A SIMULATION MODEL FOR PLANNING AND CONTROL OF FOREST HARVESTING OPERATIONS

by

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ABSTRACT

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This thesis describes a methodology for examining problems associated with the management and control of forest harvesting operations. The methodology developed is one of a systems simulation with general applicability that permits experimentation with a wide class of logging configurations.

A model, capable of simulating multi-source, single-sink configurations with variable internode distances, with various equipment types and combinations, and with various parameters and functional relationships, is described. Written in FORTRAN IV, the model allows independent users to make modifications in the routine to adapt them to the particular operating rules and policies of their operations.

The "validity" of the model is tested and demonstrated for an actual West Coast logging division used as a vehicle for model formulation. The verification procedure involves the examination of the assumptions and rules of operation of the model subsystems, and the historical confirmation that for a particular situation the subsystems together make up a system which displays the behavior and characteristics associated with the real system.

Some design and tactical considerations in the execution of the model runs are described. Some experimental design problems, together with possible ways of overcoming them, are discussed. In particular, it is shown that the control variate technique can be effectively used with the model to reduce the variance of the difference between two means under comparison.

Simulation experiments with various logging configurations indicated the nature of the interrelationships among the responses of the "logging system". These interrelationships are described with respect to a principal factor - the number of trucks in the hauling fleet.

Some practical applications of the logging simulation model are discussed and illustrated. The model can be used to evaluate and compare existing operating policies or to formulate new policies. This application is illustrated with reference to the comparison of two operation shutdown modes. The model can also be beneficial in the determination of the equipment requirements of an operation under different operating conditions. Another benefit from the model can be derived from its capability of increasing our understanding of the "logging system" - through learning how the parts of the system behave and interact and through learning how the system responds to changes in its factors. This capability can be beneficial not only in the design of better policies but also in the exercise of better control of the system.

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CHAPTER I

INTRODUCTION

An industrial activity generally involves a main flow of products or services. Industrial systems deal with this flow, the continuing transfer and transformation of materials as they pass through several intermediate nodes enroute to the consumer. A recognition of this basic nature puts many of the problems inherent in such systems into perspective. These problems generally revolve around improving the efficiency of the individual nodes of the flow and smoothing the flow through these nodes.

In forestry the materials are trees which are harvested upon "maturity", transported to the mill, and manufactured into products for subsequent consumption. The different major phases of this product flow are illustrated in Figure 1.1.

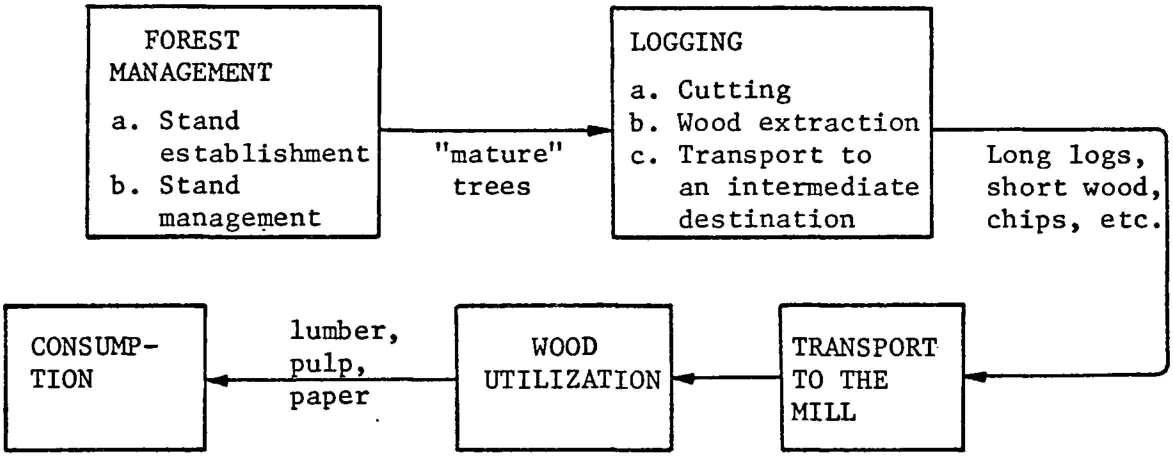


Figure 1.1 An illustration of the product flow in a forest industrial system

Figure 1.1 also illustrates the relationship among forest management, forest harvesting or logging, and wood utilization. They form links in the chain of activities necessary to bring the finished product to the consumer.

This study focuses on the logging aspect of this product flow. A study on this aspect is necessary, considering that the forest industry, faced with a public with growing concern for the improvement of its environment, and machine and labour costs which are high and difficult to stabilize, must review its system and policies for procuring and transporting raw materials for its mills. The forest industry must institute better policies, design better systems, and intensify the use of its present equipment to reduce and stabilize costs, if it is to survive competition from outside sources and if wood substitutes are to be prevented from taking over a large share of the wood market.

Additional relevant studies on logging are needed. While studies on forest management featuring the quantitative systems analytic approach are becoming extensive, the treatment of the logging aspect as found in the present literature has generally been limited to its representation as a small module or as a cost function of a larger forest management model. Although this treatment of the logging aspect may have been adequate for the purpose of these studies, a more intensive treatment is necessary for developing tools and policies which could aid the logging manager in making decisions.

In many of the studies dealing primarily with logging, the emphasis has been generally on designing machines or on component activities while the development of a total logging system for using these machines lagged. Several studies which involved the simulation of machine concepts have been designed to increase the efficiency of the individual steps in the log flow. There remains a need for a comprehensive study of the over-all logging system encompassing not only the subsystems represented by these machines but the interactions among these subsystems as well.

A study designed to fill this need faces the requirements of providing answers to the problems of total systems design while portraying the important characteristics of logging systems. Some of the characteristics of logging systems are:

1. They are dynamic, their states change with time.
2. They are diffused throughout with uncertainties. Their subsystems represent processes that are stochastic. For example, the truck travel times

the loading and unloading rates, and the yarding rates are all random variables. Since the various subsystems generally interact with each other, it is essential for an intensive logging study that their stochastic nature is maintained in their representation.

3. Their responses to change in their independent variables are, in general nonlinear. For example since each additional logging truck results in longer queues, longer waits for logs, and heavier traffic density, the daily production increases at a decreasing rate with an increase in the number of trucks.

4. They are self-regulating. They return to their initial state after being disturbed. For instance, barring any great calamity, any system disturbance is corrected - strikes are settled, broken down equipment is repaired.

The extent to which past logging studies meet the above requirements is investigated in the following section.

1.1 PAST STUDIES ON THE ANALYSIS OF FOREST HARVESTING PROBLEMS.

Early studies directly involved with logging were limited to the investigation of individual logging activities. The emphasis was on improving production and reducing cost for these individual activities. While some of the problems investigated involved two-machine activities, e.g. skidding and hauling, these investigations were fragmentary and did not look at the over-all system.

Matthews (1942) was among the first to use mathematical techniques for solving certain types of logging problems involving production and cost control. A tool he repeatedly used when comparing two or more alternatives is the break-even point chart. He also used differential calculus to find the minimum point of the cost function derived for some design problems such as the determination of the optimum road spacing for sloping ground, the determination of the maximum skidding distance for economic direct skidding under various conditions, etc.

The studies of Lussier (1959) also dealt with production and cost control. Statistics gathered from field studies on the performance of machines and their crews were used to set up production standards and control charts which then served as a basis for comparing the future performance of the machines and their crews.

In the last decade, several studies applied operations research tools to logging problems. One of the first operations research techniques used in logging and forest management was linear programming. Although this technique has been applied to a variety of forestry problems, the problems investigated involving forest harvesting generally dealt with forest production scheduling. These applications revolved around determining how much to cut and where to cut. For example, the work of Theiler (1959) and Curtis (1962) involved scheduling various compartments for cutting and subsequent replanting. Logging entered the calculations only as costs. Studies on logging production allocation and scheduling by Lonner (1968) and Carlsson (1968) used linear programming and some heuristic models which incorporated some formalized decision rules. The planning of logging was divided into three separate plans - five-year plan, one-year plan, and one-month plans - each geared towards allocating logging units to each corresponding time period and determining the labor and machine resources needed for the various logging units.

In the investigation of actual logging problems, the use of linear programming was generally limited to problems involving the determination of the optimum combination of elements (e.g. cords per acre, truck hours per cord, skidder hour per cord, ect.) subject to a certain set of scarce resources (e.g. forest acreage of various species compositions, quality, and geographical distribution; harvesting equipment; operating roads; and labour supply) and to the requirement of producing a certain amount of wood for a given period. The work of Donnelly (1963) is an example. While this class of linear programming application gives an indication of the equipment requirement for a given unit of production in terms of machine hours per unit volume, no indications can be given of the desirable equipment composition for a logging operation that would account for the various machine interactions. Also, where the comparison of system policies and designs are concerned, programming formulation and solution becomes extremely difficult unless drastic assumptions on the characteristics of the logging system are made.

Another operations research tool used in logging studies is simulation. The scope of the system investigated in most logging simulation studies, however, were either too narrow or too broad for the purpose of examining total systems problems. For instance, several simulation studies have been made to investigate the feasibility and productivity of particular machines and machine designs for a given physiography of the logging site and spatial arrangement of trees. Newnham (1968) used simulation to test the effect of varying the minimum merchantable d.b.h. on the productivity of some feller-buncher machines. The underlying purpose of the study was to design an efficient harvesting machine to harvest pulpwood.

Where the simulation studies considered the total system, the logging system was included only as a cost phenomenon or as a subsystem of a forest management model. For instance, the simulation model of a large industrial forestry enterprise designed by Clutter and Bamping (1965) to obtain management planning projections such as acres cut, volume cut, income, expenditure, present net worth, etc., and a similar study by O'Regan, et al. (1965) incorporated harvesting and hauling of wood only as cost phenomena. The management game developed by Bare (1969) simulates the operation of an industrial forest property. Its purpose is to provide an environment for students of forest management to observe and experience how the various biological and economic factors associated with operational forest management interact to effect the behaviour of the forest system. Harvesting is included among the several basic management activities, but again only as a subsystem for inventory and cost calculation.

Other simulation studies include the trucking game developed by McPhalen (1970) which functions primarily as a tool for giving the player insight into the truck dispatching process, and a river drive simulation model reported by Gillam (1968) which simulates the movement of wood through a lake and its river systems.

1.2 THE OBJECTIVES OF THIS STUDY

The main task faced by a logging manager is the production of a sufficient quantity of wood to fulfill a prescribed demand at a low and competitive cost while meeting the constraints dictated by some necessary forest management practices, some environmental considerations, and the budget. The direction of the effort expended to meet this task has been towards the improvement of the production of each activity through mechanization. Very little has been done about improving the system for planning and managing the use of these machines. Regarding this problem, W.I.M. Turner, the President of Consolidated-Bathurst, Ltd., in his keynote address to a seminar on wood costs remarked:

> "I am well aware that computer simulations have been applied to a limited extent to wood handling, delivery, river drives, inventory measurement, log sorting, etc.. Could we expand on a technique like this to help decide on a complete logging system? I am aware that differences exist in logging conditions from company to company, and even within the same operating divisions. But let us not allow the differences and variations to obscure the similarities. The variations are not infinite. We might do well, therefore, to consider an industry-wide logging simulation that all companies in Canada could share. This could be aimed at discovering the best total system of wood handling for each company's specific requirements."

While the objective of this study is not to provide an ultimate answer to this call, this study is certainly intended to be a step towards that direction. This study aims

1. To provide a conceptual framework for analyzing complex logging problems.
2. To develop a methodology for exploring this framework.

3. To develop the capability to model and experiment with logging operations with the ultimate aim of examining possible ways of improving the system.

In meeting these objectives, it is essential that the important characteristics of logging systems are taken into consideration. Logging systems are characterized by uncertainty, non-linearity, and the presence of interdependence among their variables. Problems imbedded in these types of systems are generally too intricate and too big to handle with known "analytic" models unless drastic simplifications are made. Frequently, the decisions arising from these problems involve the spending of large sums of money. Thus it is imperative that these decisions are not based solely on intuition.

The inadequancy of intuition and experience and the infeasibility of analytic models point to experimentation as a possible approach. Unfortunately, the risk of failure is inherent in each decision made and gambling on a decision could lead to ruin. This, plus the often prohibitive cost involved, puts the feasibility of conducting real-world experiments in question. Thus, experimentation in an artificial medium such as in a simulation model becomes a last resort. Since the model mimics the real-life situation, it allows the manager to observe the outcome of his decisions without having to actually endure the consequences of his decisions.

1.3 METHOD OF PRESENTATION AND CHAPTER DESCRIPTION

The subsequent parts of this thesis are developed to follow the logical steps involved in the construction of a simulation model and its application to logging problems. In Chapter II the boundaries of the physical system considered in this study are given. This is followed by a description of the different components of the physical system. The representation of a logging operation by a simulation model is discussed in Chapter III. The discussions include a description of the simulation framework, the routines which represent the physical process, and the model input and output. Following this description, the validation of the model is given in Chapter IV.

Chapter V follows with a discussion on the design, tactical, and statistical considerations in the execution of the simulation runs. Specific problems, which illustrate the classes of problems that can be handled with the model, are given in Chapter VI. Finally, the conclusions - the ramifications and general implications of the study - are presented in Chapter VII.

CHAPTER II

THE DESCRIPTION OF THE PHYSICAL SYSTEM

2.1 THE BOUNDARIES OF THE PHYSICAL SYSTEM CONSIDERED IN THIS STUDY

In the real world, systems are embedded in larger systems. Any given system exists as a part of a larger system. The limits of a specific system in a particular study extend only as far as is relevant to the objectives of that study. An improper resolution of the boundaries of a system under consideration not only needlessly complicates the problem but also obscures the significance of the results.

There is consequently a need to carefully delineate the boundaries of the system relevant to the objectives of the investigation. The objectives of this study were outlined in Chapter I. In this section, the boundaries of the physical system relevant to these objectives are defined in relation to an integrated forest products company which represents the entire organizational framework.

Figure 2.1 illustrates a hypothetical integrated forest products company. The wood production division is shown in context with the other parts of the company. Goals to attain for the fiscal year are transmitted to the wood production division by the head office of the company. These goals, in the form of production quota, are based on projected mill and sales demand. An estimate of the proportion of the total wood requirements that the division can produce and the corresponding cost of production are

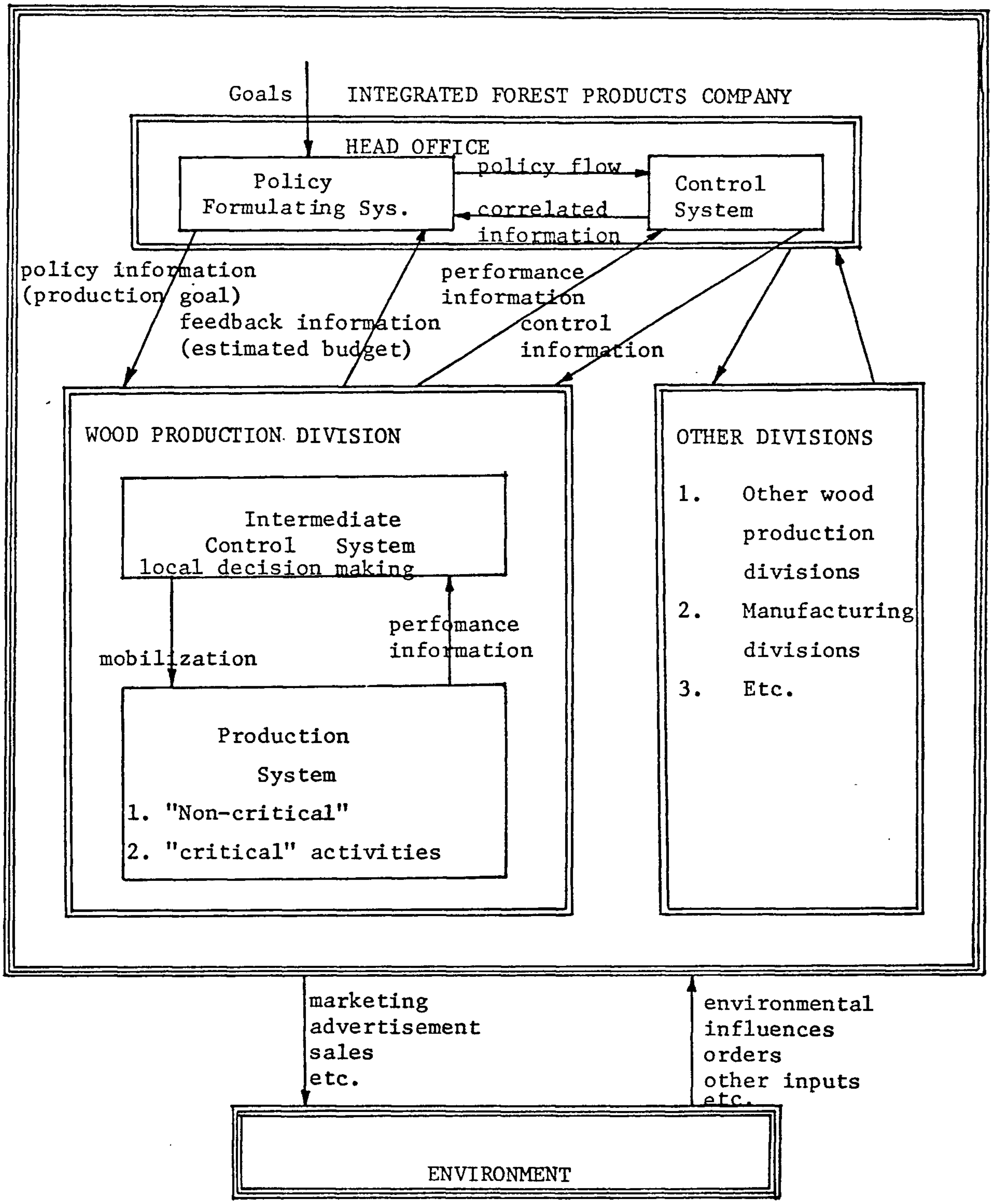


Figure 2.1 Block diagram of a hypothetical integrated forest products company and the interactions among its parts and the environment

transmitted back to the head office. The demand, the production, and the cost of production are evaluated quarterly and corresponding changes are made to accomodate any developments of the previous quarter.

While the planning and control responsibilities of the entire company rest with the head office, planning and control in the wood production division are shouldered by the logging manager. Guided by the goals he has to attain, he mobilizes and manipulates the resources of the production system. It is this planning aspect of the production system that this study deals with.

The details of the production system are shown in Figure 2.2. The production system activities are arbitrarily classified into two categories:

1. "Critical" activities - the basic day-to-day operations connected with the main function of the production system which is the production of logs at different locations in the forest and the transport of these logs to an intermediate destination. The "critical" activities include log extraction, loading, hauling, unloading, and truck dispatching, together with their subsidiary activities such as equipment management and transfer of equipment from one production location to another.
2. "Non-critical" activities - the various activities which are subsidiary to the "critical" activities. The "non-critical" activities include surveying

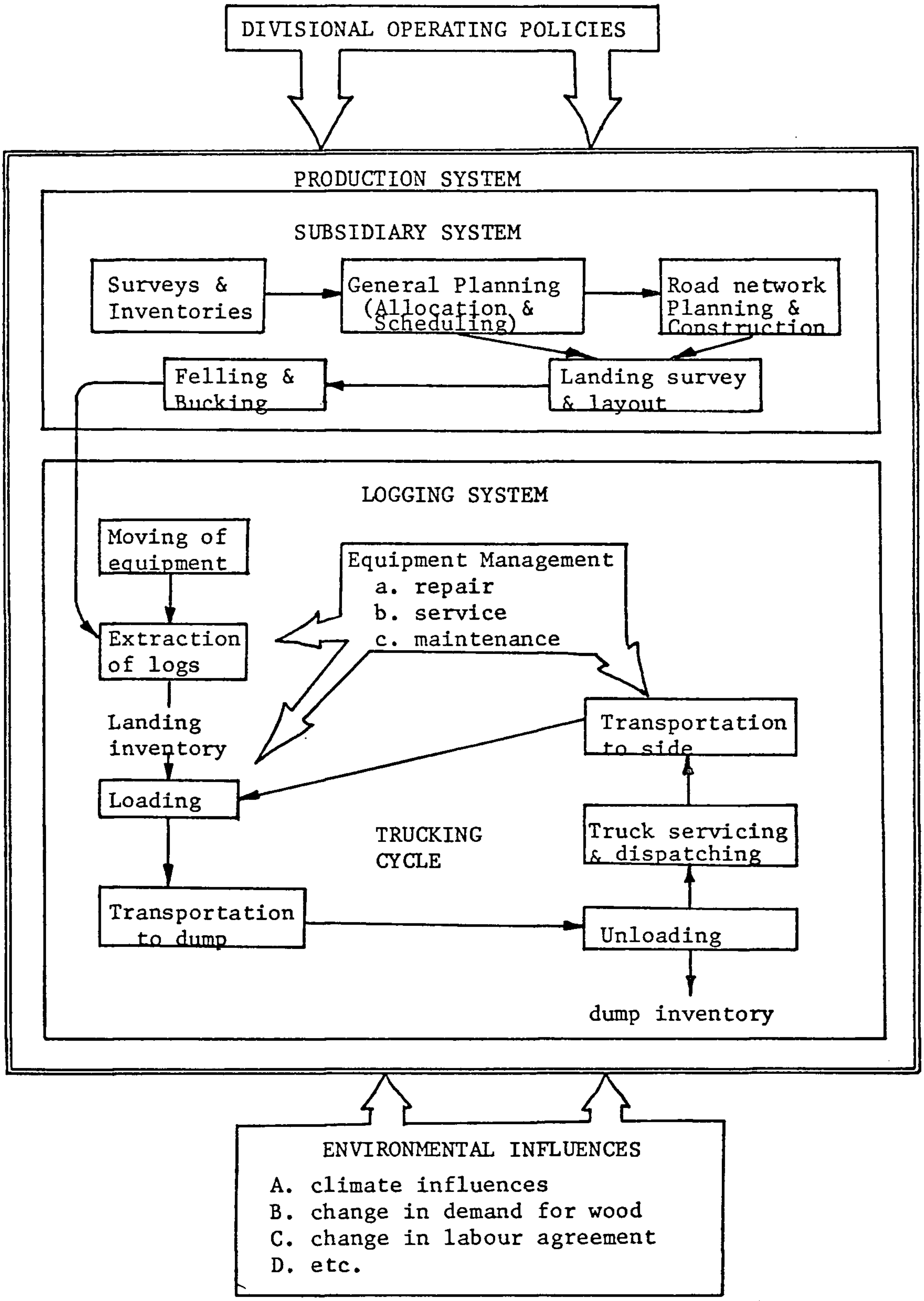


Figure 2.2 Block diagram of the wood production system

and timber cruising, allocation and scheduling of logging areas, road construction, landing survey and layout, and felling and bucking. A common characteristic of these activities is that they are done a few weeks to a year ahead of log extraction.

The limits of the system considered in this study include the "critical" activities. These activities comprise what is referred to in this study as the "logging system". The logging system boundaries encompass the extraction and transport of logs to an intermediate destination.

The "non-critical" activities comprising the "subsidiary system" are considered as exogenous activities of the logging system. They represent constraints and assumptions which are fixed for any particular examination of the logging system. However, this relationship works both ways. Feedback from the study of a logging system is useful in developing policies which govern the design and planning of the "non-critical" activities.

2.2 DESCRIPTION OF THE LOGGING SYSTEM

The characteristics of logging problems were discussed in Chapter I. Among the significant characteristics is the existence of many, generally stochastic, variables which are related to the system responses in a non-linear manner, and which are interrelated by some form of logic structure. In this section, the different subsystems of the logging system, their elements, and their activities are presented to give an appreciation of the nature of the logging system and its variables.

Logging systems in general are multi-source, multi-sink situations whose nodes are linked by a network of roads which may pass through some intermediate nodes. This arrangement is illustrated in Figure 2.3. The sources are the production locations which will be referred to as "sides". At each of the sides is a harvesting unit and in most cases, a loader. In certain cases, a loader may serve two adjacent production locations. The sinks are the immediate destination of the logs and they are referred to as "dumps". The intermediate nodes are the repair shop and the truck service facilities such as the fuel, oil, water, and tire shops. The camp usually houses these facilities.

The responsibility of the logging manager is the production of logs at the different production locations in the forest and the transport of these logs to the dumps from where they are eventually shipped to their final destination, e.g. the mill or the market. The activities connected with this responsibility may be classified into: (1) log extraction, (2) log transport, and (3) subsidiary activities. Each of the different "logging subsystems" that correspond to the activities under these categories is described in the subsequent subsections.

The description given in this chapter is necessarily a description of the static aspects of the different logging subsystems, e.g. their elements and functions. The dynamic aspects of the different logging subsystems, e.g. their events and the interaction of events, are given in the next chapter. Where applicable, the description given in this chapter is facilitated by the use of tables. These tables

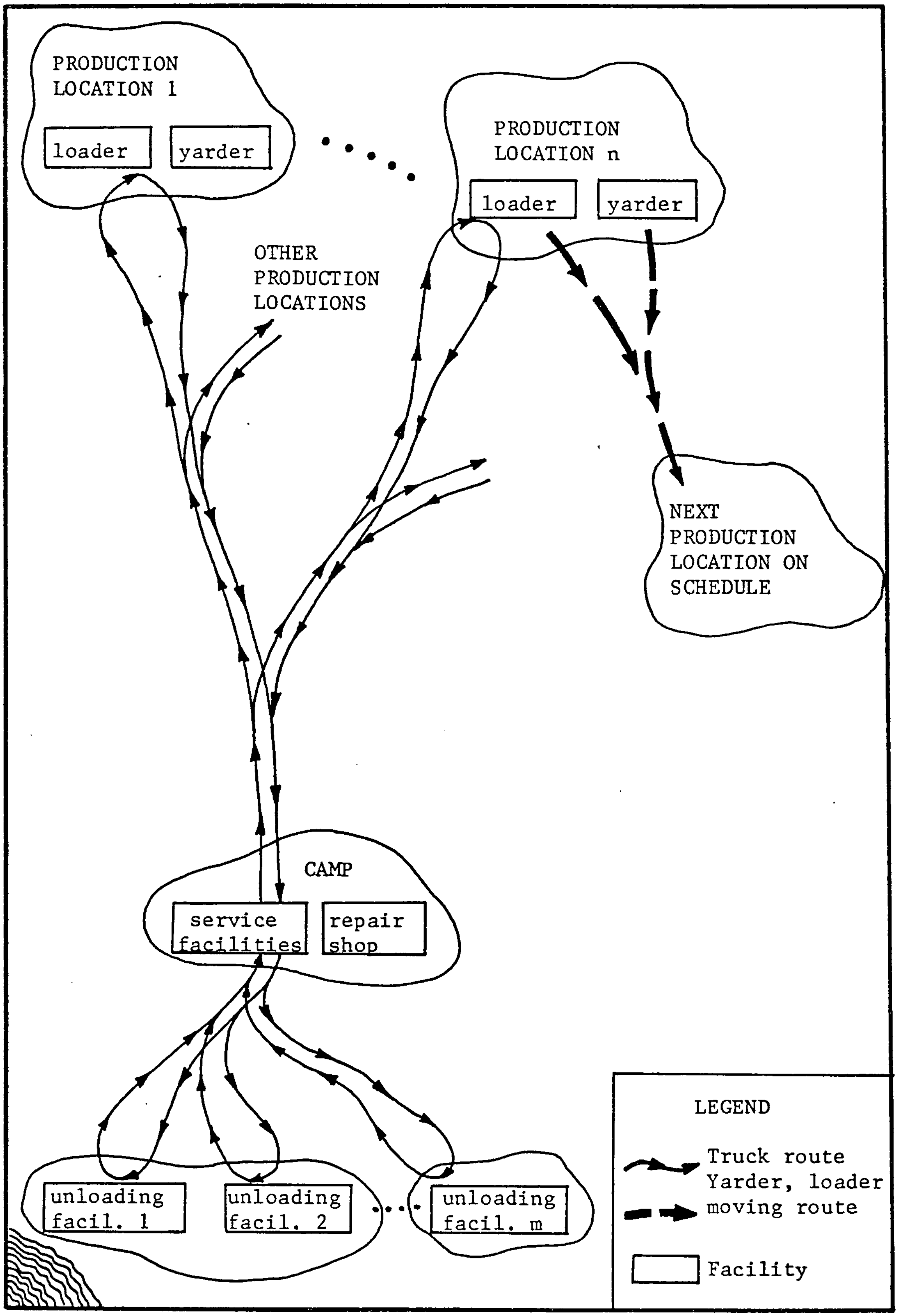


Figure 2.3 Schematic diagram of a logging system configuration with n sources, m sinks, and an intermediate node linked by a network of roads

include the elements of the logging subsystem, their attributes, their processing states, and their activities.

At this stage it is necessary to go from a generalized situation to a specific situation. In the subsequent development of this thesis, reference will be made to a specific West Coast logging division, namely that of the Canadian Forest Products Co., Ltd. logging division at Harrison Mills, B.C. The terminology, methods, and the level of technology are consequently peculiar to West Coast operations. Nevertheless, this logging division merely serves as a vehicle for model formulation and the approach may be applied to other specific situations.

This operation is a multi-source, single sink configuration with an intermediate node. Unless otherwise stated, each of the sources (sides) contains a harvesting unit (yarder) and a loader. The intermediate node is the camp where the repair shop and the several truck service facilities are located. The sink (dump) contains a single unloading facility. Adjacent to the dump is the marshalling yard where the different crews start and terminate their working day.

The "long-log" extraction and transport method, rather than the short-wood or the full-tree methods, is employed in this particular operation. That is, the trees are felled and limbed at the setting and the logs are yarded to a landing and transported to the dump unbucked when less than 60 feet. Otherwise, they are bucked once or twice to a length of 16 to 60 feet before they are yarded.

A. LOG EXTRACTION

The harvesting or yarding units may be classified into three types according to the nature of their interaction with the loader. The first type, exemplified by a Grapple yarder, works independently of the loader; thus the yarding process continues regardless of whether a truck is being loaded or not. On the other hand, the type exemplified by a "Trakloader" assumes both the yarding and loading functions; thus it can only do one function or the other at any given instant in time. The third type, exemplified by a High Lead yarder, falls into an intermediate category. Although the yarder performs only a yarding function, at particular times it interacts with the loader. Depending upon the position from which it is yarding and the location of the loader, safety considerations dictate whether or not yarding may proceed while a truck is being loaded.

Table 2.1 summarizes the components and activities of the yarding subsystem. The attributes listed directly or indirectly affect the rate at which the logs are yarded in and the amount of available yarding time. The sequence of activities listed indicates that the yarding process consists of a series of yarding cycles or "turns". Each turn results in the transfer of logs from the setting to the landing. This process is illustrated in Figure 2.4 in terms of volume-over-time step functions. The step functions consist of a series of alternating turn times and turn volumes whose magnitudes are stochastic as a result of the variability of conditions.

The slope and topography can be expected to be different for each side. When located on relatively steep hillsides, the landing size - and thus capacity - is usually small. Consequently, space becomes a major consideration since the yarding process is stopped when the landing becomes filled to capacity. This usually results from having too few

Table 2.1. The elements, attributes, and activities of the yarding subsystems

Elements	Attributes	Processing State	Sequence of Activities
Yarder	Yarder type Power and line speed Yarding road change time Rig-down and rig-up time Grappling time (for Grapple yarders)	Yarding (with choker)	1. Yarder hauls back the line 2. Crews sets choker around logs 3. Yarder hauls in the logs 4. Chaser releases the choker from the logs 5. Back to 1
Yarding crews	Hooking time Unhooking time Efficiency Experience Number of working hours	Yarding (with grapple)	1. Yarder hauls back the grapple 2. Logs are "grappled" 3. Yarder hauls in the logs 4. Logs are released at the landing 5. Back to 1
Logs	Sizes and size distribution Density (no./acre) Spatial distribution Pre-set (or not)	Not yarding (in case of: Yarder breakdown Landing filled to capacity Lunch break Yarder interacting with loader Yarder moving to another setting)	
Landing	Size and capacity		
Setting	Degree of slope and topography Amount of slash or vegetation Other ground conditions Weather conditions		

trucks dispatched to the landing.

Yarding is also stopped in the case of:

1. yarder breakdown,
2. lunch break,
3. the transfer of the yarder to another landing,
4. the re-positioning of the yarder in the same landing, and
5. other delays.

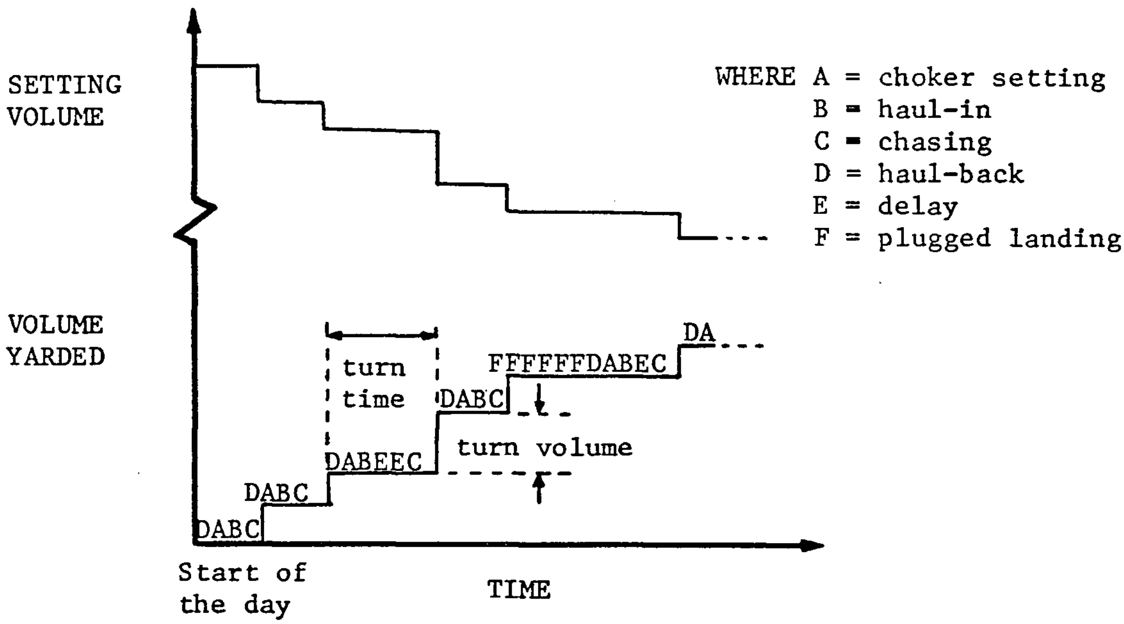


Figure 2.4 Hypothetical volume-yarded-vs.-time and setting-volume-vs.-time step functions showing the turn times and the turn volumes resulting from the turn activities.

B. LOG TRANSPORT ACTIVITIES

The transport of logs from the different production sides to the dump is done with logging trucks. The trucking fleet is composed of "small" trucks and "large" trucks. The attribute "small" refers to off-highway trucks with a design payload of 75,000 lbs. and "large" to off-highway trucks with 100,000 lbs. design playload. Each of the trucks may fail or may be assigned non-hauling duties ("bull-cooking") such as pulling a lowbed; thus the number of trucks available for hauling logs at any one time varies.

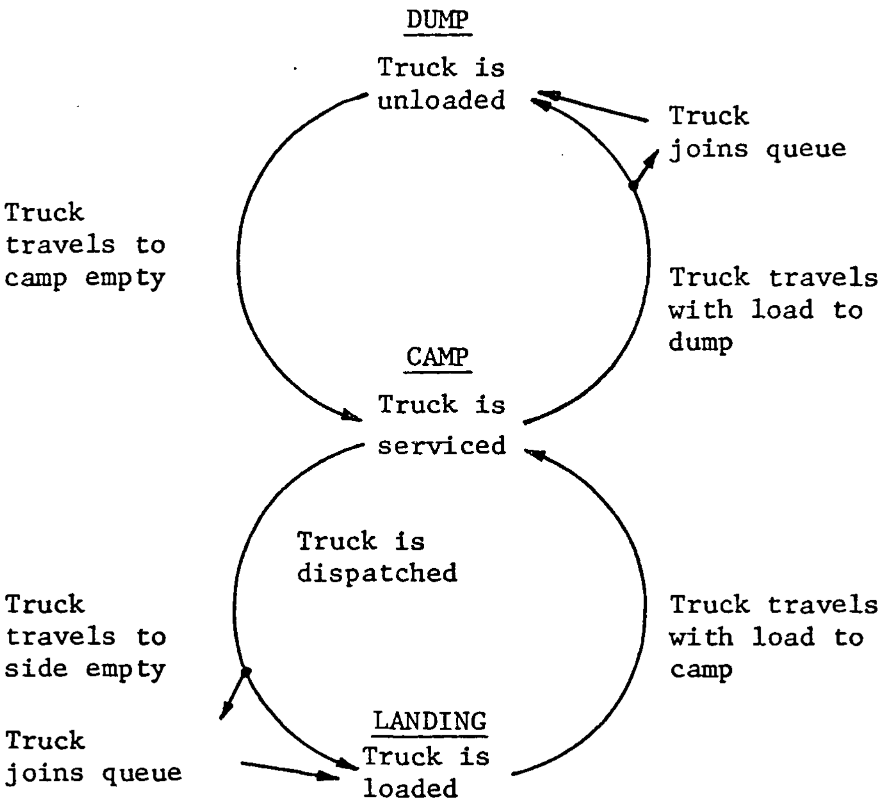


Figure 2.5 Schematic diagram of a truck round trip

Figure 2.5 illustrates a normal truck log-hauling route. Five main trucking activities can be identified, namely that the truck is:

1. being loaded,
2. travelling (empty or with a load),
3. being serviced at the camp (truck empty or with a load),
4. being unloaded, and
5. being dispatched.

Loading

Table 2.2. The elements, attributes, and activities of the loading subsystems

Elements	Attributes	Processing State	Sequence of Activities
Loader	Loader type Loading rate	The loader is busy	1. Truck arrives at the landing 2. Truck joins the queue
Truck and Trailer	Capacity Number and type of trailer Number in the queue	The loader is idle	1. Truck arrives at the landing 2. Truck positions for loading 3. Trailer is set in place 4. Loader loads logs 5. Truck leaves the landing
Logs	Sizes Size distribution Arrangement at the landing State (whether pre-loaded or not)	The loader is not in a working state in case of: 1. Loader breakdown 2. Loader moving to another landing 3. lack of logs due to yarder breakdown	Truck originally dispatched to this landing is re-dispatched to another landing

The components and activities involved in the loading of a truck are given in Table 2.2. To summarize, some of the characteristics of the loading activity are:

1. The loading of trucks is on a first-in-first-out basis. If more than one truck is at the landing at any one time, a queue developes. In certain cases when a particular truck is urgently needed for other duties, e.g. lowbed duty, the truck has a high priority in the queue.
2. As a result of the variability from time to time of several factors (e.g. loader rate, log size and size distribution, landing conditions, queue length), the time to load a truck and the volume of the load are random variables.
3. The loading time is dictated by the time necessary to yard more logs whenever the landing inventory is depleted as a result of having too many trucks dispatched to the landing within a short time.
4. When there are trucks waiting in the queue and the landing is short of logs, the truck being loaded departs with less than full load, provided "sufficient" volume has been loaded.
5. A breakdown of the loader closes the "side" temporarily. Yarding proceeds only until the landing is filled to its maximum capacity. Trucks in the queue are re-dispatched to other landings.

Travel Times

The travel time between two points of known distance for a particular vehicle type and vehicle state (e.g. loaded or empty) is also a random variable. It is a function of both the driver characteristics and the quality of the road system measured in terms of the traffic density, the number of turnouts, and the road standards of each section (i.e. the alignment, grade, width, surface, degrees of curvature, and sight distances of the road sections).

Camp delays

The truck service facilities such as the machine shop and the diesel oil, water, and tire shops are located in the camp. Trucks, whether in their loaded or empty state, arriving at the camp may stop to make use of the camp facilities. Since there are several facilities available at the camp, queues rarely form. If two trucks arrive at the camp within a short interval of each other, the truck with the shortest camp delay usually departs first.

Unloading

Table 2.3 The elements, attributes, and activities of the unloading subsystem

Element	Attributes	Processing States	Sequence of Activities
Dump	Size, shape and length of approach	The unloading facility is busy	1. Truck arrives at the dump 2. Truck joins the queue
Unloading facility	Type, efficiency unloading speed number of facilities	The unloading facility is idle	1. Truck arrives at the dump 2. Truck positions for unloading 3. Truck is unloaded 4. Trailer is set in place 5. Truck leaves the dump
Truck	Capacity trailer type number of trailers		
Load	Size		

Table 2.3 shows the components and activities involved in the unloading of a truck. Some of the characteristics of the unloading activity are:

1. Only one unloading facility handles the unloading of trucks in this particular operation. A queue forms if there is more than one truck at the dump at any one time.
2. Unloading is done on a first-in-first-out basis except that in cases where a particular truck is needed for lowbed duty, the truck is given a high priority.
3. The unloading time is a random variable. It is influenced by the unloading speed, as well as by the load characteristics.

Truck dispatching

The dispatching of empty trucks to the landings is carried out by the woods foreman. He is constantly informed through radio of the situation at each of the landings such as whether or not the loader is in working condition, what the landing volume status is, and what the length of the queue is. On this basis and knowing the location of all the other trucks, he dispatches all empty trucks that are either in or approaching the camp.

C. SUBSIDIARY ACTIVITIES

Moving of yarders and loaders to another landing

Two main types of activities connected with the "re-location" of the yarders can be recognized:

1. the re-positioning of the yarder within the same landing, and

2. the transfer of the yarder to another landing.

If one "face" of the setting is depleted of logs, it may be necessary for the yarder to be turned around before the opposite side can be accessed. In this case, the spar is "rigged down" before the yarder is turned around and "rigged up" before yarding can resume. When the setting is completely depleted of logs, the yarder is transferred to the next landing in the schedule. The transfer is done with the use of a lowbed if the moving distance is over a mile and if the yarder has a track-type undercarriage. If the moving distance is less than a mile or if the yarder has a tire-type of undercarriage, the yarder moves under its own tractive power to the next landing anchored where necessary by a logging truck. In both cases, it is necessary to "rig down" the spar and the lines and, as soon as the re-location is effected, to "rig up" the spar and the lines.

<u>Equipment maintenance, breakdown, and repair</u>

Since each yarder, loader, or truck has less than 100 per cent reliability, each of these items of equipment may fail. Upon failure, the machine stops the activity it is engaged in. In cases where a piece of equipment, at the moment of failure, is interacting with another equipment, the failure also affects the activities of the latter.

Repair of a yarder or a loader which has failed is normally undertaken in the landing by a mobile crew. When a truck fails, it is towed to the machine shop for repairs at the later part of the day by another logging truck. The machine shop generally maintains several repair crews on a double-shift basis. However, since the number of repair crews is limited, repair is done a priority basis. A yarder or a loader has a higher priority than a logging truck; thus when a yarder fails, a repair job on a truck is stopped if there is no other available crew. Whenever two machines of the same type are waiting for repair, repair is done on a first-come-first-served basis.

Each item of equipment is usually given maintenance on a regular basis. For instance, trucks are checked-up every third night. The fact that a truck is scheduled for a check-up usually affects the activities of the truck at the day's end. For instance, since the truck is required to be at the camp at the end of the day, it is not dispatched to a landing unless it is certain that it has time for a complete round trip. If the dump is already closed, a truck leaving a landing and due for a check-up is shutdown at the camp in its loaded state.

Start-up and shutdown modes

The start-up sequence of activities dictates the time of the start of each of the activities of the operation at the beginning of each day or shift. On the other hand, the shutdown mode determines the manner by which each of the machines and their crews are shutdown at the end of each regular shift. The start-up sequence of activities and the two currently practiced shutdown modes used in this study are outlined in Appendix A. The shutdown modes are further studied and compared in Chapter VI.

CHAPTER III

THE LOGGING SYSTEM SIMULATION MODEL

A simulation model is merely a laboratory where the manager can test empirically each alternative generated in the study of a problem. While the limitations of "analytic" models do not apply to simulation, the requirements for feasible experimentation must be satisfied when using simulation, if the technique is not to be restricted by the same limitations inherent in real-world experimentation. The justification for the use of simulation rests on the inadequacy of intuition, the inability of known "analytic" models to cope with the complexity of the problem, and the infeasibility of real-world experimentation. Thus it should be shown that the reasons that prevent the use of these other methods are eliminated by the use of simulation. It is imperative that the simulation model be capable of:

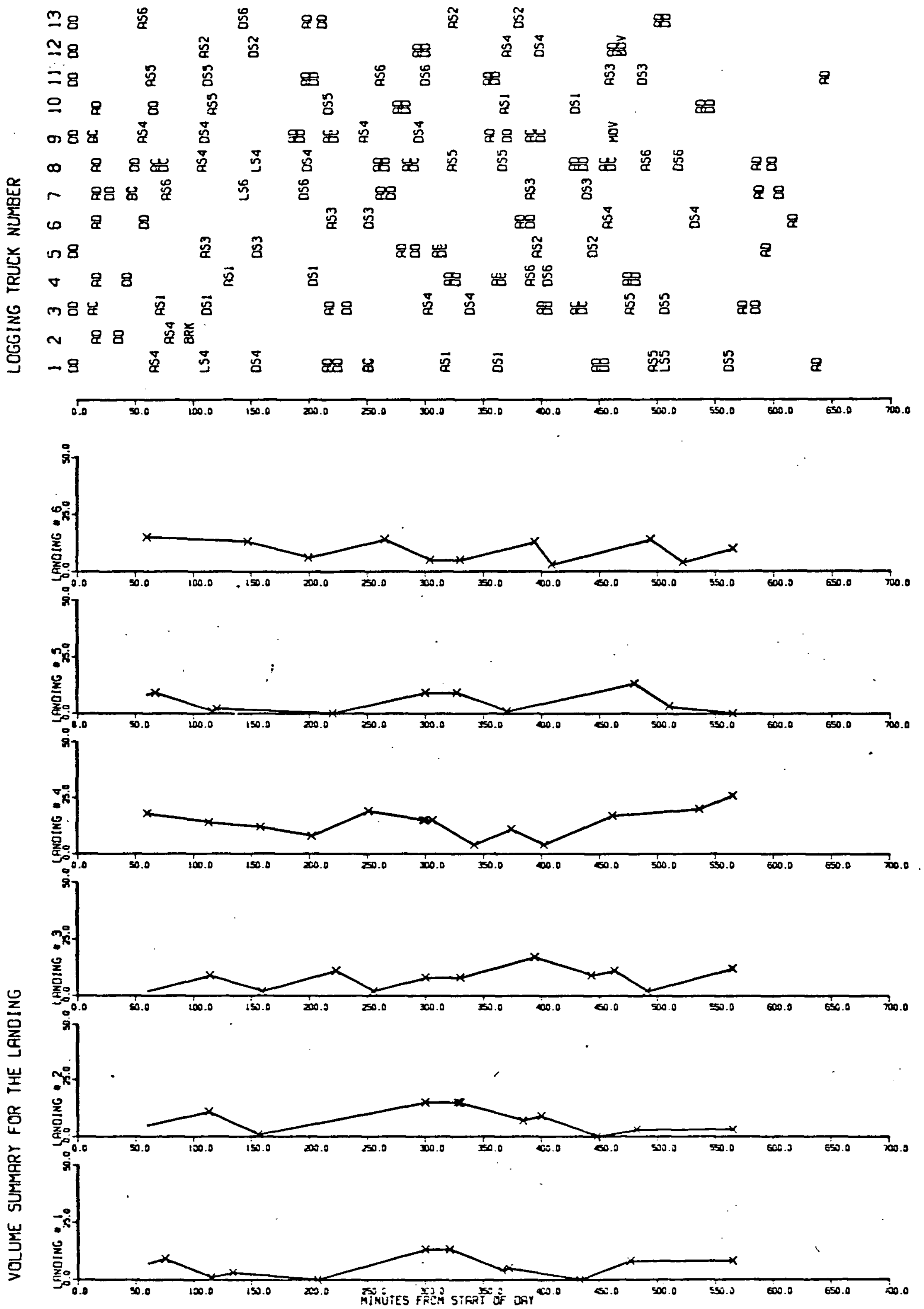
1. providing for the important characteristics of logging problems such as the existence of interacting events of stochastic nature, which affect the manner in which the independent variables of the system are related with the various system responses,
2. flexibility to enable the examination of a wide class of alternative system configurations, and
3. fast execution to make feasible the use of experimentation.

