with a means of determining the percentage of his pulpwood resource areas, subject to the assumptions heretofore described and the
specific areas chosen, that can be harvested by a specific item of equipment provided with a specified tire size.

The model is valid for evaluating vehicle performance within the areas normally worked by a pulpwood producer. If significant changes in terrain do exist within a 25-mile radius of the producer's base of operations then this model should be modified to reflect the change in terrain.

Recommendations

The assumption of three vehicle lengths being required to halt the vehicle fails to consider the extreme differences in wheelbase between large and small vehicles. It is recommended that this model be expanded to consider soft soil strictly as a function of distance rather than as a specified number of wheelbase lengths.

A statistical treatment of vegetation should be conducted to permit the expansion of this model to include true vegetation resistance rather than assumed values.

Vehicle speed as a function of obstacles and rolling resistance should be brought into this model. This expansion would permit a more refined cost analysis of a vehicle's performance on a basis of time required per acre.

Further research should consider performance evaluations of vehicles with modifications designed to reduce the problem of hydrology type obstacles which demonstrated such an adverse effect on vehicle mobility.
A cost analysis should be performed on present rubber-tired skidders operating in the Piedmont and Upper Coastal Plain regions. This analysis would be to determine if the pulpwood harvester requires the mobility of the skidder when a less costly vehicle might well be adequate.
APPENDIX A

MOBILITY INDEX CALCULATIONS

FOR TAYLOR S-112

23 x 34 Tire Size

\[
MI = \left( \frac{\text{contact pressure} \times \text{weight factor}}{\text{tire grousers factor}} \right) + \left( \frac{\text{Wheel Load Factor} - \text{Clearance Factor}}{\text{Engine Factor} \times \text{Transmission Factor}} \right)
\]

Vehicle Factor

<table>
<thead>
<tr>
<th>Contact Pressure</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nom. Tire x Outside Diam. Tire, In. x No. of Tires</td>
<td>5.71</td>
</tr>
</tbody>
</table>

\[
\frac{16,495}{23.1 \times 62.5/2 \times 4} = 5.71
\]

Weight Factor:  
- Weight Range (Lbs/Axle): 2,000 to 13,500  
  \[ Y = 0.033X + 1.05 \]  
  \[ X = \text{Gross wt in kips/axle} \]  
  \[ Y = 0.033(8.25) - 1.05 \]  
  \[ = 1.32 \]

Tire Factor:  
- Tire width, in. + 23.1
  \[ \text{Tire Factor} = \frac{10 + \text{tire width, in.}}{100} \]
  \[ = 0.33 \]

Grouser Factor:  
- Without Chains = 1.00
  \[ = 1.00 \]

Wheel Load Factor:  
- Gross Weight (Kips)
  \[ \text{Wheel Load Factor} = \frac{16.50}{\text{No. of Wheels}} \]
  \[ = 4.12 \]

Clearance Factor:  
- Clearance Factor = \[ \frac{\text{Clearance, In.}}{10} \]
  \[ = 2.10 \]

Engine Factor:  
- 710 hp/ton = 1.00
  \[ = 1.00 \]
Vehicle Factor (Continued)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Factor:</td>
<td>1.00</td>
</tr>
<tr>
<td>MI = ( \left( \frac{5.71 \times 1.32}{0.33 \times 1.00} + 4.12 - 2.10 \right) \times 1.00 \times 1.00 )</td>
<td>25</td>
</tr>
</tbody>
</table>

18 x 26 Tire Size

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Pressure Factor</td>
<td>8.3</td>
</tr>
<tr>
<td>( \frac{16,495}{18.4 \times 54/2 \times 4} )</td>
<td></td>
</tr>
<tr>
<td>Weight Factor:</td>
<td>1.32</td>
</tr>
<tr>
<td>Tire Factor:</td>
<td>0.28</td>
</tr>
<tr>
<td>( \frac{10 + 18.4}{100} )</td>
<td></td>
</tr>
<tr>
<td>Grouser Factor:</td>
<td>1.00</td>
</tr>
<tr>
<td>Wheel Load Factor:</td>
<td>4.12</td>
</tr>
<tr>
<td>Clearance Factor:</td>
<td>1.7</td>
</tr>
<tr>
<td>( \frac{17}{10} )</td>
<td></td>
</tr>
<tr>
<td>Engine Factor:</td>
<td>1.00</td>
</tr>
<tr>
<td>Transmission Factor:</td>
<td>1.00</td>
</tr>
<tr>
<td>MI = ( \left( \frac{8.3 \times 1.32}{0.28 \times 1.00} + 4.12 - 1.7 \right) \times 1.0 \times 1.0 )</td>
<td>42</td>
</tr>
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APPENDIX B