The subsequent development of this chapter and of this thesis is directed towards presenting how these requirements are met by the use of a logging system simulation model in the analysis of a wide class of logging problems.

3.1 THE SIMULATION FRAMEWORK

The model developed in this study is a discrete-event simulation model which mimics the behaviour of the real system by the examination of the system model and the updating of the variables indicated by the system operating rules at the event times. To illustrate how these are carried out, as well as to give an indication of the degree of resolution of the details incorporated in the model, Figure 3.1 is given. The figure illustrates the various events that could occur in a typical day's operation for a 6-yarder, 13-truck configuration. In using the figure, the reader is referred to the accompanying legend for the identification of the events that correspond to the given event symbols.

The state of each of the various elements of the system is described by one or more state variables. For instance, the number of round trips made, the volume hauled, the number of miles traveled, and the number of hours worked are some of the state variables that describe the performance of a logging truck. Collectively, the different state variables compose a state vector which describes the over-all state of the system at any one time. For instance, by drawing a vertical line across the individual graphs in Figure 3.1 at any given point on the time axis, and by reading or calculating the values of the different state variables, e.g. number of trucks at each location, volume at each landing, number of loads, etc., one can describe the logging system in terms of the activities and performance of its various subsystems.



PLOT FOR DAY 2 WITH 13 SMALL TRUCKS

Figure 3.1 Summary of truck events and landing volumes for a simulated day

CODED TERMS USED FOR THE TRUCK EVENTS

Code name		Definition
AD	=	arrival at the dump
DD	=	departure from the dump
AC	=	arrival at the camp
DC	=	departure from the camp
ASn	=	arrival at side n (start of loading if the loader is idle
LSn	=	starting of loading at side n (implies truck was waiting in the queue)
DSn	=	departure from side n
BRK	=	instant of breakdown
MOV	=	departure from camp to support the moving of a yarder to another landing

Note: The time interval between DSn and AD includes camp delay.

Figure 3.1 - cont.

Each of the letter symbols given in Figure 3.1 represents an event performed by the corresponding logging truck. The event is either an initial point or a terminal point of an activity whose duration is indicated by the time interval between the adjacent events. For instance, the activity "incurring a camp delay" is preceded by the event "arrival at camp" and superceded by the event "departure from camp".

By pooling all the event times in one time axis, one can observe from Figure 2.1 the sequence of events for the system for the given day. In simulating the system, each event in the schedule was "executed" one after another. The execution of each event involved (1) the updating of the state variables indicated by the operating rules of the corresponding event routine and (2) the scheduling of the next event to occur in the corresponding subsystem.

A discrete-event simulation model therefore requires an event scheduler that maintains and updates the list of events of the system and different event routines that execute the corresponding event chosen from the events list as the next event to occur. These items, together with a set of executive routines that perform the functions of initializing, coordinating, outputting, extending, or terminating a program run, constitute a simulation model of the system.

A simulation model of the system can be viewed as the union of two highly interrelated logical structures: (1) technological logic that represents the technology of the system, its description and its rules of operation, and (2) structural logic that controls the operation of the model in simulated time and performs the executive and event-selection tasks associated with discrete-event simulation models. (Pritsker and Kiviat, 1969).

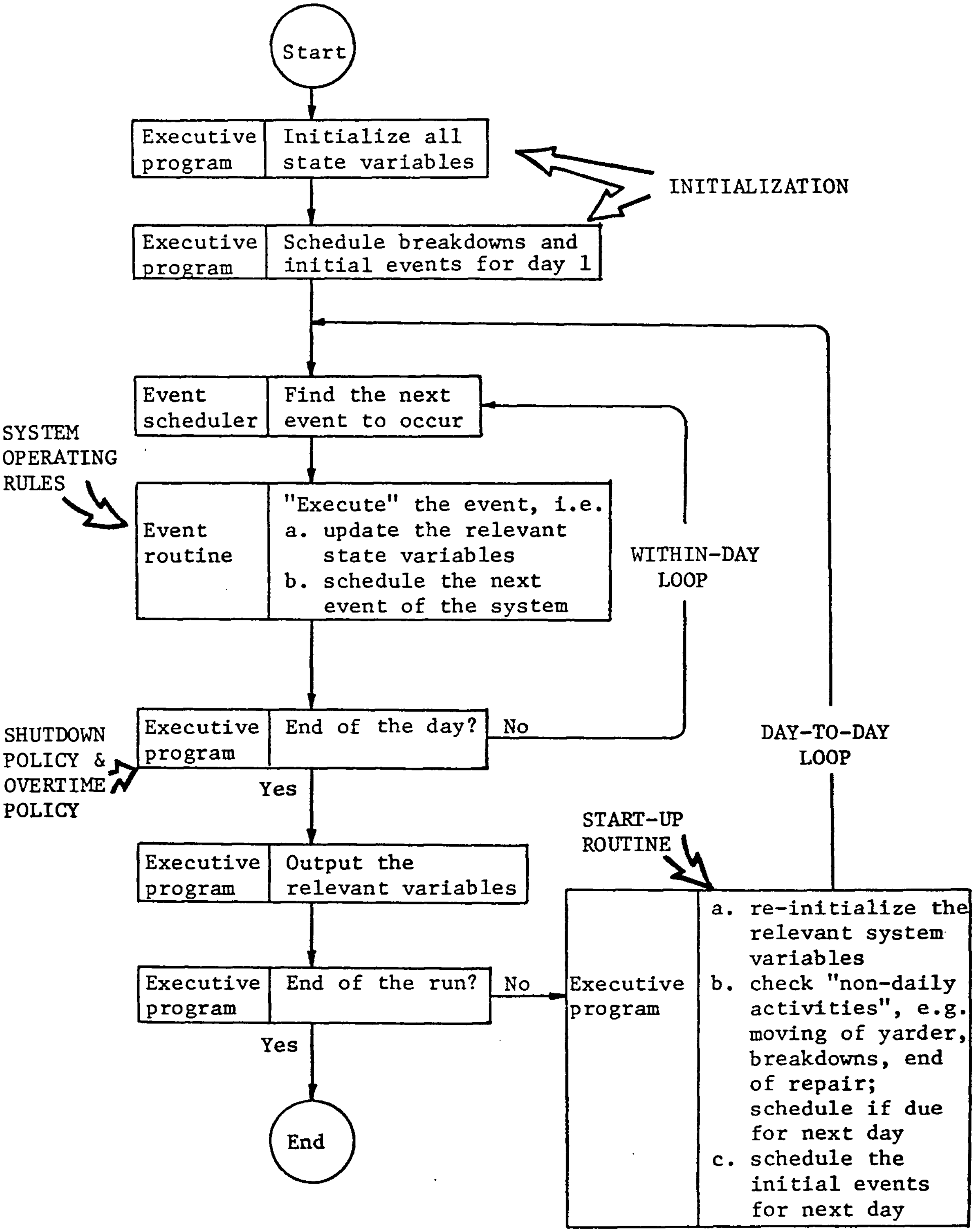


Figure 3.2 A conceptual flow diagram of the forest harvesting simulation program

Since the policies, operating rules, and level of technology of logging operations vary, each logging operation is unique and consequently each logging system simulation model is unique. However, as indicated previously, most processes involved in harvesting logs are common to all logging operations. These common features and the common structural logic inherent in all discrete-event simulation models allow the development of a general framework from which individual operations may be modeled. This framework is illustrated in a conceptual flow diagram shown in Figure 3.2. The figure shows three distinct parts of a discrete-event simulation model namely: (1) an executive program, (2) an events scheduler, and (3) a set of event routines. The succeeding sections will contain discussions of each of these items.

3.2 THE EXECUTIVE PROGRAM

Among the different functions of the executive program indicated in Figure 3.2, the executive program effects and coordinates the examination of the system at the event times. Figure 3.3 illustrates how the executive program performs this function for an event inside the "within-day activity loop", first by directing the event chosen from the events list to the proper event routine, and next by checking for end-of-day conditions before "asking" the event scheduler to select the next event.

Each of the different activities included in the model may be classified as a "daily" or a "non-daily" activity. An important function of the executive program is the checking before the start of the next simulated day for whatever "non-daily" activities, e.g. moving of yarder, equipment breakdown, end of repair, etc., that may be due to occur. For instance, if a yarder is calculated to have yarded all logs in the setting within the next day, the transfer of the yarder to another setting is initially scheduled for the next day.

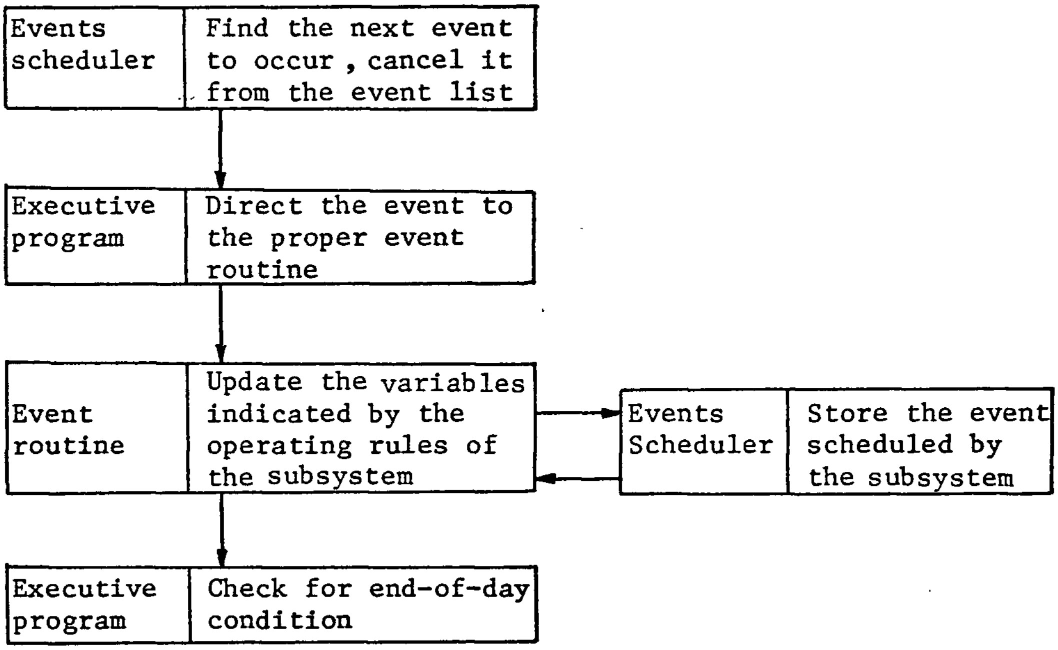


Figure 3.3 A flow diagram of the execution of a typical "within-day" event

3.3 THE EVENT SCHEDULER

There are three basic operations connected with the event scheduler, namely: initialization, event insertion, and event deletion. The initialization operation, which is performed only once during each model "run", sets up all the arrays needed by the scheduler for maintaining the event list. The event list stores the time of occurrence and other attributes of all scheduled events. In an event deletion operation, the event with the smallest time is deleted from the list and passed on to the event routine for execution. During execution, the event routine schedules the next event to occur for the subsystems. The event insertion operation handles the inclusion of this event into the events list. A detailed flow chart of each of these operations, as well as a table illustrating examples of the initialization, event insertion, and event deletion procedures, is provided in Appendix B.

It is evident from the above description of the event scheduling functions to be performed, that the event scheduler is an important factor in the development of an efficient simulation program. This consideration justified the development of an event scheduler with a "singly-linked-list" structure. The items in a "singly-linked-list" are linked by a "pointer array" which indicates, for each item in the list, the address in the computer memory of the next item to follow. Thus the deletion (or insertion) of items from the list does not require the relocation of the other items in the list to fill the space vacated by the deleted item, since this only requires the updating of two items in the "pointer array". For a more detailed description of "singly-linked-list" data structure, the reader is referred to Knuth (1968).

The routines in GASP II (Pritsker and Kiviat, 1969) a FORTRAN-based simulation language, similarly employs a linked-list structure. However, GASP II uses a "doubly-linked-list" structure which has other features not found in a "singly-linked-list" structure, but which is relatively less efficient, since two, rather than one, "pointer arrays" require updating each time an event is inserted or deleted.

3.4 THE EVENT ROUTINES

Figure 3.4 shows a schematic representation of the logging

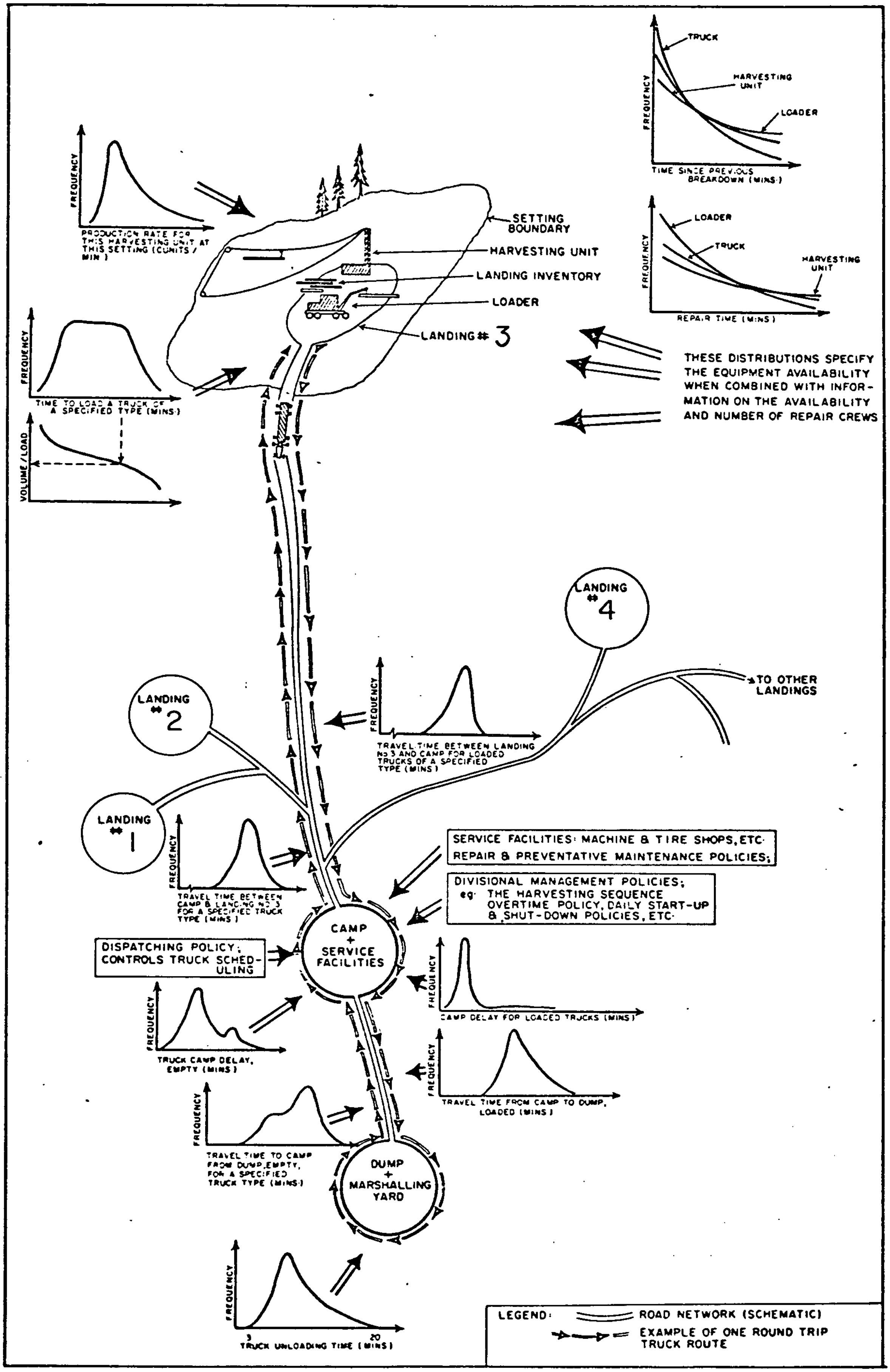


Figure 3.4 A schematic diagram of the logging system

system. The different physical subsystems are depicted together with their stochastic components. The policies and operating rules which govern the operation of the logging system are also shown. The different physical subsystems are represented in one or more event routines.

The various routines in the model include:

1. Yarding (This routine appears in several places in the program where the updating of the landing inventory is required.)
2. Loading
3. Hauling (This routine includes truck travel to the camp with a load, camp delay, and truck travel to the dump.)
4. Unloading
5. Truck travel to the camp (empty)
6. Camp delay (empty)
7. Truck dispatching and travelling to the side
8. Travel time generation
9. Time check
10. Start-up (This routine is incorporated in the executive program.)
11. Start of moving of yarder
12. Termination of moving and setting-up of yarder
13. Termination of moving of loader (The moving of a loader to another landing is initiated either in the loading routine after the last load has been loaded or in routine 12 as soon as the loader is ready to move.)
14. Arrival of support truck for moving of yarder
15. Arrival of lowbed
16. Yarding crew lunch break
17. Equipment breakdown
18. End of equipment repair and resumption of duties
19. Overtime
20. Towing of broken down truck

The flow diagrams for each of these routines are included in Appendix H.

Chapter II provided the description of the components, activities, and operating rules of each of the physical subsystems. In the succeeding subsections, additional presentation of the highlights, assumptions, and justifications not included previously in the subsystem description are given. These include:

A. The representation of the yarding process
B. The generation of the yarding rate for each simulated day
C. The loading-time - volume-loaded relationship
D. Travel time
E. Camp delay
F. Truck dispatching
G. Equipment breakdown
H. Repair times and resumption of duties after repair
I. Overtime.

A. THE REPRESENTATION OF THE YARDING PROCESS

In Chapter II, the yarding process was described as a step function consisting of a series of alternating turn times and turn volumes whose magnitudes are stochastic (Figure 2.5). This suggests a realistic representation of the yarding process by a step function, where the turn times and the turn volumes are generated from separate distribution functions. These distributions should, explicitly or implicitly, account for the effect or influence of the attributes such as log size and size distribution, number and distribution of logs per acre, yarder type, crew composition, etc. Clearly, a big disadvantage of this representation is its very fine resolution of detail which makes the entire model unnecessarily complicated.

Unless the particular problem on hand requires a realistic representation of the yarding process, a linear function, where the slope is the mean yarding rate for the day, should suffice to represent the yarding process. In this case, the mean yarding rate for each day is generated from a stochastic yarding model. This "ramp" model and the more realistic "step" model are compared in Figures 3.5 and 3.6 from a theoretical standpoint. Both models are assumed to have the same yarding rate; thus the volume-yarded-plus-initial-volume (referred to as V) curve for the step model (V_s-curve) is shown to fluctuate about the V-curve for the ramp model (V_r-curve).

Figure 3.5 illustrates the case where the total trucking capacity is less than the total yarding capability. In this case, the presence of sufficient quantity of logs in the landing prevents any

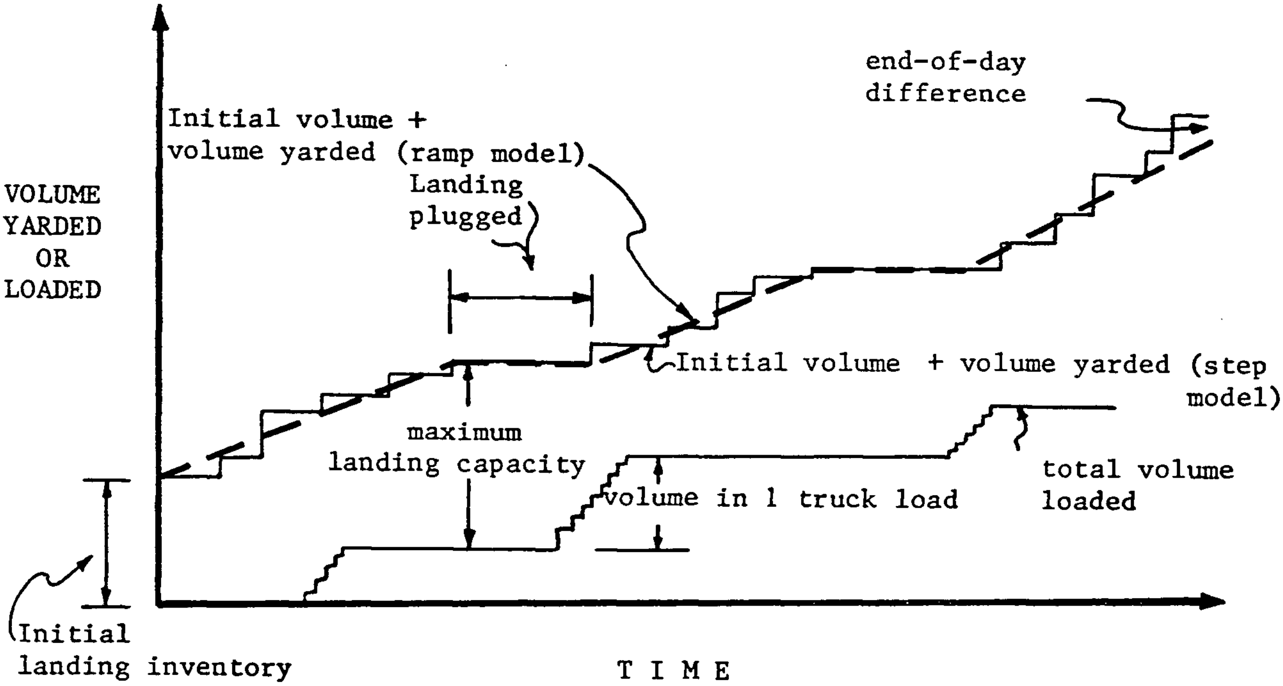


Figure 3.5 Hypothetical case: total trucking capacity less than total yarding capability resulting in plugged landings

direct interaction between yarding and loading.[1] For all practical purposes, the step model is equivalent to the ramp model in this particular case.

In the case where the total trucking capacity is equal to or greater than the total yarding capability, yarding directly interacts with loading whenever the landing inventory is not sufficient to complete the load of a truck. In this particular case, a difference between the two models exists in both time and volume. When the landing inventory is insufficient for a load and when V_r is less than V_s (lower part of Figure 3.6), the time of departure of the truck for the ramp model is a few minutes later than the departure time of the truck for the step model. This is because the truck has to wait for the yarder to supply more logs. Also since policy dictates in this case that the truck has to leave with less than a full load, the volume loaded for the ramp model is less than the volume loaded for the step model. When V_r is greater than V_s and the landing inventory is insufficient for a load (upper part of Figure 3.6), the reverse is true.

These time and volume differences between the two models are inconsistent; thus it may be safe to assume that these differences tend to cancel each other. In the absence of sufficient data at the moment to build a step model, it is difficult to assess the effect of using the linear approximation. For purely intuitive reasons, these differences are deemed small especially when the entire fleet of yarders and trucks

1 The discussion and figures in this section are representative of a Grapple or High Lead type of yarder. However, with a slight modification pertaining to the direct yarding-loading interaction, the discussion and figures should also hold for a "Trakloader" type of yarder.

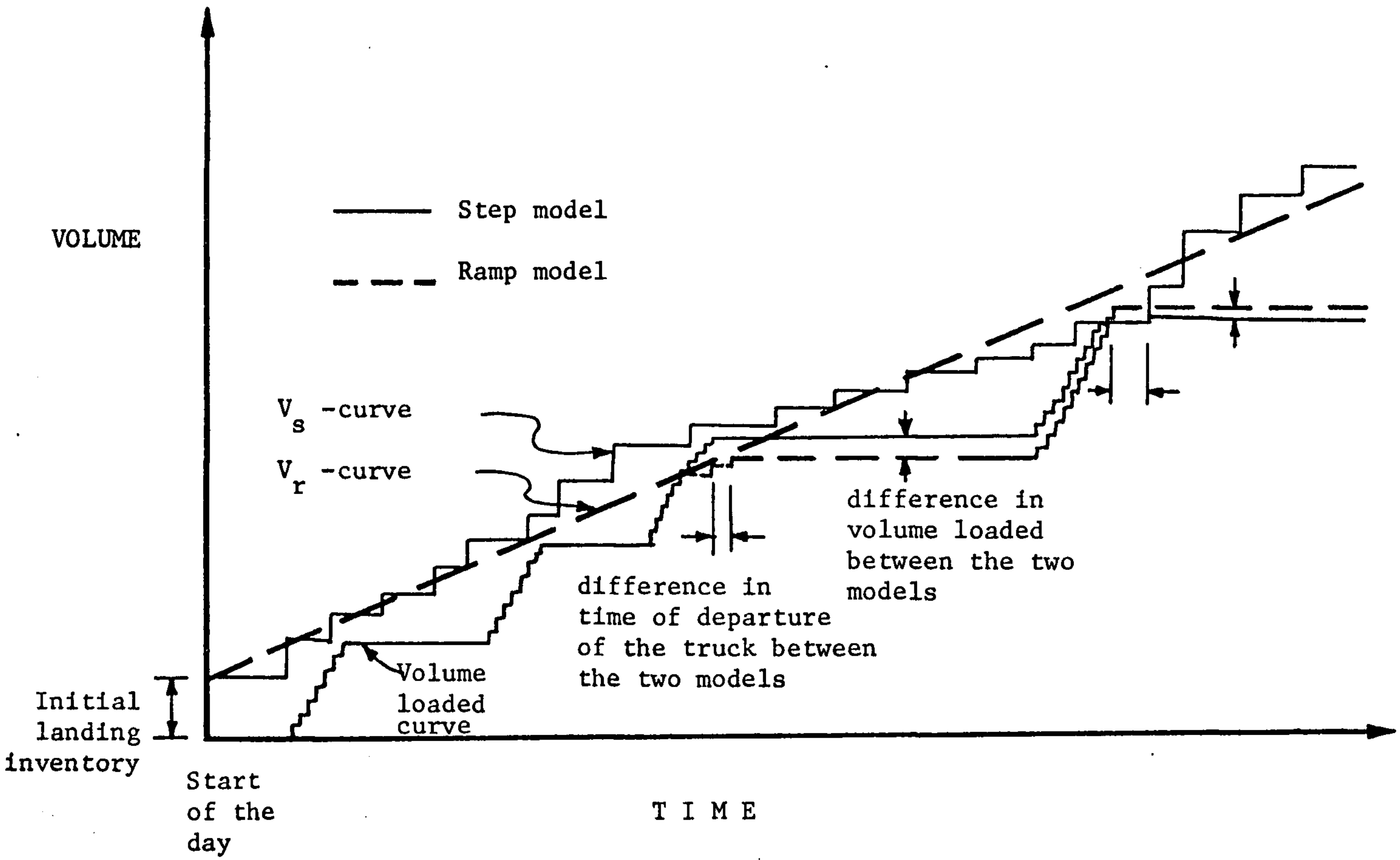


Figure 3.6 Hypothetical case: Total trucking capacity greater than or equal to the total yarding capability

are considered. Also, these differences appear only in those configurations where the number of trucks in the fleet is higher than the "optimum" number. This tendency to amplify these differences in the "non-optimal" configurations should be an advantage rather than a disadvantage. Therefore, unless the problem requires a detailed execution of each yarding turn, the ramp or linear model is deemed sufficient to simulate the yarding process, and in the subsequent development of the model, the ramp model is used.[1]

B. THE GENERATION OF THE YARDING RATE FOR EACH SIMULATED DAY

Daily production figures for 4 High Lead yarders were collected from the 1968 operation of the CANFOR logging division at Harrison Mills, B.C. with the number of observations ranging from 100 to 131. Treating the series of daily yarding production values as a stationary time series, a stochastic time series model was fitted for each of the four yarders.[2] The results show that the yarding production time series for each of the four yarders can be adequately represented by either an autoregressive process of a certain order or by a mixed autoregressive-moving average process. Of the four yarding production time series examined, two are third order autoregressive processes, one a first order autoregressive process, and the other a mixed first order autoregressive-first order moving average process.

To simulate the yarding process, the ramp model is employed using a yarding rate generated from a stochastic time series model fitted for the particular yarder. A mean yarding rate and a yarding

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1 The arguments presented in this subsection have not explicitly taken into account the dependence of the turn times on the yarding distance. Nevertheless, these arguments should hold regardless of this dependence.

2 Appendix F contains a discussion on time series analysis including the process of identifying, fitting, and checking a stochastic time series model.

rate variance are needed as parameters for the time series model. For problems involving the forecasting of logging production, the mean and the variances may be treated as endogenous variables which should reflect the stand, topographic, ground, and weather conditions for each setting.

To illustrate the generation of the yarding rate using a stochastic time series model, a set of equations for a second order autoregressive model is provided below.

$$\sigma_A^2 = \sigma^2 \; (1 - P_1C_1 - P_2C_2)$$

$$X_t = \mu + C_1 \; (X_{t-1} - \mu) + C_2(X_{t-2} - \mu) + A_t$$

$$R = X_t/475$$

where:

σ^2 = variance of the daily yarding production time series

σ_A^2 = variance of the "white noise" process $\{A_t\}$

A_t = the white noise value at t generated from a normal distribution with mean 0 and variance σ_A^2

P_i = the autocorrelation value for lag i

$C_i, i=1,2$ = the autoregressive parameters

μ = the mean daily yarding production (in cunits)

X_{t-i} = the yarding production value for day t-i (in cunits)

R = the yarding rate in cunits/minute (There are 475 minutes available for yarding in each standard shift.)

C. THE LOADING-TIME-VOLUME-LOADED RELATIONSHIP

The activity of loading a truck is represented in the model by the generation of an aggregate loading time and an aggregate volume loaded. Aggregation is done to avoid cluttering the model with unnecessary details. Unaggregated, the loading activity includes: (1) the positioning of the truck for loading, (2) the setting up of the trailer, (3) the loading of each log onto the trailer, and (4) the binding of the load. These four activities can be aggregated as the loading activity. With aggregation, the physical subsystem can be modeled with more clarity than can be achieved without aggregation.

Inverse cumulative distribution functions are available for generating both the loading time and the volume loaded.[1] In the absence of previous studies relating these two variables, the following hypothetical relationships were tested:

1. That the volume loaded is independent of the loading time.

   i.e. volume loaded = $f(X)$ where $X \sim \text{Uniform } [0,1]$
   loading time = $g(Y)$ where $Y \sim \text{Uniform } [0,1]$
   X and Y are generated separately, and where f and g are inverse c.d.f.'s.

2. That the relationship can be represented by the use of common random variates,

   i.e. volume loaded = $f(X)$
   Loading time = $g(X)$ where $X \sim \text{Uniform } [0,1]$

   (Note that a direct relation: volume loaded = h(loading time) reduces to: volume loaded = $h(g(X))$ which further reduces to $f(X)$ after setting $f=h.g$.)

1 The data collection and fitting of inverse cumulative distribution functions are discussed in Section 3.6.

3. That the relationship can be represented by the use of "antithetic" random variates,

i.e. volume loaded = f(1-X)

loading time = g(X) where $X \sim$ Uniform $[0,1]$.

Results of the several runs tabulated in Table 3.1 show no significant differences among the three relationships for each of the five system responses. This shows that the model is insensitive to change in the structure of the relationship between loading time and the volume loaded, at least in those forms considered.

The model, in its present form, uses the third relationship. This relationship is preferred over the other two given since it is intuitively more appealing. Using this relationship, an average loading time results in an average volume loaded. A low loading time results in a high loaded volume as would happen when large logs are loaded. On the other hand, a high loading time results in a low volume loaded as would happen when small logs are loaded.

D. TRAVEL TIME

It is assumed in the model that the road network is divided into distinct road sections, each having a different set of road standards. For a given direction of travel, generating a travel time between two points requires (1) the generation of an average velocity for each section included between the two given points, (2) the calculation of the travel time for each section as a function of the section distance and the generated average velocity, and (3) the summing up of the individual travel times. Assuming that there are n sections and m truck types, the model will require mn different average velocity generating functions for each of the two truck states (empty and loaded) or a total

Table 3.1 The means of the indicated dependent variable for the specified loading-time-volume-loaded relationship and the number of trucks in the hauling fleet.

Dependent variable	Relationship between the loading time and the volume loaded	Number of trucks 9	14	20
(Total) $/cun.	Antithetic variates	19.34	15.11	15.89
	Common variates	19.31	15.10	15.89
	Independent variates	19.53	15.14	15.92
Cunits hauled	Anthithetic variates	261.54	378.49	383.48
	Common variates	259.54	378.81	383.03
	Independent variates	256.31	375.78	382.90
% Utilization (Trucks)	Antithetic variates	96.42	92.90	83.17
	Common variates	96.46	92.75	83.58
	Independent variated	96.66	92.82	83.32
% Utilization (Yarders)	Antithetic variates	69.88	97.86	98.96
	Common variates	69.92	97.76	98.62
	Independent variates	68.83	97.54	99.30
Number of loads hauled	Antithetic variates	19.64	29.73	32.17
	Common variates	19.51	29.79	32.15
	Independent variates	19.23	29.29	32.21

Length of the runs = 75 days

Number of yarders = 6

The standard error of the mean varies from 0.30 to 4.83 per cent of the mean.

of 2mn generating functions.

The above representation assumes that (1) traffic density differences do not significantly affect travel time over the entire set of logging configurations examined in the investigation, and that (2) the travel times can be generated independently.

The first assumption arises because, although traffic density is implicitly incorporated in the empirically based generating functions for the basic configuration where the data were collected, the model uses the same set of generating functions for configurations different from the basic configuration. Nevertheless, this assumption is justified in the case of loaded trucks since they always have the right-of-way. In the case of empty trucks, the assumption is justified for road sections wide enough to accomodate two-way traffic. For narrow road sections with an adequate number of turnouts, the effect of this assumption should be negligible.

As a result of the second assumption, it is not ensured in the model that when two trucks are dispatched to the same destination, the first truck dispatched is the first to arrive. This situation is possible since minor breakdowns, e.g. flat tire, are incorporated in the travel time distributions. In any case, the improvement resulting from a more realistic representation is deemed insignificant and insufficient to justify the added complexity it imposes.

E. CAMP DELAY

The facilities for minor truck repairs and for truck maintenance and service are located at the camp. While these are separate facilities, in the model the frequency distribution of the length of time spent by the trucks in these facilities are pooled into one frequency distribution. This representation is justified by the relatively insignificant magnitude of these "camp delays" compared to the entire round trip time.

F. TRUCK DISPATCHING

The dispatching of empty trucks to the settings is handled by a dispatching routine. The dispatching routine requires a set of information such as the setting distances, the inventory at each landing, the number of trucks previously assigned to each setting, the yarder productivity, and the length of the different queues. This is analogous to the real-world dispatcher possessing the most recent information and being kept informed through radio of the situation at each landing.

The underlying objective followed for the dispatching routine is the maximization of production subject to the available resources. For the dispatching routine to meet this objective, both the yarding and trucking considerations must be appraised. Enough trucks must be assigned to each landing to prevent the stoppage of yarding resulting from lack of space in the landing. At the same time, truck delays due to queueing or waiting for more logs should be minimized.

At any given instant that a dispatching decision is required, the underlying objective of maximizing production cannot be clearly laid out. Instead it is translated to the above secondary objectives, i.e to balance the landing volumes and to minimize the trucking delays due to queueing or waiting for logs. A set of rules geared towards meeting these objectives is followed by the dispatching routine. The dispatching routine goes through the following steps:

1. Check all landings for feasibility of assignment:

   a. If the loader is "down", cancel the arrival of all previously dispatched trucks and re-dispatch these trucks.

   b. If the yarder is "down", check the number of loads the landing inventory is equivalent to. This number should not be exceeded.

   c. If the yarder is moving to another landing, check if enough trucks have been dispatched to clear the old landing.

   d. Note the landing inventory, the yarding rate, the length of the queue, and the number of scheduled arrivals.

2. Classify the landings into two groups:

   a. Landings which can give a ready load, i.e landings without any queue and whose landing inventory is at least a load.

   b. Landings which can give a truck load after only a few minutes wait (due to queueing or lack of logs).

3. Rank the landings according to the following set of rules:

   a. To enable the early transfer of the loader to the next landing, give the highest priority to landings whose yarder is moving to the next landing provided that the remaining landing inventory can support another load and that there is no queue at the landing.

   b. Rank landings in group 2a according to volume if the time is earlier than 1:00 P.M. or according to distance from the dump if the time is after 1:00 P.M..

   c. Rank landings in group 2b according to waiting time.

4. Rank the trucks to be dispatched first according to capacity (large trucks first) and next according to time of departure from camp.

5. Match the trucks to the landings according to rank, i.e. let T_i denote truck with rank i and L_i to landing

with rank i. Assuming that the number of trucks is greater than the number of landings by m, matching proceeds as follows:

Match T_1 to L_1
....
T_n to L_n

T_{n+1} to L_1
....
T_{n+m} to L_m

(provided the landing is capable of loading the truck within the same day. Otherwise, the truck(s) stays at the camp.)

G. EQUIPMENT BREAKDOWN

Studies by Drinkwater and Hastings (1967) on army vehicles and by Lambe (1970) on Ford passenger vehicles show that the frequency of breakdown follows a Poisson distribution. Their studies also show that the cost of repair can be represented as a random sample from an exponential distribution. Vandenboom (1971) found for CANFOR logging truck components that the frequency of failure is characterized by a time-dependent Poisson process. This implies that the inter-failure time for logging trucks may be represented as a random sample from an exponential distribution whose parameter is dependent upon the age of the vehicle.

In this model, it is assumed that each logging truck, yarder, and loader has an inter-failure and repair time generated from separate exponential distributions. It is also assumed that a rigorous and careful maintenance policy is followed for the unloading facility and thus its probability of breakdown can be considered negligible. As used here, inter-failure time is not measured in terms of clock time but in terms of the time the machine actually spent on its function. For instance, the number of minutes that yarding stops, due to too much wood accumulating in the landing resulting from loader breakdown or too few trucks dispatched, is excluded when calculating the "time to next breakdown" for yarders.

At the start of each run, a "time to next breakdown" is randomly assigned to each yarder, loader, and logging truck. This operation is included in the breakdown initialization routine. After each simulated day, "the time spent on the job" for each machine is subtracted from the "time to next breakdown". If the updated "time to next breakdown" is small enough, the breakdown of the equipment is scheduled for the following day.

H. REPAIR TIMES AND RESUMPTION OF DUTIES AFTER REPAIR

As previously mentioned, it is assumed that each yarder, loader, and truck has a repair time generated from an exponential distribution. After repairs, the resumption of duties for the yarder and the loader follows immediately. For the truck each breakdown is considered a major breakdown and since its repair does not start until after it is towed to the shop, the resumption of activities after repair does not proceed until the following day.

I. OVERTIME

An interface for combining the simulation model with an overtime policy submodel is provided. The decision to go into overtime is made before 2:00 P.M. each day in accordance with labour agreements. The overtime routine relays information on the availability, productivity, and landing inventory of each side; the production of the whole operation until that time; and the expected production if the operation does not work overtime. Assuming a decision to work overtime has been made, the overtime routine requires as input the number of extra trips to be made and the identification of the sides (yarding and loading crews) to work overtime. The simulation of the day's operation proceeds until the rquired number of extra round trips is completed.

Since only a certain number of sides may be available for overtime, an overtime dispatching routine is provided as an alternate to the main dispatching routine. The overtime dispatching routine consists of assigning serially each side on overtime to the trucks to be dispatched.

3.5 THE SIMULTANEOUS OCCURRENCE OF SEVERAL EVENTS

So far the presentation has dealt only with events occuring singly or in series, for instance truck travel followed by arrival at the side and loading or queueing. The real world, however, behaves in an unpredictable manner and several events may occur simultaneously or within short intervals of each other causing activities or conditions which overlap and interact. Assuming that there are n simple events known for the system, theoretically there are $\sum_{i=1}^{n} \binom{n}{i} = 2^n - 1$ possible events and event combinations of order ≥ 2 that could occur. The model of the system should be capable of accounting for each combination of events that may occur.

Of the total possible number of combination of events, the majority is composed of mutually exclusive or non-interacting events. The effect of third and higher order interactions are usually confounded with the effect of second order interactions; thus "pure" interactions of order greater than two are virtually non-existent. Also, a considerable number of event combinations do not produce significant effect on the system performance. Nevertheless, regardless of whether or not the effects of a combination of events on the system responses are significant, the model should cope with such occurrences. Since in the real situation each simultaneous occurrence of several events is adequately handled, the representation should reflect this stability. Earlier experiences with the logging model have shown that models show grossly unrealistic results if no appropriate branches in the logic flow account for possible combinations of events, even when such combinations do not contribute significantly to the overall performance of the system.

A significant problem in the simulation of a system is the immediate recognition of non-obvious combination of events which may affect the performance of the system. After recognizing these event combinations, the remaining modelling task consists of determining which event combinations to consider significant, providing extra routines to handle the more significant event combinations, and providing default branches to handle the less significant event combinations.

Whenever a possible event combination has been identified, the criteria used to decide what courses of action to follow in its representation are:

1. The likelihood of its occurrence.
2. The magnitude of its effect on the system responses.
3. The ease of its representation.
4. The computer time and storage requirements for its inclusion.

In modelling a system, the first priority is placed on the "adequate" representation of the main events occurring either singly or in sequence. When accounting for the second-order interactions, past experience with the logging model has shown that, although there is a need to represent these interactions in the model, simplifications can be made without significantly affecting the system responses. That is, the representation of these interactions is more important than the degree of realism that is introduced (assuming that the representation is reasonable). If the object of the study is to compare two or more alternatives, it is not necessary to provide a realistic representation to interactions that have no obvious bearing on the comparison. There is a certain danger that the inclusion of provisions, which enhance the realism of the model but are nevertheless minor, may obscure the significance of the results.

Some of the more significant second-order interactions are listed below, together with their effects. Almost all of the interactions listed are results of equipment failure.

1. Loading on yarding - If the yarder is of the type similar to a "Trakloader" or a "Mobile Logger" which performs both the loading and the yarding functions, yarding is stopped so that the arriving truck may be loaded. Grapple yarders and, in general, High Lead yarders do not have this type of interaction.

2. Loader breakdown on yarding - The effect of this interaction is delayed or indirect. Yarding continues until the landing is filled to capacity and then yarding stops.

3. Loader breakdown on landing - Loading stops. The truck being loaded proceeds to the dump if the volume already loaded is greater than 5 cunits. Otherwise, it is dispatched to the other sides. The trucks waiting in the queue are dispatched as well.

4. Loader breakdown on the scheduled moving of the yarder - This has no effect if the landing has adequate space to accomodate the rest of the unyarded logs. Otherwise, the moving of the yarder is postponed.

5. Loader breakdown on the moving of the loader - The moving is postponed until the loader is repaired.

6. Loader breakdown on truck dispatching - The side is momentarily closed down. Trucks already dispatched are recalled and re-dispatched to the other sides.

7. Loader breakdown on overtime activities - If the side has been scheduled to work overtime and it is too late to get a replacement, the required number of extra round trips may have to be readjusted to avoid excessive queueing at the other sides.

8. Yarder breakdown on loading - Loading continues if the landing inventory is enough for a load (greater than 5 cunits). Otherwise, the truck being loaded, as well as the trucks in the queue (if any), are dispatched to the other sides.

9. Yarder breakdown on the moving of the yarder - The moving is postponed. The trucks already scheduled to support the moving resume their log-hauling duties.

10. Yarder breakdown on overtime activities - The loader works overtime until the landing is depleted of logs.

11. Truck breakdown on the moving of a yarder or a loader - Since the probability of the event (that the truck supporting the moving of a yarder breaks down) is small, it is assumed in the model that this event can never occur.

12. Truck breakdown on dispatching - If the truck dispatched to a side which urgently needs a logging truck (when the landing is filled to capacity) breaks down, ideally another truck (which may have been already dispatched to another side) should be

dispatched to the (first) side. In the dispatching routine of the model, this is not taken into account owing to the disproportionate complexity of the respresentation involved relative to the improvement it effects.

3.6 THE PROBABILITY TRANSFORM THEOREM AND THE CONSTRUCTION OF AN EMPIRICAL INVERSE CUMULATIVE DISTRIBUTION FUNCTION

The previous discussion made mention of the provisions for the uncertainties in the physical system through the use of variates generated from inverse cumulative distribution function (c.d.f.'s). This is made possible by the use of a uniformly distributed pseudo-random number generator and the following "probability transform theorem".[1]

A variate with cumulative distribution function F(X) is transformed into a variate P with a uniform cumulative distribution function by the transformation

$$P = F(X).$$

Thus to generate a variate X with c.d.f. F(X), a uniform pseudo-random number P is first obtained from the generator, and then X is obtained from $X = F^{-1}(P)$. From a set of samples collected through observations, the inverse c.d.f. may be obtained through:

1. a sequence of hypothesis tests to determine if the distribution of the set of samples conform with a known function, or through
2. the construction of an empirical inverse c.d.f..

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1 Proof is provided in Evans, et. al., 1967 p. 186.

For instance, using a set of data on inter-failure times for CANFOR logging truck components, Vandenboom (1971) showed that the inter-failure time can be presented as a random sample from an exponential distribution whose parameter is dependent upon the age of the vehicle. An empirical c.d.f. was constructed for each of the sets of data on travel times, loading times, volume loaded, camp delays, and unloading times, after a series of chi-squared tests failed to show at the 5% level of significance that the sets of data followed the normal, exponential, gamma, or log normal density functions. The various inverse c.d.f.'s, based on data gathered at the Harrison Mills Logging Division of CANFOR were constructed as follows:[1]

1. Assuming that n observations of, say, travel time t have been recorded, order the observations in a monotonic sequence.

$$t_{MIN} = t_1 \leq t_2 \leq \dots \leq t_i \leq \dots \leq t_n = t_{MAX}.$$

2. Form a set of vectors $(r_i, t_i)_{i=1,\dots,n}$ where $r_i = i/n$.

3. Using the method of least squares, fit a low order polynomial to the set of vectors $(r_i, t_i) i=1,\dots,n$,i.e.,

$$t = P_n(r) = a_o + a_1 r + a_2 r^2 + \dots + a_n r^n = F^{-1}(r)$$

for $0 \leq r \leq 1$ such that $t \leq 0$.

3.7 FLEXIBILITY OF THE MODEL FOR REPRESENTING VARIOUS CONFIGURATIONS

The model in its present form is capable of representing various multiple-source, single-sink logging configurations. For instance,

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1 The author is indebted to James McPhalen for the collection of data.

the following may be changed in the model:

1. The number of yarders. (Up to ten yarders may be used.)

2. The combination of the type of yarders. (Any of the yarders may be a Grapple yarder, a High Lead yarder or a "Trakloader".)

3. The number of trucks. (Up to 30 trucks may be used.)

4. The truck size. (A choice between 75,000 lbs. or 125,000 lbs. payload is provided.)

5. The distance between nodes.

6. The breakdown and repair parameters.

7. The yarding schedule, the setting volumes, and the landing capacities.

8. The functional relationships, e.g. the various inverse c.d.f.'s and the cost functions.

The above items may be changed by merely manipulating the set of inputs to the model or, in the case of item 8, by substituting the particular relationship for the one provided in the model. In addition, two different shutdown models are available. With some modifications, the model can be made capable of representing situations where one loader may serve two adjacent landings, where there is more than one unloading facility, or where there is more than one shift.

3.8 PROGRAM INPUT REQUIREMENTS AND PROGRAM OUTPUT

The use of simulation requires complete information on the characteristics, behavior, and operating rules of each part of the system. It is based on the premise that much is known about the behavior of each part of the system but not how the parts interact to produce the overall system behavior. Thus the entire system is broken down into parts for which operating rules can be given.

Although adequate knowledge of the different parts of the system may be available to represent the "backbone" of the system, a meaningful use of the model requires a detailed knowledge of the functional relationships and numerical value of the parameters of the system. The set of inputs used in the simulation model developed in this study are listed in Appendix C. Appendix D shows the cost values assumed for all the runs made with the model.

The empirical derivation of each of the various inverse c.d.f.'s requires a sufficiently long time studies to obtain a reliable estimate of the required distributions. In this particular study, about a month of time studies was made to obtain the various inverse c.d.f.'s used as inputs to the program.

To develop the yarding models for "predictive" purposes, it is necessary to obtain an estimate of the mean and the variance of the performance of each yarder on each of its settings. These estimates may be obtained through data on the past performances of the given yarder on settings under similar conditions or through a person who is familiar with the given yarder's performance. Also, extensive data on the past consecutive daily performance of each yarder are needed to obtain a measure of the time-dependent properties of the yarding process corresponding to the given yarder.

The model yields two types of output.

1. A detailed breakdown of the times spent by each of the trucks, yarders, and loaders in their corresponding activities, together with the cost and production

summaries for trucking, yarding, loading, and unloading. A sample output of this type is given in Appendix E.

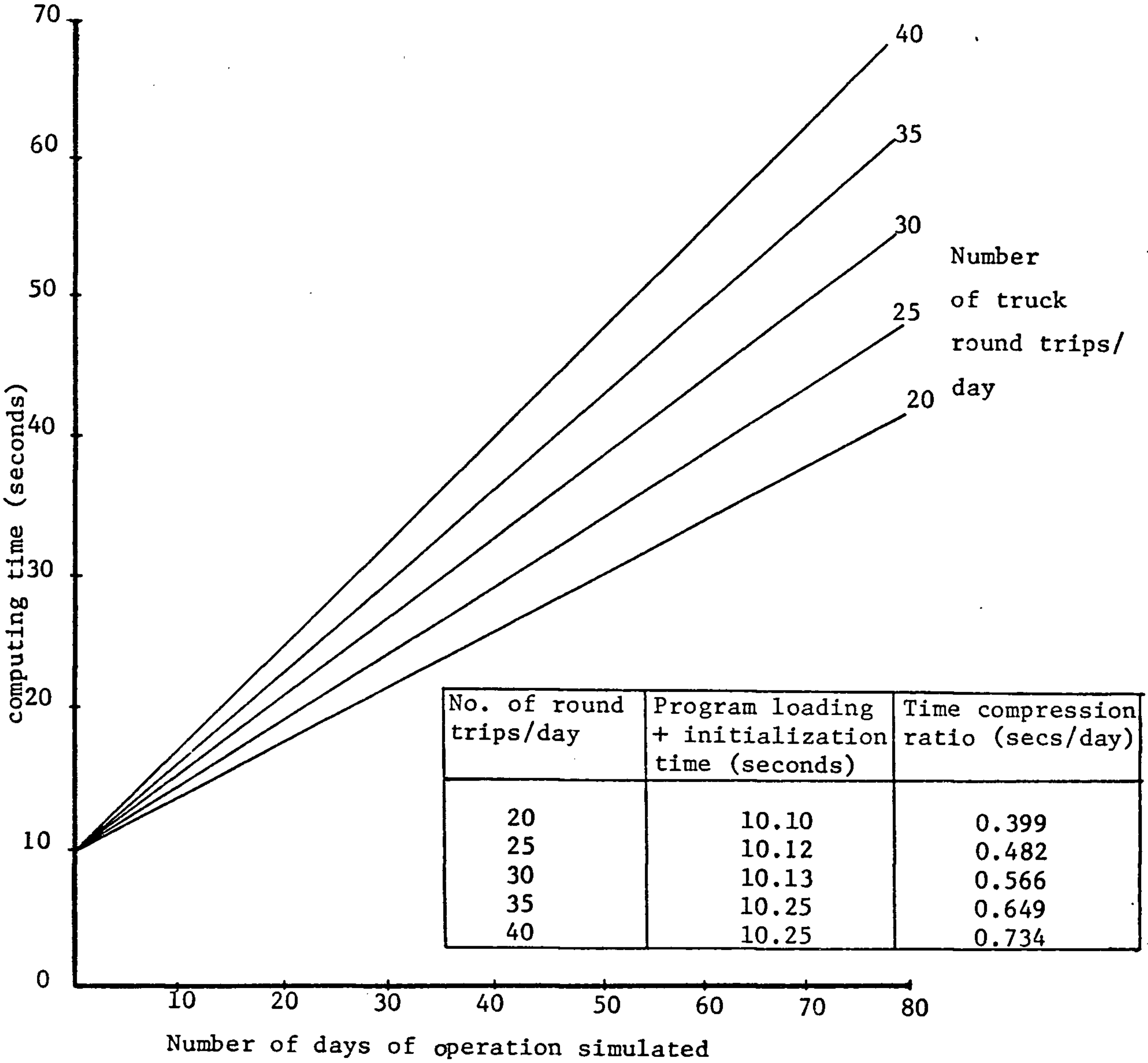
2. The values of the different dependent variables or responses of the system. These include the unit cost (broken down into yarding, trucking, loading, and unloading $/cunit); the production in cunits for each of the yarding, trucking and dumping activities; per cent availability and per cent utilization of the machines; and the total number of loads hauled by the trucking fleet. This information may be read into a file or punched into cards for subsequent statistical analysis. Appendix E (part 2) shows a sample list of the daily values of the dependent variables of the system.

Both types of output are generated at the end of each simulated day. In addition, after the inclusion of extra output statements in the program, the model is capable of yielding a set of output from which a plot similar to Figure 3.1 may be produced.

3.9 MODEL PROGRAMMING AND COMPUTING REQUIREMENTS

The programming and computing requirements for the implementation of the logging simulation model are highly dependent on the experience of the modeller with simulation models and on his familiarity with logging systems. For instance, the logging simulation model described in this study was the first large-scale simulation model developed by the modeller and over half a year of programming and about five thousand "computer dollars" were spent to develop the model for the first shutdown mode. However, to develop the model for the second shutdown mode, only two weeks and five hundred "computer dollars" were spent despite the extensive revisions on the first model that needed to be done.

The computer time requirement for each simulation run varies depending upon the number of days and the logging configuration simulated. Using the number of truck round trips as an index for the different logging configurations, the computing time requirement for a simulation run of the logging model in an IBM 360/67 system is shown in Figure 3.7 as a function of the number of days of simulation. The table included in Figure 3.7 shows that the "time compression" ratio ranges from 0.40 to 0.73 seconds per day.



No. of round trips/day	Program loading + initialization time (seconds)	Time compression ratio (secs/day)
20	10.10	0.399
25	10.12	0.482
30	10.13	0.566
35	10.25	0.649
40	10.25	0.734

Figure 3.7 The computing time requirement as a function of the number of days of simulation and the number of round trips/day

CHAPTER IV

MODEL VALIDATION

Learning though a model of a real-world system involves: first, the representation or modelling of those aspects of reality which are to be investigated; second, the getting of relevant insights from the model or representation; and third, the conversion of these insights from the model into conclusions on the aspects of the real system under study. It is clear that making valid conclusions about the real system through insights from the model requires that there exists a "true" correspondence between the behavior of the real system and the behavior of the model of that system. There is, therefore, a need to "validate" the model. Otherwise, insights derived from it will contribute nothing to the understanding of the system being studied.

This need for model validation applies to all types of models - linear programming models, waiting line models, inventory models, or any other programming model. Why then the preoccupation on validation in the context of simulation? Richard Van Horn (1969) has this to say:

"Simulations tend to become far more complex than other Management Science models. Most analytic models either deal with small problems - for example queuing models - or deal with common parts of large problems - input-output models. Simulators allow the modeller to include many different parts and processes in one model and allow the parts to interact in non-linear, non-stationary modes.

"In addition, simulators conceal their assumptions and processes, certainly from the casual observer, and often from their designer. The simple statement that model x is a linear programming model conveys a great deal of information about its structure, assumptions, and limitations. The statement that model y is a simulation conveys virtually no information. Finally, simulators, either explicitly or implicitly often claim to represent "reality"."

4.1 SOME CONCEPTS ON THE VALIDATION PROCESS

The problem of validating simulation models is one of the most difficult of all unresolved methodological problems associated with computer simulation techniques. Much of the difficulty arises since.... "to prove that a model is "true" implies (1) that we have established a set of criteria for differentiating between those models which are "true" and those which are not "true", and (2) that we have the ability to apply the criteria to any given model". (Naylor and Finger, 1967) Clearly it is difficult to agree upon a set of criteria for differentiating when a model is proven "true".

Naylor and Finger (1967) reported three major methodological positions on the problem of verification in economics. These are: (1) rationalism which... "holds that a model is simply a system of logical deductions from a series of synthetic premises of unquestionable truth not themselves open to empirical verification or general appeal to objective experience," (2) empiricism which rejects any postulate or assumption that cannot be independently verified through observation, and (3) positive economics which contends that a model should be validated on the basis of the accuracy of its predictions on the behavior of the dependent variable of the model, rather than on the basis of the validity of its assumptions.

Naylor and Finger (1967) suggested yet a fourth - multi-stage verification which incorporates the methodology of rationalism, empiricism, and positive economics. It contends that each of the aforementioned is a necessary but not sufficient procedure for validating simulation experiments.

Van Horn (1969) maintains that seldom, if ever, will validation result in a "proof" that the simulator is a correct or "true" model of the real process. Thus is seems more realistic to view validation as the process of building an acceptable level of confidence that the inference about a simulated process is a valid inference for the real process (Van Horn 1969). That is, instead of focusing on whether or not a model is "true", the emphasis should be on the degree of confirmation of the model. The model is subjected to a series of tests and confidence in the model increases when no negative results are found.

4.2 MULTI-STAGE VALIDATION

For building confidence in the model, it appears that the Naylor and Finger approach to verification is appropriate. This three-stage approach includes:

1. A formulation of a set of hypotheses or postulates for the process using all available information - observations, general knowledge, relevant theory, and intuition.
2. An attempt to "verify" the postulates on which the

model is based subject to the limitations of existing statistical tests.

3. A test of the model's ability to predict the behavior of the system being studied.

In short, this approach consists of checking the relationships, structure, and policy of each component of the model and confirming that these components, when combined, display the overall characteristics and behavior associated with the real system.

In an attempt to perform the steps indicated by the first two stages, the previous discussions on the important aspects of the components of the model were presented to consider one or more of the following actions:

1. Associating a high degree of confidence on the representation of processes which are easy to observe and measure. For instance, some physical processes of machines may be represented by production functions with a substantial degree of confidence.

2. Associating a high degree of confidence on the representation of processes which had undergone previous validation in similar experiments or studies.

3. Associating a high degree of confidence on the representation of processes backed up by the existence of an extensive body of research.

4. The empirical testing of those representations which are amenable to some form of statistical tests or the performing of sensitivity analyses as a substitute to the more costly empirical testing. Through sensitivity analyses, a result may be found to hold for a class of distributions or even for a general distribution.

The third stage of the multi-stage verification procedure involves subjecting both the real system and the model to the same set of input, and comparing the input-output transformations generated by the model to those generated by the real system. This stage is of great importance since obviously a great deal of confidence on the model rests upon the confirmation of its ability to transform input to output in a similar manner to the real system.

Several ways of making this comparison have been suggested. An appropriate way is by time series analysis. The real system, as well as the model, produces some stochastic processes - a set of time series of some relevant system responses. Assuming two processes are stationary, testing their equivalence involves the testing of the three elements that completely describe a stationary process; namely: the mean, the variance, and the auto-correlation structure or equivalently the spectrum of the process.[1] Studies by Fishman and Kiviat (1967) on spectral analysis resulted in a test for comparing two spectra. The next section will be devoted to the input-output transformation in the

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1 For a more detailed discussion on time series analysis, refer to Appendix F.

model and the application of the test to compare the time series produced by the model to the corresponding observed time series.

4.3 A COMPARISON OF INPUT-OUTPUT TRANSFORMATIONS

Several arrays of daily values of some system dependent variables are generated both by the real system and the model. Among these arrays or time series of importance are unit cost, total yarding production, total trucking production, total number of loads, per cent utilization of trucks, per cent utilization of yarders etc.

Of the several mentioned, the total yarding production time series is particularly interesting for two reasons: (1) as will be discussed later, the relationship between yarding production and the other dependent variables can be traced, and (2) the transformation of the total yarding production time series as it evolves from the input time series can also be traced.

As mentioned earlier, the potential daily production of any given side is generated from that side's parametric model. The sum of these generated values for a given day represents the ceiling of the total yarding production for that day. The series of these sums can be considered an input series.

A model, unlike the real system, can be manipulated so that only certain particular aspects of it can be observed while others are suppressed. In so doing, the effect of the suppressed aspect can be separated and the resultant behavior can be attributed only to the observable aspects. For instance, in several consecutive experiments, the following aspects were investigated:

Experiment 1. The input series. (This corresponds to the time series of the sum of the individual yarding production. All the other aspects were suppressed.)

Experiment 2. The input series plus the yarding-loading-trucking-unloading interactions. (This corresponds to a hypothetical case where all equipment has 100 per cent availability and all settings have inexhaustible supplies of logs.

Experiment 3. The input series with the various subsystem interactions plus the breakdown of equipment. (In this case, only the moving of yarders and loaders was suppressed from the model.)

Experiment 4. The input series with the various subsystem interactions and equipment breakdown plus the moving of yarders and loaders. (In this case, the model is complete.)

For all four experiments, four high lead yarders and nine logging trucks were used. The input for these experiments is included as the entries in Appendix C corresponding to the first four yarders. The mean and variance of the total yarding production time series for each of the above cases are shown in Table 4.1. Figure 4.1 shows the spectrum of each of the four time series.

Experiment 1 vs. Experiment 2 - Since series 1 is the input series, each daily element of the series represents the maximum total yarding production for that day. The mean yarding production should therefore decrease as more aspects that interact with the yarding subsystem are introduced into the model. For instance, the mean of series 2 (series 1 + yarding-trucking-dumping interactions) is less than the mean of series 1. The loss in production can be interpreted as the reduction due to the interaction among the processes, e.g. yarding-trucking interaction. The decrease in variance is caused by the stabilizing effect of the different interactions. As will be shown later, the optimum number of trucks for this configuration is greater than 9. This implies that, on the average, the total trucking capacity is less than the total yarding capability thus resulting in the loss of yarding production. This loss is disproportionately higher in the "high daily production" elements of the series than in the "low daily production" elements. Consequently, the range of these values, as well as the variance of the series, decreases.

Experiment 2 vs. Experiment 3 vs. Experiment 4 - A further decrease in the mean yarding production is observed with the incorporation of: (1) breakdown of equipment and (2) moving of yarders and loaders. The breakdown of a loader or a truck affects the yarding production as a consequence of the yarding-loading-trucking interaction, and clearly, the breakdown or moving of a yarder interrupts the yarding process. Each single or concurrent occurrence of the aforementioned events reduces the yarding production for that day. As a result, the range of the values of the series and the variance of the series increase.

Table 4.1 The mean and variance for each of the four experiments

EXPERIMENT	MEAN (Mfbm)	VARIANCE ($Mfbm^2$)
1	183.45	354.47
2	180.64	291.64
3	174.34	392.08
4	165.41	588.84

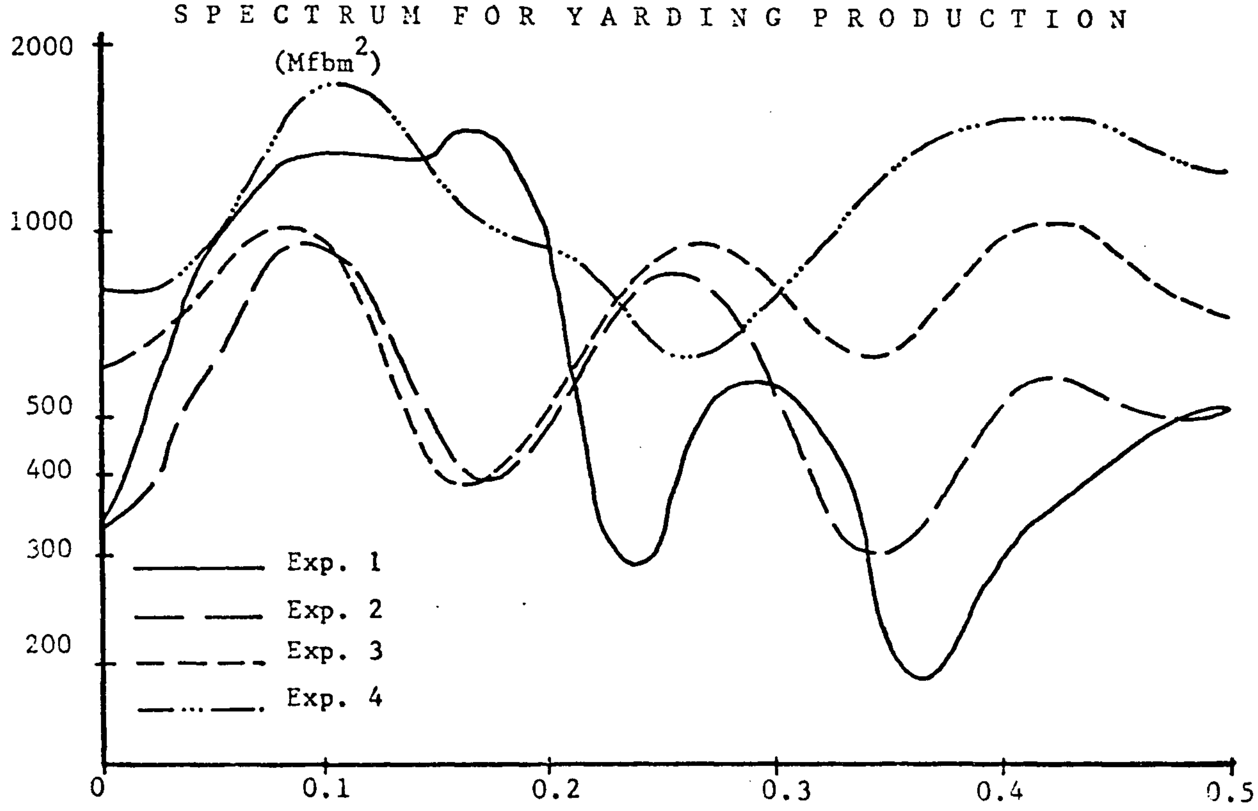

Figure 4.1 Spectrum for each of the four experiments

Although the shift in the spectrum as the observation proceeds from experiments 1 through 4 is interesting from a time series transformation standpoint, the physical interpretation of the individual spectrum is difficult. Normally, the interpretation of the spectrum is done by looking for true and well resolved peaks in the spectrum, noting the frequency at which the peak occurs, and looking back to the physical process to see if the observed frequency relates to a regular physical phenomenon. This interpretation is highly subjective and difficulties arise when several sources of variation occur in a given frequency range, and when a given disturbance occurs at an irregular frequency.

Series 1, the input series, is the sum of four "potential" yarding production time series, two of which are generated from third-order autoregressive processes whose spectra are dominated by low frequencies.[1] The big shift in the spectrum from series 1 to series 2 indicates the effect of the various machine interactions on the input series. This is contrasted by the insignificant change in the low - and mid-frequency bands, but a relatively greater change in the higher frequencies as the breakdown of equipment is introduced into the model (Exp. 3 vs. Exp. 2 in figure 4.1). A pronounced peak forms at frequency 0.42 (=1/2.4) cycles per day in the spectrum of series 3. The pooled breakdown frequency of all trucks, yarders, and loaders at around 1/2.2 explains the difference in this part of the spectrum between series 2 and 3. The big shift in the mean, variance, and

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1 The individual spectrum for each of the four yarding processes is given in Appendix F.

spectrum from series 3 to series 4 indicates the effect of the inclusion of the moving of equipment into the model. Not only does a yarder and a loader stop its main function to move to a new location, but one or two trucks are taken from the hauling fleet to support this transfer. Consequently a significant effect on production is expected.

It may be concluded that the input-output transformation in the model is plausible and added confidence on the model may result from this fact. But how does the output series generated by the model compare with the time series generated by the real system if both the real system and the model are subjected to as similar a set of inputs as possible? The answer to this question requires a test of equivalence between the time series generated by the real system and the time series generated by the model. Each of these time series is a "record" or "realization" from a stochastic process. Testing their equivalence is determining whether these separate realizations come from the same ensemble; thus it requires a comparison of their respective means, variances, and spectra.

Two 69-day time series - the total yarding production and the total number of loads, time series - were compiled from the 1968 records from the Harrison Mills Division of CANFOR. In the 1968 configuration, your yarders and nine trucks were used. The parametric yarding model for each of the your yarders is shown as the first four entries of Table C.1 in Appendix C. The yarding schedule, setting distances, landing capacities, and setting volumes for the 69-day period are shown as the entries for the first four yarders of table C.3

Figure 4.2 Yarding production time series of CANFOR data and two simulation runs

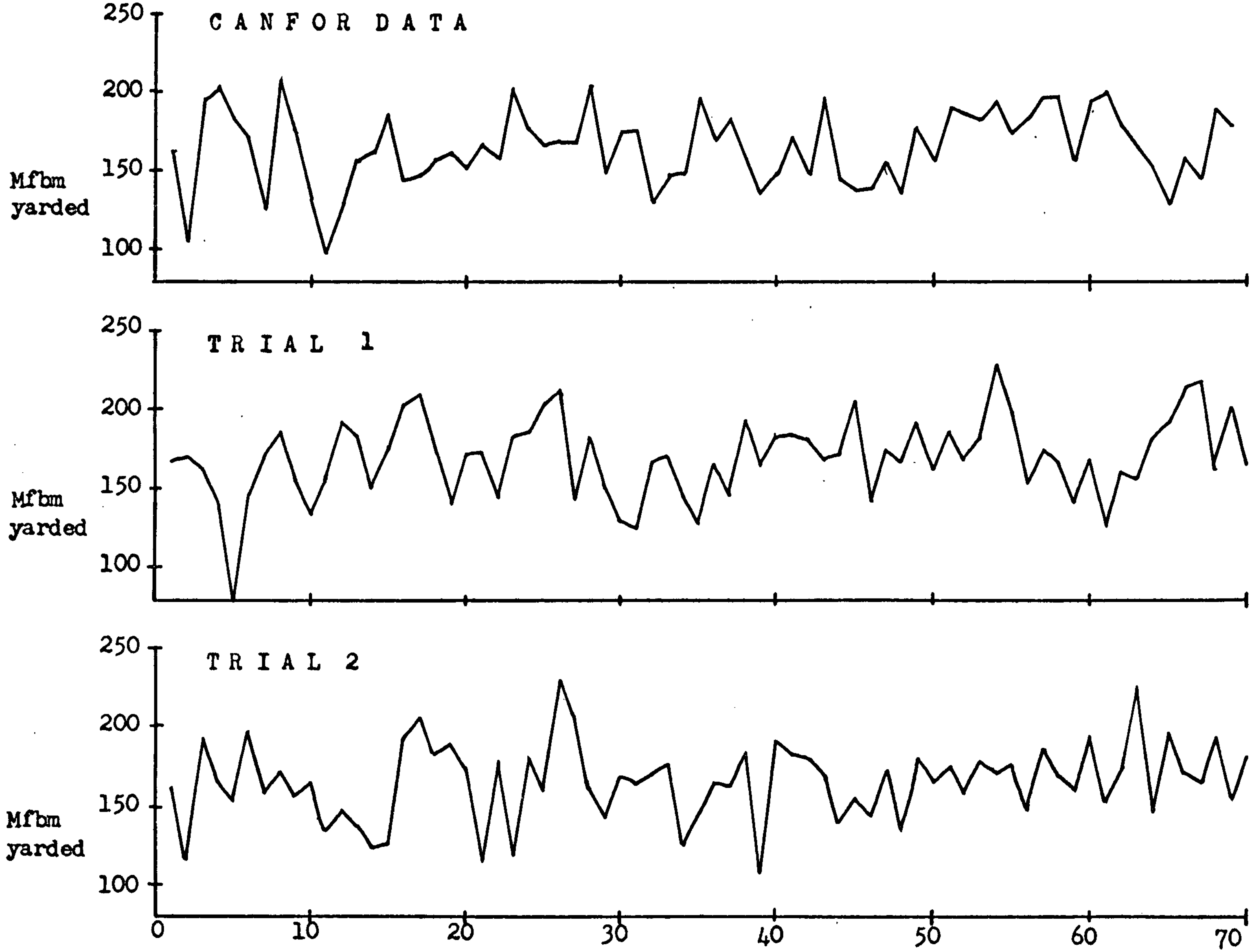

Table 4.2 The mean and variance for the yarding production and number of loads time series

	Mean yarding production (Mfbm)	Variance	Mean number of loads	Variance
CANFOR	164.87	570.03	18.39	5.77
TRIAL 1	168.88	640.07	17.99	5.06
TRIAL 2	165.41	588.84	18.85	4.74

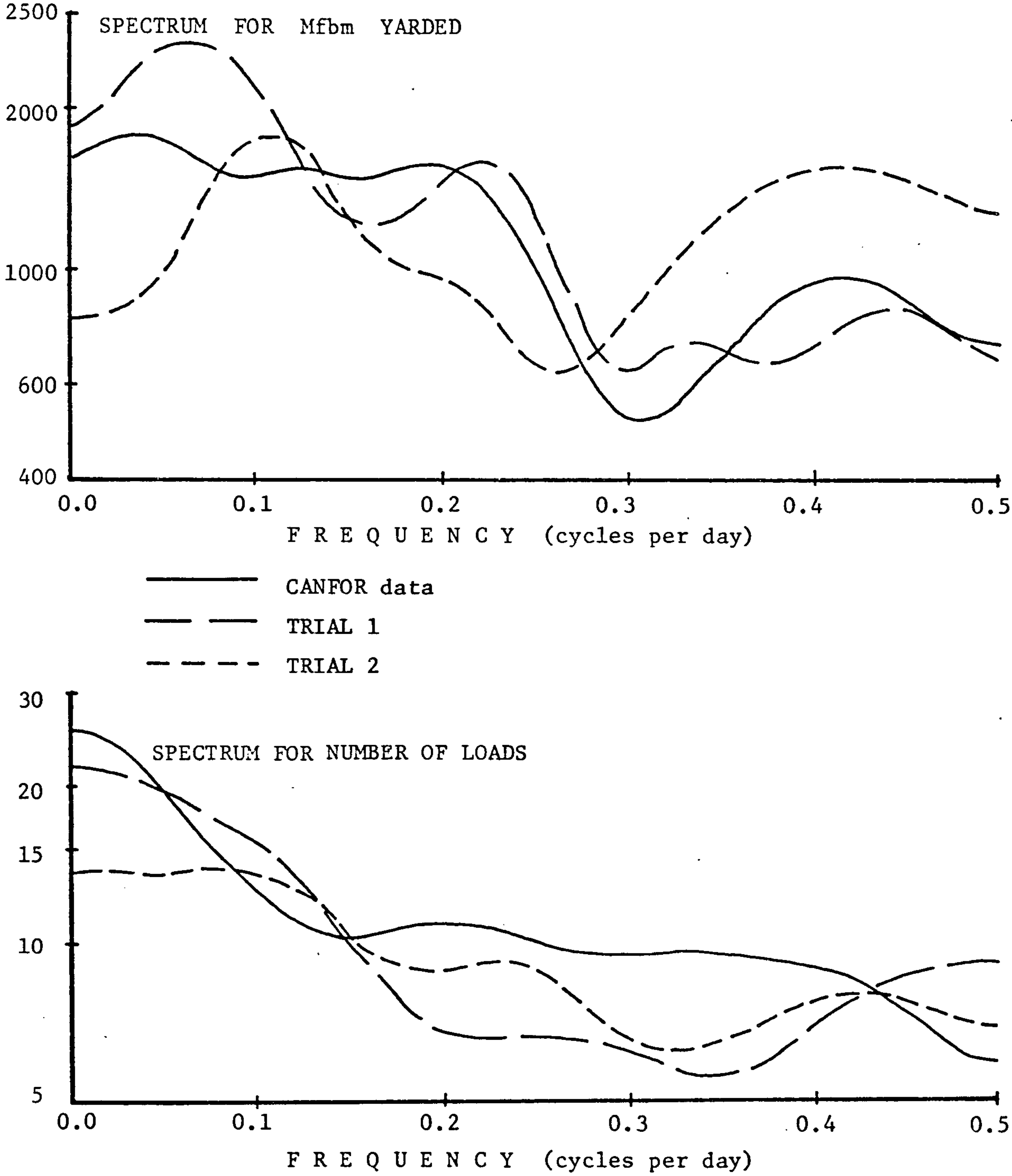

Figure 4.3 Spectra for the yarding production and the number of loads time series

in Appendix C. These values were used in the model as part of the input.

Two separate trials were performed using different series of random numbers. Figure 4.2 shows the graph of the yarding production time series for the CANFOR data and for the results of the two trials. The respective means and variances of the three time series are summarized in Table 4.2 while their respective spectra are shown in Figure 4.3.

The statistical comparison of the yarding production and number of loads mean and variance, between the CANFOR data and the model output for both trials, showed no significant difference at P = .95. Using a statistical test reported in Fishman and Kiviat (1967), no significant difference (at P = .95) was observed, for all frequencies, between the spectrum of the CANFOR data and the spectrum of the model output (for both trials) for both the yarding production and the number of loads. These statistical comparisons are included in Appendix F.5.

Following the verification of the various components of the model and the ability of these components to display the overall characteristics and behavior associated with the real system, the model is used to explore situations for which no empirical data exists. This is essentially an extrapolation procedure, but it is expected that the model will yield acceptable results. The results from the various "runs" of the model are, themselves, basis for building confidence in the model. If the model continuously yields realistic and acceptable results, confidence in the model increases.

CHAPTER V

SOME DESIGN, TACTICAL, AND STATISTICAL CONSIDERATIONS IN THE EXECUTION OF THE SIMULATION RUNS

Following the construction and validation of the model, the next phases in an investigation of a problem by simulation involve:

1. The design of experiments - the selection of the factors and factor levels to use in the simulation runs, the determination of the sampling techniques to apply, and the determination of the number of replications.
2. The tactical planning of the simulation runs to ensure that the experimental design is carried out properly.
3. The statistical analysis of results and the derivation of conclusions about the problem.

Depending upon the purpose and the nature of the problem to be investigated, a particular design is chosen for the problem. For this reason, the experimental design for each of the problems considered in this study is given in the next chapter. However, some general considerations in the design of computer simulation experiments are given in this chapter. Other considerations, tactical as well as statistical, are also presented in this chapter.

5.1 SOME CONSIDERATIONS IN THE DESIGN OF SIMULATION EXPERIMENTS

Computer simulation experiments are considered synthetic experiments. They are, nevertheless, real experiments and their differences from real-world experiments can be directly attributed only to the difference in experimental medium. Consequently, the same problems inherent in real-world experimentation are present in computer simulation experimentation. These problems are intensified in the case of computer simulation experimentation by the fact that computer time is not a free resource. Naylor, et.al. (1969) pointed out that in the design of simulation experiments, careful attention should be given to; the problem of motive, the problem of stochastic convergence, the problem of size, and the multiple response problem.

A. THE PROBLEM OF MOTIVE

Let f denote a functional relationship or "response surface" which relates a given dependent variable or response X to the independent variables or factors $Y_i, i=1,\ldots,n$, of the system; that is,

$$X = f(Y_1,\ldots,Y_n).$$

The underlying objective in a study of a system is to learn more about the system. In particular, the objective may be: (1) to describe and explore the response surface over some region of interest in the factor space, or (2) to optimize the response over some feasible region in the factor space.

Associated with the objective of an experimental investigation is an appropriate experimental design. The design may only involve the planning for a simple t-test if the objective is to compare two levels of a particular factor while leaving the levels of the other factors fixed. The design may involve a more complicated response surface design if the objective of the experiment is to see how the response surface behaves with changes in the levels of the different factors. If the determination of the optimum combination of factor levels is the objective, the design may involve the use of a random sampling method or a systematic sampling method such as the method of steepest ascent.

B. THE PROBLEM OF STOCHASTIC CONVERGENCE

An estimate of the population average of one or more responses is generally required in a simulation experiment. Accompanying each estimate or sample average is a measure of its deviation from the population average, namely the standard error of the mean. As the number of samples used to calculate the sample average is increased, the standard error of the mean is expected to decrease and converge to zero.

The problem associated with stochastic convergence is keeping the length of the run and the number of replications down to an economical level while meeting the desired standard error of the estimate. Several variance-reduction techniques have been introduced for simulation experiments (see Hammersley and Handscomb, 1964), two of which are found appropriate for this study, namely the use of control variates and the use of antithetic variates.

When the outcomes of two similar processes differing only in some minor respects are to be compared, the variance of the differences of their respective means can be reduced if a positive correlation between the outcomes of the two processes is induced. For instance, let

X_1 and X_2 be some series of n values of a response X observed respectively from the first and second processes. That is

$$X_1 = X_{11}, X_{12}, \ldots, X_{1n} \text{ with mean } \bar{X}_1$$

and

$$X_2 = X_{21}, X_{22}, \ldots, X_{2n} \text{ with mean } \bar{X}_2.$$

The variance of the difference between the two means is expressed as

$$\mathrm{Var}(\bar{X}_1 - \bar{X}_2) = \mathrm{Var}\ (\bar{X}_1) + \mathrm{Var}\ (\bar{X}_2) - 2\ \mathrm{Cov}(\bar{X}_1, \bar{X}_1).$$

Clearly, Var $(\bar{X}_1 - \bar{X}_2)$ is reduced if Cov $(\bar{X}_1, \bar{X}_2)$ can be made positive.

Positive correlation between the outcome of two processes is generally induced by the use of the same sequence of random numbers in the simulation run for each process. Since it is not certain for most simulation models that the ith random number will generate the same events for the two processes if the same sequence is used in the simulation run for both processes, this technique of inducing positive correlation is made more effective in the model by the use of four sequences of random numbers, namely:

1. A sequence used in the generation of interfailure and repair times for logging trucks.
2. A sequence used in the generation of interfailure and repair times for yarders and loaders.
3. A sequence used in the generation of the yarding rates.
4. A sequence used in the generation of the rest of the variates.

If the calculation within a specified precision of the mean of a response is desired, the variance of the mean may be reduced by increasing the length and hence the number of observations η of the run. However, because of autocorrelation, it is not certain that the variance will decrease in the order of $1/\eta$ if η is increased.[1] If the variance is still large for a reasonable length of the run, a second replication may be made. A variance smaller than half the average of the variances of the two replications can be achieved if a negative correlation between the outcomes of the two replications is induced.

Let the outcomes of the first replication be X_{11}, $X_{12}, \ldots,$ X_{1n} with mean $\bar{X}_1$ and for the second replication $X_{21}, X_{22}, \ldots X_{2n}$ with mean $\bar{X}_2$. The overall mean is $X = \frac{\bar{X}_1 + \bar{X}_2}{2}$

with variance

$$\mathrm{Var}\ (\bar{X}) = \mathrm{Var}\ (\tfrac{1}{2}(\bar{X}_1 + \bar{X}_2)\ ) = \tfrac{1}{4}\mathrm{Var}\ (\bar{X}_1) + \tfrac{1}{4}\ \mathrm{Var}\ (\bar{X}_2) + \tfrac{1}{2}\ \mathrm{Cov}\ (\bar{X}_1, \bar{X}_2).$$

Thus if Cov $(\bar{X}_1, \bar{X}_2)$ is made less than 0, Var $(\bar{X})$ is reduced.

Negative correlation between the outcomes of the two replications may be induced by the use of "antithetic" sequences of random numbers. That is, if the sequence $r_1, r_1, \ldots r_n$ is used in the first replication, the sequence $(1-r_1), (1-r_2), \ldots, (1-r_n)$ is used in the second replication. Again for large-scale models it is not certain that this technique will cause Cov $(\bar{X}_1, \bar{X}_2)$ to be negative. In the logging model, for instance, this technique, except for some rare instances, does not cause Cov $(\bar{X}_1, \bar{X}_2)$ to be negative.

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1 The determination within a specified standard error of the length of the run for single experiments or for comparing two experiments is given in Appendix F.

Noting that a large part of the variation is caused by the stochastic yarding rate, the method of using antithetic variates was extended to induce a negative correlation between the respective yarding rates of two replications. To recapitulate, the yarding parametric model which generates the yarding rate is of the form

$$X_t = \mu + \sum_{i=1}^{n} \phi_i (X_{t-i} - \mu) - \sum_{i=1}^{m} \theta_i a_{t-i} + a_t$$

where

$\mu = E(X)$

ϕ_i = ith autoregressive weight or parameter

θ_i = ith moving average weight

a_t = white noise generated from $N[0,\sigma_a^2]$

n = order of the autoregressive term (≥ 0)

m = order of the moving average terms (≥ 0).

a_t in the model is generated normally with mean 0 and variance σ_a^2. Since the variate generated in the computer is normally distributed with mean 0 and variance 1, the transformation

(1) $a_t = \rho\sigma_a$ where $\rho \sim N[0,1]$

is used. A second transformation

(2) $a_t = -\rho\sigma_a$

is used for the second replication to induce a negative correlation between the yarding rates of the two replications. Since

$$E(a) = E(-\rho\sigma_a) = -\sigma_a E(\rho) = 0 \text{ and}$$

$$\text{Var }(a) = \text{Var }(-\rho\sigma_a) = (-1)^2 \sigma_a^2 \text{ Var }(\rho) = \sigma_a^2,$$

the second transformation gives the same mean and variance for a_t as the first transformation. However, when $a_t > 0$ using (1), $a_t < 0$ using (2) and vice versa.

When the outcomes of two similar processes are compared and a second replication is necessary to get the desired precision, a combination of the control variate and antithetic variate techniques may be applied. However, this technique may be inferior to either the control variate or the antithetic variate technique used singly, since if $\bar{X}_{ij}$ denotes the mean of jth replication of the ith process, then for a two-process situation

$$\begin{aligned} \text{Var } (\bar{X}_1-\bar{X}_2) &= \text{Var } \tfrac{1}{2}(\bar{X}_{11}+\bar{X}_{12}) - \tfrac{1}{2}(\bar{X}_{21}+\bar{X}_{22}) \\ &= \tfrac{1}{4}\text{Var } (\bar{X}_{11}) + \tfrac{1}{4} \text{ Var } (\bar{X}_{12}) + \tfrac{1}{4} \text{ Var } (\bar{X}_{21}) + \tfrac{1}{4} \text{ Var } (\bar{X}_{22}) \\ &+ \tfrac{1}{2} \text{ Cov } (\bar{X}_{11},\bar{X}_{12}) + \tfrac{1}{2} \text{ Cov } (\bar{X}_{21},\bar{X}_{22}) - \tfrac{1}{2} \text{ Cov } (\bar{X}_{11},\bar{X}_{21}) \\ &- \tfrac{1}{2} \text{ Cov } (\bar{X}_{11},\bar{X}_{12}) - \tfrac{1}{2} (\bar{X}_{12},\bar{X}_{21}) - \tfrac{1}{2} \text{ Cov } (\bar{X}_{12},\bar{X}_{22}) \end{aligned}$$

and when a positive correlation is induced between the outcomes of the two processes while a negative correlation is induced between the outcomes of the replications, not only will Cov $(\bar{X}_{11},\bar{X}_{12})$ and Cov $(\bar{X}_{21},\bar{X}_{22})$ be < 0 but also will Cov $(\bar{X}_{11},\bar{X}_{22})$ and Cov $(\bar{X}_{12},\bar{X}_{21})$. If the sum of the last two covariances is greater than the sum of the first two covariances, clearly the combination of the two techniques is inferior to the simple use of the control variate technique.

C. THE PROBLEM OF SIZE

The problem of size arises when too many factors and too many factor levels are thought to influence the response under consideration. The several factors - independent variables, functional relationships, and policies - of the logging system include the number and capacity of trucks, breakdown and repair parameters for each class equipment, setting distances, number and composition of yarders, mean travel time between any two points in the road system, yarding rates, shutdown modes, and various functional relationships. Since some of these factors are non-quantitative (e.g. shutdown modes, functional relationships), they are held fixed for any particular investigation. The remaining factors, some integer-valued but nevertheless quantitative, may be grouped into classes according to the nature of the investigation. For instance, for a study on repair and maintenance policies of equipment, the breakdown and repair parameters for each class of equipment may be assigned different levels while the rest of the factors are held fixed. Thus for three classes of equipment, only six factors (the various breakdown and repair parameters) need be used. By noting that the range of the levels of some factors is naturally narrow, further reductions in the number of observable factors can be made. An example is the repair time of a yarder. Since it is likely that yarder repair times are already near-optimal, very little can be done with the repair policy to significantly reduce the repair time. Hence, only one level for the yarder repair parameter need be used.

Thus for some investigations, the number of factors and factor levels may in effect be only a few and the number of simulation runs required becomes manageable. In this case, a full factorial design may be used, or where less than full information from the design is tolerable, designs which require fewer "cells" than full factorial may be used.

D. THE MULTIPLE RESPONSE PROBLEM

The multiple response problem is the problem of selecting an appropriate index of performance for a system. For problems requiring the comparison of different combinations of the factors $y_1, y_2, \ldots y_m$, there may be several appropriate responses, $X_1, X_2, \ldots, X_n$, that may be used. Which response should be examined more intensively?

Among several responses of the logging system are:

1. unit cost
2. total daily cost
3. daily yarding production, daily trucking production, daily production at the dump
4. % utilization of the trucks
5. % utilization of the yarders
6. daily number of truck round trips.

Logging managers invariably plan towards minimizing the unit cost of attaining the required level of production; that is, the unit cost response is generally used as the index of performance of the logging system with production as the constraining response. The logging manager lists the available alternatives that satisfy the production constraint and he selects the one offering the least unit cost.

In this thesis, when optimization is the object of the problem under investigation, the unit cost is used as the index of performance. Indeed, business problems are easier resolved and understood when expressed in concrete terms, e.g. in terms of dollars.

As will be seen later, the minimization of the unit cost does not proceed at the expense of production. It is compatible with the objective of maximizing production, but the reverse does not hold.

Because of the close relationship among the given system responses, observations on the behavior of unit cost and production can usually be explained through the other responses. The first section of the next chapter will be devoted solely to the exploration of the interrelationships among these responses.

5.2 TACTICAL CONSIDERATIONS IN THE EXECUTION OF THE SIMULATION RUN

Two important problems arise in the generation of data for a simulation experiment. These are the determination of the point where data gathering starts and the selection of the measurement mode. Since a simulated system is started abruptly, the conditions existing during the initial part of the run may be considered transient. The data collected from the initial part of the run should be excluded since they tend to bias the results. The gathering of data should only start when the conditions or states of the system are deemed to be independent of the starting conditions and close to the equilibrium conditions. With respect to this consideration, the comment of Conway (1963) is relevant:

> "It is important to recognize that equilibrium is a limiting condition which may be approached but actually never attained. This means that there is no single point in the execution of the simulation experiment, beyond which the system is in equilibrium. The difference between the temporal and limiting distributions presumably decreases with time and one seeks a point beyond which he is willing to neglect the error that is made by considering the system to be in equilbrium."

A. CHOICE OF STARTING CONDITIONS

The early part of the run, which is considered as a transient phase, is dependent upon the starting conditions. Making this phase as short as possible requires that a reasonable set of starting conditions is chosen for each run. However, to eliminate the possibility of biasing the results, each of the program runs should use an identical set of starting conditions.

The set of starting conditions established for the simulation model includes:

1. The initial location of yarders and loaders.
2. The initial location and activity of the trucks (implying also the initial length of the queues).
3. The initial volume at each landing.
4. The initial volume at each setting.
5. The initial schedule of the breakdown of each equipment.
6. The initial yarding rates (for the autoregressive yarding processes).

The selection of the values of the set of starting conditions was made arbitrarily using means when available, e.g. mean yarding rates, and other values deemed "realistic". The values for items 1 to 4 are included with the input to the model given in Appendix C. These same set of starting values are used in all the runs made with the model.

B. DELETION OF THE EARLY PART OF THE RUN

To determine how much of the early part of the run to delete, the "rough guide" suggested in Conway (1963) was used. This involves the truncation of the initial series of measurements until the first of the series is neither the maximum nor the minimum of the remaining set. This is not done for each run. A fixed-length stabilization period is chosen from pilot runs and the same length is deleted thereafter from the results of each run.

For this study, the deletion of the first five observations is deemed sufficient to render the state of the system independent of the starting conditions. As used here, an observation corresponds to a day's performance. In over a hundred runs made with the model the sixth observation was found to satisfy Conway's criterion; that is, it is neither the maximum nor the minimum of the remaining set.

C. THE MEASUREMENT MODE

Two possible measurement modes may be used. The first one - periodic sampling - requires the collection of samples separated by an intervening period of time which should be long enough to safely assume the samples to be uncorrelated. The second measurement mode involves a continuous, rather than intermittent, measurement.

Continuous measurement is a better choice for economic reasons. Since continuous measurements are made, there are no intervening time periods between samples and, therefore, no measurements are discarded. The use of continuous measurements, however, has a major disadvantage. The series of values of the various system responses resulting from continuous measurements form a time series. The adjacent elements in a time series are correlated; thus the implementation of continuous measurements entails the use of more complicated statistical methods. Statistical techniques that require the assumption of independence of sample errors can not be used unless the presence of autocorrelation is accounted for. Ignoring autocorrelation is unacceptable since the reliability of the means and the variance are thereby overestimated (Fishman and Kiviat, 1967); thus the validity of t-tests becomes questionable.

Continuous measurement is used in the generation of data from the model. The subsequent calculation of variances and covariances accounts for the presence of autocorrelation. The appropriate formulae used are given in Appendix F (parts 2 and 3).

CHAPTER VI

SOME APPLICATIONS OF THE LOGGING SIMULATION MODEL

The task of modelling is the creation of a medium for the investigation of real problems without having to deal directly with the real system. The usefulness of the model rests on its capacity to be manipulated and experimented upon. Assuming that confidence on the one-to-one correspondence between the behavior of a given system and the behavior of the model of that system has been established, operational plans, designs, or strategies are applied to the real system.

Accordingly, the utility of the logging simulation model rests on its capacity to aid in the evaluation of the various alternative configurations that are presented as possible means for satisfactorily meeting the system objectives. The flexibility of the model allows the investigation of a wide class of logging problems and in this chapter, various examples are presented to demonstrate this capability. These examples are in no way exhaustive; they are merely used to illustrate some of the problems that can be examined.

6.1 INTERRELATIONSHIP AMONG THE LOGGING SYSTEM RESPONSES

Before the main examples on the applications of the logging simulation model are presented, the multiple-response problem introduced earlier will be discussed further. In this study, the unit cost response is used as the index of performance of the logging system with production as the constraining response. In this section some justifications are given for this choice. Using production as a basis, the interrelationship among the various responses of the logging system will be explored. Several simulation runs for various logging configurations provided insights and observations about the nature of these interrelationships. These insights and observations provided a basis for the derivation of the relationships presented.

A. YARDING PRODUCTION vs. TRUCKING PRODUCTION vs. PRODUCTION AT THE DUMP

Because of the existing limit on the capacity of the different facilities, e.g. on the landing capacity, on the trucking capacity, etc., a "bottleneck" occurs whenever the amount of output from one sybsystem exceeds the amount of input that the next subsystem in the production sequence can handle. For instance, the landings become frequently filled to capacity whenever the total yarding capacity exceeds the total trucking capacity. The production of the system is limited by its lowest producing subsystem; consequently, in the long run the production of each of the main subsystems becomes identical. For this reason, production is subsequently regarded as an output of the logging system without further classification into yarding production, trucking production or production at the dump.

B. PRODUCTION vs. TRUCK PER CENT UTILIZATION

An important response of the logging system is the per cent utilization of each class of equipment. While equipment availability reflects the divisional repair and maintenance policies, utilization is an index of the management and operating policies. Since utilization is a measure of the degree of system interactions, it is extremely difficult and perhaps impossible to evaluate the degree of equipment utilization in a complex and dynamic stochastic system of the type being considered without following a simulation approach.

In this study, truck per cent utilization is defined as follows:

Let U_t = truck per cent utilization

A_t = truck per cent availability

μ_{b_t} = mean truck interbreakdown time

μ_{r_t} = mean truck repair time.