PROGRAM LISTING
**THE DECK CONTAINS FUNCTION VALUES FOR SENSITIVITY ANALYSIS OF THE PROGRAM**

* SIMULATION MODEL TO EVALUATE MOBILITY IN CONVENTIONAL GROUND VEHICLES *

**DECK ONE**

**VARIABLES TO BE DEFINED**

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1. **VARIABLE K108** - WHEELBASE
2. **VARIABLE K136** - HORSEPOWER
3. **VARIABLE K22** - WHEELS
4. **VARIABLE K218** - LENGTH
5. **VARIABLE K21** - GRND CLEARANCE
6. **VARIABLE K43** - HGT OF C.G.
7. **VARIABLE K16** - VEHICLE TRACK
8. **VARIABLE K40** - APPROACH ANGLE
9. **VARIABLE K100** - DEPARTURE
10. **VARIABLE K145** - BREAK ANGLE
11. **VARIABLE K2** - SUSPENSION
12. **VARIABLE K1** - FLOATATION
13. **VARIABLE K92** - TURNING RADIUS
14. **VARIABLE K23** - TIRE WIDTH
15. **VARIABLE K10995** - WEIGHT
16. **VARIABLE K4** - NO. OF TIMES
17. **VARIABLE K2** - NO. OF AXLES
18. **VARIABLE K100** - TRANS. FACTOR
19. **VARIABLE K6000/V1+K3** - NUMBER OF LOOPS
20. **VARIABLE V15/V22** - AXLE LOAD
21. **VARIABLE K12000** - DRAWBAR PULL

**TRACTIVE EFFORT OF WHICH THE VEHICLE IS CAPABLE**
GWINNETT COUNTY - AREA ONE

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* This function defines the major slope grouping

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* This function defines the resistance of the small vegetation to the vehicle

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* This function defines the resistance of the medium sized vegetation.

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* This function defines the resistance of the large sized vegetation.

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* This function defines the break angle.

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* This function defines the approach angle.

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* This function defines water depth.

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* This function defines step height.

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THE MODEL BEGINS

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MOBILITY INDEX VERSUS VEHICLE CONE INDEX

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THE VEHICLE HAS NOW BEEN DEFINED AND ITS CHARACTERISTICS ASSIGNED AN
PARAMETERS THE VEHICLE NOW ENTERS THE TEST TRACK FOR EVALUATION.

* * *

200 SEIZE 2 FACTOR FAMILY

205 SAVEX 3 X2
206 SAVEX 4 X1
207 SAVEX L FN2

THE CONE INDEX OF THE SOIL IS GENERATED BY A RANDOM NUMBER IN THESE BLOCKS

208 SAVEX 4 VN3
209 ADVANCE 210

* * *

210 ADVANCE 3 ADVANCE 210 214
211 COMPARE 4 b E K0 215
214 LOOP 3
215 ADVANCE 215
216 COMPARE 4 FN1 L VN3 220 225
221 ASSIGN 61 K1 222
222 SAVEX 10 PB 290
225 LOGIC K1 290
290 RELEASE 2 600

* * *

300 SEIZE 3 301 ENTERING

* * *

FACTOR FAMILY 2- SLOPE AND MICROSCOPETRY
THE SLOPE OF THE GROUND IS GIVEN BY FUNCTION 4 WHICH IS ASSIGNED TO THE MODEL
AS PARAMETER 8

THE EFFECT OF THE MICROSCOPETRY IS COMPUTED IN VARIABLES
THE VARIABLES LISTED BELOW COMPUTE THE STABILITY OF THE VEHICLE

FUNCTION PB D46
0 0 1 1750 2 3495 3 5280 4 6980 5 8720
1 1045 7 1219 8 1392 9 1584 10 1776 11 1968
2 2079 13 2520 14 2419 15 2588 16 2756 17 2924
3 3090 19 3256 20 3420 21 3544 22 3746 23 3907
4 4067 25 4226 26 4384 27 4540 28 4595 29 4848
5 5000 31 5150 32 5299 33 5446 34 5565 35 5736
6 5878 37 6018 38 6157 39 6293 40 6428 41 6561
7 6691 43 6820 44 6947 45 7071