Then $$U_t = \left(1 - \frac{\text{queueing time at the dump and at the side} + \text{waiting time for more logs}}{\text{total available time}}\right) \times 100$$

where the total available time $= \frac{A_t}{100} \times$ total time

$$= \frac{\mu_{b_t}}{\mu_{b_t} + \mu_{r_t}} \times \text{total time} .$$

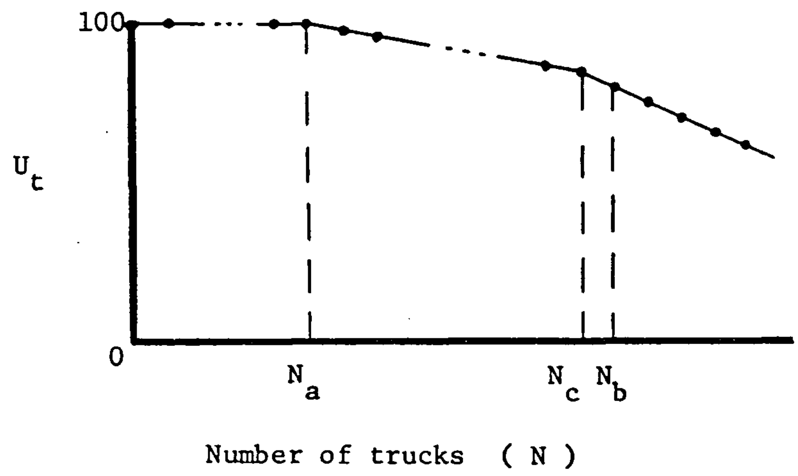

Figure 6.1 The truck per cent utilization as a function of the number of trucks in the fleet

Figure 6.1 shows the nature of the truck per cent utilization as a function of the number of trucks in the hauling fleet. This characteristic behavior is common in the various configurations examined. Sample U_t graphs for several configurations are provided in Appendix G.

In Figure 6.1, N_a is the number of trucks when queueing time starts to become significant; that is, when $N>N_a$, increasing queueing time contributes to the decrease in the truck per cent utilization. For N less than or equal to the number of production sides (M), queueing time at the sides can be assumed to be zero. Since the unloading time is small relative to the total time, queueing time at the dump is expected to be small (found to be near 1% of the total time). Thus N_a is expected to be approximately equal to M.

In Figure 6.1 a change in slope is seen at $N=N_c$. At this point the effect of waiting time for more logs starts to become significant. Clearly this condition occurs just before the total trucking capacity starts to exceed the total yarding capability (i.e. at $N<N_b$). In fact, for a deterministic system with a "sound" dispatching policy, N_c and N_b coincide.

Let N = the average daily production per truck given that there are N trucks in the fleet; that is

$\rho_N = P_N/N$ where P_N = the total daily production

It is seen in figure 6.2 that $\rho_N > \Delta P_N = P_N - P_{N-1}$ for $N>N_a$. Furthermore, regression results from the model runs given in Appendix G indicated that ρ_N is linearly proportional to the truck per cent utilization for

N trucks in the range examined ($77 \leq U_t \leq 98$), that is

$\rho_N = k_1 \cdot U_{t,N} + k2$ where k_1 and k_2 are parameters peculiar to the specific configuration,

$U_{t,N}$ = truck per cent utilization for N trucks,

and $77 \leq U_{t,N} \leq 98$.

As will be seen in the following discussions, this relationship, plus the linear behavior of the U_t- curve as a function of N, results in a quadratic and concave production curve at a given domain. This implies that for the particular domain, the "increase in marginal production per unit increase in number of trucks" is a decreasing function.

The relationship between production and truck per cent utilization may be summarized as follows:

1. $0<N\leq N_a$

   In Figure 6.1 it is seen that for $0<N\leq N_a$, $U_{t,N} = 100\%$. This implies that for this domain ρ_N is a constant; thus the average daily production for N trucks (P_N) is a linear function of N since $P_N = N\rho_N$.

2. $N_a < N \leq N_c$

   In this case, $P_N = N\rho_N = N\ (K_1 U_{t,N} + K_2)$ and $\Delta P_N = P_N - P_{N-1} = N\ (K_1 U_{t,N} + K_2) - (N-1)\ (K_1 U_{t,N-1} + K_2)$. By linearity of the U_t-curve, $U_{t,N-1} - U_{t,N}$ = some positive constant S. Thus $\Delta P_N = N(K_1 U_{t,N} + K_2) - (N-1)\ K_1\ (U_{t,N} + S) + K_2$

   $= K_1\ (U_{t,N} - NS + S) + K_2$.

The second difference

$$\Delta^2 P_N = K_1\ U_{t,N} - NS + S - (U_{t,N-1} - (N-1)S+S)$$

$$= -\ 2K_1 S, \text{ a negative constant.}$$

This implies that for $N_a<N\leq N_c$, P_N may be expressed as

$P_N = aN^2 + bN + c$ where a,b, and c are parameters peculiar to the specific configuration with $2a = -2K_1 S<0$ implying the concavity of the production curve.

Similarly, at the "narrow" interval $N_c < N < N_b$, P_N may be expressed as

$P_N = a'N^2 + b'N + C'$ where $2a' = -\ 2K_1 S'$ with $S' = U_{t,N-1} > S$.

3. <u>For $N \geq N_b$</u>, the yarding production becomes limiting so that production becomes independent of the truck per cent utilization. In this case the production curve levels off at P=Pmax (Figure 6.2).

The relationship between truck per cent utilization and production, therefore, indicated that the production curve is linear ($P_N = N \rho_N$) for $0<N\leq N_a$ and quadratic ($P_N=aN^2 + bN + C$) for $N_a<N\leq N_c$ and for $N_c<N<N_b$. A hypothetical production curve is shown in figure 6.2.

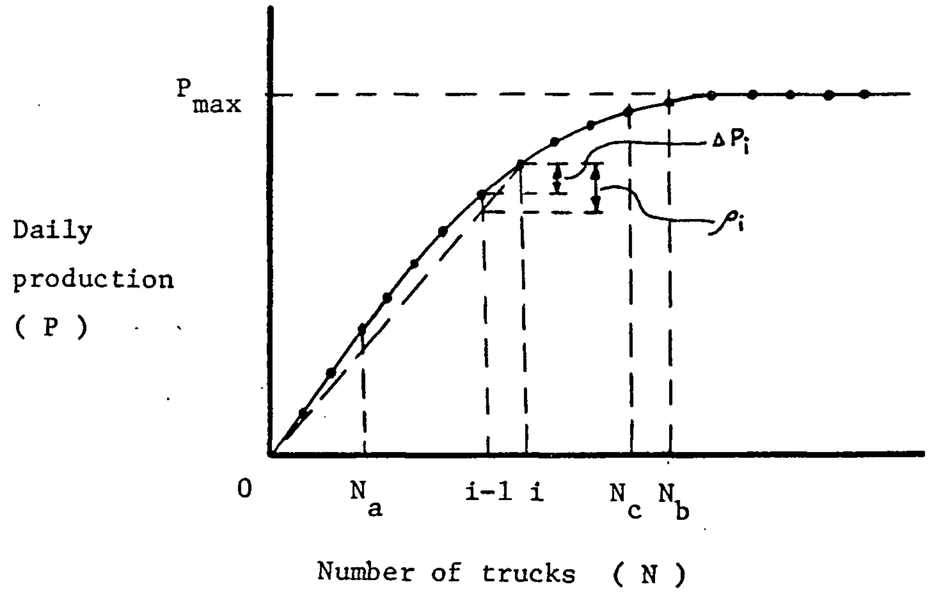

Figure 6.2 Divisional daily production as a function of the number of trucks

C. PRODUCTION vs. NUMBER OF TRUCKS ROUND TRIPS

For N number of trucks in the fleet, the expected daily production may be expressed as

$P_N = L_N T_N$ where L_N = the average load volume given that there are N trucks in the fleet.

T_N = the average number of round trips per day given that there are N trucks in the fleet.

This expression is only an approximation for $N>N_c$ since, as will be discussed, T_n and L_n are not independent at this range.

In an earlier discussion on the loading policies, it was stated that where there are trucks waiting in the queue and the landing is short of logs, the truck being loaded departs with less than full load, provided that a minimum load volume requirement (L_{min}) has been met. Consequently, the average load volume is a function of the number of trucks in the hauling fleet. Figure 6.3 shows that at $N=N_c$, at which the waiting time for more logs starts to become significant, the average load volume begins to decrease. This decrease continues until the average load volume is equal to L_{min}.

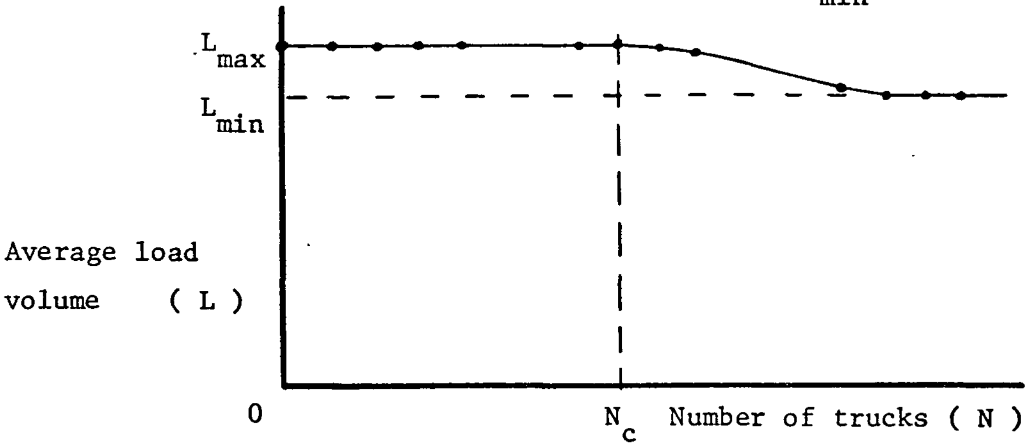

Figure 6.3 The average load volume as a function of the number of trucks in the fleet.

Figure 6.4 shows the average number of round trips per day as a function of the number of trucks. This function reaches a ceiling at $N>N_b$, i.e. later than does the production curve, since the average load volume decreases after $N>N_b$. The ceiling represents the maximum number of loads that the given configuration can support. It is given by

$T_{max} = P_{max}/L_{min}$ where P_{max} = maximum daily prodution potential of the configuration,

and L_{min} = minimum average load volume.

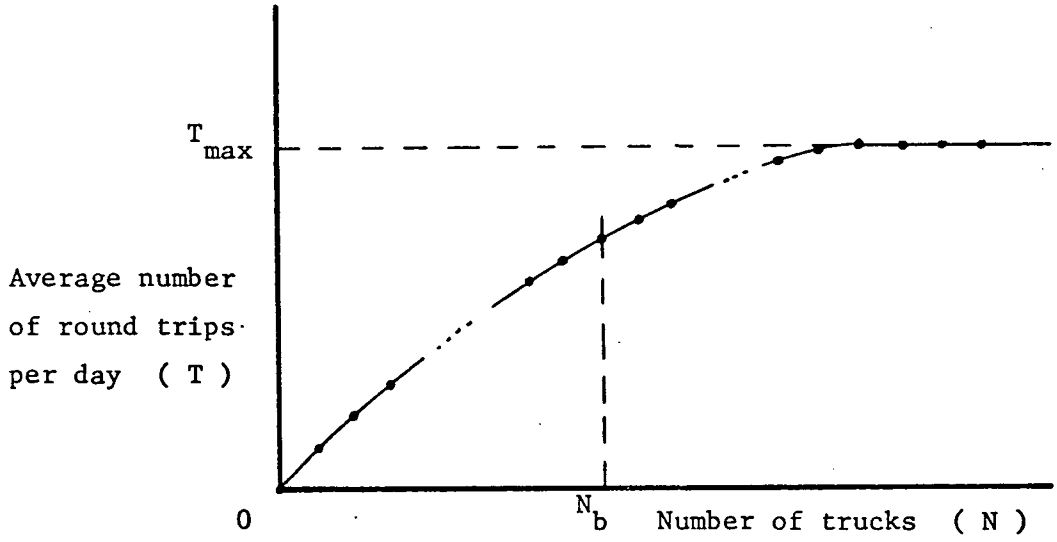

Figure 6.4 The average number of round trips per day as a function of the number of trucks in the fleet.

D. PRODUCTION vs. UNIT COST

The total unit cost is defined as

$$C_n = \frac{\text{daily yarding, loading, unloading, and trucking costs for N trucks}}{\text{daily production for N trucks}} .$$

For any given configuration, the total daily yarding, loading, and unloading cost is independent of the number of trucks in the hauling fleet, assuming that the time of shutdown of the yarders, the loaders, and the unloading facility is not influenced by the number of trucks.[1] Thus the unit daily yarding, loading, and unloading cost ($C_{1,N}$) is given by

$C_{1,N} = \frac{B_1}{P_N}$ where B_1 = the daily total yarding, loading

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1 This assumption holds for the second shutdown mode presented earlier. This assumption strictly does not hold for the first shutdown mode, since in this case, the time of shutdown of the dump is affected by the number of trucks in the fleet. However, the variation in the unloading cost resulting from the difference in number of trucks is, for all practical purposes, negligible.

and unloading cost for M sources
and one sink

P_N = the daily production for N trucks.

Since B_1 is constant for a given configuration, while P_N is an increasing function of N for $N<N_b$, $C_{1,N}$ is a decreasing function of N. P_N levels off after $N=N_b$, so that $C_{1,N}$ is constant for $N \geq N_b$.

The daily trucking cost may be partitioned into a cost component fixed with respect to mileage and the number of operating hours, a cost component varying with mileage, and a cost component varying with the number of operating hours. Although each standard shift has a fixed number of hours, the number of truck operating hours exceeds this fixed number since trucks in their loaded state are generally shutdown at the dump and extra time is necessary to bring the trucks to the dump. The number of overtime hours per day is influenced by the number of trucks in the fleet. For instance, in a situation where there are too many trucks, the number of overtime hours is less than when there are too few trucks.

Let B_2 = the fixed cost per truck[1]

B_3 = the cost per mile

B_4 = the cost per overtime hour

G_N = the expected total truck mileage per day

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1 B_2 is assumed to include the operator's wages for the standard shift but not the overtime wages.

H_N = the expected number of overtime hours per day.[1]

The average unit trucking cost ($C_{2,N}$) is given by

$$C_{2,N} = \frac{NB_2 + G_N B_3 + H_N B_4}{P_N}$$

and $\Delta C_{2,N} = C_{2,N} - C_{2,N-1}$ is given by

$$\Delta C_{2,N} = \frac{B_2}{P_N} + \frac{B_3 (G_N - G_{N-1}) + B_4 (H_N - H_{N-1})}{P_N}$$

for $N > N_b$. $G_N - G_{N-1} > 0$ while $H_N - H_{N-1} < 0$. As N increases, both $G_N - G_{N-1}$ and $H_N - H_{N-1}$ decrease in magnitude; thus the second term in $\Delta C_{2,N}$ tends to zero. The simulation results for various configurations indicated that for $N > N_b$, $\Delta C_{2,N}$ may be assumed constant; i.e. the effect of the second term in $\Delta C_{2,N}$ is small. This implies that, for all practical purposes, C_N may be assumed linear for $N > N_b$.

Let C_{min} = the minimum value of the total unit cost. C_{min} occurs at M if and only if $\Delta C_{N-1} > \Delta C_N < \Delta C_{N+1}$ where $\Delta C_{N-1} < 0$ and $\Delta C_{N+1} > 0$. For all $N \geq N_b$, $\Delta C_{1,N} = 0$ while $\Delta C_{2,N} > 0$; thus C_{min} can not occur at $N \geq N_b$.

Let C_{min} occur at some N_{min}. For any specified production curve the location of N_{min} is dependent on the values of B_1 and B_2. Figure 6.5 shows the values of N_{min} in situations where B_2 is fixed while B_1 is varied, and where B_1 is fixed while B_2 is varied.

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1 H_N is the sum of the individual overtime hours after these are rounded off to the next half-hour as per labour agreement.

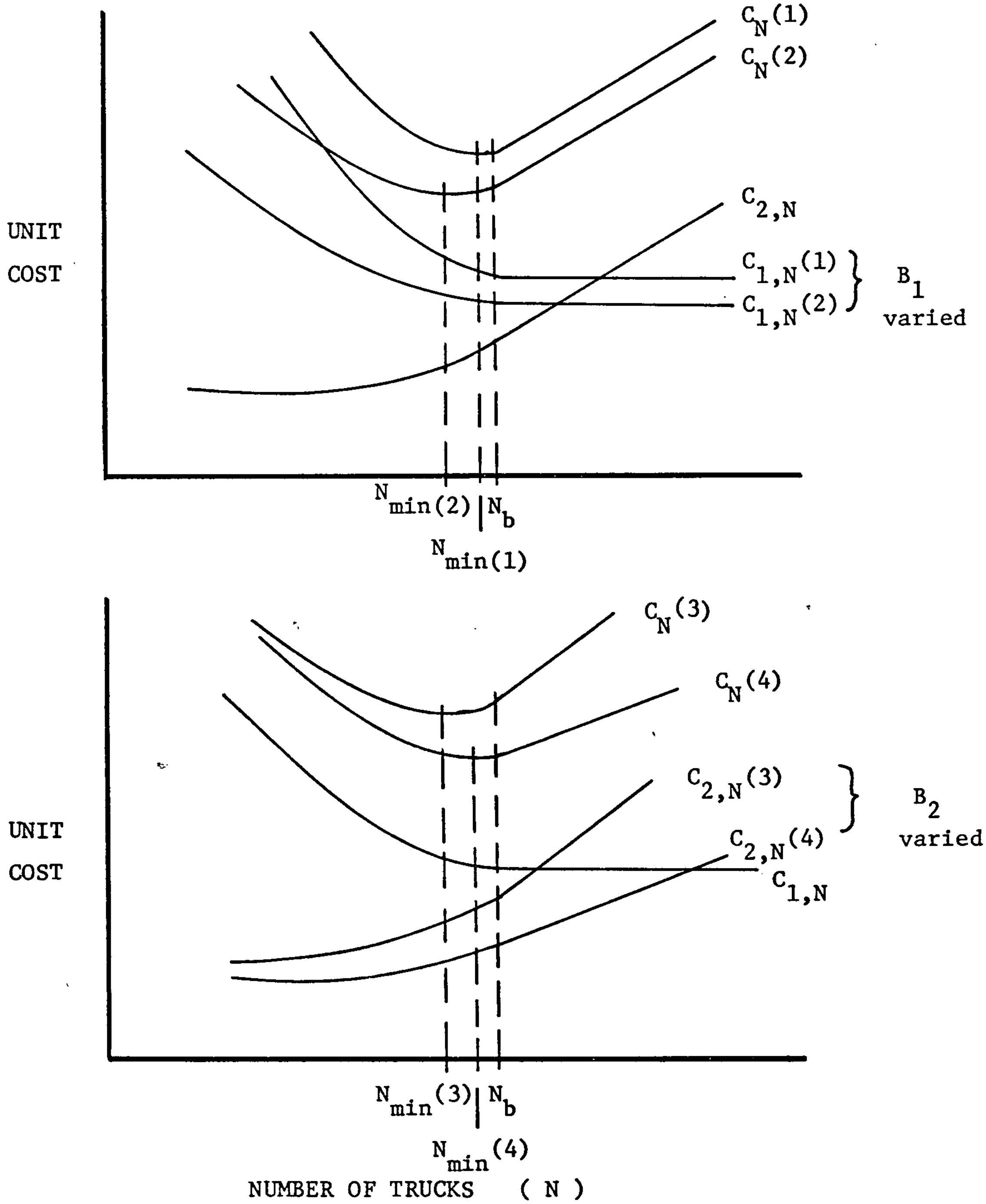


Figure 6.5 The unit cost and its components as functions of the number of trucks in the hauling fleet

E. PRODUCTION vs. YARDER PER CENT UTILIZATION

The yarder per cent utilization U_y is defined as

$$U_y = \frac{\text{total time spent on the yarding function}}{\text{total available time}} \times 100$$

For a particular side the expected production P_s is given by

$$P_s = \text{total time spent yarding} \times \text{mean yarding rate}$$

$$= \frac{U_{y,s}}{100} \times \frac{A_{y,s}}{100} \times \text{total time} \times \text{mean yarding rate}$$

(where $A_{y,s}$ = per cent availability of yarder s)

$$= \frac{U_{y,s}}{100}\alpha_s \quad \text{where} \quad \alpha_s = \frac{A_y}{100} \times \text{total time} \times \text{mean yarding rate of side s.}$$

Thus the total expected production for M sides is given by

$$P = \sum_{s=1}^{M} P_s$$

$$= \sum_{s=1}^{M} \frac{U_{y,s}\alpha_s}{100}$$

$$\approx \frac{\bar{U}_y \alpha}{100} \quad \text{where} \quad \bar{U}_y = \text{mean per cent utilization for the yarders}$$

$$\alpha = \sum_{s=1}^{M} \alpha_s .$$

Assuming that the number of trucks dispatched to any given side is proportional to the side's productivity, $U_{y,s} = \bar{U}_y$ for all S. Thus production and yarder per cent unilization have a simple linear relationship. For $N>N_b$, $\bar{U}_y$ reaches a maximum which is approximately 98% for the configuration examined with the model. The 2% accounts for the non-productive time spent in moving and rigging the yarder.

In the illustrative application of the simulation model which will be covered in the following sections, the unit cost response will be emphasized. The unit cost is chosen as the index of performance in standard practice and in this study because it provides a meaningful measure of the system performance. From the schematic production curve (Figure 6.2), it is seen that the number of trucks at which production is maximum is not unique, and that a relatively high production does not necessarily imply a low unit cost. For this reason, production is an inferior index of performance of the system. For a similar reason, the yarder per cent utilization and the number of truck round trips are inferior indices of system performance. Since a high truck per cent utilization invariably implies that the system can still accomodate more trucks, the truck per cent utilization is also not a good index. These responses are nevertheless useful in explaining various unit cost phenomena.

6.2 SOME ILLUSTRATIVE APPLICATIONS OF THE SIMULATION MODEL

In the sections to follow, some classes of problems which can be handled using a simulation approach will be presented in a general context. Specific problems will be given to illustrate the application of the model to these classes of problems.

A. COMPARISON OF DIFFERENT OPERATING POLICIES

For any given degree of mechanization, logging systems can be better designed through the examination of the different system operating rules and policies. In some specific situations, the cost of production can be reduced without an additional outlay of equipment through the use of better operating policies. A comparison of different operating policies is illustrated in the following example.

Sample Problem

Two notable policies with regard to the shutting down of equipment at the end of the standard shift are currently practiced in the West Coast. These shutdown modes were described earlier and are laid out in detail in Appendix A. The major differences between the two shutdown modes may be summarized as follows;

	Shutdown Mode 1	Shutdown Mode 2
Dump	shuts down as soon as a specified number of empty trucks are parked for the night	shuts down at a given time
Loaders	shut down after 8 hours unless a truck is waiting to be loaded or is approaching the side for a load	shut down after 8 hours of work
Yarders	shut down after 8 hours unless a truck being loaded requires more logs for a reasonable load	shut down after 8 hours of work
Trucks	shutdown either at the camp or at the dump	shutdown either at the camp or at the dump if loaded, may be parked overnight, at at the landings or along roadsides if empty

The questions to be examined are:

1. Under the conditions existing in a basic logging configuration, which shutdown mode gives a lower unit cost?

2. If the conditions are varied from those of the basic configurations, will this shutdown mode consistently give a lower unit cost?

As used in this thesis, the basic configuration is defined as a 6-source, single-sink configuration whose sources are High Lead production sides and whose functional relationships, parameters, cost and yarding schedule are given in Appendices C and D. Logging trucks with 75,000 lbs. payload are used for this configuration. The other configurations examined in this sample problem include:

1. A four-High Lead yarder configuration.
2. An eight-High lead yarder configuration.
3. An six-High lead yarder configuration whose settings are five miles closer to the camp then those of the basic configuration.
4. A six-High lead yarder configuration whose settings are five miles further from the camp than those of the basic configuration.

For each of the five configurations examined, the number of trucks providing the least unit cost was determined first. A t-test was then made to test the significance of the difference in unit cost between the two shutdown modes.

To find the number of trucks which provides the least unit cost for the configuration, a simulation run is done for each choice of number of trucks. Each simulation run consists of 75 autocorrelated observations (simulated days). An additional run is made if the first run has failed to provide the desired standard error of under 2% of the mean unit cost. However, the more variable extreme points selected to complete the shape of the unit cost curve are exceptions. In these cases, a standard error of up to 5% of the mean is allowed. The procedure used for making the runs is as follows:

1. Run the model of the particular configuration 3 times initially using a different number of trucks each time. Previous runs for the other configurations may be helpful in providing a good guess on what number of trucks to use.
2. The number of trucks providing the least unit cost is N if $C_{N-1} > C_N < C_{N+1}$. If the runs made have not included the minimum, make additional runs. The unit cost derived from previous runs should be helpful in locating the minimum point.

Discussion of results

The unit cost curves and the production curves for the basic configuration are shown respectively in Figures 6.6 and 6.7. Figure 6.6 shows that for the number of trucks (N) $\geq$ 10, the second shutdown mode yields a lower unit cost. The t-test made at N=14 shows that the difference of 0.54 \$/cunit between the two modes is highly significant. A breakdown of the unit cost into its component unit costs (Figure 6.8) shows that the difference in the unit trucking costs accounts largely for the difference in the total unit cost. Since, for the first mode, the trucks have to be shutdown either at the camp or at the dump, a greater number of overtime hours results. This made the difference in the unit trucking cost although extra travel time costs for the truck drivers were accounted for in the model for the second mode.

The first mode, however, tends to produce a higher number of round trips and it is probably for this reason that it is being employed. Because of the relatively higher number of round trips for the first mode, it is seen in Figure 6.7 that for $N \lesssim 12$, the first mode yields a higher production. Consequently, the unit yarding and loading costs for the first mode are initially lower than for the second mode (Figure 6.8). Nevertheless, if the trucking production can be improved, then this implies that the productivity of the trucks, rather than of the yarders, is the limiting factor. An increase in the number of trucks, in this case, will not only improve production but will also reduce the unit cost. Indeed at $N \gtrsim 14$, the production for both shutdown modes becomes identical; yet the second mode yields a lower unit cost.

It is seen from Figures 6.9 and 6.10 that the same observations apply when:

1. The number of yarders is varied, and
2. the distances of the settings from the camp is reduced or increased by five miles.

Table 6.1 shows that, in all the five configurations examined, the second shutdown mode consistently yields a significantly lower unit cost than does the first shutdown mode in the given region of interest (about $N = N_{min}$).

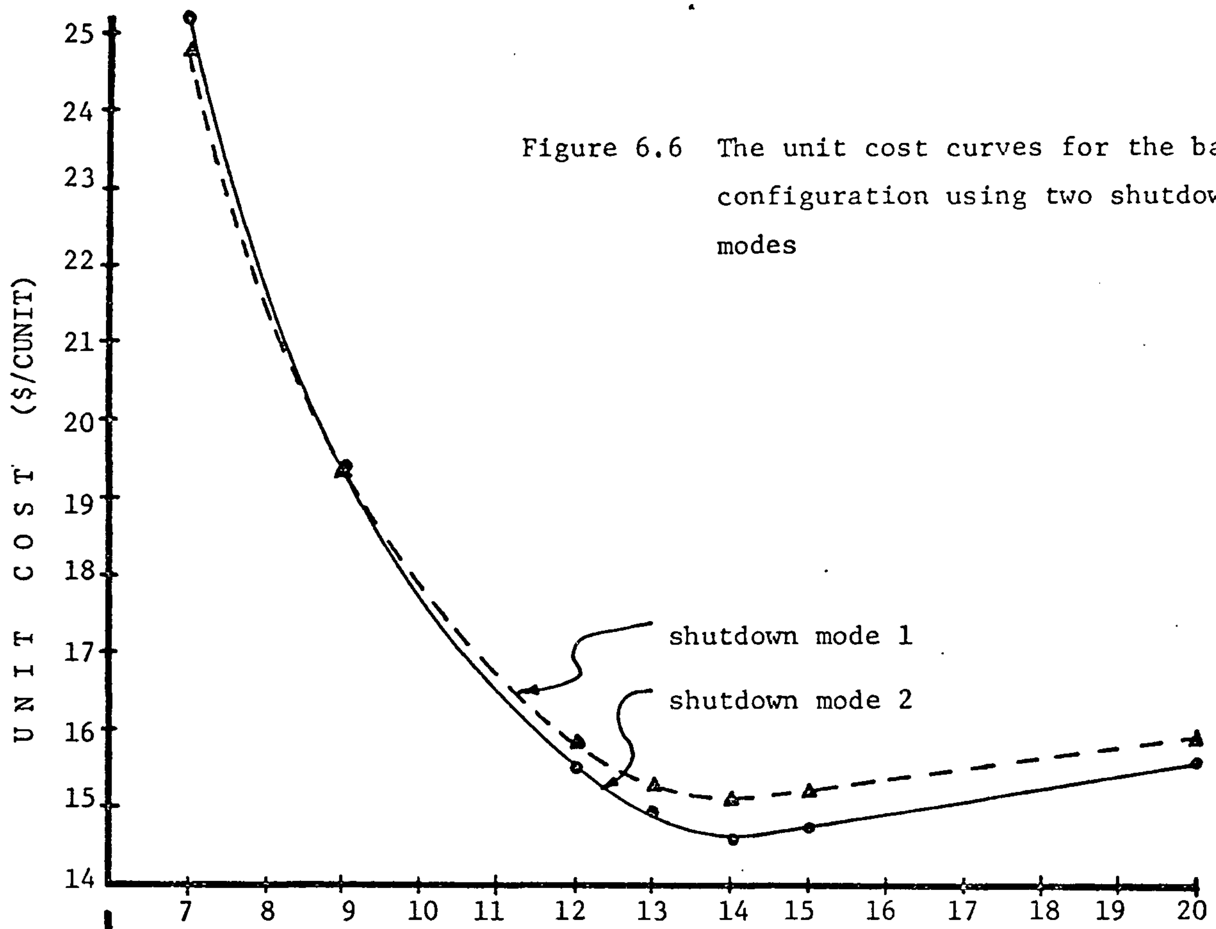


Figure 6.6 The unit cost curves for the basic configuration using two shutdown modes

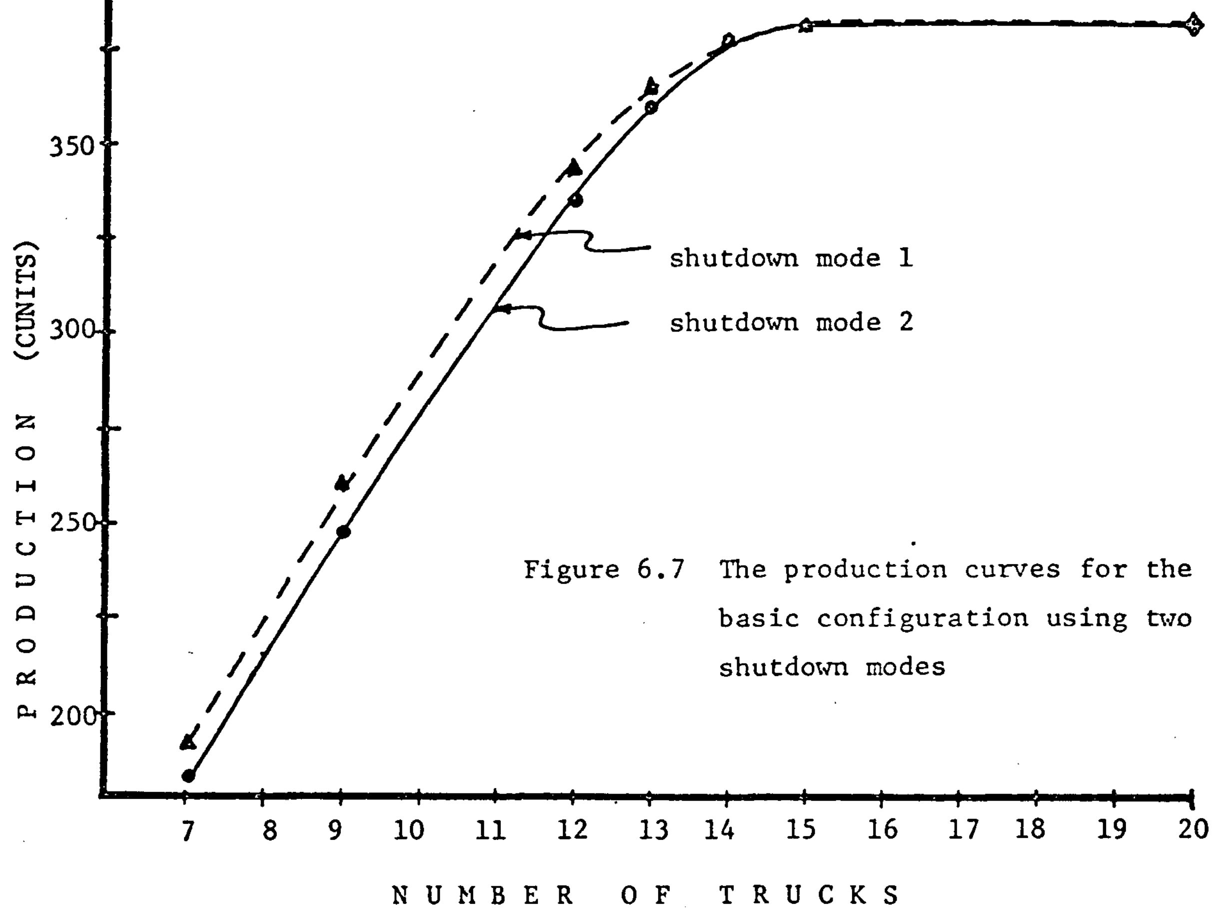


Figure 6.7 The production curves for the basic configuration using two shutdown modes

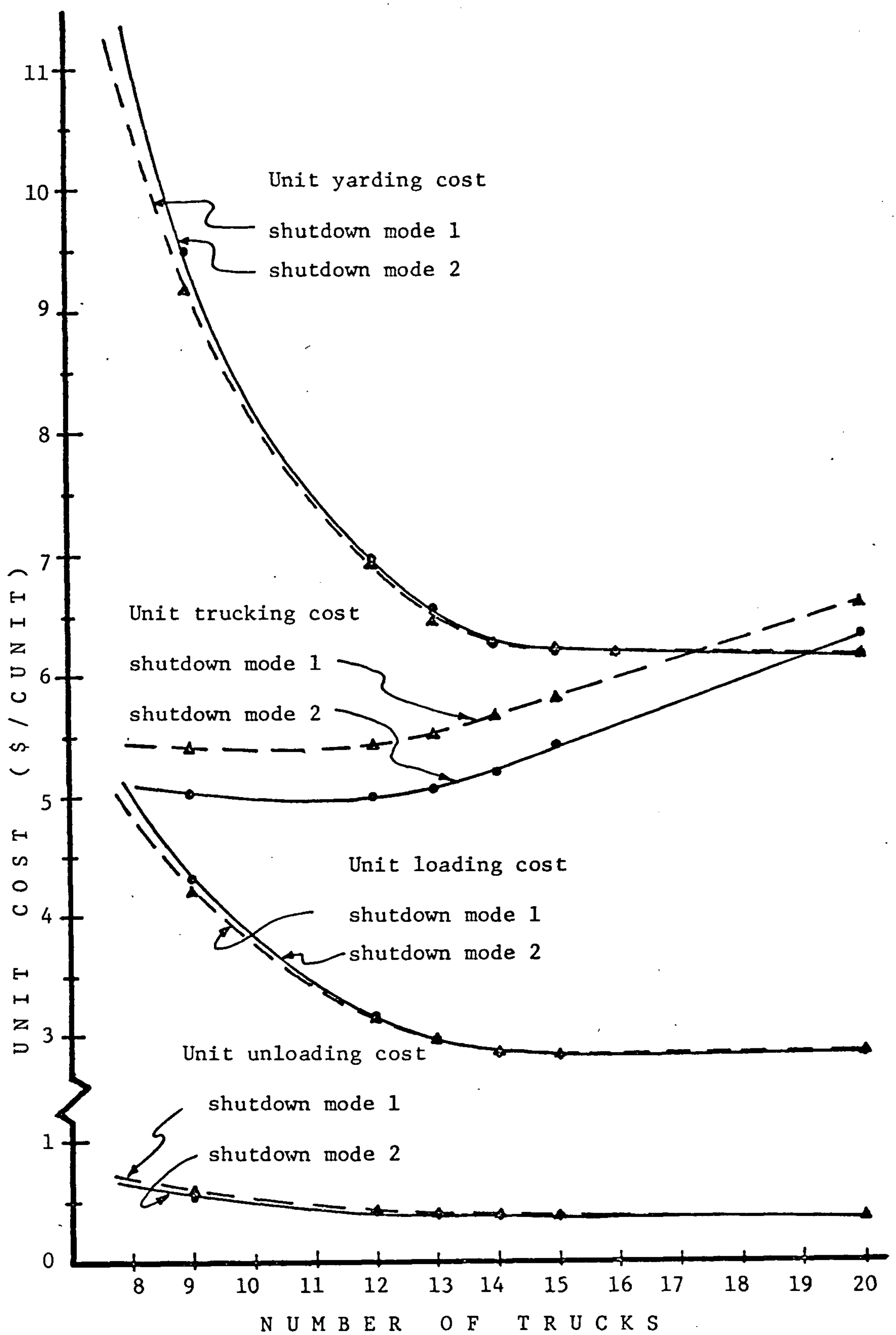


Figure 6.8 The unit yarding, loading, trucking, and unloading costs for the basic configuration using different shutdown modes

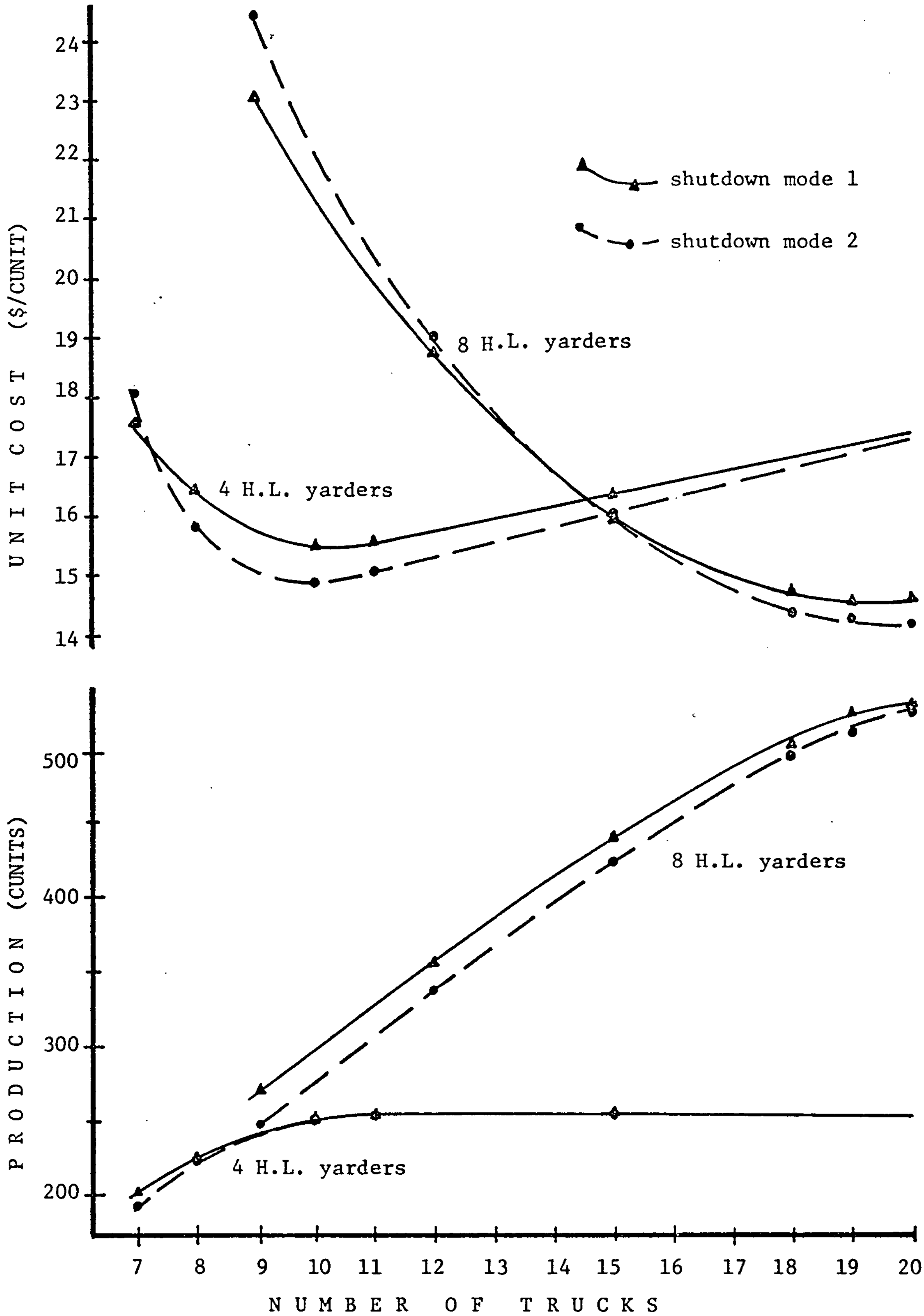


Figure 6.9 The unit cost and production curves for the 4- and the 8-yarder configurations using two different shutdown modes

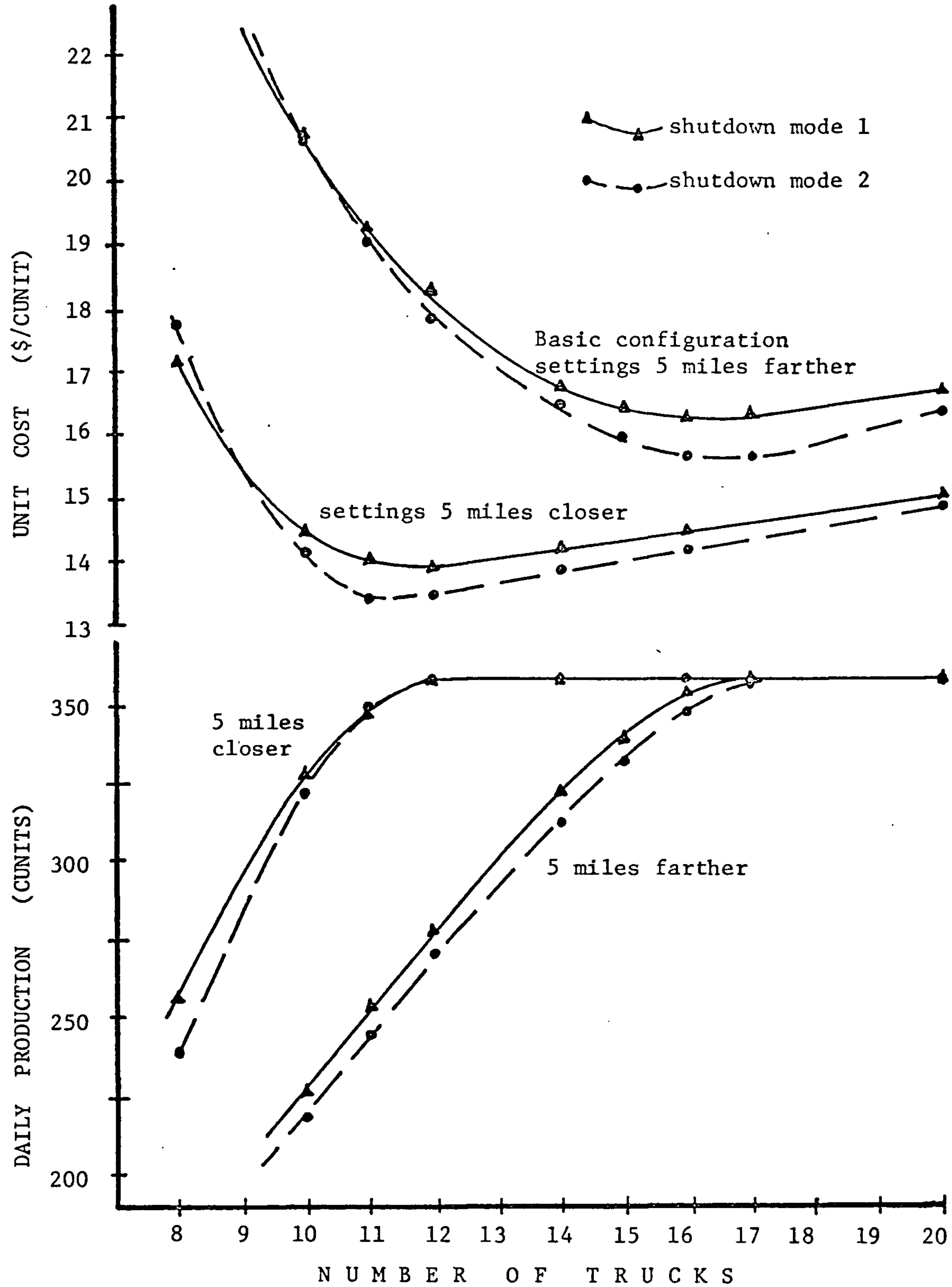


Figure 6.10 The unit cost and production curves for the basic configuration using two different shutdown modes when the settings are 5 miles farther and when the settings are 5 miles closer to the camp

Table 6.1 Production and unit cost for the two shutdown modes for various configurations

Configuration/ No. of trucks	Production (Cunits) Mode 1	Production (Cunits) Mode 2	Unit Cost ($/Cunit) Mode 1	Unit Cost ($/Cunit) Mode 2	U.Cost Diff. $(\bar{C}_1-\bar{C}_2)$	$S_{\bar{C}_1-\bar{C}_2}$
Basic configuration						
13	365.80	360.38	15.28	14.96	0.32	0.17
14	378.49	379.32	15.11	14.57	0.54**	0.07
15	381.42	381.56	15.19	14.70	0.49**	0.06
4 High Lead Yarders						
10	251.43	251.88	15.49	14.88	0.61**	0.15
11	254.59	254.30	15.55	15.06	0.49**	0.07
8 High Lead Yarders						
18	504.77	495.82	14.75	14.39	0.36**	0.08
19	526.91	510.28	14.56	14.33	0.23*	0.12
20	530.03	525.56	14.64	14.14	0.50**	0.02
6 High Lead Yarders, 5 miles closer						
10	353.58	347.68	14.47	14.13	0.34	0.29
11	371.08	374.43	14.03	13.40	0.63**	0.21
12	382.21	380.82	13.91	13.48	0.43**	0.05
6 High Lead Yarders, 5 miles farther						
16	379.13	372.44	16.24	15.62	0.62**	0.07
17	381.60	380.83	16.35	15.60	0.75**	0.06

* -significant at 95%
** -significant at 99%

B. DETERMINATION OF THE EQUIPMENT REQUIREMENT FOR VARIOUS CONFIGURATIONS

An important area of concern for logging manager is the determination of the equipment requirements for their operation to attain a specified level of production. The class of problems dealing with equipment requirement not only deals with the selection of the desired combination of equipment, but also the mode for using them. For instance, to increase productivity a logging manager may have several alternatives at his disposal, e.g.

1. purchase or lease more equipment,
2. hire contractors,
3. operate the existing equipment overtime or on double shifts.

On the other hand, to reduce productivity a logging manager needs to lay off some equipment. Which piece of equipment should he lay off?

As examples of this class of problem, the following are considered:

1. The determination of the truck requirements for different numbers of High Lead production sides as the distances of the settings get progressively further from the camp.
2. The determination of the truck requirement for a 5-High Lead, 1-Grapple yarder configuration.
3. The determination of the truck requirement for the basic configuration using different combinations of "small" and "large" trucks.

The truck requirement for different number of High Lead production sides and setting distances

In a newly established multi-source, single-sink logging operation, the sources or production sides are usually close to the camp. In the course of several years of operation, the closer settings are logged over; hence the production sides get progressively farther from the camp.

In the winter, a logging operation generally starts with relatively fewer production sides and additional sides are opened as soon as a more favorable weather condition permits. Also, an increase in demand for wood may have the same effect of causing an increase in the number of production sides. In this example, the combined effect of these two factors - the distances of the production sides from the camp and the number of production sides - on the truck requirement of the logging operation, as well as on unit cost and production, will be explored.