FUNCTION PD D46
0 0 1 9998 2 9994 3 9990 4 9976 5 9962
1 9958 7 9925 8 9903 9 9877 10 9848 11 9816
2 9781 13 9744 14 9703 15 9659 16 9613 17 9563
3 9511 19 9455 20 9397 21 9336 22 9272 23 9205
4 9135 25 9063 26 8988 27 8910 28 8829 29 8746
5 8660 31 8572 32 8480 33 8387 34 8290 35 8192
6 8090 37 7986 38 7880 39 7771 40 7660 41 7547
7 7431 43 7214 44 7193 45 7071

FUNCTION V4 D46
0 0 1 10000 75 9999 349 9999 523 9996 698 9976 873 9962
1 1045 9995 1291 9992 523 9990 1264 9847 1733 9698 1928 9816
2 2079 9781 4250 9744 2410 9703 2766 9659 3746 9613 4028 9633
3 3090 9511 3256 9455 3920 9397 3288 9346 3746 9372 3907 9295
4 4067 9135 4226 9063 4384 8988 4540 8910 4695 8829 4848 8746
5 5000 8660 5150 9463 5329 8680 5564 8467 5752 8290 5736 8192
6 5878 8090 6018 7986 6157 7888 6293 7771 6428 7660 6561 7547
7 6691 7431 6820 7214 6947 7193 7071 7071

ASSIGN V46 302
ASSIGN FN4 303
ASSIGN FN5 305
ADVANCE 4 7 L
COMPAR V49 311
ASSIGN B1 312
SAYEX PB 390
LOGIC RC 390
RELEASE 600

SEIZE 4 4005 FACTOR FAMILY IS THE VEGETATION OF THE AREA

VARIABLE VD9+FD9+V510+V59+FD11

VARIABLE VD9+V50+VF9+VF10+VF11
THE VEHICLE IS CONSIDERED TO HAVE THREE CHANCES TO ATTEMPT PASSAGE OF VEGETATION TYPE OBSTACLES. THIS WOULD BE THE MANEUVERING OF THE DRIVER.  AS HE ATTEMPTS TO BACK AND TURN AROUND THE OBSTACLE.

LET K1 = 0

VARIABLE V90/V1296D0

ASSIGN K3 = K1

ADVANCE MOTH 411 420

COMPARE V42 L V41 412

ASSIGN K1 = K1

SAVEX M PB 490

LOOP 5 410 425

* THE VEHICLE IS CONSIDERED TO HAVE THREE CHANCES TO ATTEMPT PASSAGE OF VEGETATION TYPE OBSTACLES. THIS WOULD BE THE MANEUVERING OF THE DRIVER.

AS HE ATTEMPTS TO BACK AND TURN AROUND THE OBSTACLE.

LOGIC 40 490

RELEASE 505

*******************************

SEIZE 5 501

*******************************

ADVANCE X10 L E FN15 504 505

ADVANCE MOTH 506 525

COMPARE 416 GE FN16 507 530

ADVANCE MOTH 508 530

COMPARE V0 G E FN17 511 535

ADVANCE MOTH 512 540

COMPARE V02 G FN18 517 540

STEP HEIGHT

VARIABLE V12/K2

ADVANCE X 504

ASSIGN M K1 540

ASSIGN K2 540

ASSIGN q K3 540

ASSIGN q K4 540

SAVEX M 549

LOGIC 54

ASSIGN K1 = K1

SAVEX 590

RELEASE 590

*******************************

Assemble 6 600

Assemble 6 600

Assemble 6 600

ADVANCE MOTH 612 620

GATE L51 613

ADVANCE MOTH 614 620

GATE L52 615

ADVANCE MOTH 616 620

GATE L53 617

ADVANCE MOTH 618 620

GATE L64 620

ADVANCE 700

LOOP 5 182 700

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**Note:** The above text appears to be a listing or code for a computer program, possibly in a language like BASIC or a similar dialect. The table and code are not clearly legible, but it seems to involve saving and printing values.
APPENDIX C

RESULTS OF EXPERIMENTS
## Results of Experiment 1

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23.4 x 34 Tire Size

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*Unless indicated otherwise, distance is 337.*
LITERATURE CITED


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45. Bassett et al., op. cit.


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Knight, S. J., "Vehicle Mobility," *Miscellaneous Paper No. 4-241*, U. S. Army Engineer Waterways Experiment Station, Vicksburg, October 1957.