Experimental design -

Since all yarders have different locations at any one time, and since each yarder moves from one location to another, it is necessary to define a single measure of distance for each configuration to be used as one of the independent variable. This measure - the mean setting distance ($\bar{D}$) for any specified configuration - is defined as

$$\bar{D} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\sum_{j=1}^{m_i} D_{ij}V_{ij}}{\sum_{j=1}^{m_i} V_{ij}}\right)$$

where n = the number of yarders

m_i = the number of locations scheduled for yarder i

D_{ij} = the distance from the camp of the jth location of yarder i

V_{ij} = the volume of the jth setting of yarder i

Three levels of $\bar{D}$ for each number of yarders are used, designated by γ_n-5, γ_n, and γ_n+5 where γ_n is the mean setting distance for n yarders whose individual setting distances are given in Appendix C. Four levels of the number of yarders are used: 4, 5, 6, and 7 yarders. For each of the configurations, or cells, resulting from the combination of different levels of $\bar{D}$ and the number of yarders, the truck requirement was determined using the procedure described in the previous section.

To fit a unit cost response surface, it is necessary to partition the response surface into two sections, since as previously described, the unit cost as a function of the number of trucks has linear and non-linear components. The model initially chosen for the first section of the unit cost response surface is a second order model of the form

$$C = b_o + b_1N + b_2M + b_3\bar{D} + b_4NM + b_5N\bar{D} + b_6M\bar{D} + b_7NM\bar{D}$$
$$+ b_8NM^2\bar{D} + b_9NM^2 + b_{10}M^2\bar{D} + b_{11}N^2 + b_{12}M^2 + b_{13}\bar{D}^2 + e$$

where N = the number of trucks

M = the number of yarders

$\bar{D}$ = the mean setting distance from the camp

C = the unit cost

b_i, i=0,...,13 = the regression coefficients

for the region defined by all the specified levels of

$\bar{D}$ and M, and $N_{ij} \leq N_{opt_{ij}} + 1$, $i=4,\ldots,7$, $j = \gamma_i - 5$, γ_i, $\gamma_i + 5$.

Since $N_{opt_{ij}}$ is different for each configuration ij, the values of N_{ij} are staggered; thus the design is not orthogonal. However, this design is necessary to ensure that the N_{opt}'s derived from the response surface are close to the observed N_{opt}'s. Three levels of N are used for the four- and five- yarder configurations. For the six- and seven-yarder configurations, four levels of N are used since the region is wider for these two cases. Thus a total of 2x3x3 + 2x3x4 = 42 simulation runs were used to fit the first section of the unit cost response surface assuming that only one simulation run is made for each combination of factor levels.

To obtain a "smooth" surface when the two sections of the unit cost response surface are joined, the slope of the linear sections are first determined using a model of the form

$$S(M,\bar{D}) = q_o + q_1 M + q_2 \bar{D} + q_3 M\bar{D} + q_4 M^2 + q_5 \bar{D}^2 + q_6 M^2 \bar{D} + e$$

where $S(M,\bar{D})$ = the slope of the linear section of the unit cost function for the configuration defined by M and $\bar{D}$

q_i = the regression coefficients.

The unit cost for k trucks, i yarders, and mean setting distance j is then determined using

$$C_{kij} = C_{N_{opt_{ij}}+1} + kS(i,j).$$

To fit $S(M,\bar{D})$ a total of 2x3x4 = 24 simulation runs were made.

Discussion of results -

After a stepwise elimination of the non-significant variables, the best regression equation for the second order section of the unit cost response surface is

$$C = 12.587 - 0.1005N\bar{D} + 0.2570M\bar{D} - 014471NM - 010085M^2\bar{D} + 0.1472N^2 + 0.0145\bar{D}^2$$

where M = the number of yarders

$\bar{D}$ = the mean setting distance from camp

N = the number of trucks

and $N \leq N_{opt_{M\bar{D}}} + 1$.

All the regression coefficients are highly significant in the above regression equation which accounts for 97.455% of the total variation.

Similarly, the best equation obtained for $S(M,\bar{D})$ is

$$S(M,\bar{D}) = -0.9972 + 0.1201\bar{D} - 0.0478M\bar{D} -0.0509M^2 = 0.0046M^2\bar{D} .$$

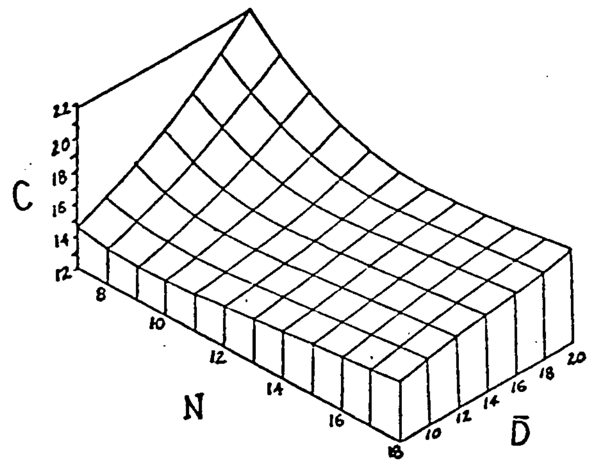
The regression equation for $S(M,\bar{D})$ accounts for 98.258% of the total variation. All of its regression coefficients are highly significant.

For $N > N_{opt_{M\bar{D}}} + 1$, the unit cost response surface is given by

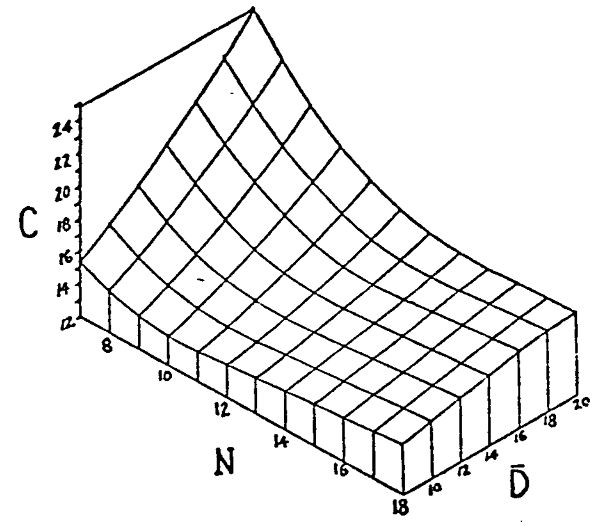
$$C = C(N_{opt_{M\bar{D}}} + 1, M, \bar{D}) + N \cdot S(M,\bar{D})$$

where the first term is obtained through the model for the second order section.

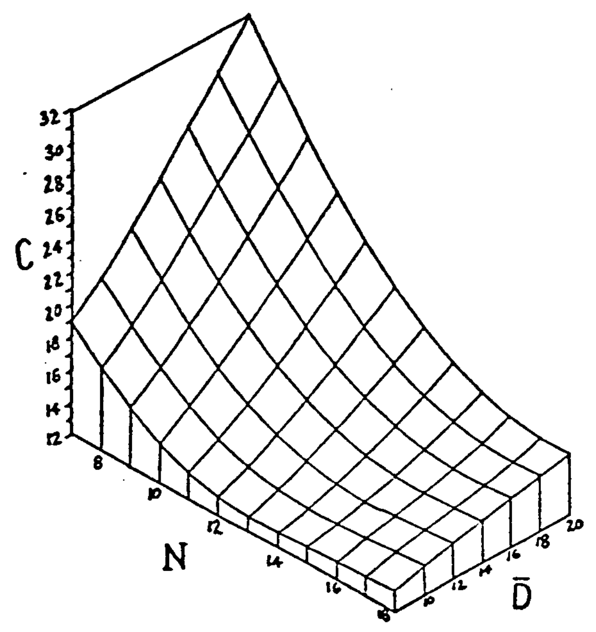
Figure 6.11 shows the unit cost response surface as a function of the number of trucks (N) and the mean setting distance ($\bar{D}$) for each of the 4-, 5-, 6-, and 7-yarder configurations. The following can be observed from Figure 6.11:



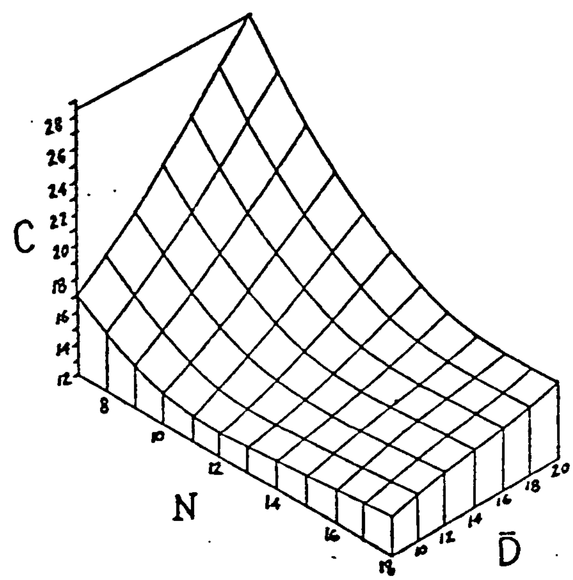
4-yarder configuration



5-yarder configuration



7-yarder configuration



6-yarder configuration

Figure 6.11 The unit cost response surface over different values of the number of trucks and the mean setting distance for the 4- , 5- , 6- , and 7-yarder configurations

1. For any M-yarder configuration, when there are excess trucks, changes in the mean setting distance have less effect on unit cost than when there are too few trucks.

2. Let $\Delta C_{N,M}$ = the change in unit cost per unit increase in the number of trucks (N) for a given M-yarder configuration. In section 6.1 it was shown that for any given M-yarder configuration and for $N>N_b$ [1]

$$\Delta C_{N,M} \approx \frac{B_2}{P_{max,M}}$$

where B_2 = the added cost of an extra truck

$P_{max,M}$ = the maximum daily production for the M-yarder configuration.

Since B_2 is a constant and $P_{max,4} < P_{max,4} < P_{max,6} < P_{max,7}$, it follows that $C_{N,4} > C_{N,5} > C_{N,6} > C_{N,7}$ for any fixed $\bar{D}$ and for $N > N_b$. This implies that the slope of the linear section of the unit cost curve for the configuration $M\bar{D}$ is relatively less for greater number of yarders M.

3. At the "second order section" of the unit cost surface (i.e. $N<N_{opt}$), $|\Delta C_{N,i}| > |\Delta C_{N,j}|$ for i > j. This implies that for this section, the addition of a truck reduces the unit cost more when there are more production sides.

4. For any given $\bar{D}$, the 7-yarder configuration gives the least unit cost at N_{opt}. The 6-yarder configuration gives the next least unit cost. This is brought about

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1 N_b is assumed equal to N_{opt} + 1 for these response surfaces.

by two factors:

a. Decreasing unit unloading cost. Since only one unloading facility is used in all configurations, more production implies less unit unloading cost.

b. Higher average productivity assigned to the sixth and seventh yarders.

In the concluding paragraph of Chapter IV it was stressed that results from the various model runs are, themselves, bases for building confidence in the model. The above observations have shown what can be regarded as an intuitively acceptable behavior of a system response. However, perhaps the greatest benefit from the results can be derived from their indication of the level and the rate of the response for various combinations of the given factors.

Without making additional simulation runs, the truck requirement for various mean setting distances of an M-yarder configuration, M=4,5,6,7, whose individual yarding potential is not the same as those already simulated, may be determined. This requires a graph (Figure 6.12) showing N_{opt} as a function of the production at N_{opt} and the mean setting distances. A graph such as this can be constructed from the unit cost and production response surfaces.[1] The points in the graph

1 The production response surface used to construct Figure 6.12 is given by

$$P = \begin{cases} 141.097 + 1.1985N\bar{D} + 9.7064NM - \\ \quad 0.2020M^2N - 2.0185N^2 & \text{for } N \leq N_{opt_{M\bar{D}}} \\ P_{max_{M\bar{D}}} \qquad \text{for } N > N_{opt_{M\bar{D}}} \end{cases}$$

A sample plot of this response surface for M = 6 yarders is shown in Figure 6.13

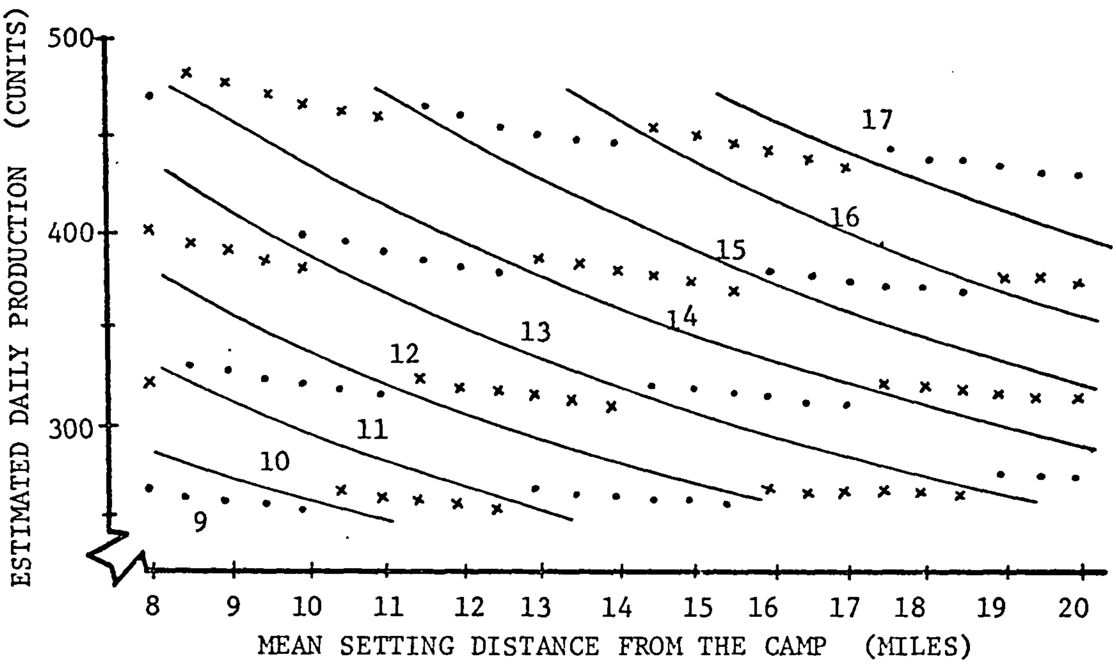

Figure 6.12 The truck requirement for various combinations of estimated daily production and mean setting distance

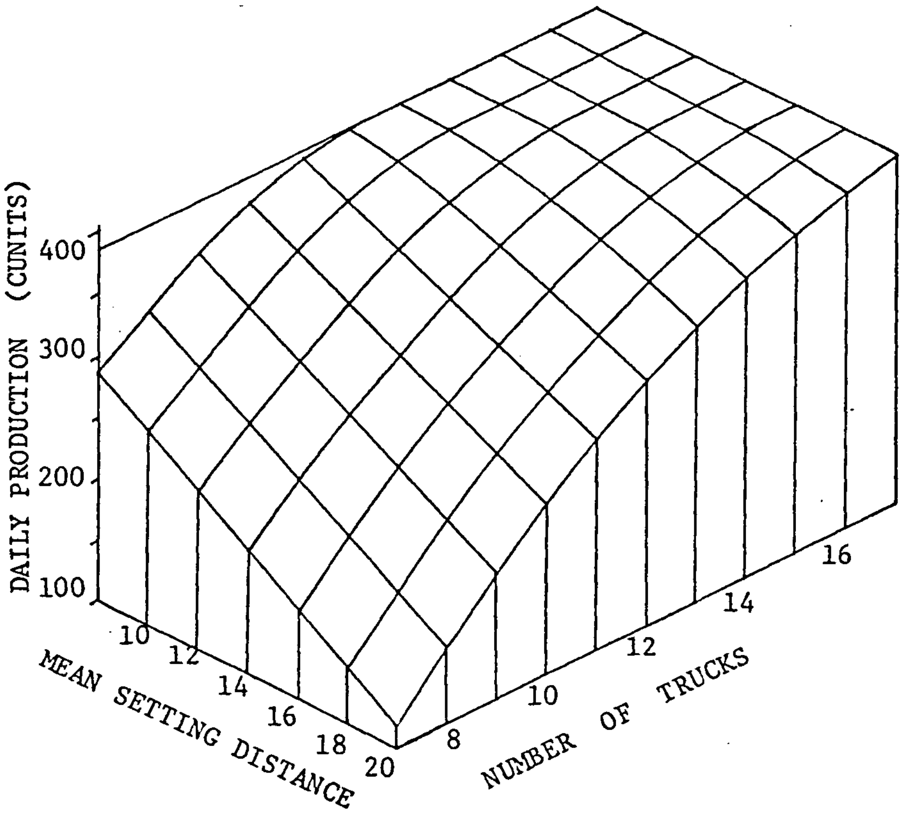

Figure 6.13 The production response surface for the basic configuration

are taken from these response surfaces. The points corresponding to the same number of trucks, say N, determine the band of optimum applicability for N trucks.

A graph such as Figure 6.12 can be used to find the additional truck requirement to match an increased yarding productivity, or to find the number of trucks to lay off as a result of a reduced yarding productivity. However, the graph applies only for the costs assumed in the model. Also, the effectiveness of the graph is not known for configurations whose variance of their setting distances is much different from that of the model. The use of Figure 6.12 is illustrated by an example in the section to follow.

Truck requirement for a 5-High Lead, 1-Grapple yarder configuration

The logging equipment manufacturer's answer to the problem of reducing logging costs is the design of new machinery which is not only more efficient, but which requires less manpower as well. One of such machines produced is the Grapple yarder. A description of some early developments of the Grapple yarder is given by Sommer (1969).

The purpose of this example is to illustrate the change in the truck requirement resulting from the introduction of a highly productive machine such as the Grapple yarder. In this hypothetical example, it is assumed that a Grapple yarder is added to five High Lead yarders already in operation.

The total daily yarding production for the five High Lead yarders and the Grapple yarder is given by

$$P = P(\text{for the 5 yarders}) + \frac{U_y A_y}{1000} \times \text{(the potential daily productivity of the Grapple yarder)}$$

where A_y = the yarder % availability assumed at 99%

U_y = the yarder % utilization assumed at 98% at N_{opt} trucks.

Using the mean of the Grapple yarder autoregressive model (given in Appendix C) as the potential Grapple yarder daily productivity, P was calculated as 423 cunits per day. The mean setting distance from the camp ($\bar{D}$) for the settings scheduled for the six yarders is 14.6 miles. From Figure 6.12, it is seen that 15 trucks will be required for this 5-High Lead, 1-Grapple yarder configuration. A series of simulation runs for this configuration arrived at 15 trucks as having the least unit cost.

The unit cost and production as functions of the number of trucks for this configuration, for the original 5-yarder configuration, and for a 6-High Lead yarder configuration are shown in Figure 6.14. It is seen that unless three or four additional trucks are provided to balance the added production of the Grapple yarder, the full benefit of the introduction of this yarder will not be realized. At 12 trucks, the 5-High Lead, 1-Grapple yarder operation produces only an extra 38 cunits and at a higher cost. At 16 trucks the same operation produces around 417 cunits at 14.45 \$/cunit. In comparison, a similar 6-High Lead yarder operation with 14 trucks produces 378 cunits at 15.11 \$/cunit.

<u>Truck requirement for the basic configuration using different combinations of "small" and "large" trucks</u>

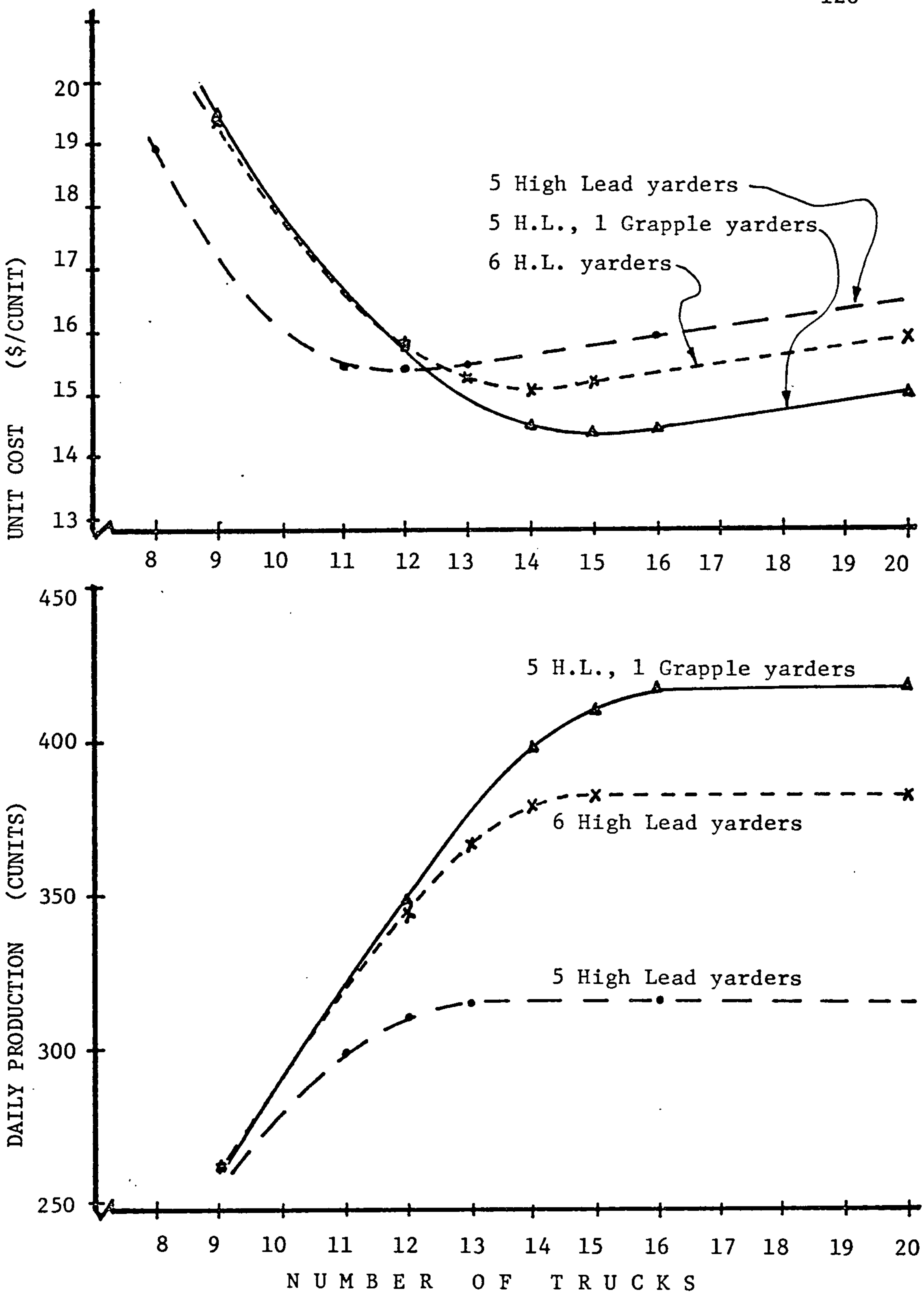

Figure 6.14 The unit cost and production curves for a 5-High Lead yarder configuration, a 5-H.L.-1-Grapple yarder configuration, and a 6-High Lead yarder configuration

The presentation, so far, involved the use of only one type of truck referred to in this study as "small" truck with a 75,000 lbs. design payload. A second type of truck considered in the model has a payload of 100,000 lbs. While the purchase price and operating costs of these "large" trucks are higher, these are more than offset by their increased capacity. In this section, the effect of using different combinations of "small" and "large" trucks on unit cost and production will be explored.

Table 6.2 shows an estimate of the purchase price, operating cost, capacity, and average loading time for the two types of trucks. Although separate loading time and load volume distributions are used in the model for these two truck types, the same travel time distributions are used. The available data on the travel times for the "large" trucks indicated no significant difference between the travel times of these two truck types.

	"small" trucks	"large" trucks
Purchase price ($)	47,000	69,000
Depreciation and insurance ($/shift)	27	40
Operating cost (fuel, lube, tires, supplies, etc.) ($/mile)	0.77	0.89
Average load (cunits)	13.16	17.88
Average loading time (min)	38.93	40.83

Table 6.2 Estimates of the purchase price, operating cost, capacity, and average loading time for "small" and "large" trucks

Figure 6.15 summarizes the unit cost and production results of the simulation runs made with the basic (6-yarder) configuration using various combinations of "small" and "large" trucks. For the costs and functional relationships assumed in this study, Figure 6.15 indicates that a lower unit cost can be realized when a fleet of all "large" trucks is used. For any number of trucks N, the values for any system response for a fleet of all "small" trucks and for a fleet of all "large" trucks respectively represent the extreme values. That is, for any N, either $R_s \lesssim R_c \lesssim R_l$ or $R_s \gtrsim R_c \gtrsim R_l$ holds, where

R_s = the vaule of the response R when a fleet of all "small" trucks is used

R_l = the corresponding value when a fleet of all "large" trucks is used

R_c = the corresponding value when a combination of "small" and "large" trucks is used.

For instance, in Figure 6.15 at N = 10,

$$C_s > C_c > C_l \quad \text{and} \quad P_s < P_c < P_l,$$

but at N = 15

$$C_s < C_c < C_l \quad \text{and} \quad P_s = P_c = P_l.$$

The unit cost curve using "small" trucks and the unit cost curve using "large" trucks intersect at some point i on the N-axis. It can be shown that at N=i the unit cost is the same for all combinations of "small" and "large" trucks; that is, $C_s = C_c = C_l$. At N=i, while the total fixed cost for a fleet of "small" trucks is lower than for a fleet of "large" trucks, it takes more round trips for the "small" trucks to yield the same production as the "large" trucks. Hence, the

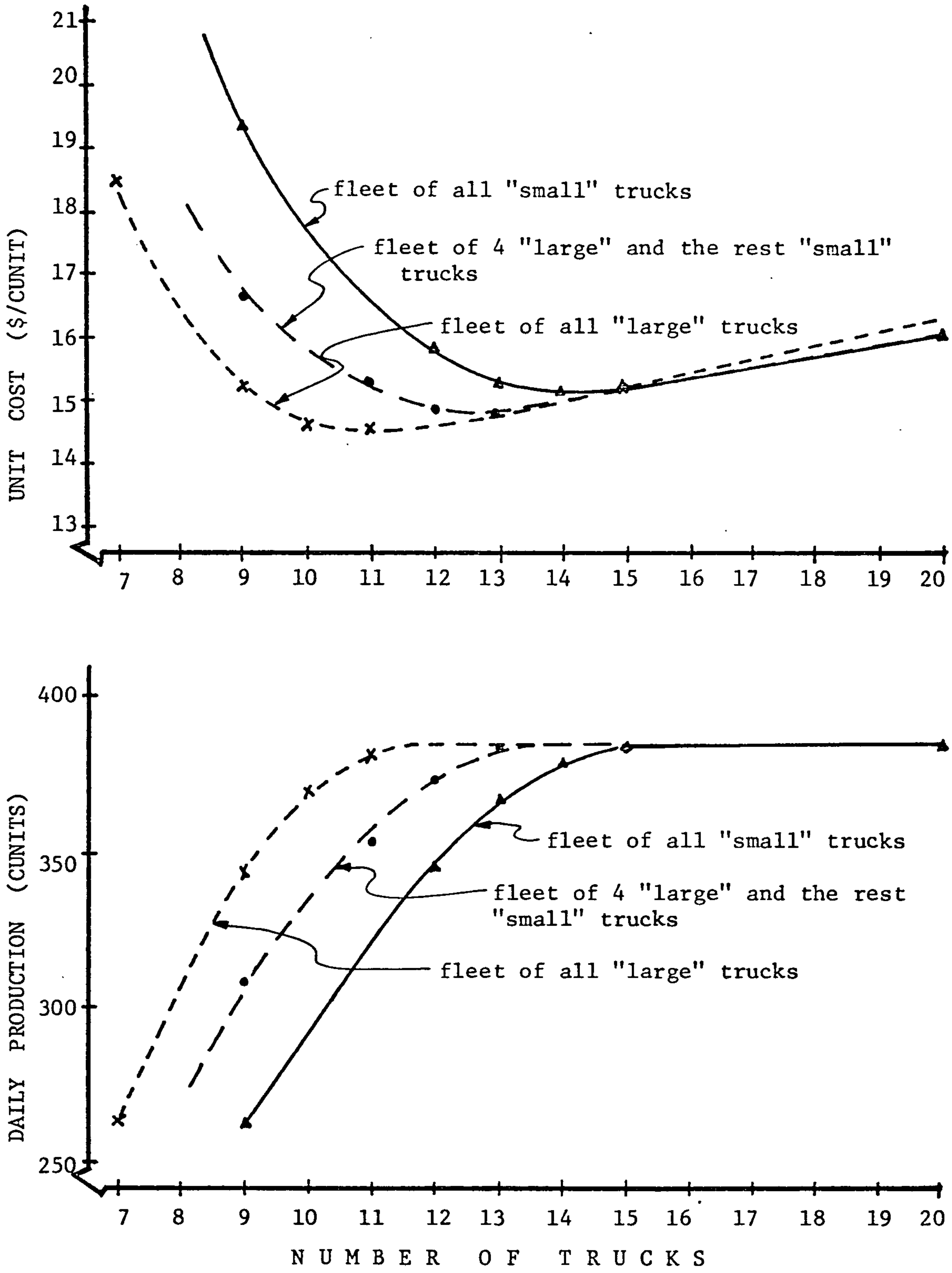

Figure 6.15 The unit cost and production curves for the basic configuration using different fleet of trucks

lower fixed cost for the "small" trucks is neutralized by a higher variable cost.

Figure 6.16 shows the iso-unit cost curves over different combinations of "large" and "small" trucks.

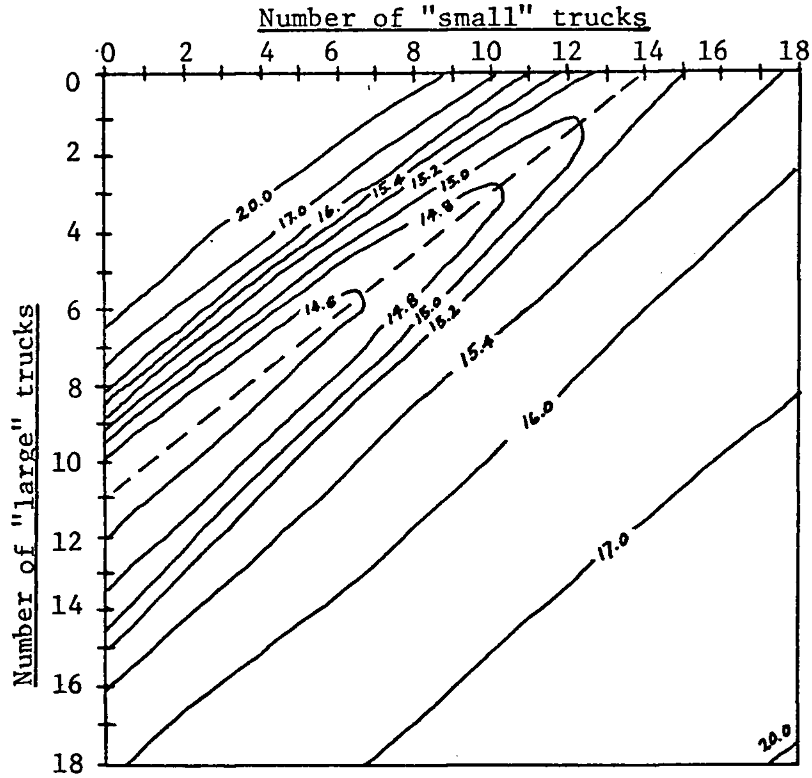

Figure 6.16 Iso-unit cost curves over different combinations of "large" and "small" trucks

C. SENSITIVITY ANALYSIS: THE RELATIVE EFFECT OF SOME EQUIPMENT AVAILABILITY PARAMETERS ON PRODUCTION

The sample applications presented thus far have examined the effect on unit cost and production of several factors, namely:

1. number of trucks
2. truck type
3. number of yarders and yarder productivity
4. mean setting distance

5. shutdown mode.

While these applications are, in effect, analyses of the sensitivity of the system to the listed factors, the approach has been to examine a class of factors while keeping the rest of the factors fixed at their respective specified levels. This approach, of course, has a major disadvantage in that it cannot provide a measure of the interactions between the various levels of the "fixed" factors and the levels of the "varied" factors. This approach, however, has been necessitated because of the problem of too many factors. As Conway, et.al. (1959) have pointed out, while in principle simulation can be used to investigate the effect of any conceivable factor, relationship, or policy, in practice this results in factorial experiments whose dimensions dwarf the most powerful computer or the most lavish budget. Because of this problem of size, a complete factorial experiment becomes a luxury. The grouping of factors into classes according to the nature of the investigation becomes a necessity.

In the discussions to follow, the relative effect of some equipment availability parameters on production will be examined. While the model may be used to examine particular problems[1], the purpose of this investigation is to rank the various availability parameters according to their effect on the production of the basic configuration.

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1 An example is the following: Is a machine with relatively low productivity but with high availability more economical than a potentially more productive machine which produces disruptive surges of wood through the system?

Equipment availability can be measured in terms of the equipment breakdown and repair parameters, μ_b and μ_r respectively. In the following example, the effect on production of four parameters will be examined. These parameters are:

1. μ_{bt} = the mean truck inter-breakdown time
2. μ_{rt} = the mean truck repair time
3. μ_{by} = the mean yarder inter-breakdown time
4. μ_{bl} = the mean loader inter-breakdown time.

Noting that the aim of this example is to rank the above parameters according to their effect on production, a significant reduction in the number of simulation runs can be realized if only the main effects are estimated while the interaction effects of the various levels of the parameters are sacrificed. Hence, a one-ninth replicate of a 3^4 design is used. Nine runs are required for this design, namely:

0000	1011	2022
0121	1102	2110
0212	1220	2201

where in each run the four numbers indicate the levels of the factors μ_{bl}, μ_{by}, μ_{bt}, and μ_{rt}, respectively. The values of these levels are shown in Table 6.3.

Table 6.3 The levels used for each of the four equipment availability parameters.

Level	μ_{bl}	μ_{by} (Thousand minutes)	μ_{bt}	μ_{rt}
0	24	15	10	0.7
1	30	20	16	1.0
2	36	25	22	1.3

The initial regression model used was

$$P = a_o + a_1\mu_{bl} + a_2\mu_{by} + a_3\mu_{bt} + a_4\mu_{rt} + a_5\mu_{bl}^2 + a_6\mu_{by}^2 + a_7\mu_{bt}^2 + a_8\mu_{rt}^2 + e.$$

After a stepwise elimination of the non-significant variables, the regression equation obtained is

$$P = 374.223 + 0.4672\mu_{bt} - 5.1579\mu_{rt}^2.$$

This equation accounts for 73.96% of the total variation. The regression analysis, therefore, indicated that for the basic configuration and for the given range of the levels of the different factors, the mean truck repair time has the greatest effect on production among the factors examined. The mean truck inter-breakdown time also significantly affects production, but the mean yarder and loader inter-breakdown times are indicated to contribute no significant effect on production. Noting that the levels of μ_{bl} and μ_{by} are quite high compared to the levels of μ_{bt}, it can be concluded that the availability of the yarders and the loaders is sufficiently high so that changes in μ_{bl} and μ_{by} do not result in significant changes in production.

Further examination of μ_{bt} and μ_{rt} was undertaken to investigate their interaction effect. Using a full factorial design, six simulation runs were made to collect sufficient data for the model:[1]

$$P = a_o + a_1\mu_{bt} + a_2\mu_{rt} + a_3\mu_{bt}\,\mu_{rt} + c.$$

The regression equation obtained is

$$P = 433.523 - 2.4730\mu_{bt} - 59.8124\mu_{rt} + 2.7395\mu_{bt}\ {}_{rt}.$$

All regression coefficients in the above equation are significant. The equation accounted for 96.58% of the total variation. Figure 6.17 shows the daily production response surface over the values of the mean truck repair time and the mean truck inter-breakdown time. It is seen that the higher the value of the mean truck inter-breakdown time is, the lesser is the effect on production of the mean truck repair time. On the other hand, the higher the value of the mean truck repair time is, the greater is the effect on production of the mean truck inter-breakdown time.

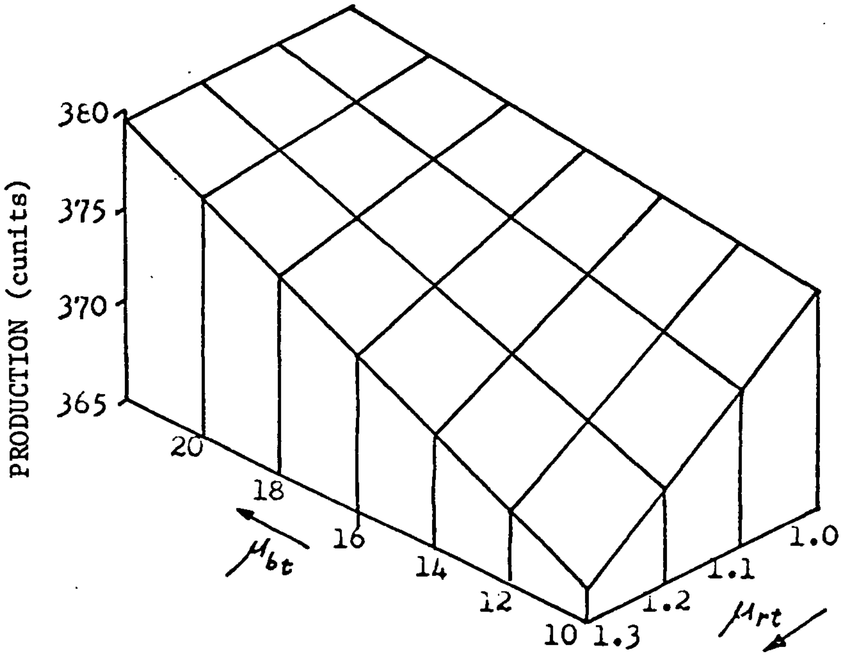

Figure 6.17 Production response surface for the basic configuration over different values of μ_{bt} and μ_{rt}

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1 Two extra runs were made to enable the examination of a wide range of μ_{bt}. The levels used were 1.0 and 1.3 thousand minutes for μ_{rt} and 10, 16, and 22 thousand minutes for μ_{bt}.

CHAPTER VII

SUMMARY AND CONCLUSIONS

This thesis has described a methodology for examining problems associated with the management and control of forest harvesting operations. The methodology developed accounts for the relevant characteristics inherent in forest harvesting systems in that:

1. it preserves the probabilistic nature of these systems, which dictates the interplay of the variables that govern the system behavior;
2. it preserves the dynamic character of these systems thus allowing the interplay of the system variables;
3. it preserves the inherent response-factor relationships which account for the interactions of the system variables; and
4. it preserves the self-regulating behavior of these systems.

The methodology developed is one of a systems simulation with general applicability that permits experimentation with a wide class of logging configurations. Of modular structure, the model developed is capable of simulating multi-source, single-sink configurations with variable internode distances, with various equipment types and combinations, and with various parameters and functional relationships. Written in FORTRAN IV, the model allows independent users to readily make modifications in the routines to adapt them to the particular operating rules and policies of their operations. Furthermore, the model is capable of fast execution; thus it permits extensive experimentation at a manageable cost.

The validity of the model has been tested and demonstrated for an actual West Coast logging division used as a vehicle for model formulation. The verification procedure involved the independent examination of the assumptions and rules of operation of the model subsystems, and the historical confirmation that for a particular situation the subsystems together made up a system which displays the behavior and characteristics associated with the real system. The historical verification involving two outputs of the system, namely daily yarding production and number of daily round trips, showed that the model can "process" the production "input series" to produce a resultant series which is compatible with the series observed for a real situation. While no model can be said to be valid in the absolute sense, confidence in the model rests largely on the confirmation of its ability to display the behavior and characteristics expected of the real system.

A simulation model is constructed in the hope that it will successfully mimic a particular real world system so that inferences on the real system can be made through the model. As Hunter and

Naylor (1969) pointed out, one's understanding of a complicated and involved system through a complex model such as a simulation proceeds only when one is able to synthesize the system in terms of simple explanations. This synthesis requires the identification of the major factors affecting the responses and the evaluation of the empirical relationships associating the factors with the responses. In other words, simple empirical models are super-imposed on the larger detailed simulation models. Conclusions on the real system can then be derived once an empirical understanding has been acquired.

The investigation of the various system responses has established some simple relationships among the responses in association with a principal factor - the number of trucks. The comparison of the responses led to the choice of unit cost as the measure of system performance with production as a constraining response.

The execution of the model runs has been discussed. Some experimental design problems and some tactical considerations have been presented. Some ways for overcoming such design problems have been suggested. In particular, it has been shown in the text and presented in more detail in Appendix F.3 that the control variate technique can be effectively used with the model to reduce the variance of the difference between two means. In addition, it has been shown that the method of antithetic variates can be used to further reduce the variance of the mean of a response when a second replication is necessary.

Some practical applications of the logging simulation model have been discussed and illustrated. The model can be used to evaluate and compare existing operating policies or to formulate new policies. This application has been illustrated with reference to the comparison of two operation shutdown modes. The results showed that while the first shutdown mode results in more production than the second shutdown mode, this is true only when the number of trucks is less than the optimum number required. The higher unit cost of the first mode resulting from a larger number of truck overtime hours makes it inferior to the second mode.

The model has also been shown to be useful in the determination of equipment requirements under different operating conditions. using a simulation approach, the equipment requirements for a particular operation are given not merely in terms of a required productivity per unit time, but in terms of an explicit statement of the type and combination of equipment.

The model can also be used to compare the costs and productivity of an operation using trucks of different capacities. This capability can be utilized in the development of trucking policies and in truck design, addressed to the question of what truck specifications best suit a given operation.

Perhaps the greatest benefit from a simulation model can be derived from its capability of increasing our understanding of the system - through learning how the parts of the system behave and interact and through learning how the system responds to changes in its factors. These capabilities can be beneficial not only in the design of better policies but also in the exercise of better control of the system.

Simulation has been regarded by many as a last resort technique, perhaps rightly so, because of the many difficulties inherent in a simulation approach. Simulation requires extensive data and complete information about the processes of the system. As Miller and Starr (1969) have pointed out, simulation is not a substitute for knowledge. The misuse of simulation has largely been due to the forgetting of this crucial fact. Simulation is based on the premise that much is known about the parts of the system, but not how they interact to display the over-all system behavior.

Difficulties also arise in the formulation of the model. Logging problems are diverse in nature, and no general model is likely to be developed that can handle all classes of logging problems. Since the degree of resolution of detail in a representation is problem-dependent, the task of building a general model will be set back by the problem of determining the proper balance between faithfulness of reproduction and simplicity of representation while attaining the flexibility to describe any specific problem. In the absence of an all-inclusive model, there may well be different models for different classes of problems. This study has been based on the realization that some classes of problems, for instance those involving the evaluation of different system designs, policies, and system input combinations, require adequate realism provided by a descriptive type of model.

Difficulties also stem from the nature of simulation. A simulation model can be equated to a manager's experimental laboratory. Hence, it is subject to some methodological problems concerning:

1. Validity. The desription of a system by a model invariably carries with it some assumptions on the properties and behavior of the system. Confidence and use of the model should be based on the awareness of these assumptions.
2. Motive. Simulation is more suitable to problems involving relationships between a cause and its effects. Simulation is not inherently optimizing, optimization must be superimposed on the model by varying the level of the pertinent factors one at a time. In essence, this is translating the problem into a cause-and-effect structure.
3. Variability and size. There is a need to carefully consider the design of the experimental runs. As in real world experimentation, simulation is beset by the same experimental design problems of keeping the amount of experimental effort down to a manageable level in obtaining the desired precision of the results.

Further developments of the model should be made in two areas:

1. Revision. Revisions based on extensive sensitivity analysis can be made on the model. Through sensitivity analysis, the factors which cause more profound changes in the system behavior can be identified. On this basis, more aggregation and simplification can

be made on the routines of the model.

2. Extension. The model presented in this thesis describes a system as it is, rather than what it should be or could be. A crucial need, however, lies in the design of a better system of handling the product flow. Further developments should be directed towards satisfying this need.

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APPENDIX A

START-UP AND SHUTDOWN MODES

A.1 START-UP SEQUENCE

The start-up sequence of activities of the operation at the beginning of each day is as follows:

At 6:30 the shop crews leave the marshalling yard for the camp.

At 7:00 the empty trucks at the camp and at the dump start up.

At 7:20 the dump starts unloading the trucks parked overnight at the dump in their loaded state.

At 7:45 the trucks parked overnight at the side of the road start up.

At 8:00 yarding and loading start.

A.2 SHUTDOWN MODE I

The shutdown sequence for the first shutdown mode near the end of the regular shift is as follows:

After 2:45 P.M any truck arriving at the dump is shut down. Assuming that there are n production sides, the first n trucks arriving after this time are unloaded before they are shut down. All other arrivals are shut down in their loaded state.

After 3:00 P.M. no trucks are dispatched to the side except when required to support the moving of a yarder or a loader.

At 4:25 P.M. yarding stops unless a truck being loaded requires more logs to complete the load.

At 4:30 P.M. the yarding and loading crews leave for the marshalling yard. If there are trucks waiting to be loaded at the side or approaching the side for a load, the loading crew stays until these trucks are loaded. Thus no trucks stay overnight at the side.

A.3 SHUTDOWN MODE II

The regular shift shutdown sequence for the second shutdown mode is as follows:

After 3:00 P.M. no trucks are dispatched to the side except when required to support the moving of a yarder or a loader.

At 3:20 P.M. the dump closes. Unloading goes beyond this time only if the truck is scheduled for check-up or for lowbed duty.

At 4:25 P.M yarding and loading stops. If a truck is being loaded, loading stops and is completed the next day. All trucks queueing at the side stay overnight at the side.

At. 4:45 P.M. trucks travelling to the side are parked by the roadside. All loaded trucks, however, continue to the dump (or to the camp if it is scheduled for check-up).

APPENDIX B

THE EVENT SCHEDULER

The event scheduler maintains a list of all events scheduled to occur. The event list stores the time of occurrence and other attributes of all scheduled events. The items in the list form a "singly-linked list", the link being the array which chronologically links the items in the list by indicating, for each event, the address of the next chronological event.

There are three basic operations connected with the event scheduler namely: initialization, event insertion, and event deletion.

B.1 INITIALIZATION

Figure B.1 shows the flow chart of the initialization operation. This operation sets up all the arrays needed by the scheduler. It is performed only once and it is initiated by the calling sequence CALL ISCHED (1). The arrays set up include:

1. TMLIST, which contains the time the scheduled events are to occur.
2. LISTTP, three arrays which contain the attributes of the scheduled events.
3. KPOINT, the array which links the events chronologically.

4. IACVEC, which contains the address of the storage spaces available for event insertion.

B.2 EVENT INSERTION

An event insertion is the inclusion of an event into the events lists. The calling sequence CALL SCHED (2,TIME,NTYPE) causes the scheduler to search through TMLIST to determine the chronological order of the event described by the variables TIME and NTYPE. The array KPOINT is then updated to accomodate the event, and the contents of TIME and NTYPE are transferred to their corresponding places in the array TMLIST and LISTTP. This operation is shown in Figure B.2.

B.3 EVENT DELETION

The variable NEXT contains the address of the first item in the singly-linked list. The calling sequence CALL SCHED (3,TIME, NTYPE) causes the transfer of the contents of TMLIST AND LISTTP at the address NEXT to TIME and NTYPE respectively. Figure B.3 shows the flow chart of this operation. Examples of the initialization, event insertion, and event deletion procedures are given in Figure B.4. The figure shows the contents of the several events lists when a series of calling sequences is transmitted to the events scheduler.

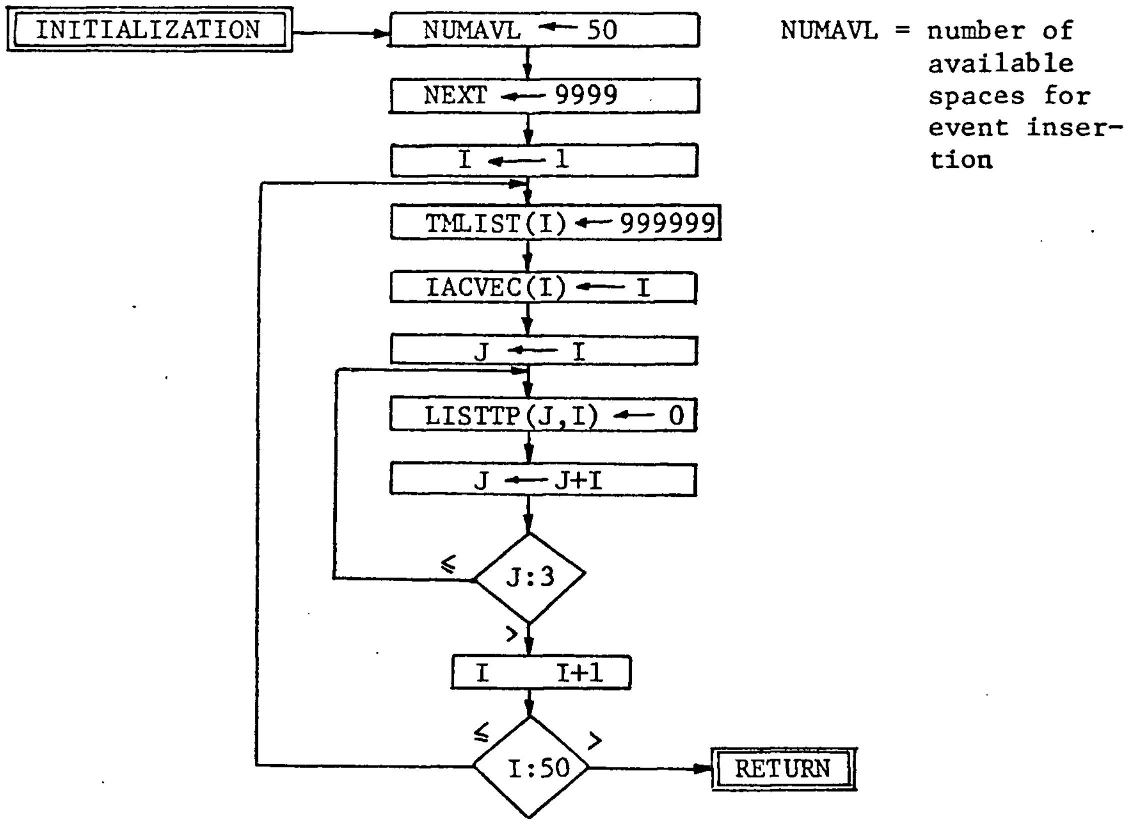


Figure B.1 Flow chart of the "event scheduler" initialization routine

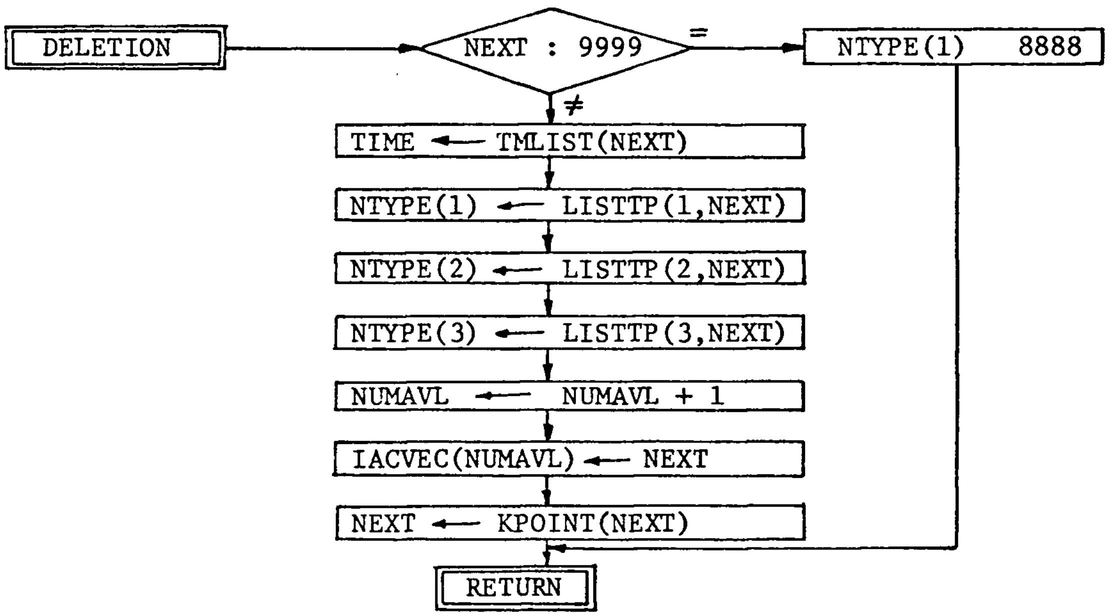


Figure B.2 Flow chart of the event deletion routine

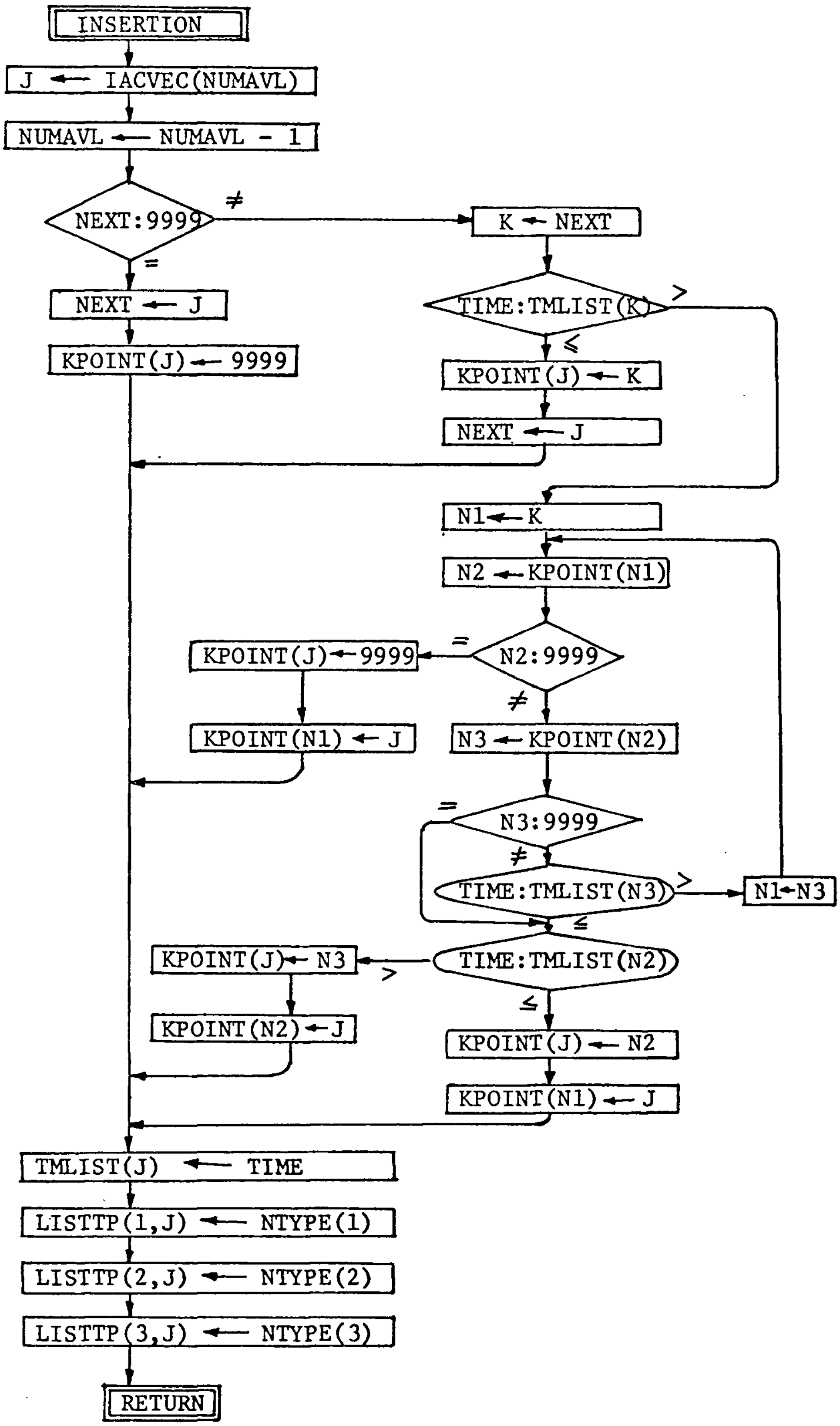


Figure B.3 Flow chart of the event insertion routine

CALLING SEQUENCE	IACVEC (J)	ADDRESS J	TMLIST (J)	LISTTP (1,J)	→	LISTTP (3,J)	KPOINT (J)	
CALL ISCHED(1)	1	1	∞	-	-	-	-	
	2	2	∞	-	-	-	-	
(Initialization)	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
* [P] →	50	50	∞	-	-	-	-	NEXT = 9999
CALL SCHED(2,15,NTYPE)								
(Insertion)	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
[P] →	49	49	∞	-	-	-	-	
	50	50	15	x	x	x	9999	NEXT = 50
CALL SCHED(2,35,NTYPE)								
(Insertion)	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
[P] →	48	48	∞	-	-	-	-	
	49	49	35	x	x	x	9999	
	50	50	15	x	x	x	49	NEXT = 50
CALL SCHED(2,20,NTYPE)								
(Insertion)	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
[P] →	47	47	∞	-	-	-	-	
	48	48	20	x	x	x	49	
	49	49	35	x	x	x	9999	
	50	50	15	x	x	x	48	NEXT = 50
CALL SCHED(3,TIME,NTYPE)								
(Deletion)	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
	47	47	∞	-	-	-	-	
[P] →	50	48	20	x	x	x	49	NEXT = 48
	49	49	35	x	x	x	9999	
	50	50	contents transfered to TIME, NTYPE					
CALL SCHED(2,55,NTYPE)								
(Insertion)	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
[P] →	47	47	∞	-	-	-	-	
	50	48	20	x	x	x	49	NEXT = 48
	49	49	35	x	x	x	50	
	50	50	55	x	x	x	9999	
CALL SCHED(3,TIME,NTYPE)								
(Deletion)	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
	47	47	∞	-	-	-	-	
[P] →	48	48	contents transfered to TIME, NTYPE					
	49	49	35	x	x	x	50	NEXT = 49
	50	50	55	x	x	x	9999	

* NOTE: P = IACVEC(NUMAVL) — gives the immediately available space for event insertion when there are NUMAVL spaces left

Figure B.4 Examples of the initialization, event insertion, and event deletion procedures

APPENDIX C

INPUTS TO THE LOGGING MODEL

C.1 FUNCTIONAL RELATIONSHIPS

Table C.1 The stochastic yarding models and the inverse cumulative density functions used in the simulation runs

Stochastic yarding models

Yarder 1: $X_t = 10.4937 + 0.7586X_{t-1} + A_t - 0.4861A_{t-1}$

where X_t = the potential production for the 8-hour shift in Mfbm.
$A_t \sim N(0,8.014)$

Yarder 2: $X_t = 36.9817 + 0.17855X_{t-1} + A_t$, $A_t \sim N(0,9.76)$

Yarder 3: $X_t = 26.6979 + 0.43390X_{t-1} + 0.1331X_{t-2} - 0.1823X_{t-3} + A_t$

$A_t \sim N(0,9.05)$

Yarder 4: $X_t = 37.2363 + 0.3928X_{t-1} - 0.0507X_{t-2} -0.046X_{t-3} + A_t$

$A_t \sim N(0,9.20)$

Yarder 5: $X_t = 14.35 + 0.5X_{t-1} + 0.15X_{t-2} + A_t$, $A_t \sim N(0,7.15)$

Yarder 6: $X_t = 30.0 + 0.4X_{t-1} + A_t$, $A_t \sim N(0,8.93)$

Yarder 7: $X_t = 27.0 + 0.45X_{t-1} + 0.1X_{t-2} + A_t$, $A_t \sim N(0,9.03)$

Yarder 8: $X_t = 31.5 + 0.3X_{t-1} + A_t$, $A_t \sim N(0,9.05)$

Grapple yarder: $X_t = 45.0 + 0.4X_{t-1} + A_t$, $A_t \sim N(0,10.0)$

Loading time for small trucks (minutes)

$$T = 12.56295 + 178.05948X - 941.79077X^2 + 2652.5993X^3 - 3274.1838X^4 + 1467.09253X^5 , \quad X \sim \text{Uniform}(0,1)$$

Table C.1 - cont.

Loading time for large trucks (minutes)

$$T = 19.4 + 50.17746X - 139.01392X^2 + 594.2793X^3 - 965.54053X^4 + 549.05298X^5 \quad , \quad X \sim \text{Uniform}(0,1)$$

Camp delay for loaded trucks (minutes)

$$T = -0.52135 + 35.35252X - 268.17603X^2 + 833.32178X^3 - 1101.88208X^4 + 521.74536X^5 \quad , \quad X \sim \text{Uniform}(0,1) \text{ and } T \geqslant 0$$

Camp delay for empty trucks (minutes)

$$T = -0.57894 + 23.72041X - 205.78593X^2 + 729.8051X^3 - 993.3894X^4 + 466.75806X^5 \quad , \quad X \sim \text{Uniform}(0,1) \text{ and } T \geqslant 0$$

Travel time from camp to dump (7.8-mile distance) (loaded trucks) (min.)

$$T = 10.0744 + 166.36107X - 965.48706X^2 + 2490.88794X^3 - 2845.25537X^4 + 1184.40723X^5 \quad , \quad X \sim \text{Uniform}(0,1)$$

Travel time from dump to camp (empty trucks) (minutes)

$$T = 16.19785 + 23.13339X - 107.70125X^2 + 368.198X^3 - 511.14917X^4 + 246.9175X^5 \quad , \quad X \sim \text{Uniform}(0,1)$$

Unloading time (minutes)

$$T = 3.32663 + 34.88907X - 210.3049X^2 + 573.31982X^3 - 680.90576X^4 + 294.97192X^5 \quad , \quad X \sim \text{Uniform}(0,1)$$

Travel velocity for empty trucks to the sides (miles per hour)

Section 1 $V = 6.41803 + 34.42258X - 50.94272X^2 + 27.7094X^3$

Section 2 $V = 21.5242 - 136.59778X + 688.72266X^2 - 1341.01147X^3$

$$X \sim \text{Uniform}(0,1)$$

Travel velocity for loaded trucks to the camp (miles per hour)

Section 1 $V = 6.41803 + 34.42258X - 50.94272X^2 + 27.7094X^3$

Section 2 $V = 21.5242 - 136.59778X + 688.72266X^2 - 1341.01147X^3 + 1124.04687X^4 - 326.03052X^5 \quad , \quad X \sim \text{Uniform}(0,1)$

C.2 INITIAL CONDITIONS

Table C.2 The intial values assumed for the landing inventory at each production sides and the initial location of each truck

Initial landing inventory (Mfbm.)

Side 1 :	20.0	Side 6 :	12.0
Side 2 :	16.0	Side 7 :	24.0
Side 3 :	10.0	Side 8 :	17.0
Side 4 :	6.3	Side 9 :	21.2
Side 5 :	5.0	Side 10:	9.7

Initial location of the logging trucks

Truck No.	Location	Status	Load volume (Mfbm.)
1	camp	empty	
2	dump	empty	
3	dump	loaded	9.0
4	dump	loaded	6.9
5	dump	loaded	7.0
6	camp	empty	
7	dump	empty	
8	dump	loaded	8.0
9	dump	loaded	8.1
10	dump	loaded	8.5
11	dump	loaded	9.3
12	dump	loaded	9.7
13	dump	empty	
14	dump	loaded	7.6
15	camp	empty	
16	dump	empty	
17	dump	empty	
18	dump	loaded	7.9
19	dump	loaded	8.8
20	dump	loaded	9.9

C.3 THE YARDING SEQUENCE AND SETTING STATISTICS

Table C.3 The yarding sequence and setting statistics used during the validation runs

Yarder Number	Setting Number	Distance from camp (miles)	Distance from prev. (miles)	Landing capacity (Mfbm.)	Setting volume (Mfbm.)
0904	9363	25.6		36	58
	9365	25.7	0.1	36	285
	9363	25.6	0.1	36	354
	9355	26.0	2.0	18	740
	7643	20.5	18.5	18	888
	7644	20.6	0.1	27	120
0905	5462	17.0		24	312
	5462	17.0		18	450
	5557	16.8	2.0	45	839
	5464	16.4	2.75	36	1304
	6841	18.1	6.0	45	343
0909	9350	25.8		36	479
	9343	25.7	0.1	36	504
	9343	25.7		36	381
	9345	25.9	0.2	36	214
	9155	24.7	3.8	18	572
	9154	24.5	0.2	45	139
	9171	24.3	0.7	36	449
0911	8359	19.0		9	13
	8358	18.9	0.1	45	299
	7854	18.3	11.0	45	286
	7896	20.8	2.5	36	387
	7955	22.0	1.2	27	1274
	7998	22.4	0.4	18	305

Table C.4 The yarding sequence and setting statistics used during the various simulation runs

Yarder number	Yarding order	Moving distance of yarder (miles)	Distance from camp (miles)	Setting volume (cunits)	Landing capacity (cunits)
1	1	0.10	17.90	407.52	53.28
1	2	0.10	18.00	211.64	53.28
1	3	2.00	17.90	210.16	53.28
1	4	18.50*	18.30	1095.20	26.64
1	5	-1.00	12.80	281.20	26.64
1	6	-1.00	12.80	230.88	26.64
1	7	-1.00	12.80	250.12	26.64
1	8	-1.00	12.80	398.12	26.64
1	9	0.10	12.80	153.92	26.64
1	10	0.0	12.90	1200.00	39.96
1	11	0.0	12.90	500.00	39.96
2	1	-1.00	18.10	448.59	53.28
2	2	-1.00	18.10	279.72	53.28
2	3	0.10	18.10	313.76	53.28
2	4	0.0	18.00	745.92	53.28
2	5	-1.00	18.00	230.88	53.28
2	6	0.20	18.00	333.00	53.28
2	7	3.80	18.20	316.72	53.28
2	8	-1.00	17.00	390.72	26.64
2	9	0.20	17.00	455.84	26.64
2	10	0.70	16.80	205.72	66.60
2	11	-1.00	16.60	540.20	53.28
2	12	0.0	16.60	1200.00	53.28
2	13	0.0	16.60	500.00	53.28
3	1	0.10	11.30	227.70	14.80
3	2	11.00	11.20	442.52	66.60
3	3	2.50	10.60	423.28	66.60
3	4	1.20	13.10	572.76	53.28
3	5	-1.00	14.30	136.16	39.96
3	6	-1.00	14.30	651.20	39.96
3	7	-1.00	14.30	125.80	39.96
3	8	0.40	14.30	972.36	39.96
3	9	-1.00	14.70	267.88	26.64
3	10	0.0	14.70	1200.00	26.64
3	11	0.0	14.70	500.00	26.64

* Moving distance = -1.00 means that the yarder is only turning around, i.e. same setting.
= 0.0 means that the moving distance is negligible

Table C.4 - cont.

Yarder number	Yarding order	Moving distance of yarder (miles)	Distance from camp (miles)	Setting volume (cunits)	Landing capacity (cunits)
4	1	0.0	9.30	853.22	35.52
4	2	2.00	9.30	666.00	26.64
4	3	-1.00	9.10	566.84	66.60
4	4	2.75	9.10	674.88	66.60
4	5	-1.00	8.70	740.00	53.28
4	6	-1.00	8.70	759.24	53.28
4	7	6.00	8.70	324.12	53.28
4	8	0.0	10.40	1200.00	66.60
4	9	0.0	8.70	500.00	53.28
5	1	0.10	15.00	1000.00	40.00
5	2	0.25	15.10	650.00	40.00
5	3	1.05	15.35	425.00	40.00
5	4	0.40	16.40	890.00	40.00
5	5	0.80	16.00	1200.00	40.00
5	6	0.0	16.80	900.00	40.00
5	7	0.0	16.80	750.00	40.00
6	1	0.20	15.40	890.00	40.00
6	2	-1.00	15.60	550.00	27.00
6	3	1.10	15.60	625.00	27.00
6	4	0.30	16.70	720.00	40.00
6	5	0.10	17.00	357.00	53.00
6	6	0.30	16.90	502.00	53.00
6	7	0.90	16.60	1250.00	40.00
6	8	0.0	17.50	900.00	40.00
6	9	0.0	17.50	700.00	40.00
7	1	0.60	17.10	760.00	40.00
7	2	1.10	17.70	420.00	40.00
7	3	-1.00	18.80	650.00	53.00
7	4	0.30	18.80	1100.00	53.00
7	5	-1.00	18.50	420.00	53.00
7	6	1.05	18.50	610.00	40.00
7	7	-1.00	19.55	352.00	40.00
7	8	0.25	19.55	711.00	40.00
7	9	0.0	19.80	1500.00	40.00
7	10	0.0	19.80	580.00	40.00
8	1	0.10	11.10	1100.00	40.00
8	2	-1.00	11.20	510.00	53.00
8	3	0.40	11.20	920.00	53.00
8	4	0.50	11.60	450.00	40.00
8	5	-1.00	12.10	790.00	40.00
8	6	0.40	12.10	940.00	40.00
8	7	0.0	12.50	1400.00	40.00

APPENDIX D

COSTS ASSUMED IN THE MODEL

Table D.1 Summary of the costs assumed in the model

Equipment	Cost per 8-hr. day ($)	Overtime ($/hr.)	No. of men in the crew
High Lead yarder	358.48	47.16	5
Grapple yarder	390.52	43.56	3
Trakloader	293.50	39.00	4
Loader	167.00	19.92	2
Unloading facility	130.00	7.08	1
Logging truck	**Fixed cost ($/8-hr.day)**	**Operating cost ($/mile)**	**Overtime ($/hr.)**
"small"	27.00	0.77	7.62
"large"	40.00	0.89	7.62

The yarder, loader, and dump costs include (where applicable):

Cost per 8-hr. day:

machine fixed cost - depreciation ("straight-line" depreciation over 16,000 hours assuming a 15% salvage value) and insurance

machine operating cost - wire rope (depreciated over 25,700 hours with no salvage value, chokers, fuel, oil, tires, repairs (63% of the depreciation)

labour - the basic wage for the crew plus 20% induced overhead (to cover the workmen's compensation dues, unemployment insurance, paid holidays, paid vacations, pensions); one hour travel time pay; extra ½ hour for the yarding engineer for the maintenance (oiling) of the yarder

Overtime: machine operating cost and labour cost [(basic wage + 20%) x 1.5]

The truck operating cost includes fuel and oil, repair and maintenance labour and supplies, and tires on a per mile basis.

APPENDIX E

SAMPLE OUTPUT FROM THE SIMULATION PROGRAM

E.1 OUTPUT TYPE 1

This type of output consists of a detailed breakdown of the activities of each of the yarders, loaders, and trucks, and a summary of the cost and production in each of the yarding, loading, trucking, and unloading activities. An example is shown in Tables E.1 and E.2.

In Table E.1, all times are given in minutes, while all volumes are given in cunits. In the trucking summary, BCKNG stands for the amount of time spent in "bullcooking" duties, e.g. moving of yarder, towing of truck. In the setting summary, the symbol (M) under yarding overtime denotes moving to another setting. WAIT LOG denotes the total number of minutes the logging trucks waited for the yarding of more logs in the designated side.

E.2 OUTPUT TYPE 2

This type of output consists of the daily series of values for several responses. Output type 1 and output type 2 are obtained from separate computer logical units; hence, a run may be allowed to yield one type of output while suppressing the other type.

Table E.1 The trucking, setting, and dump summaries for a day's operation

END OF DAY 2

TRUCKING SUMMARY

TRK NO.	PRODUCTIVE TIMES LDNG	UNLDG	HLNG	BCKNG	DELAY CAMP	TIMES SIDE QUEU	DUMP QUEU	TOTAL	C/T	LOADS NO. HALD	NO. DMPD	VOL HALD	MILES TRVLD	%U	%A
1	144.	15.	417.	0.	10.	54.	0.	640.	160.	3	2	34.9	118.	91.6	100.0
2	0.	7.	44.	0.	0.	0.	11.	63.	0.	0	1	0.0	18.	82.0	13.2
3	106.	24.	434.	0.	17.	0.	7.	588.	108.	3	3	40.5	118.	98.8	100.0
4	88.	20.	331.	0.	7.	0.	19.	465.	0.	2	3	25.4	80.	96.0	100.0
5	93.	8.	469.	0.	23.	0.	3.	597.	117.	2	1	26.6	110.	99.4	100.0
6	107.	17.	410.	0.	33.	0.	33.	600.	120.	2	2	26.6	90.	94.4	100.0
7	101.	23.	379.	0.	3.	67.	15.	588.	108.	2	3	28.2	88.	86.0	100.0
8	116.	34.	337.	0.	23.	46.	26.	582.	102.	3	4	39.8	106.	87.6	100.0
9	101.	16.	243.	324.	29.	0.	5.	717.	237.	2	2	30.0	110.	98.8	100.0
10	161.	22.	300.	0.	4.	0.	41.	529.	49.	2	3	26.6	82.	92.3	100.0
11	115.	13.	509.	0.	10.	0.	0.	647.	167.	3	2	40.7	124.	100.0	100.0
12	71.	15.	382.	114.	5.	0.	0.	587.	107.	2	2	26.6	120.	100.0	100.0
13	143.	12.	343.	0.	7.	0.	6.	511.	31.	2	2	26.6	90.	98.7	100.0

SETTING SUMMARY

SIDE	YRDNG O/T	LDNG O/T	DOWN TIMES YDR BKDN	LDR BKDN	PLUG LDNG	QUEU TIME	WAIT LOG	V O L U M E S TOTL YRDD	TOTL TRKD	VOL NOW	REM VOL	NUM OF LOADS	YDR %U	Y %A	L %A
1	192.(M)	30.	0.	0.	0.	0.	56.	54.3	53.3	7.7	1500.0	4	100.0	100.0	100.0
2	0.	0.	83.	0.	0.	0.	14.	37.8	40.0	3.3	811.3	3	100.0	82.7	100.0
3	0.	30.	0.	0.	0.	0.	0.	64.8	54.9	12.0	102.8	4	100.0	100.0	100.0
4	0.	30.	0.	0.	0.	90.	0.	104.3	95.7	26.2	104.1	7	100.0	100.0	100.0
5	0.	30.	0.	0.	-0.	10.	57.	54.9	63.0	0.0	345.6	5	100.0	100.0	100.0
6	0.	30.	0.	0.	0.	67.	0.	60.7	66.0	9.6	589.7	5	100.0	100.0	100.0

DUMP SUMMARY

TOTAL VOLUME DUMPED = 405.6
TIME SPENT DUMPING = 227.
DUMP OVERTIME = 108.

Table E.2 The yarding, loading, trucking, and unloading cost summaries for a day's operation

END OF DAY 2

COST SUMMARY

YARDING COST

HIGH LEAD SPARS			GRAPPLE YARDERS			T R A K L O A D E R S		
TOTAL COST	TOTAL YRDD	$/CUN	TOTAL COST	TOTAL YRDD	$/CUN	TOTAL COST	TOTAL YRDD	$/CUN
2294.50	376.8	6.09	0.0	0.0	0.0	0.0	0.0	0.0

LOADING COST

TOTAL COST	TOTAL LOADD	$/CUN
1051.80	372.7	2.82

TRUCKING COST

TOTAL COST	TOTAL HAULD	$/CUN
2013.09	372.7	5.40

DUMPING COST

TOTAL COST	TOTAL DUMPD	$/CUN
142.75	405.6	0.35

TOTAL COST FOR 2 DAYS ENDING DAY 2 =$ 10982.61
TOTAL VOLUME DUMPED DURING SAME PERIOD = 848.2 CUNITS

Table E.3 Sample output: Daily series of values for several responses

DAY	YARDED HI LEAD	YARDED GRPL	YARDED TRKL	CUNITS HAULED	CUNITS DUMPED	% U TRK	% A TRK	% U YDR	% A YDR	% A LDR	$/CN YDRS	$/CN LDRS	$/CN TRKS	$/CN DUMP	$/CN TOTAL	LOADS
1	341.3	0.0	0.0	370.7	382.5	91.1	100.0	100.0	100.0	100.0	6.72	2.86	5.72	0.35	15.65	30
2	414.6	0.0	0.0	419.9	434.3	96.2	94.1	98.7	100.0	100.0	5.53	2.55	5.58	0.32	13.98	34
3	389.8	0.0	0.0	386.9	383.7	94.1	93.3	99.1	93.1	93.8	5.83	2.70	5.72	0.36	14.61	31
4	405.0	0.0	0.0	393.8	393.1	95.6	91.7	99.6	100.0	100.0	6.13	2.70	5.66	0.35	14.83	31
5	432.3	0.0	0.0	430.9	400.6	89.7	93.3	100.0	100.0	100.0	5.30	2.49	5.48	0.35	13.62	33
6	360.1	0.0	0.0	383.0	393.1	93.1	100.0	99.8	100.0	100.0	6.69	2.77	5.92	0.34	15.73	31
7	354.0	0.0	0.0	340.3	342.1	89.7	98.6	100.0	100.0	100.0	6.48	3.12	6.11	0.39	16.10	29
8	321.1	0.0	0.0	327.1	328.6	85.6	100.0	100.0	100.0	100.0	7.14	3.25	6.16	0.41	16.95	27
9	347.3	0.0	0.0	336.3	334.5	91.1	100.0	100.0	100.0	100.0	6.60	3.16	6.02	0.40	16.17	27
10	361.3	0.0	0.0	367.3	383.7	94.5	89.8	100.0	100.0	100.0	6.34	2.89	6.02	0.37	15.62	30
11	436.3	0.0	0.0	384.3	380.9	95.9	86.7	100.0	100.0	100.0	5.25	2.79	5.53	0.37	13.94	30
12	303.9	0.0	0.0	358.8	377.9	95.6	86.7	99.7	100.0	100.0	7.70	3.04	5.86	0.38	16.98	27
13	411.7	0.0	0.0	337.6	320.8	94.3	80.2	99.8	98.9	100.0	6.02	3.15	5.88	0.43	15.47	27
14	288.8	0.0	0.0	338.3	380.2	89.1	86.7	89.3	94.4	100.0	8.29	3.14	6.12	0.37	17.92	26
15	416.5	0.0	0.0	382.6	330.0	94.3	88.6	99.3	100.0	100.0	5.50	2.80	5.63	0.42	14.35	31
16	371.4	0.0	0.0	395.3	400.7	88.6	86.7	100.0	93.5	98.3	6.13	2.70	5.24	0.34	14.41	30
17	392.2	0.0	0.0	410.9	404.1	87.8	93.3	100.0	100.0	100.0	5.85	2.63	5.65	0.34	14.46	34
18	405.3	0.0	0.0	386.1	396.3	92.6	100.0	98.4	100.0	100.0	6.12	2.75	5.89	0.35	15.11	30
19	386.4	0.0	0.0	390.7	373.6	93.9	100.0	100.0	100.0	100.0	5.93	2.72	5.73	0.36	14.74	32
20	384.6	0.0	0.0	389.6	392.1	94.7	100.0	99.6	100.0	100.0	5.96	2.75	5.79	0.35	14.85	30
21	342.4	0.0	0.0	333.9	317.7	95.0	100.0	99.3	100.0	96.7	7.11	3.15	6.55	0.42	17.23	27
22	417.7	0.0	0.0	430.4	442.1	95.4	95.5	98.7	100.0	100.0	5.49	2.51	5.42	0.31	13.73	34
23	413.7	0.0	0.0	400.1	407.1	93.3	97.4	100.0	100.0	100.0	5.54	2.65	5.85	0.34	14.38	32
24	370.1	0.0	0.0	367.7	377.4	93.2	93.3	100.0	100.0	100.0	6.19	2.89	5.79	0.36	15.23	30
25	360.0	0.0	0.0	369.7	372.0	88.4	93.3	100.0	100.0	100.0	6.37	2.87	5.91	0.36	15.51	30
26	393.5	0.0	0.0	376.1	368.0	93.9	93.3	99.5	100.0	100.0	5.83	2.82	5.79	0.37	14.32	30
27	427.4	0.0	0.0	405.7	407.2	88.7	89.6	97.0	100.0	100.0	5.36	2.64	5.56	0.35	13.91	32
28	372.2	0.0	0.0	377.9	393.1	95.0	84.7	95.5	100.0	100.0	6.16	2.81	5.45	0.36	14.78	28
29	364.0	0.0	0.0	317.3	341.1	89.2	78.5	90.1	100.0	100.0	6.49	3.35	5.99	0.40	16.23	24
30	312.8	0.0	0.0	336.5	362.4	80.4	80.0	83.1	100.0	94.7	8.37	3.11	5.99	0.38	17.85	26
31	341.5	0.0	0.0	396.4	354.9	87.4	93.3	98.5	100.0	100.0	6.85	2.68	5.61	0.41	15.54	29
32	282.0	0.0	0.0	282.1	274.1	94.4	100.0	100.0	96.1	100.0	8.43	3.76	7.27	0.49	19.94	23
33	363.9	0.0	0.0	368.9	360.8	92.4	94.2	99.8	100.0	100.0	6.62	2.88	5.85	0.37	15.72	30
34	413.1	0.0	0.0	384.3	382.4	84.0	93.3	99.6	100.0	100.0	5.55	2.76	5.60	0.36	14.27	31
35	398.3	0.0	0.0	396.6	372.5	92.7	100.0	100.0	100.0	100.0	5.76	2.68	5.75	0.36	14.54	33
36	370.0	0.0	0.0	406.4	417.8	89.4	100.0	99.8	100.0	100.0	6.26	2.61	5.76	0.33	14.96	33
37	403.5	0.0	0.0	384.3	402.0	91.5	100.0	100.0	100.0	100.0	5.80	2.76	5.75	0.33	14.64	30
38	380.3	0.0	0.0	333.9	342.5	90.0	93.3	100.0	100.0	97.7	6.03	3.16	6.25	0.39	15.83	26
39	283.8	0.0	0.0	287.0	293.3	89.7	100.0	85.2	100.0	78.5	7.94	3.50	6.63	0.46	18.52	24
40	398.6	0.0	0.0	434.7	398.5	96.2	93.3	100.0	100.0	100.0	5.75	2.44	5.26	0.34	13.80	34
41	431.7	0.0	0.0	416.6	401.8	92.6	100.0	100.0	100.0	99.2	5.31	2.54	5.48	0.33	13.67	33
42	452.5	0.0	0.0	448.3	473.7	93.5	100.0	99.8	100.0	100.0	5.22	2.39	5.33	0.29	13.23	34
43	425.4	0.0	0.0	404.0	390.8	93.5	96.5	100.0	100.0	100.0	5.39	2.63	5.59	0.34	13.95	32
44	406.3	0.0	0.0	414.8	419.7	95.0	93.3	100.0	100.0	100.0	5.64	2.56	5.20	0.32	13.72	31
45	387.8	0.0	0.0	372.9	403.0	89.7	88.2	98.6	100.0	100.0	5.97	2.85	5.73	0.34	14.89	28
46	362.5	0.0	0.0	443.6	409.9	89.1	93.3	97.1	100.0	100.0	6.78	2.44	5.23	0.34	14.79	34
47	417.6	0.0	0.0	360.6	375.1	90.1	100.0	99.8	100.0	100.0	5.72	2.94	6.16	0.37	15.18	30
48	374.2	0.0	0.0	398.1	381.6	91.6	100.0	98.8	100.0	100.0	6.13	2.67	5.81	0.36	14.96	33
49	345.5	0.0	0.0	324.7	344.6	87.1	100.0	99.8	100.0	100.0	6.84	3.27	6.19	0.39	16.68	27
50	405.7	0.0	0.0	436.4	413.9	93.9	100.0	95.5	100.0	94.6	5.62	2.40	5.47	0.33	13.82	36
51	418.8	0.0	0.0	419.4	410.0	89.9	100.0	99.4	100.0	100.0	5.47	2.53	5.57	0.33	13.91	34
52	344.6	0.0	0.0	344.9	362.7	88.8	100.0	99.8	100.0	100.0	6.93	3.08	6.50	0.38	16.88	29
53	453.8	0.0	0.0	433.5	432.5	93.2	100.0	98.8	95.3	99.8	5.02	2.49	5.51	0.32	13.35	35
54	386.0	0.0	0.0	392.9	384.3	94.2	100.0	100.0	100.0	100.0	5.94	3.11	6.00	0.35	15.39	32
55	373.3	0.0	0.0	345.3	357.1	92.2	99.2	100.0	100.0	100.0	6.14	3.08	6.02	0.37	15.61	29
56	392.9	0.0	0.0	419.7	400.8	93.5	100.0	100.0	100.0	100.0	5.83	2.55	5.50	0.33	14.22	33
57	360.2	0.0	0.0	341.1	358.1	91.6	99.9	100.0	100.0	100.0	6.36	3.11	6.27	0.37	16.12	29
58	389.1	0.0	0.0	391.5	374.9	89.1	93.3	100.0	100.0	100.0	5.89	2.74	5.51	0.36	14.50	31
59	383.0	0.0	0.0	395.9	384.3	94.7	100.0	100.0	100.0	100.0	5.99	3.11	6.01	0.35	15.45	32
60	391.1	0.0	0.0	389.5	393.5	91.1	100.0	100.0	100.0	100.0	5.86	2.73	5.74	0.34	14.67	32
61	432.8	0.0	0.0	427.3	436.4	92.0	97.9	99.8	100.0	100.0	5.84	2.53	5.52	0.31	14.20	33
62	338.3	0.0	0.0	333.1	351.4	93.5	100.0	99.8	100.0	100.0	7.54	3.19	6.70	0.38	17.81	27
63	423.5	0.0	0.0	404.5	392.6	91.9	100.0	100.0	100.0	100.0	5.41	2.65	5.67	0.34	14.07	33
64	394.7	0.0	0.0	405.3	400.4	93.7	99.9	99.6	100.0	100.0	5.31	2.62	5.67	0.33	14.44	32
65	419.9	0.0	0.0	438.1	441.1	95.8	100.0	100.0	100.0	100.0	5.46	2.42	5.62	0.32	13.82	35
66	381.5	0.0	0.0	378.7	380.9	90.3	100.0	99.8	100.0	100.0	6.26	2.80	5.80	0.35	15.21	31
67	439.4	0.0	0.0	389.5	383.7	94.1	97.0	100.0	100.0	100.0	5.22	2.73	5.87	0.36	14.17	32
68	424.6	0.0	0.0	387.9	397.0	87.8	91.7	96.0	100.0	100.0	5.40	2.76	5.58	0.34	14.08	30
69	404.4	0.0	0.0	430.9	410.0	95.2	93.3	98.9	100.0	100.0	6.08	2.53	5.18	0.33	14.12	32
70	403.2	0.0	0.0	399.5	435.6	89.0	90.2	99.0	100.0	100.0	5.69	2.68	5.58	0.32	14.27	31
71	308.3	0.0	0.0	328.8	345.3	86.4	88.4	90.2	100.0	100.0	8.20	3.23	6.18	0.39	18.00	26
72	385.9	0.0	0.0	396.7	362.2	86.3	93.3	88.3	100.0	89.9	5.89	2.63	5.60	0.39	14.51	32
73	348.8	0.0	0.0	353.8	364.3	95.3	97.2	99.1	100.0	100.0	6.57	3.00	6.11	0.37	16.05	29
74	375.6	0.0	0.0	423.4	402.7	93.8	93.3	100.0	100.0	100.0	6.10	2.51	5.40	0.34	14.35	33
75	354.9	0.0	0.0	343.4	347.6	83.7	93.3	100.0	100.0	100.0	6.46	3.12	6.06	0.38	16.03	28
76	446.7	0.0	0.0	408.4	418.9	93.1	96.8	100.0	100.0	100.0	5.13	2.65	5.81	0.34	13.92	34
77	409.8	0.0	0.0	407.5	396.1	93.2	93.3	100.0	100.0	100.0	5.59	2.61	5.30	0.34	13.84	31
78	388.3	0.0	0.0	391.7	415.0	83.5	93.3	99.8	100.0	100.0	6.45	2.71	5.54	0.32	15.02	30
79	390.8	0.0	0.0	419.3	397.4	93.3	100.0	100.0	96.1	100.0	5.84	2.53	5.59	0.34	14.31	34
80	322.3	0.0	0.0	327.2	329.7	89.8	99.9	99.8	100.0	100.0	7.11	3.76	6.60	0.41	17.89	28

APPENDIX F

STATISTICAL PROCEDURES FOR THE ANALYSIS OF TIME SERIES

Sets of data generated serially from real-world or simulated processes are generally time-dependent. The elements in these sets of data are autocorrelated. In dealing with this type of data, the statistical techniques commonly applied to sets of independent observations cannot be applied since the reliability of the sample means and variances are overestimated when autocorrelation is ignored (Fishman and Kiviat, 1967). Thus the analysis requires that: (1) uncorrelated data are collected, (2) correlated data are transformed to remove the time dependences, or (3) statistical techniques that account for the time dependence are used. The third alternative is used throughout this thesis. The statistical procedures used in the analysis of autocorrelated data are described in the following sections:

1. Definitions and assumptions
2. Calculation of the mean, variance, autocorrelation, and spectrum of a time series
3. Calculation of the variance to use in defining the confidence limits for a mean of a response or in comparing the means of two processes differing only in some minor respects
4. The determination of the length of the simulation runs
5. Test for equivalence of two spectra
6. Fitting of stochastic time series models

These sections contain some results from the references given below. These sections also contain some examples pertaining to logging processes.

References

1. Box, G.E.P. and Jenkins, G.M. TIME SERIES ANALYSIS forecasting and control. San Francisco: Holden-Day, Inc. 1970

2. Fishman, G.S. and Kiviat, P.J. "The Analysis of Simulation-Generated Time Series." Mgt. Science, 13(7) (March, 1967), pp. 525-557.

3. Jenkins, G.M. and Watts, D.G. Spectral Analysis and Its Applications. San Francisco: Holden-Day, Inc. 1968

4. Fishman, G.S. "The Allocation of Computer Time in Comparing Simulation Experiments." Operations Research, V. 16 (1968), pp. 280-295.

5. Fishman, G.S. "Problems in the Statistical Analysis of Simulation Experiments: the comparison of means and the length of sample records." Comm. of the ACM, 10 (2) (February, 1967), pp. 94-99.

In the following sections, the numbers in parenthesis indicate the number of the references from where the results were taken.

F.1 DEFINITIONS AND ASSUMPTIONS (1,2)

Stochastic processes concern sequences of events occurring in time according to probabilistic laws. Symbolically, a stochastic process $(X_t , t \in T)$ is a sequence of random variables indexed on a continuous parameter t which takes on all values in the set T. The index t may correspond to discrete units in time $T = (0,1,2,3,\ldots)$.

A time series is a set of observations generated sequentially in time. It is one particular realization, produced by the underlying probability mechanism, of the stochastic process.

The subsequent sections deal with a class of stochastic processes, called stationary processes. A stochastic process is said to be strictly stationary if it is invariant under translation along the axis; i.e. if

$$P(X_{t_1} \leq x_1, X_{t_2} \leq x_2, \ldots, X_{t_n} \leq x_n) = P(X_{t_1+k} \leq x_1, \ldots, X_{t_n+k} \leq x_n)$$

for arbitrary real values of s and for all n. A stochastic process is said to be weakly stationary of order m if the moments (of its probability distribution) up to some order m are finite and depend only on time differences.

If the probability distribution associated with the process is a multivariate Normal distribution, the process is called a Normal or Gaussian process. Since the multivariate distribution is fully characterized by its first and second moments, second order stationary plus Normality would be sufficient to produce strict stationarity.

F.2 THE MEAN, VARIANCE, AUTOCORRELATION, AND SPECTRUM OF STATIONARY TIME SERIES (1,2,3)

A stationary process has a constant mean

$$\mu = E(X_t) = \int_{-\infty}^{\infty} XP(X)\,dx$$

and a constant variance

$$\sigma_x^2 = E\,(X_t - \mu)^2 = \int_{-\infty}^{\infty} (X - \mu)^2 P(X)\,dX\,.$$

The estimators of the mean and the variance are

$$\bar{X} = \frac{1}{N}\sum_{t=1}^{N} X_t \quad \text{and} \quad \hat{\sigma}_x^2 = \frac{1}{N}\sum_{t=1}^{N} (X_t - \bar{X})^2$$

respectively. By the stationary assumption, the joint probability distribution $P(X_t, X_{t+k})$ is the same for all times t, t+k which are k time lag apart. The covariance between X_t and X_{t+k} called the autocovariance at lag k is defined by

$$\gamma_k = \text{Cov}(X_t, X_{t+k}) = E((X_t - \mu)(X_{t+k} - \mu)).$$

The autocorrelation at lag k is defined by

$$\rho_k = \frac{E((X_t - \mu)(X_{t+K} - \mu))}{E((X_t - \mu)^2)E((X_{t+k} - \mu)^2)^{\frac{1}{2}}} = \frac{\gamma_k}{\sigma_x^2}$$

In (1) it is indicated that the most satisfactory estimate of γ_k is C_k given by

$$C_k = \frac{1}{N}\sum_{t=1}^{N-k}(X_t - \overline{X})(X_{t+k} - \overline{X})$$

and the estimate of ρ_k is r_k given by $C_k/\hat{\sigma}_x^2$. To test the hypothesis that the ρ_k's are essentially zero beyond $k > q$, the variance of r_k given by

$$\text{Var}(r_k) \approx \frac{1}{N}\left(1 + 2\sum_{v=1}^{q} r_v^2 \right), \quad k > q ,$$

is used.

The variance of a process is made up of the individual variations caused by some disturbances. The <u>spectrum</u> of a time series describes how the variance of a time series is distributed with the frequency of occurrence of these disturbances. As shown in (1) pp. 45-46, the spectrum is the Fourier cosine transform of the autocovariance function; that is

$$g(\lambda) = 2(\gamma_o + 2\sum_{k=1}^{\infty}\gamma_k \cos 2\pi\lambda k), \quad 0 \leq \lambda \leq \tfrac{1}{2}$$

where $g(\lambda)$ is the spectrum

λ is the frequency in cycles per unit time.

The sample spectrum is shown in (3) to fluctuate about the theoretical spectrum. A "smoothed" estimate of the spectrum is given by

$$g^*(\lambda) = 2(C_o + 2\sum_{k=1}^{M} C_k W_M(k)\cos 2\pi\lambda k), \quad 0 \leq \lambda \leq \tfrac{1}{2}$$

where $W_M(k)$ = suitably chosen weight called a lag window

M = largest lag chosen after a "window-closing" procedure.

Several "lag windows" have been designed. These are given, together with their advantages and disadvantages in (3). The "lag windows" used in this study are:

1. Parzen lag window given by $W_M(k) = 1 - k^2/M^2$
2. Tukey lag window given by $W_M(k) = \frac{1}{2}(1 + \cos\frac{\pi k}{M})$.

The "window-closing" procedure is fully described in (3). Essentially it consists of observing the change in the spectral estimates as M is increased. Ideally, the spectrum will change markedly as M increases and then will settle down. The best M is chosen at this point since as M is further increased, sampling variability will introduce spurious detail in the spectrum. Figure F.1 illustrates this "window-closing" procedure.

As given in (3), the interval between $\left[\frac{vg^*(\lambda)}{\chi_v(1-\frac{\alpha}{2})}, \frac{vg^*(\lambda)}{\chi_v(\frac{\alpha}{2})}\right]$ is a $100(1-\alpha)\%$ confidence interval for $g^*(\lambda)$. Here, v is the degrees of freedom given by $3.71\frac{N}{M}$, where N is the length of the time series, for the Parzen window and $2.667\frac{N}{M}$ for the Tukey window. The values for $\frac{v}{\chi_v(1-\frac{\alpha}{2})}$ and $\frac{v}{\chi_v(\frac{\alpha}{2})}$ are given as functions of v and α in (3) Figure 3.10 p. 82. On an ordinary scale, the confidence interval is not a constant, since the limits depend on λ. When the spectrum is plotted on a log scale, the confidence interval is represented by constant interval about the spectral estimate (as shown in Figure F.1).

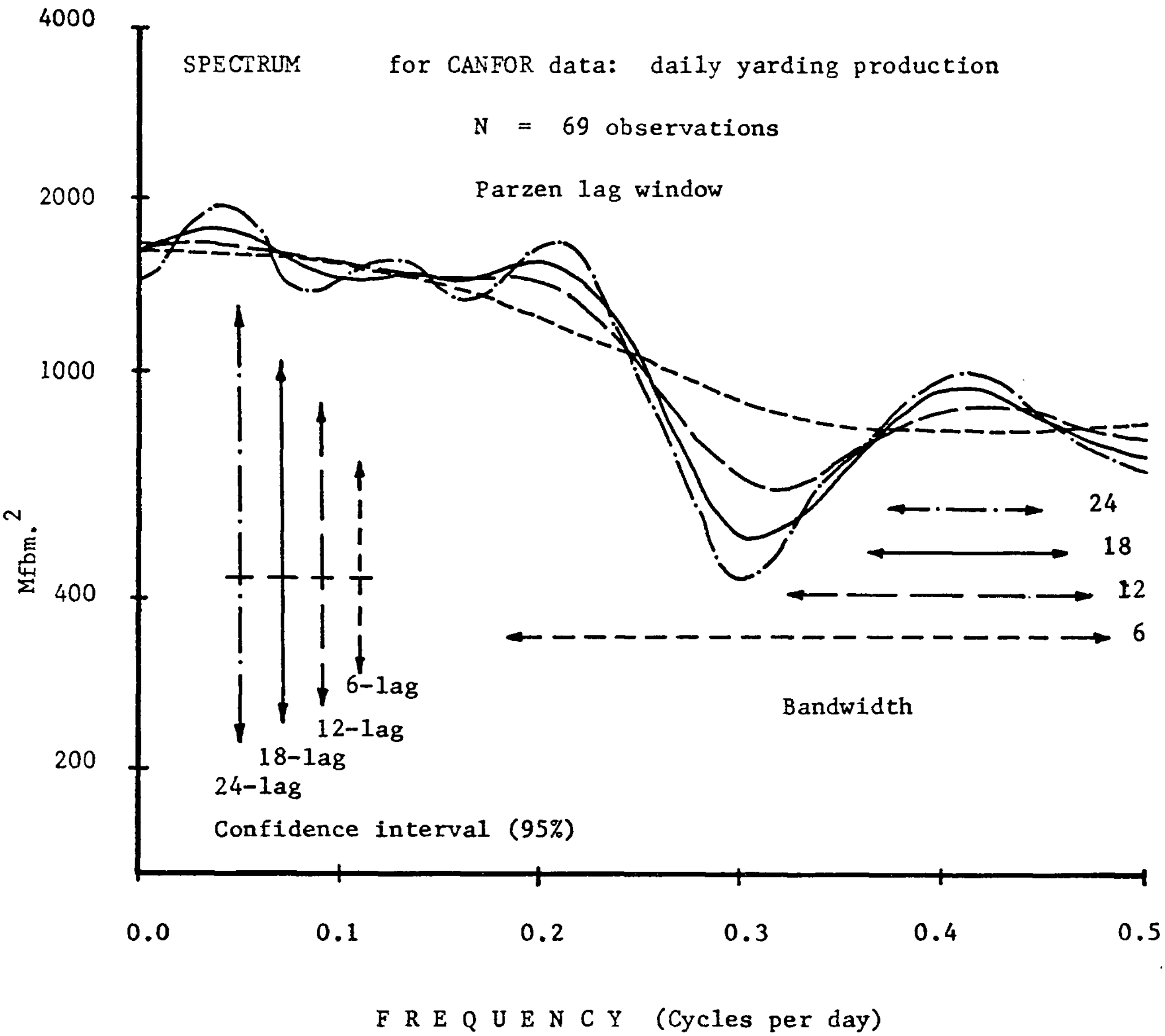


Figure F.1 Graphs of "smoothed" spectra illustrating the "window-closing" procedure

F.3 CALCULATION OF VARIANCES AND COVARIANCES (4)

To calculate the confidence interval of a mean μ, the statistic

$$t = \frac{\bar{X} - \mu}{\mathrm{Var}\ (\bar{x})}$$

is regarded as Normally distributed with mean 0 and unit variance. For autocorrelated data, Var $(\bar{X})$ is calculated from

$$\mathrm{Var}(\bar{X}) = \frac{1}{N(1-M/N)} \left(C_o + 2 \sum_{k=1}^{M} (1-k/M) C_k \right).$$

As in the "window-closing" procedure, M is chosen such that a good resolution is obtained with acceptable realiability. The factor $(1-M/N)^{-1}$ compensates for the bias resulting from the formula used to calculate the autocovariances C_k.

When two runs of equal length N, with means $\bar{X}_1$ and $\bar{X}_2$ respectively, are made, the variance of the overall mean $\frac{1}{2}(\bar{X}_1 + \bar{X}_2)$ is given by

$$\mathrm{Var}\ (\tfrac{1}{2}(\bar{X}_1 + \bar{X}_2)) = \tfrac{1}{4}\mathrm{Var}(\bar{X}_1) + \tfrac{1}{4}\mathrm{Var}(\bar{X}_2) + \tfrac{1}{2}\mathrm{Cov}(\bar{X}_1, \bar{X}_2).$$

To calculate Cov $(\bar{X}_1, \bar{X}_2)$ when the method of antithetic variates is used, the covariances between the first and second runs are calculated using

$$C_{12,k} = \frac{1}{N} \sum_{i=1}^{N-|k|} (X_{1,k} - \bar{X}_1)\ (X_{2,i+k} - \bar{X}_2),\ k = 0, \pm 1, \ldots, \pm M$$

and

$$\mathrm{Cov}\ (\bar{X}_1, \bar{X}_2) = \sum_{k=-M}^{M} (1 - |k| /M) C_{12,k} \frac{1}{N(1-M/N)}$$

The method of antithetic variates as described in Chapter V was used to make two runs for the basic configuration with 14 trucks. For the production and truck per cent utilization responses, the calculated $Cov(\bar{X}_1,\bar{X}_2)$ was approximately ¼ of $(Var(\bar{X}_1) + Var(\bar{X}_2))$. Thus two antithetic replications of length N is equivalent to 2.67N observations on 1 replication. The increased efficiency as the result of using the method of antithetic variates was negligible in the case of the unit cost response for this particular configuration.

To compare the means of two similar processes differing only in some minor respects, the control variate technique may be used. Assuming $\bar{X}_1$ and $\bar{X}_2$ are the respective means of the two processes, the variance of their difference is given by

$$Var\ (\bar{X}_1-\bar{X}_2) = Var\ (\bar{X}_1) + Var(\bar{X}_2) - 2Cov(\bar{X}_1,\bar{X}_2).$$

$Cov(\bar{X}_1,\bar{X}_2)$ is calculated as in the method of antithetic variates, with $N = \max(N_1,N_2)$ if the respective length N_1 and N_2 of the two runs are not equal. While the method of antithetic variates was not always effective, the control variate technique was observed to be consistently effective.

F.4 THE DETERMINATION OF THE LENGTH OF THE SIMULATION RUNS

To determine the length of the simulation run(s) to obtain a given variance, the following formulae are used:

1. For the mean of a given response

   $N = m/Var(\bar{X})$

   where $m = \frac{1}{1-M/Q}\ (C_o + 2 \sum_{k=1}^{M} (1-k/M)C_k)$

   and where the autocovariances are initially calculated from a pilot run of length Q. Q should be sufficiently long so that well-resolved estimate of m is obtained. If N is calculated to be too long to be conveniently included in a single run, two antithetic replications may be made.

2. For the difference between two means

When the pilot runs made to compare the respective means of two processes have indicated a difference, but the length of the runs was not sufficient to establish the statistical significance of the difference, the length N of each run to obtain a given $Var(\bar{X}_1-\bar{X}_2)$ is calculated using

$$N = \frac{m_1 + m_2 - 2m_3}{Var(\bar{X}_1 - \bar{X}_2)}$$

where m_1 and m_2 are calculated as in m and

$$m_3 = \left\{ \sum_{k=-M}^{M} (1- |k| /M) C_{12,k} \right\} \frac{1}{1-M/Q} .$$

This assumes that the control variate technique is used and that the respective runs for the two processes have equal length. To save computer time, it is advisable to design the simulation program so that a run can be continued after it has been stopped.

F.5 TEST FOR EQUIVALENCE OF TWO SPECTRA

To test whether a sample spectrum $g_1^*(\lambda)$ is significantly different from another sample spectrum $g_1^*(\lambda)$, the test reported in (2) is applied. In this test, the statistic

$$t = \frac{\{\ln(g_1^*(\lambda)) - \ln(g_2^*(\lambda))\} - \{\ln(g_1(\lambda)) - \ln(g_2(\lambda))\}}{\sqrt{\Psi(M_1,N_1) + \Psi(M_2,N_2)}}$$

where $g_i(\lambda)$ = the theoretical spectrum at frequency λ of series i

M_i = the number of lags chosen in the calculation of the sample spectrum

N_i = the length of series i

$\Psi(M_i, N_i)$ = $.539^{M_i}/N_i$ for the Parzen window

= $.750^{M_i}/N_i$ for the Tukey window

= the variance of $\ln(g_i^*(\lambda))$

is regarded as Normally distributed with mean 0 and variance 1. The null hypothesis $g_1(\lambda) = g_2(\lambda)$ is tested against the alternative hypothesis $g_1(\lambda) > g_2(\lambda)$. The null hypothesis is rejected if $t > t_\alpha$ which, after some simplifications, is equivalent to

$$g_1^*(\lambda) / g_2^*(\lambda) \geq \exp(t\alpha\sqrt{\Psi(M_1, T_1) + \Psi(M_2, T_2)}) = \underline{a} .$$

This test is applied to each frequency λ. Thus it is convenient to graph $g_1^*(\lambda) / g_2^*(\lambda)$ versus λ to determine if each point along the graph falls under the horizontal line of height a.

In many simulation experiments, the time series of interest may not be Gaussian. However, as indicated in (2), the assumptions about $\ln(g^*(\lambda))$ are fairly insensitive to the stochastic process $\{X_t\}$ being Gaussian and, consequently, the logarithmic test of the null hypothesis is reasonably valid for non-Gaussian processes.

As examples, the spectrum for the observed data from CANFOR is compared with the corresponding spectra for two simulation trials for both the yarding production and the number of loads responses. Their respective $g_1^*(\lambda) / g_2^*(\lambda)$ - graphs are shown in figure F.2. Since each of the curves fall inside their corresponding acceptance level a, it can be concluded that for all λ's, no significant difference is observed between the spectrum of the CANFOR data and those of the trials for both responses.

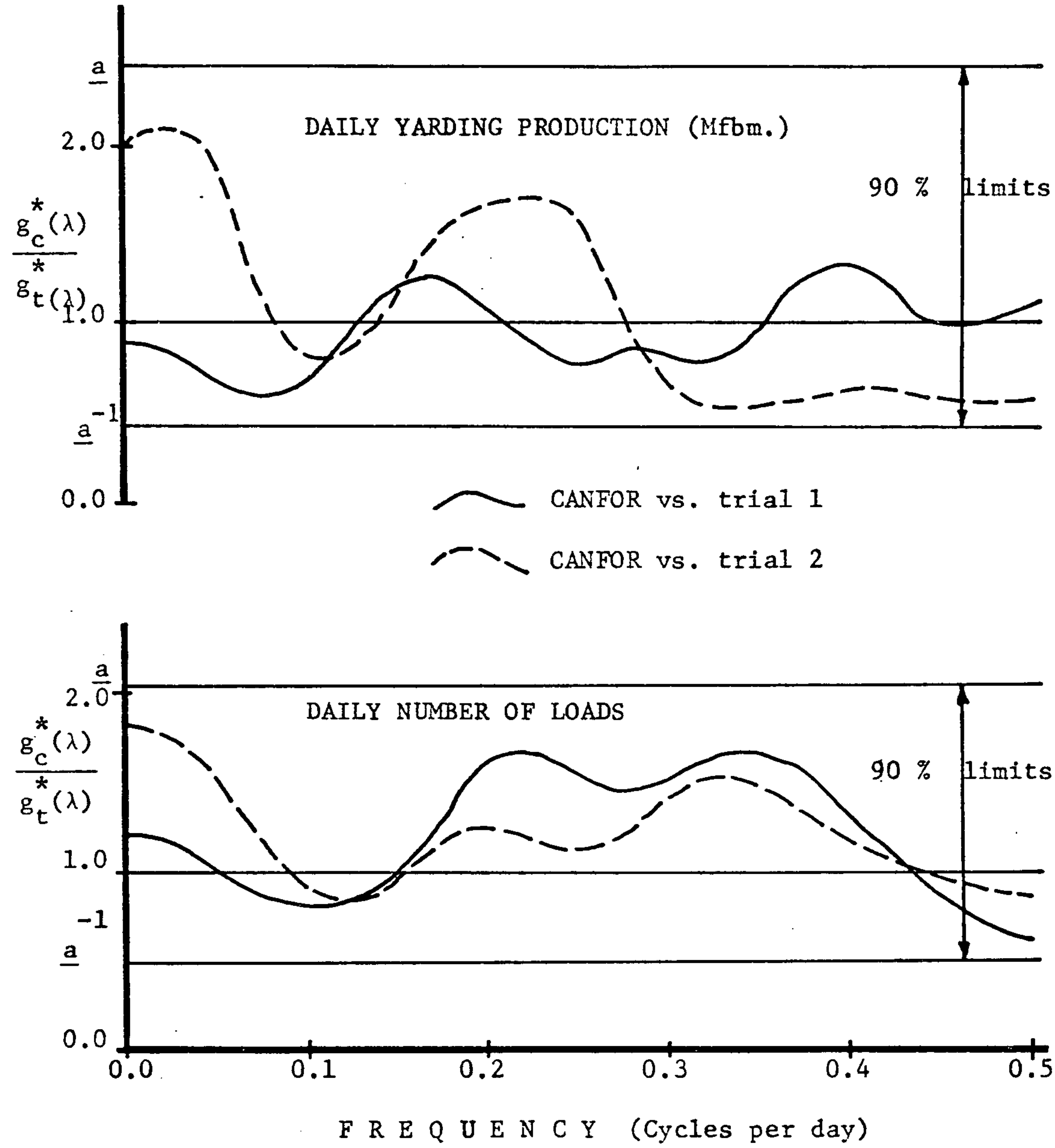


Figure F.2 $g_c^*(\lambda)/g_t^*(\lambda)$- graphs comparing the daily yarding production spectrum and the daily number of loads spectrum of the CANFOR data with the corresponding spectra of the two simulation trials

F. 6 FITTING OF STOCHASTIC TIME SERIES MODELS

This section describes the fitting of stochastic time series models, specifically the fitting of the stochastic yarding models described in Chapter III. This section covers the following:

1. Data preparation
2. Verification of the stationarity assumption
3. Model identification
4. Estimation of parameters
5. Diagnostic checking.

Data preparation

From the historical records of CANFOR logging division at Harrison Mills, B.C. was obtained the raw data of the daily production in thousand board feet for each of four yarders numbered 0904, 0905, 0909, and 0911. These raw data correspond to the net yarding production of the yarder, i.e. it includes:

1. reduction in production due to the moving and rigging of the yarder,
2. reduction in production due to the turning around of the yarder,
3. reduction in production due to "plugged landing" caused by loader breakdown,
4. reduction in production due to "plugged landing" caused by an insufficient number of trucks dispatched to the side,
5. reduction in production due to yarder breakdown, and
6. reduction in production due to delays caused by accidents.

Adjustments by linear extrapolation were made on the raw data to account for these reductions in production. For example, if the records indicated that yarding for yarder 0904 was delayed for two hours due to "plugged landing", the per-hour production is calculated by dividing the recorded production by 6. An extra production for 2 hours is then added to the recorded production to adjust the production to a value corresponding to 8 hours. The adjusted data is then used in the subsequent analyses.

Verification of the stationarity assumption

From section F.1 it was mentioned that second order stationarity plus Normality is sufficient to produce strict stationarity. A second order stationarity implies the existence of a time-invariant mean, and autocovariances which are dependent only on time differences. The verification of the stationarity assumption for the time series of adjusted daily production for each of the four yarders proceeded with the test that the mean and autocovariances for the first half of each time series are not different from the corresponding values for the second half of the time series.

Table F.1 shows the frequency distribution of daily yarding production of each of the four yarders. To test the null hypothesis that the daily yarding production is normally distributed, the expected frequency distribution and the resulting chi-square were computed for each of the four yarders. Table F.2 shows that the computed chi-squared for all four cases is less than the tabular value. Thus there is no reason to reject the null hypothesis and it is concluded that the Normal distribution provides a good fit for the distribution of the daily production for all four yarders.

After inspecting the mean production for the two halves of the daily production time series for each of the four yarders, it was readily apparent that no differences exist and it was concluded as such

Class boundaries	O_i	E_i	$(O_i - E_i)^2/E_i$	
Yarder 0911				
8.5 - 32.5	15	16.58	0.151	
32.5 - 40.5	23	28.18	0.952	
40.5 - 48.5	42	34.71	1.531	
48.5 - 56.5	27	23.75	0.445	
56.5 - 72.5	8	11.45	1.040	
totals	115	114.67	4.119	Chi-square
Yarder 0909				
16.5 - 32.5	11	11.91	0.070	
32.5 - 40.5	25	25.62	0.015	
40.5 - 48.5	44	36.74	1.435	
48.5 - 56.5	24	28.10	0.598	
56.5 - 72.5	13	14.36	0.129	
totals	117	116.73	2.247	Chi-square
Yarder 0904				
16.5 - 32.5	10	12.54	0.515	
32.5 - 40.5	31	31.84	0.022	
40.5 - 48.5	46	42.60	0.271	
48.5 - 56.5	23	25.92	0.329	
56.5 - 72.5	11	8.04	1.090	
totals	121	120.94	2.227	Chi-square
Yarder 0905				
24.5 - 40.5	9	10.35	0.176	
40.5 - 48.5	25	22.44	0.292	
48.5 - 56.5	26	31.06	0.824	
56.5 - 64.5	28	23.84	0.726	
64.5 - 80.5	12	11.83	0.002	
totals	100	99.52	2.020	Chi-square

$$\chi^2_{.05,2} = 5.991$$

Table F.1 Observed and expected frequencies of the daily yarding production and the resulting chi-square for each of the four yarders without any further t-test. Using the test for equivalence of two spectra described in the previous section, the hypothesis that the spectrum for the first half of the daily production time series is not different from that of the second half, for all four yarders, was tested at the 90% level of significance. The results showed no significant difference for all frequencies for the yarders 0904 and 0905. A significant difference at the frequencies, $0.28 < \lambda < 0.38$, was observed for yarder 0909. However, these frequencies are non-dominant since the peak in the spectrum occurs in the lower frequencies. For yarder 0911, a significant difference was observed at the dominant frequencies, $0.02 < \lambda < 0.12$. This fact is temporarily ignored on the condition that if it results in poor fit in the model, some data transformations are made.

From the foregoing it is seen that stationary yarding production time series do exist, at least for certain time periods. This resulted from the fact that the settings yarded were close to each other and are, therefore, reasonably homogeneous. For certain cases where the settings to be yarded are not homogeneous, it may not be valid to assume stationarity in the mean and the variance of the production time series. However, it may be assumed that the correlation of daily production on past days remains the same. Therefore, a procedure that could be followed is to fit a model over a period where the settings are homogeneous and to use the same model for settings which are different from the previously observed settings, but only after substituting the estimated mean and variance into the model.

Model identification

The model fitted to each of the four given time series belong either to a class of autoregressive models or to a class of mixed autoregressive-moving average models (ARMA) models of the form

$$\tilde{X}_t = \sum_{i=1}^{m} \phi_i \tilde{X}_{t-i} + \sum_{j=1}^{n} \theta_j a_{t-j} + a_t$$

where $\tilde{X}_t$ = the deviation $X_t - E(X)$
ϕ_i = ith autoregressive parameter
Θ_j = jth moving average parameter
a_{t-j} = white noise generated from $N\left(0,\sigma_a^2\right)$
m = order of the autoregressive terms
n = order of the moving average terms.

The calculated autocorrelation and partial autcorrelation functions were used to initially identify which ARMA model to use. The partial autocorrelations, ϕ_{kk}, are calculated using

$$\phi_{kk} = \begin{cases} r_1 & k = 1 \\ \dfrac{r_k - \sum_{j=i}^{k-1} \phi_{k-1,j} r_{k-j}}{1 - \sum_{j-1}^{k-1} \phi_{k-1,j} r_j} & k = 2,3,\ldots,L \end{cases}$$

where

$$\phi_{kj} = \phi_{k-1,j} - \phi_{kk}\phi_{k-1,k-j} \quad j = 1,2,\ldots,k-1$$

r_k = the autocorrelation for lag k.

The ARMA model is initially identified with the aid of Table F.2 given below. In the triplet (a,b,c), a refers to the order of the autoregressive terms, c the order of the moving average terms, and b the

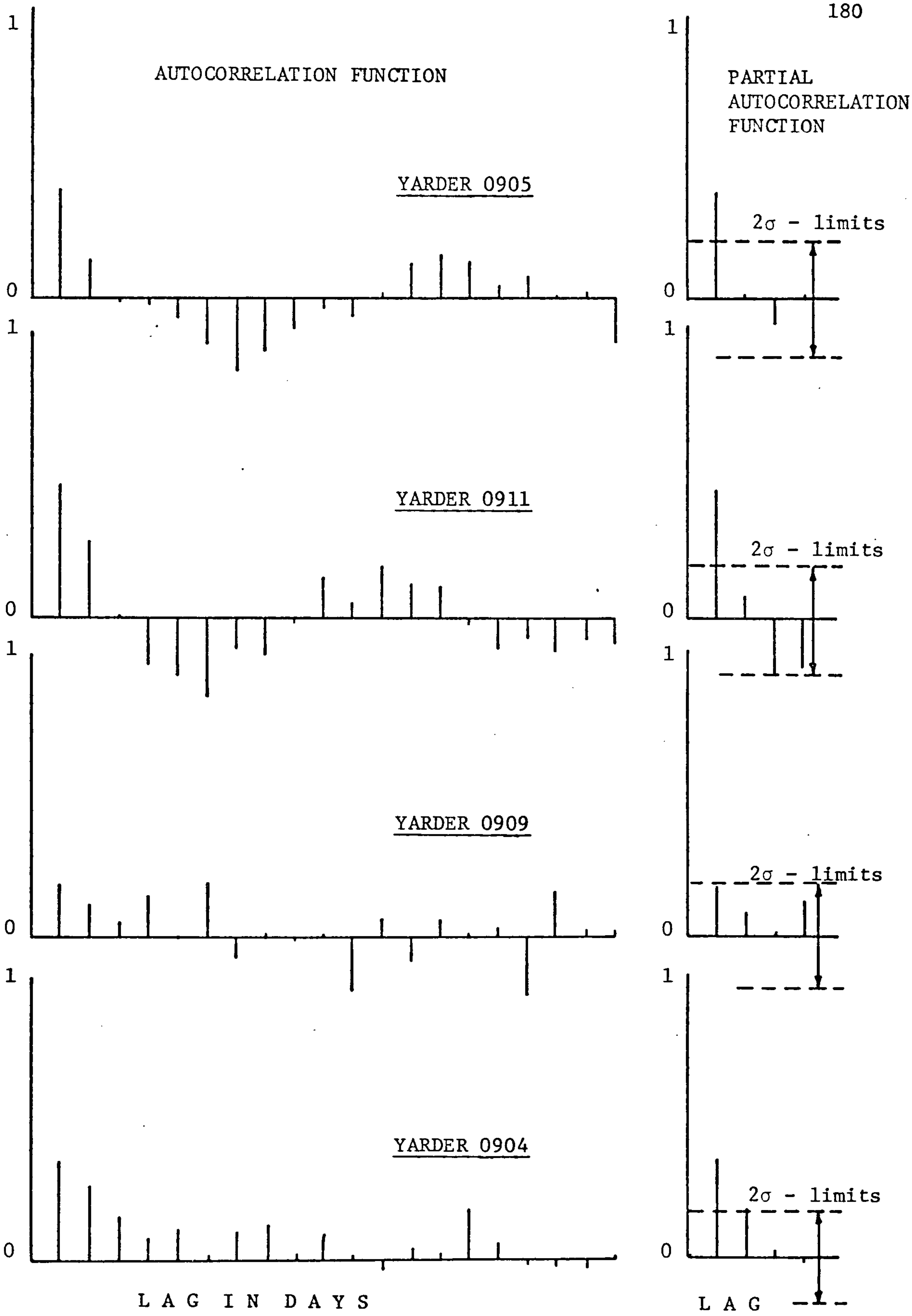


Figure F.3 The autocorrelation functions for each of the four yarders degree of differencing made on the time series.

Figure F.3 shows the autocorrelation functions for each of the four yarders. Table F.2 and Figure F.3 indicate initially a (2,0,0) - model for yarders 0905 and 0911, a (1,0,0)- model for yarder 0909, and a (1,0,1) - model for yarder 0904.

Table F.2 Behavior of the autocorrelation functions for the dth difference of various ARIMA models (source: (1) p.176)

	(1,d,0)	(0,d,1)
Behavior of r_k	decays exponentially	only r_1 nonzero
Behavior of ϕ_{kk}	only ϕ_{11} nonzero	decays exponentially
	(2,d,0)	(0,d,2)
Behavior of r_k	mixture of exponentials or damped sine wave	only r_1 and r_2 nonzero
Behavior of ϕ_{kk}	only ϕ_{11} and ϕ_{22}	dominated by mixture of exponentials or damped sine waves
	(1,d,1)	
Behavior of r_k	decays exponentially from first lag	
Behavior of ϕ_{kk}	dominated by exponential decay from first lag	

Calculation of parameters

Preliminary estimates of the parameters were obtained using:

for (1,0,0) model

$$\sigma_1 = r_1 \quad , \quad -1 < \phi_1 < 1$$

$$\sigma_a^2 = \sigma_x^2 (1 - \phi_1^2)$$

theoretical spectrum: $$g(\lambda) = \frac{2\sigma_a^2}{1 + \phi_1^2 - 2\phi_1 \cos 2\pi\lambda} \quad 0 \leq \lambda \leq \tfrac{1}{2}$$

for 2,0,0) model

$$\phi_1 = \frac{r_1(1-r_2)}{1-r_1^2}$$

$$\phi_2 = \frac{r_2 - r_1^2}{1-r_1^2} \quad , \quad \begin{matrix} -1 < \phi_2 < 1 \\ \phi_2 + \phi_1 < 1 \\ \phi_2 - \phi_1 < 1 \end{matrix}$$

$$\sigma_a^2 = \sigma_x^2 (1 - \phi_1 r_1 - \phi_2 r_2)$$

theoretical spectrum: $$g(\lambda) = \frac{2\sigma_a^2}{1 + \phi_1^2 + \phi_2^2 - 2\phi_1(1-\phi_2)\cos 2\pi\lambda - 2\phi_2 \cos 4\pi\lambda}$$

for (1,0,1) model

ϕ_1 and θ_1 obtained by solving $$r_1 = \frac{(1 - \phi_1\theta_1)(\phi_1 - \theta_1)}{1 + \theta_1^2 - 2\phi_1\theta_1}$$

and $r_2 = r_1\phi_1$, $-1<\phi_1<1$, $-1<\phi_1<1$

$$\sigma_a^2 = \frac{\sigma_x^2 (1 - \phi_1^2)}{1 + \theta_1^2 - 2\phi_1\theta_1}$$

theoretical spectrum: $$g(\lambda) = 2\sigma_a^2 \frac{(1+\theta_1^2 - 2\theta\cos 2\pi\lambda)}{(1+\phi_1^2 - 2\phi\cos 2\pi\lambda)} \quad , 0 \leq \lambda \leq \tfrac{1}{2}$$

A more accurate estimates of the parameters can be obtained through a constrained least squares technique given in (1). For instance, for a (2,0,0) model, $\tilde{X}_t = \phi_1\tilde{X}_{t-1} + \phi_2\tilde{X}_{t-2} + a_t$, the parameters ϕ_1 and ϕ_2 can be estimated through a regression model constrained so that the intercept is zero. a_t is considered the residual and σ_a^2 is merely the residual variance.

Diagnostic checking

To determine the adequacy of the fitted model, several techniques are given in (1). For this study it is deemed sufficient to check if the theoretical spectrum of the fitted data is not significantly different from the spectrum of the original data. Using this procedure, the (2,0,0) model was found to be inadequate for yarders 0905 and 0911. However, the (3,0,0) model subsequently fitted was found adequate for yarders 0905 and 0911. The resulting fitted models for the four yarders are given below. Their theoretical spectrum are plotted in Figure F.4 and F.5.

0905 $X_t = 37.2363 + 0.3928X_{t-1} - 0.0507X_{t-2} - 0.0460X_{t-3} + a_t$

$\sigma_a^2 = 84.6359$

0911 $X_t = 26.6979 + 0.4339X_{t-1} + 0.1331X_{t-2} - 0.1823X_{t-3} + a_t$

$\sigma_a^2 = 81.9031$

0909 $X_t = 36.9817 + 0.1785X_{t-1} + a_t$, $\sigma_a^2 = 95.2049$

0904 $X_t = 10.4937 + 0.7586X_{t-1} + a_t - 0.4861a_{t-1}$, $\sigma_a^2 = 64.2259$

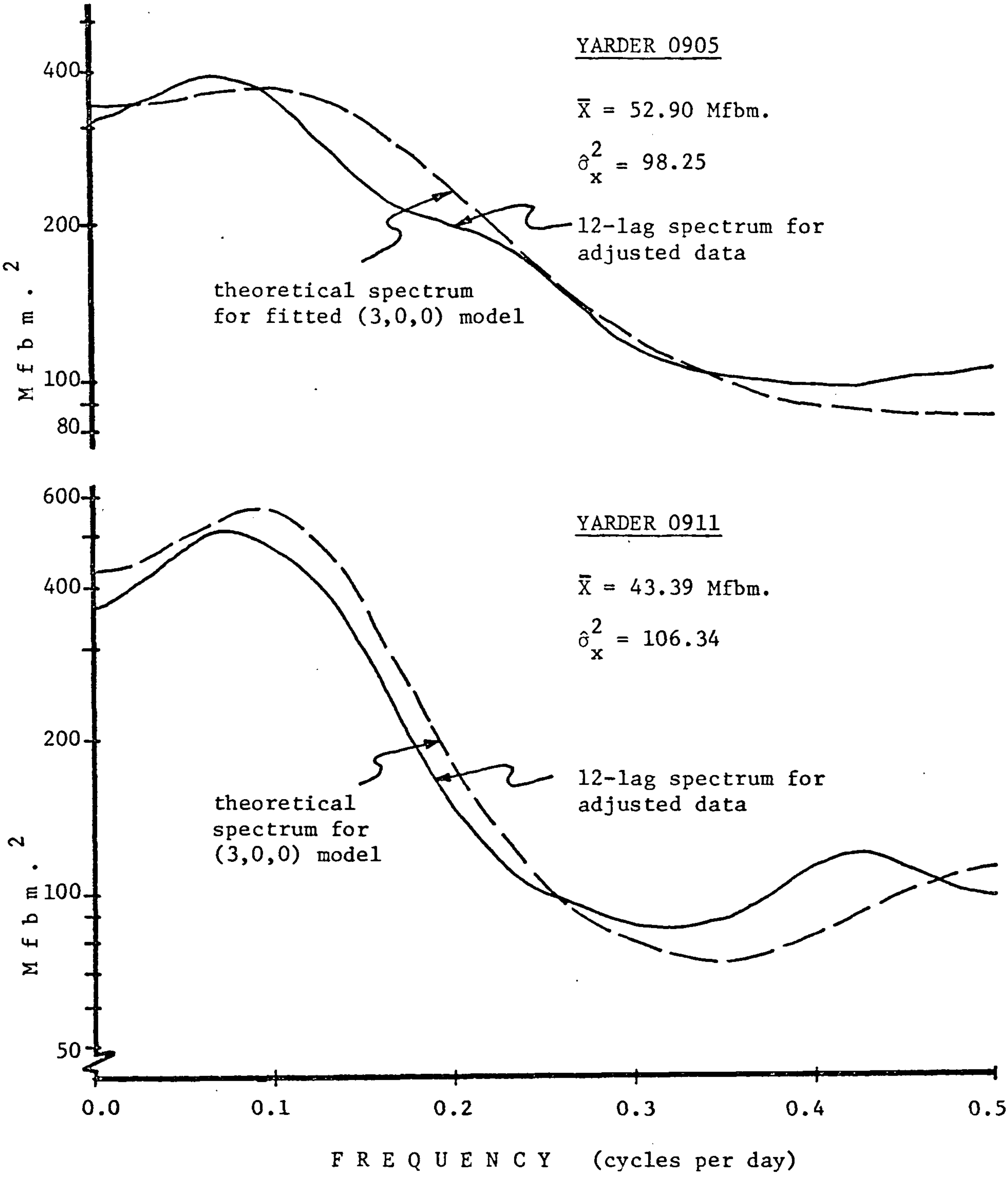


Figure F.4 The 12-lag spectrum for the adjusted yarding production data and the theoretical spectrum for the fitted model for yarders 0905 and 0911

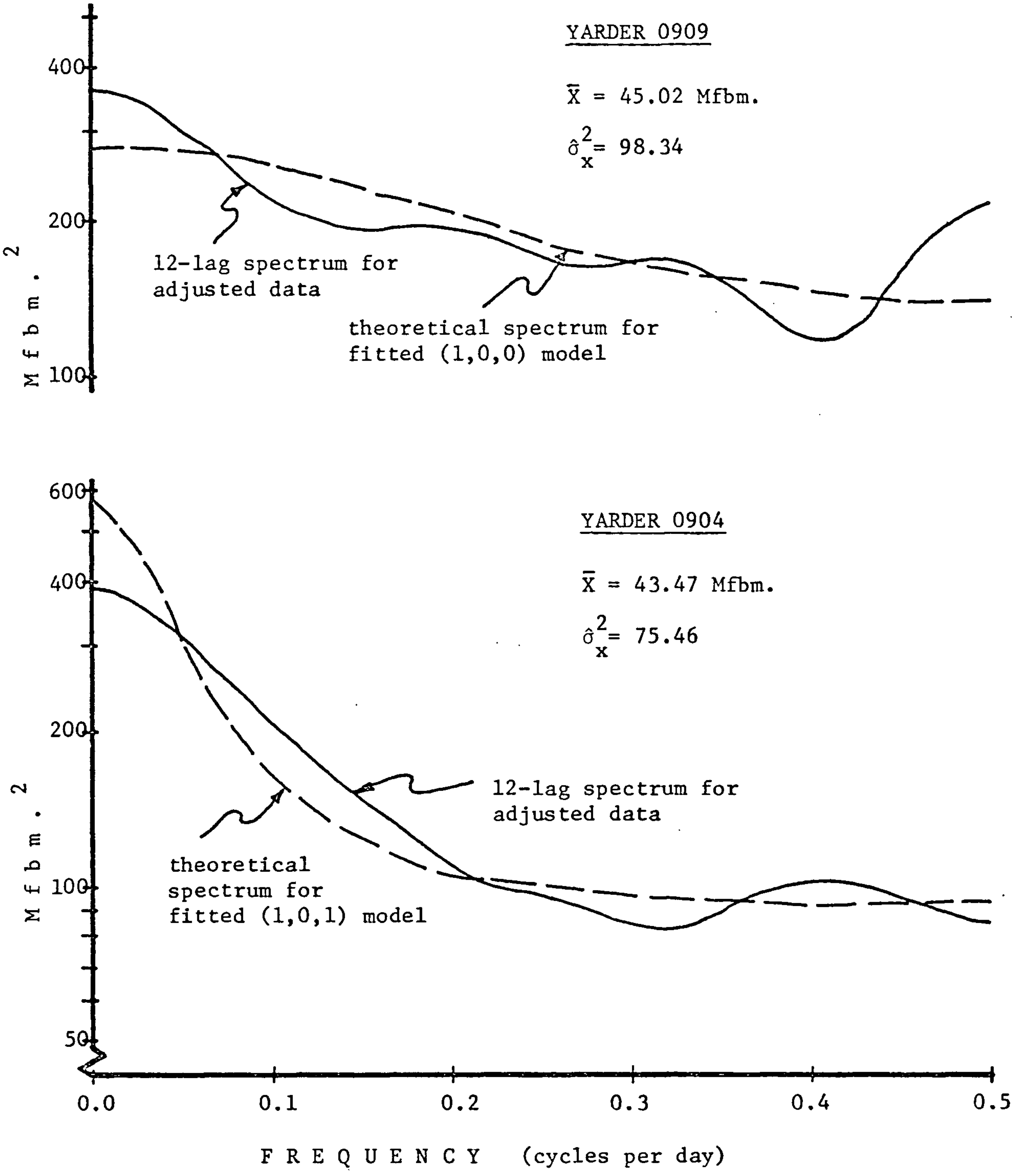
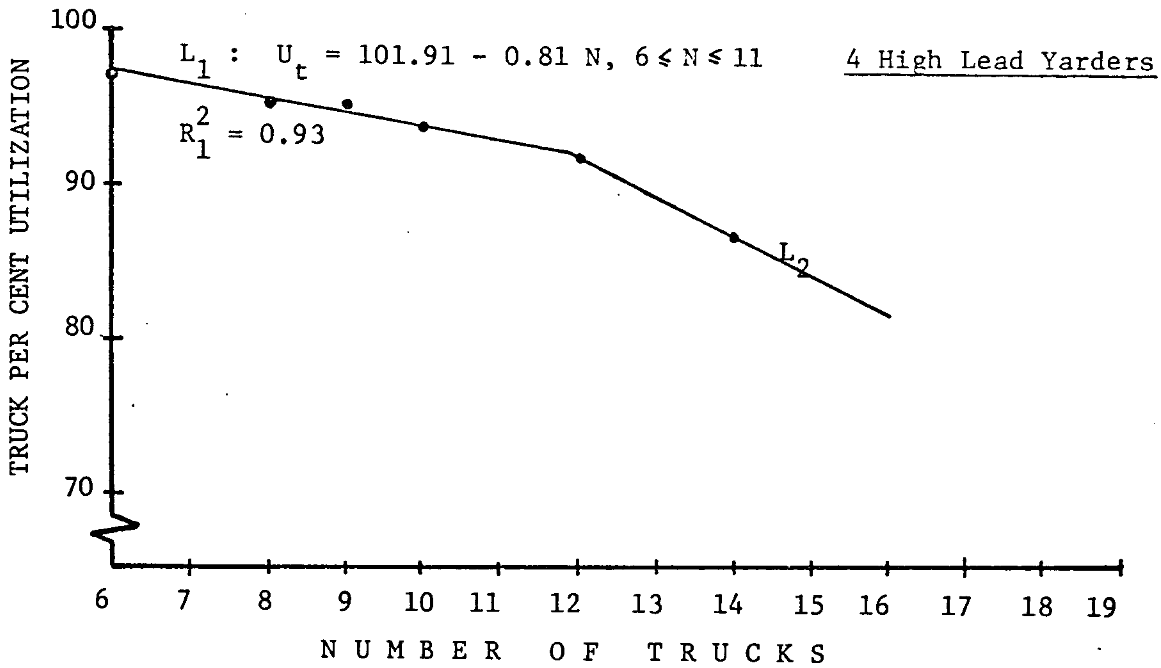


Figure F.5 The 12-lag spectrum for the adjusted yarding production data and the theoretical spectrum for the fitted model for yarders 0909 and 0904

APPENDIX G

PER CENT UTILIZATION GRAPHS



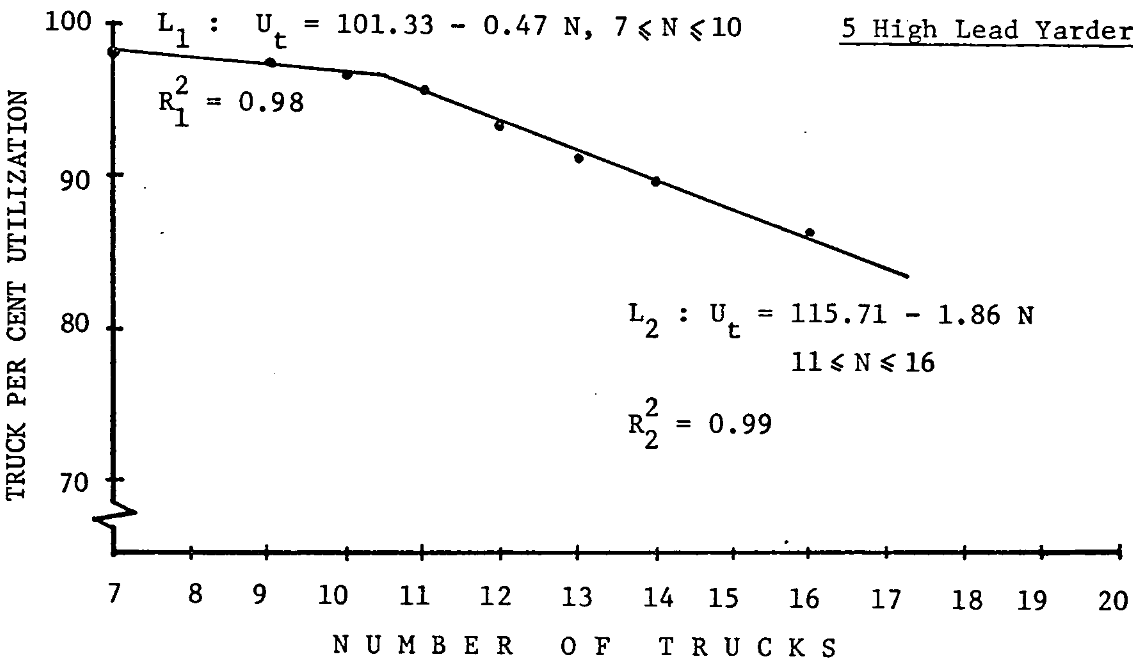
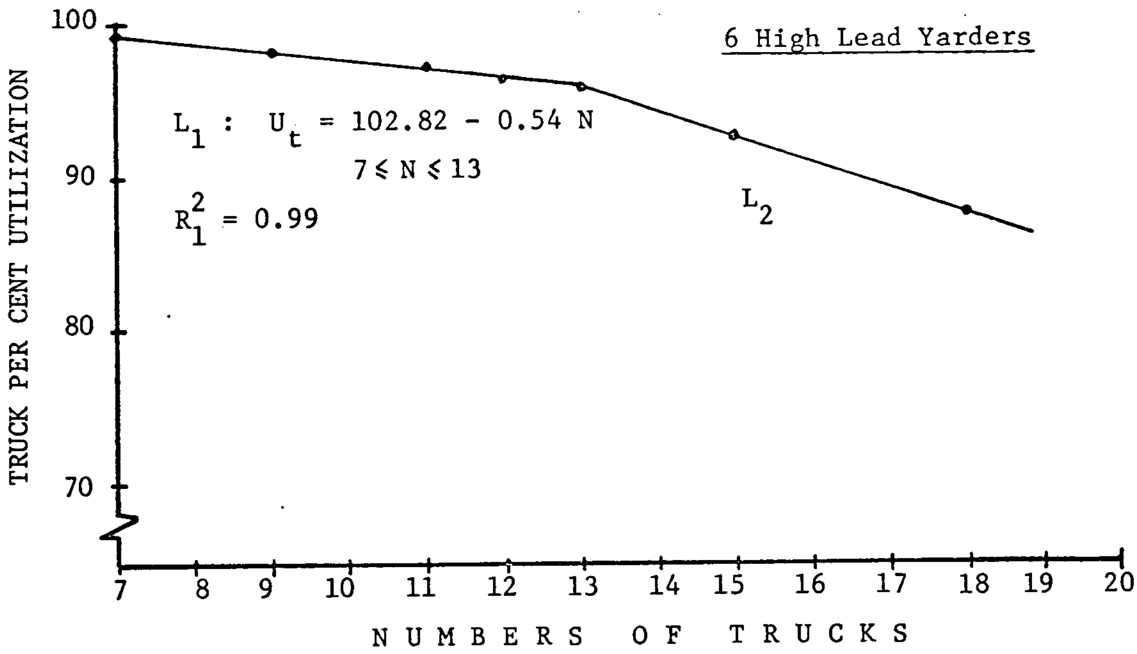


Figure G.1 U_t-graphs for various configurations

(Source: different replications from those used in the text)



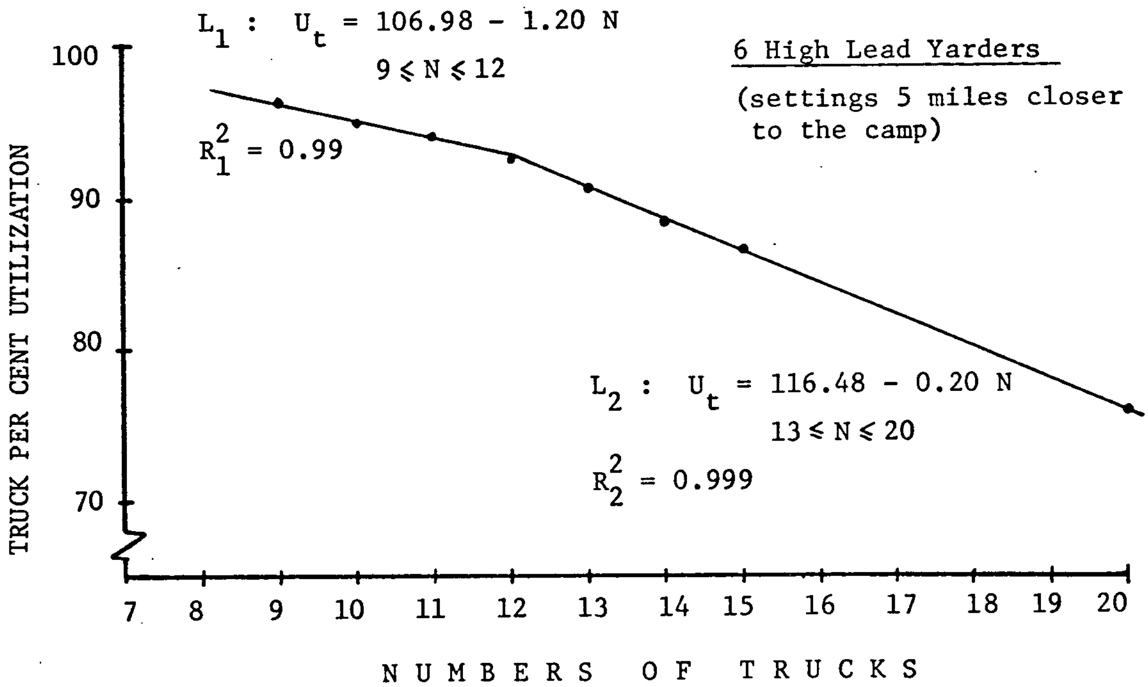
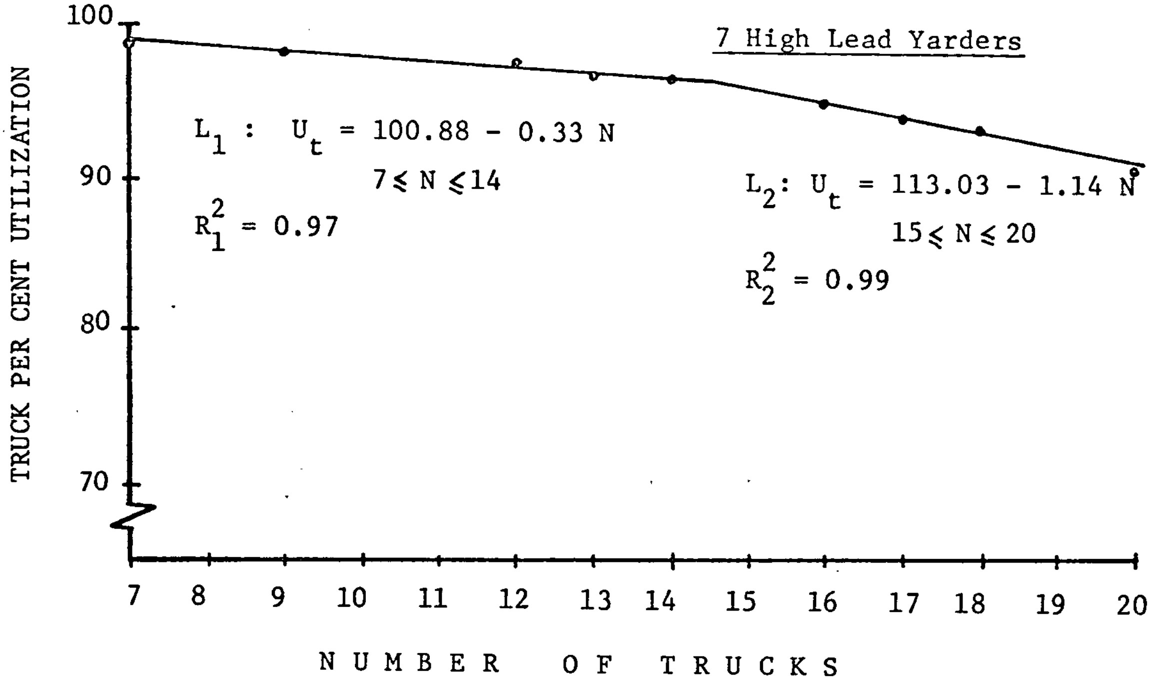


Figure G.1 - cont.



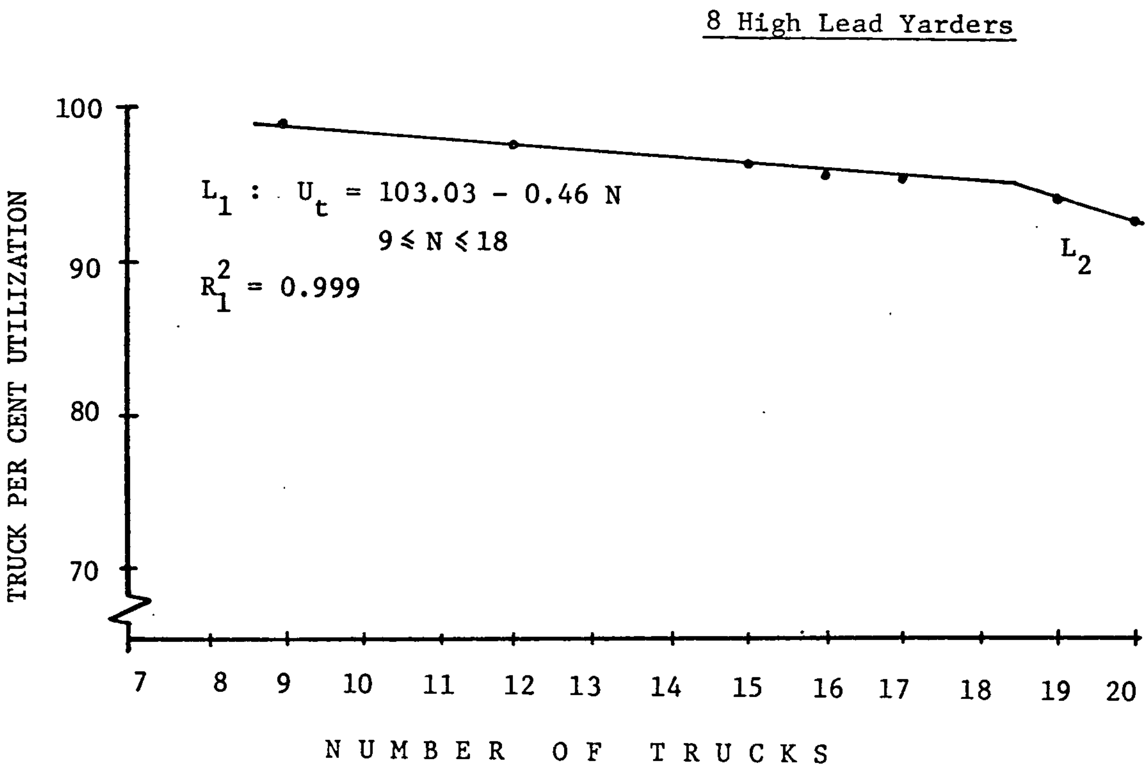


Figure G.1 - cont.

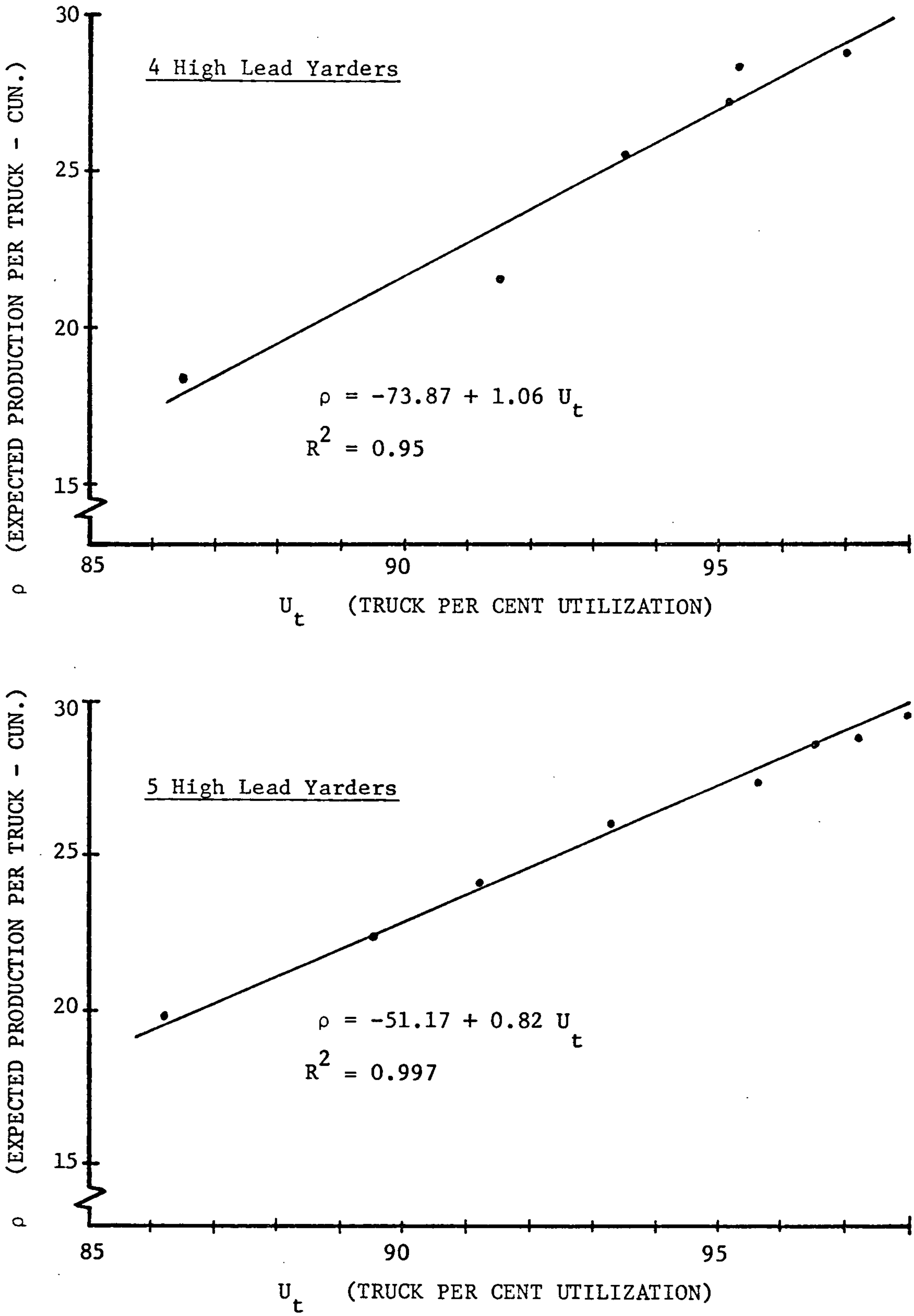
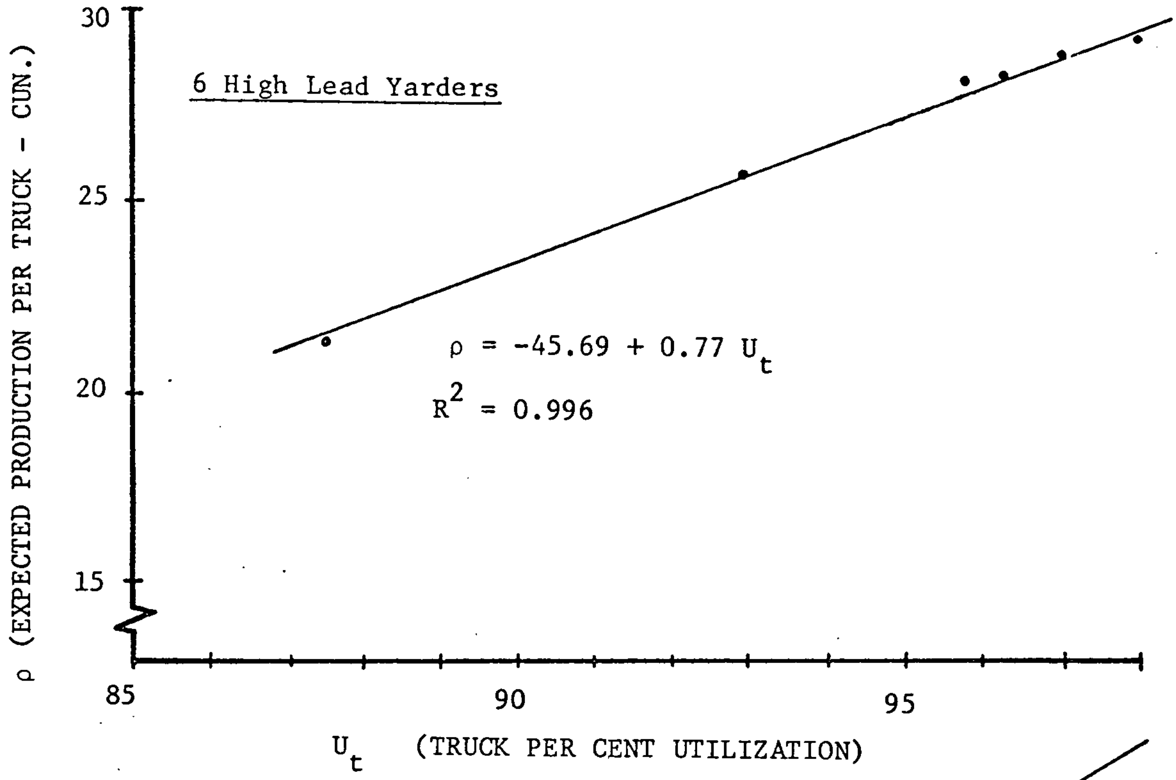


Figure G.2 Expected daily production per truck as a function of the truck per cent utilization for various configurations



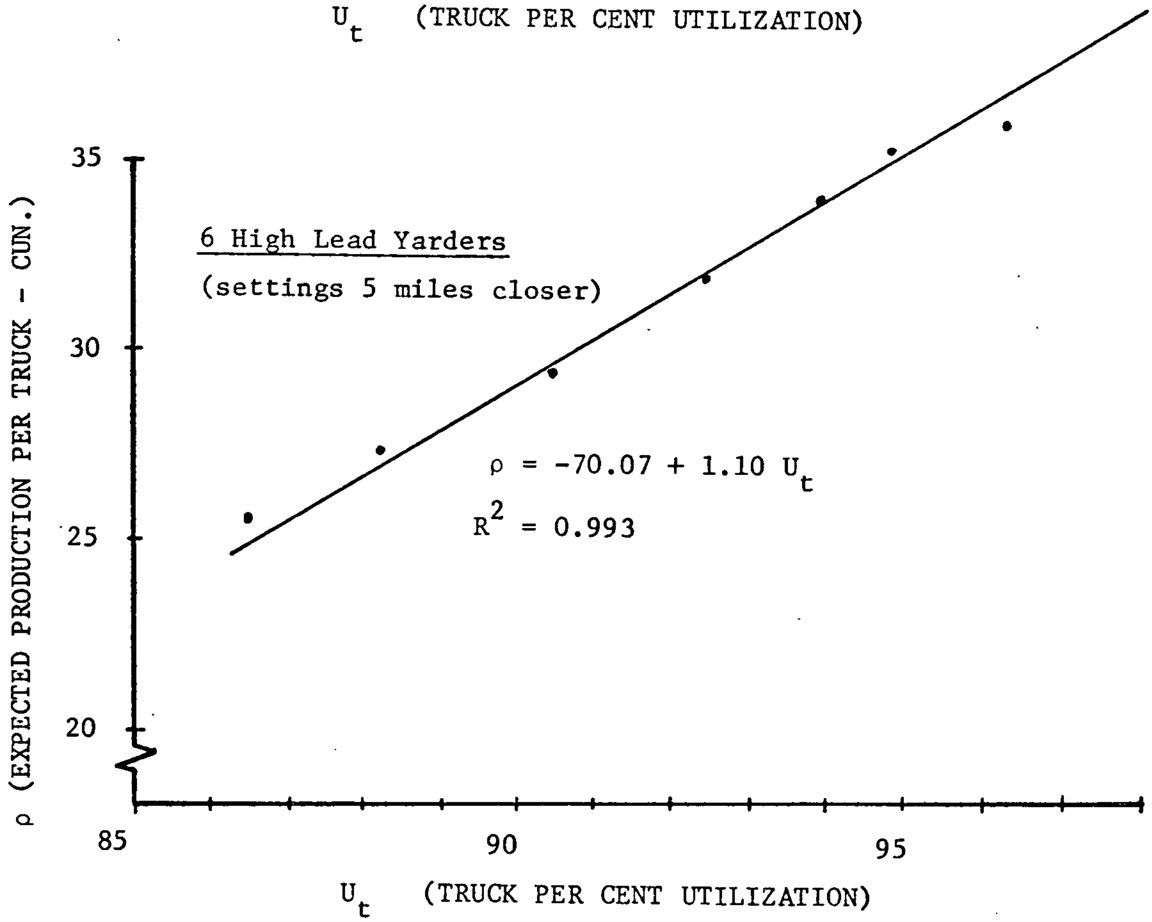
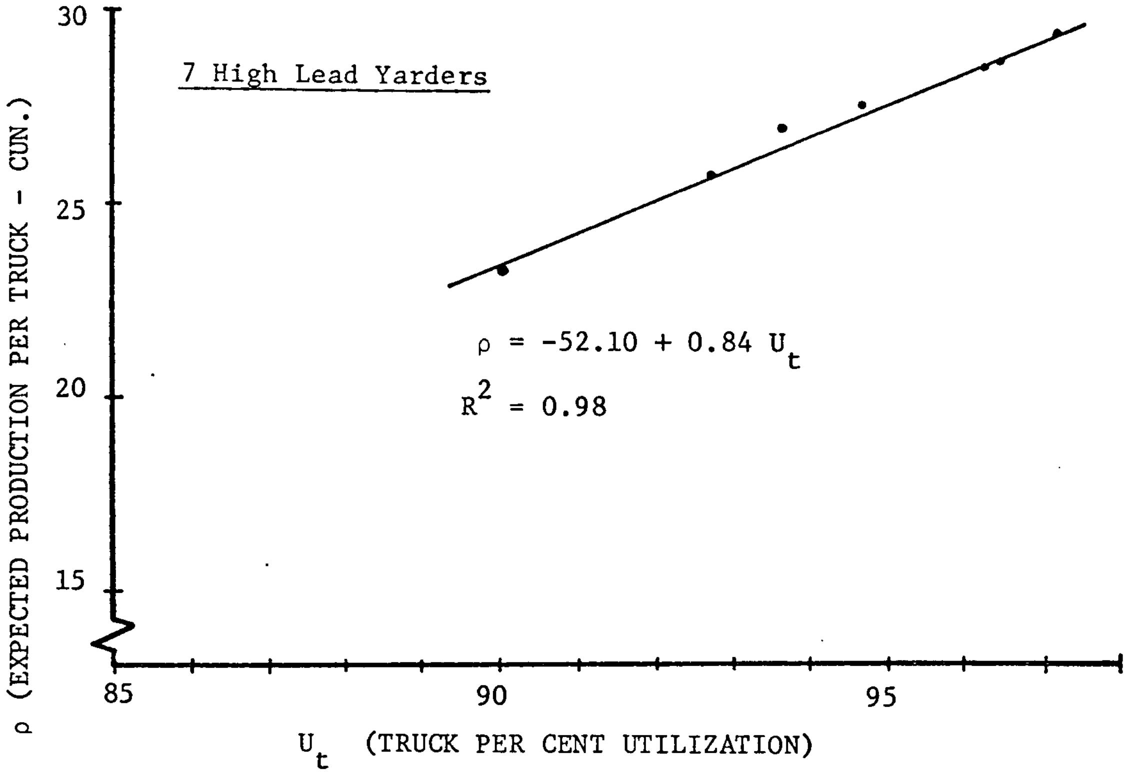


Figure G.2 - cont.



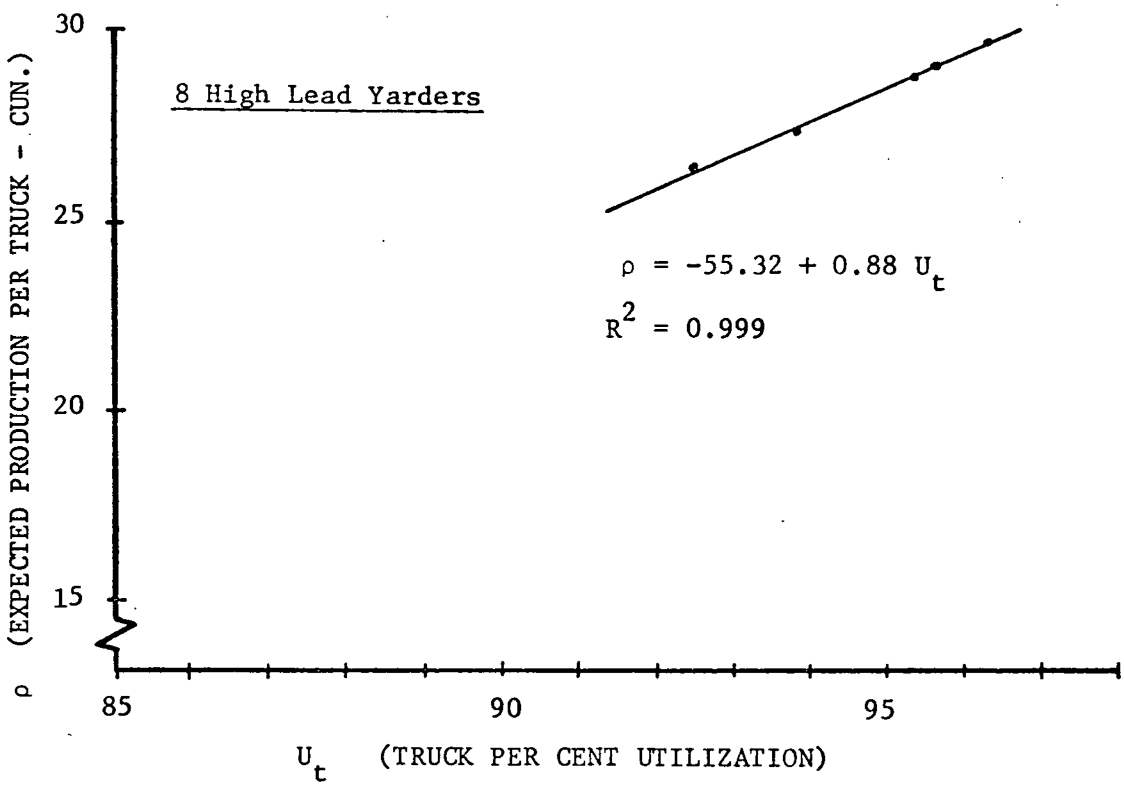


Figure G.2 - cont.

APPENDIX H

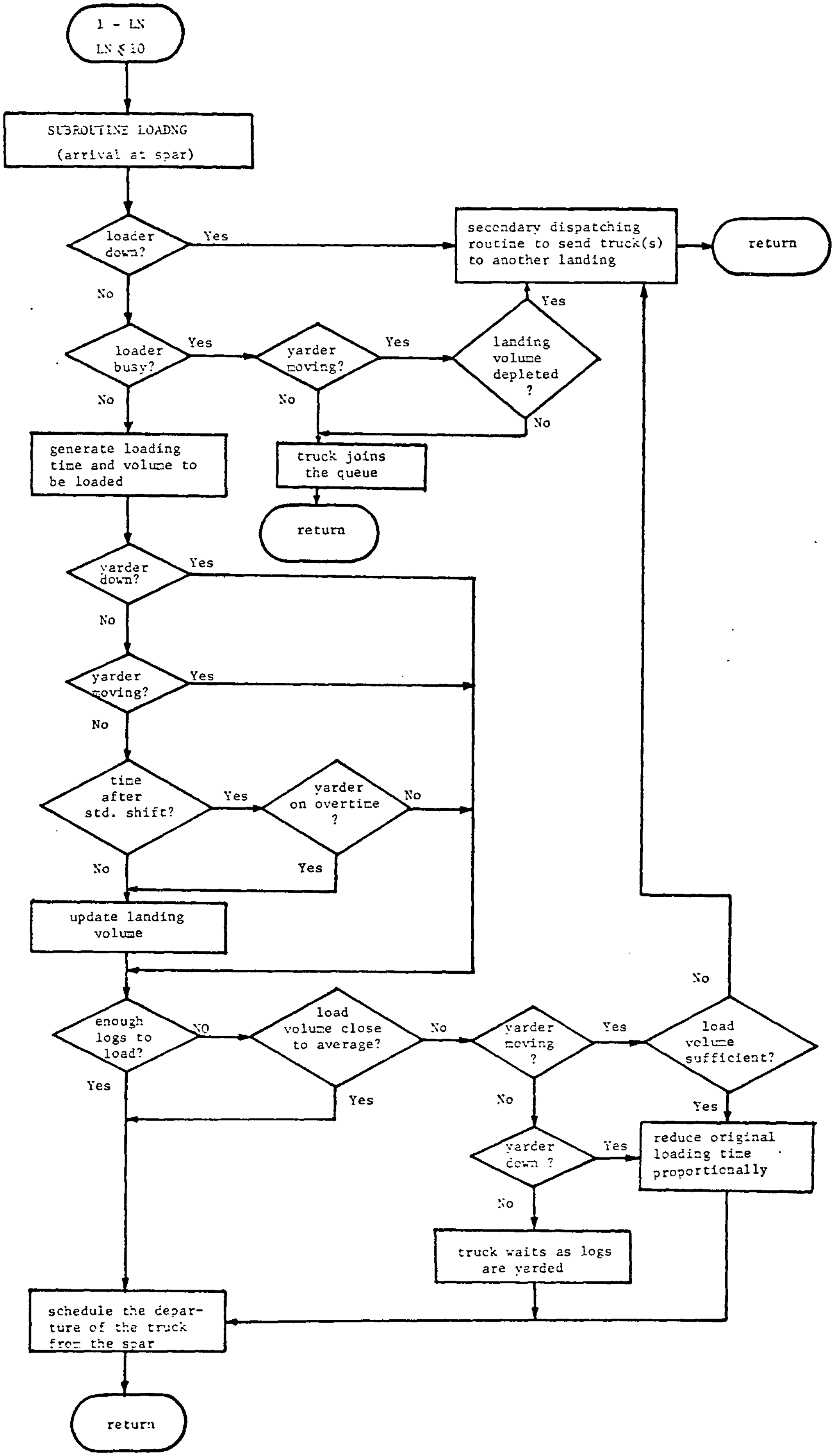
FLOW CHART OF THE VARIOUS ROUTINES IN THE PROGRAM

In the following pages, the flow chart of each of the event routines listed on page 39, with the exception of four routines, are given. The four routines are:

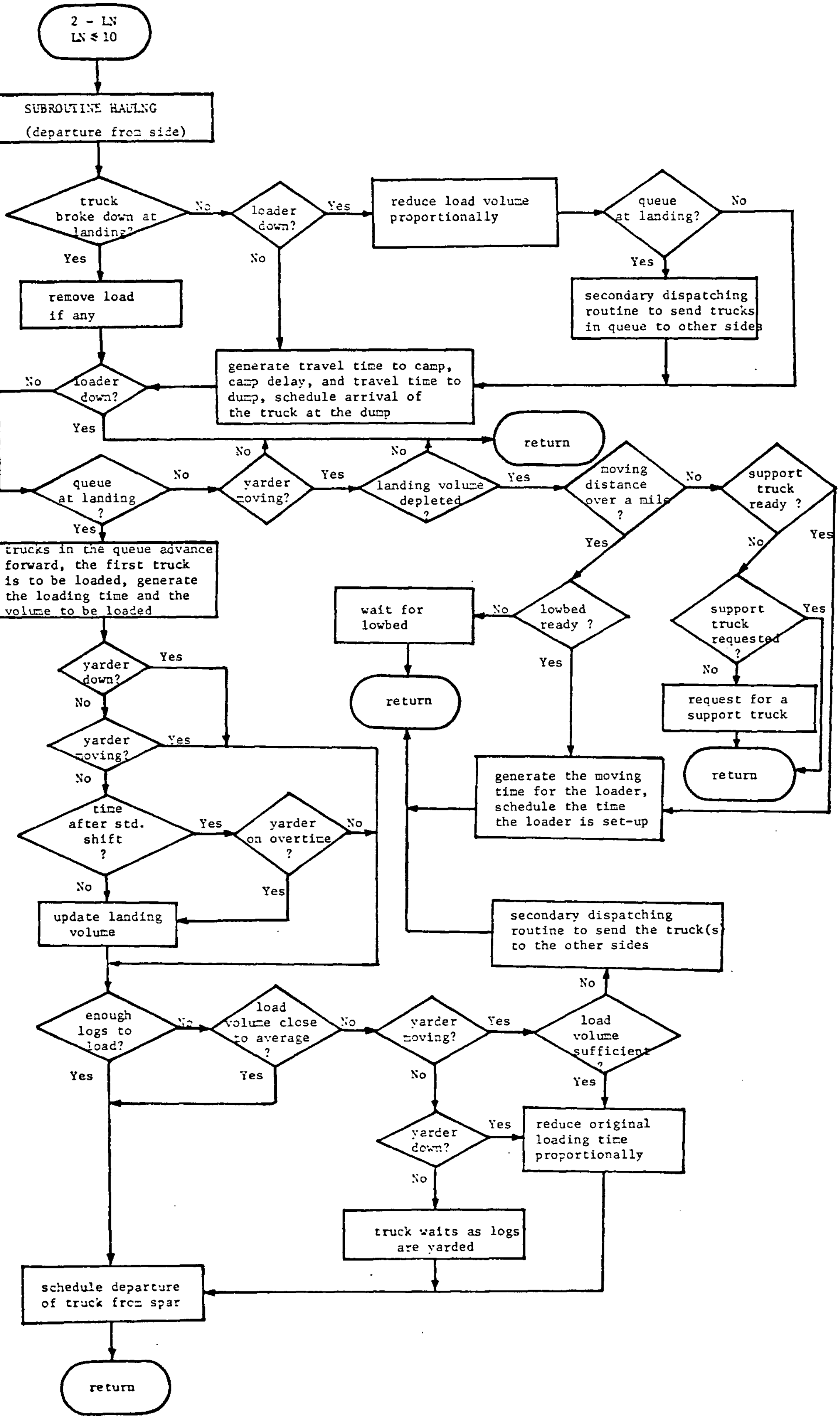
1. Yarding
2. Travel time generation
3. Overtime
4. Start-up.

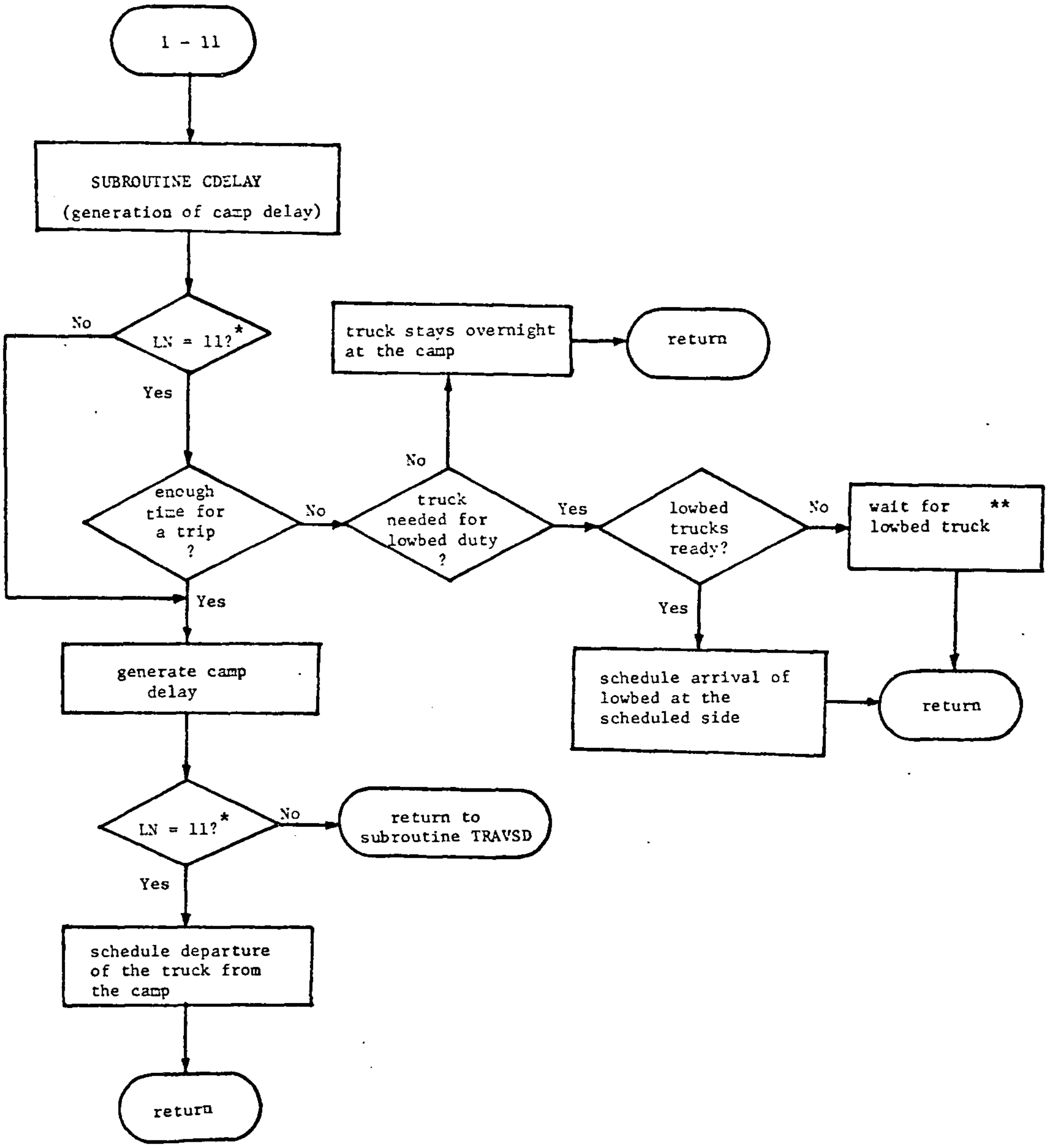
The first three of the four routines listed above are adequately described in the text. The "Start-up routine", on the other hand, is incorporated in the executive program (see Figure 3.2).

The computer listing of the logging simulation program (approximately 55 "print-out" pages) is available at the University of British Columbia Faculty of Forestry and may be obtained on request.



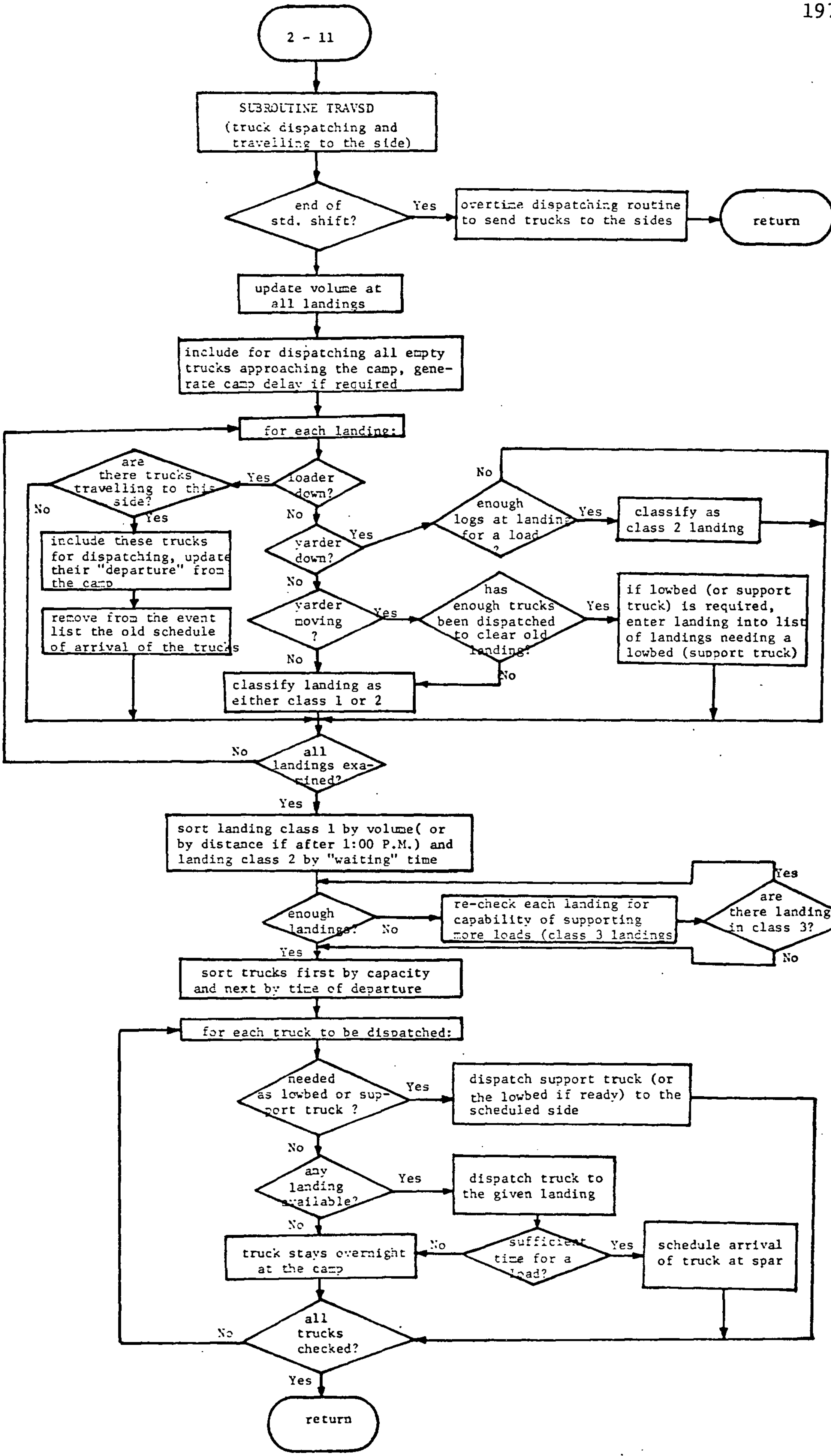
1 - LN
LN ≤ 10
SUBROUTINE LOADNG
(arrival at spar)
loader down?
Yes
No
secondary dispatching routine to send truck(s) to another landing
return
loader busy?
Yes
No
yarder moving?
Yes
No
landing volume depleted ?
Yes
No
generate loading time and volume to be loaded
truck joins the queue
return
yarder down?
Yes
No
yarder moving?
Yes
No
time after std. shift?
Yes
No
yarder on overtime ?
No
Yes
update landing volume
enough logs to load?
NO
Yes
load volume close to average?
No
Yes
yarder moving ?
Yes
No
load volume sufficient?
No
Yes
yarder down ?
Yes
No
reduce original loading time proportionally
truck waits as logs are yarded
schedule the departure of the truck from the spar
return

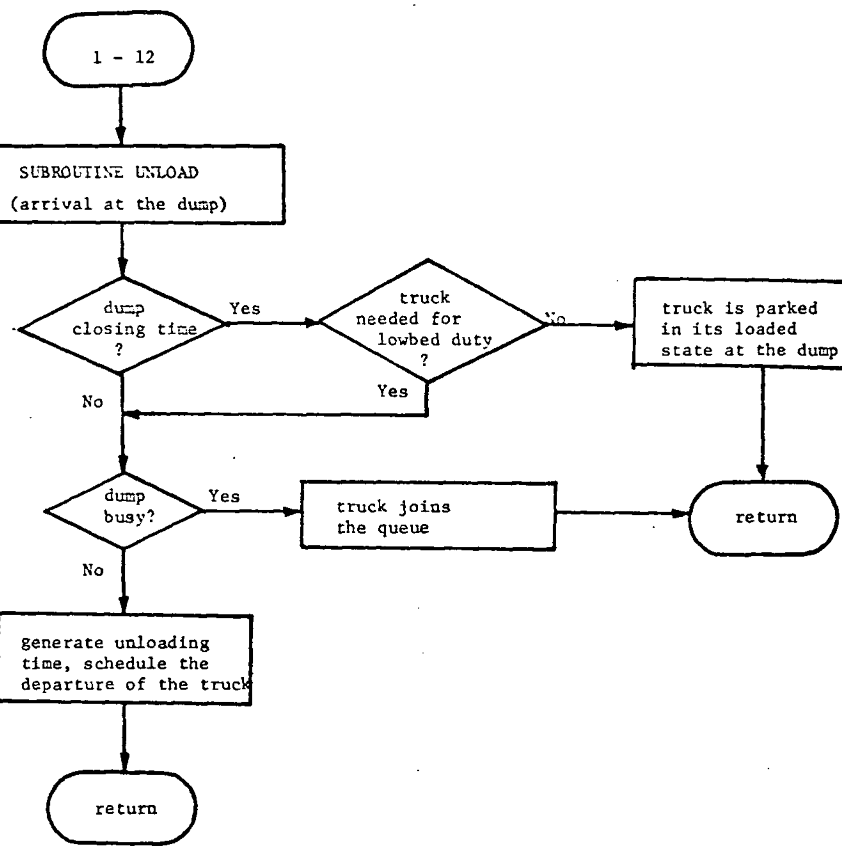

2 - LN
LN ≤ 10
SUBROUTINE HAULNG
(departure from side)
truck broke down at landing?
No
loader down?
Yes
reduce load volume proportionally
queue at landing?
No
Yes
secondary dispatching routine to send trucks in queue to other sides
Yes
remove load if any
No
generate travel time to camp, camp delay, and travel time to dump, schedule arrival of the truck at the dump
No
loader down?
Yes
return
queue at landing ?
No
yarder moving?
Yes
landing volume depleted ?
Yes
moving distance over a mile ?
No
support truck ready ?
Yes
trucks in the queue advance forward, the first truck is to be loaded, generate the loading time and the volume to be loaded
wait for lowbed
No
lowbed ready ?
Yes
support truck requested ?
Yes
No
request for a support truck
return
yarder down?
Yes
No
yarder moving?
Yes
No
time after std. shift ?
Yes
yarder on overtime ?
No
Yes
return
generate the moving time for the loader, schedule the time the loader is set-up
update landing volume
secondary dispatching routine to send the truck(s to the other sides
enough logs to load?
No
load volume close to average ?
No
yarder moving?
Yes
load volume sufficient ?
Yes
Yes
yarder down?
Yes
reduce original loading time proportionally
No
truck waits as logs are yarded
schedule departure of truck from spar
return

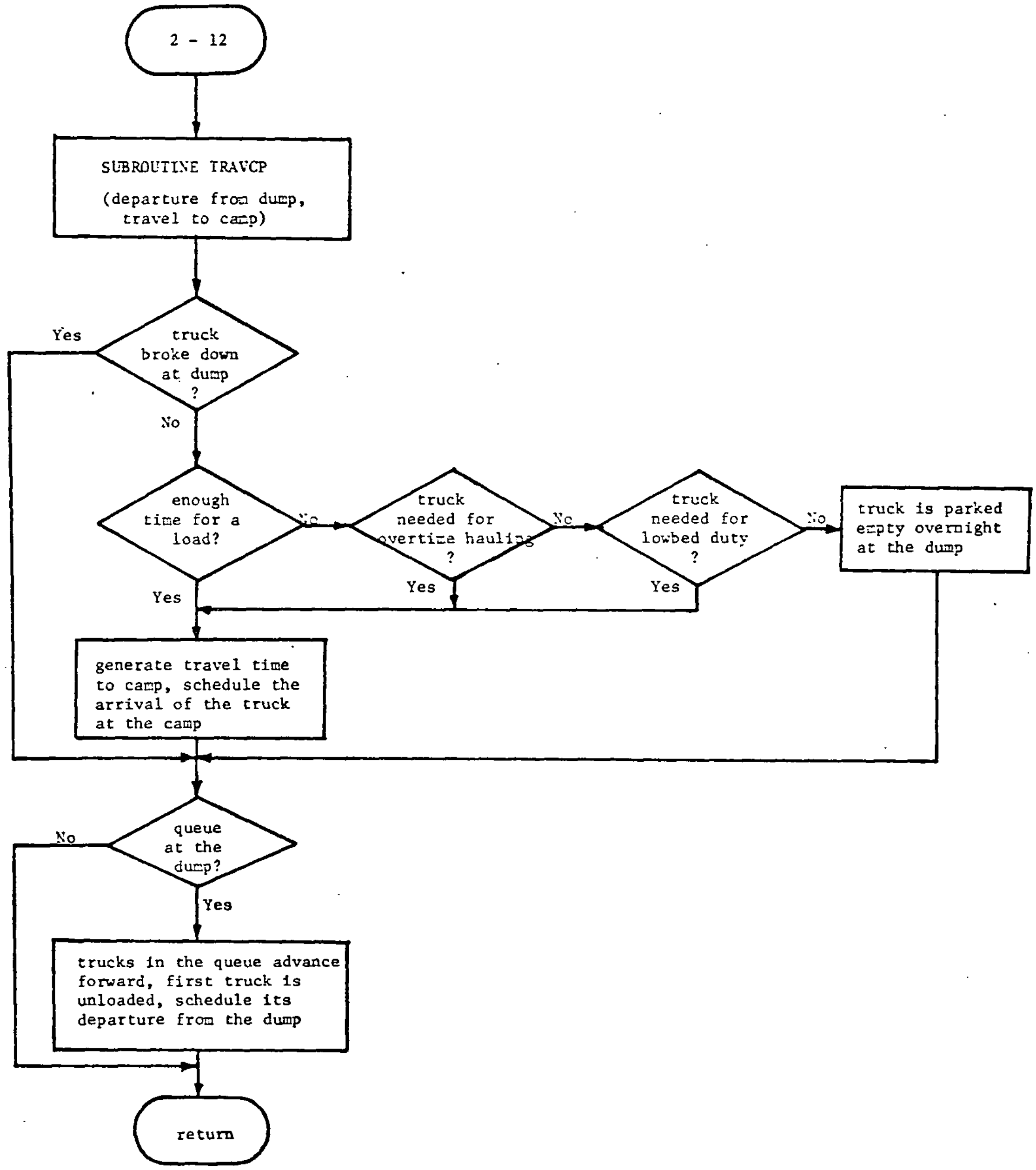


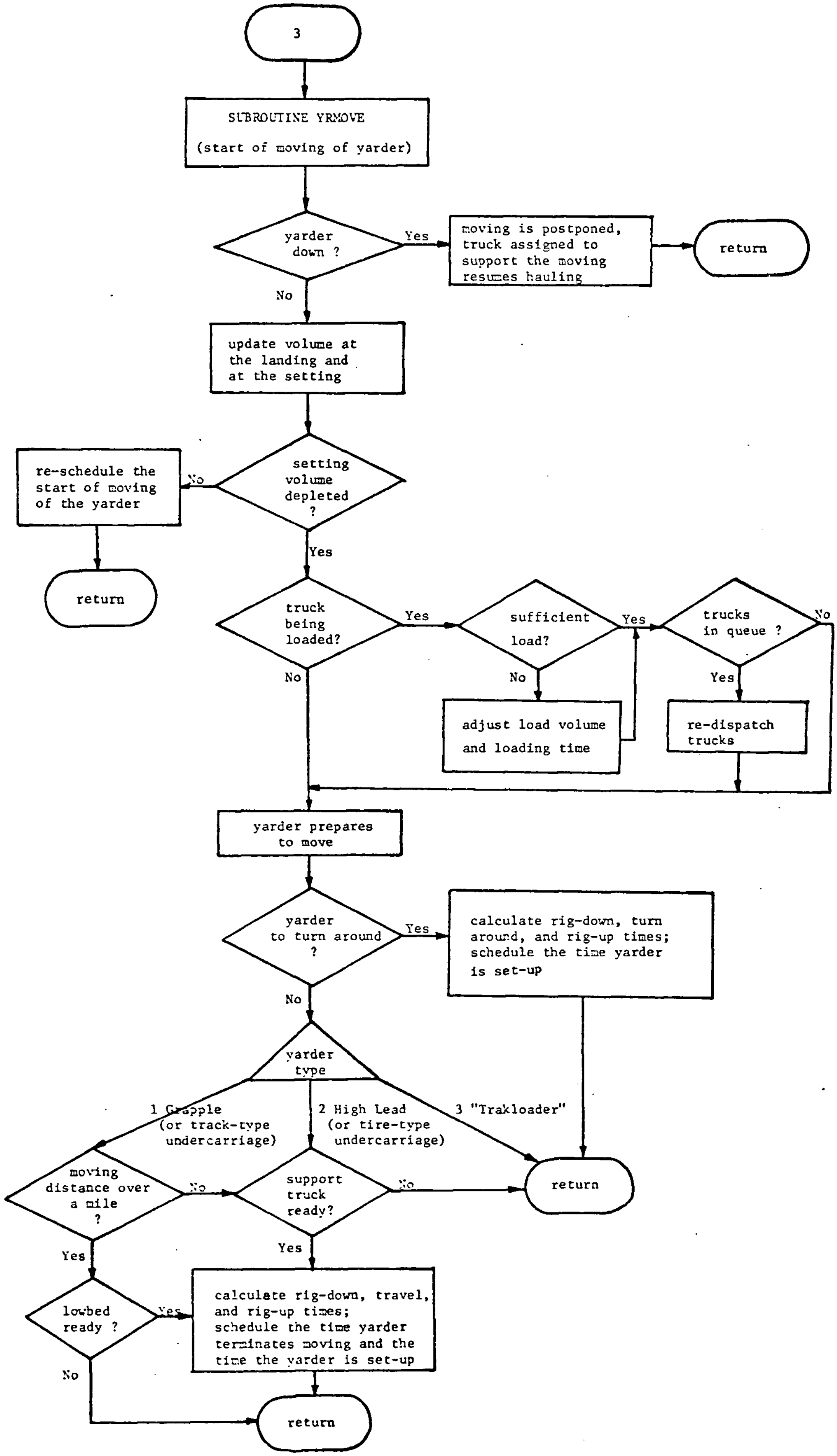
* LN ≠ 11 implies this subroutine is called from subroutine TRAVSD to generate camp delay for trucks approaching the camp to be dispatched.

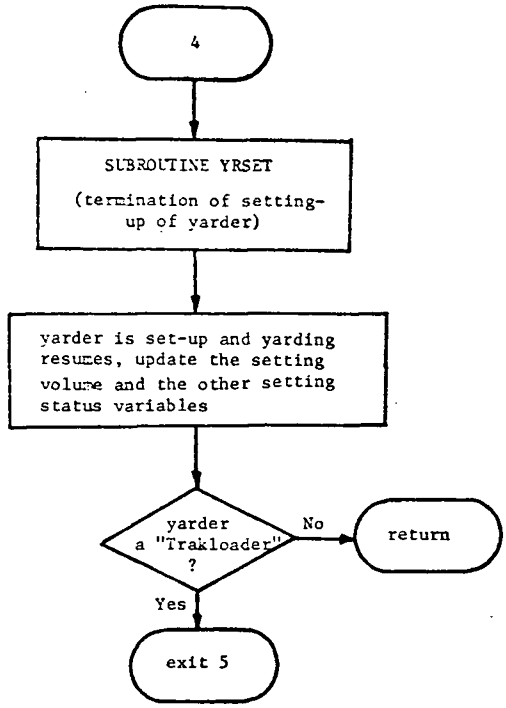
** It is assumed that two trucks are needed to pull the lowbed (as in the Harrison Mills logging division).

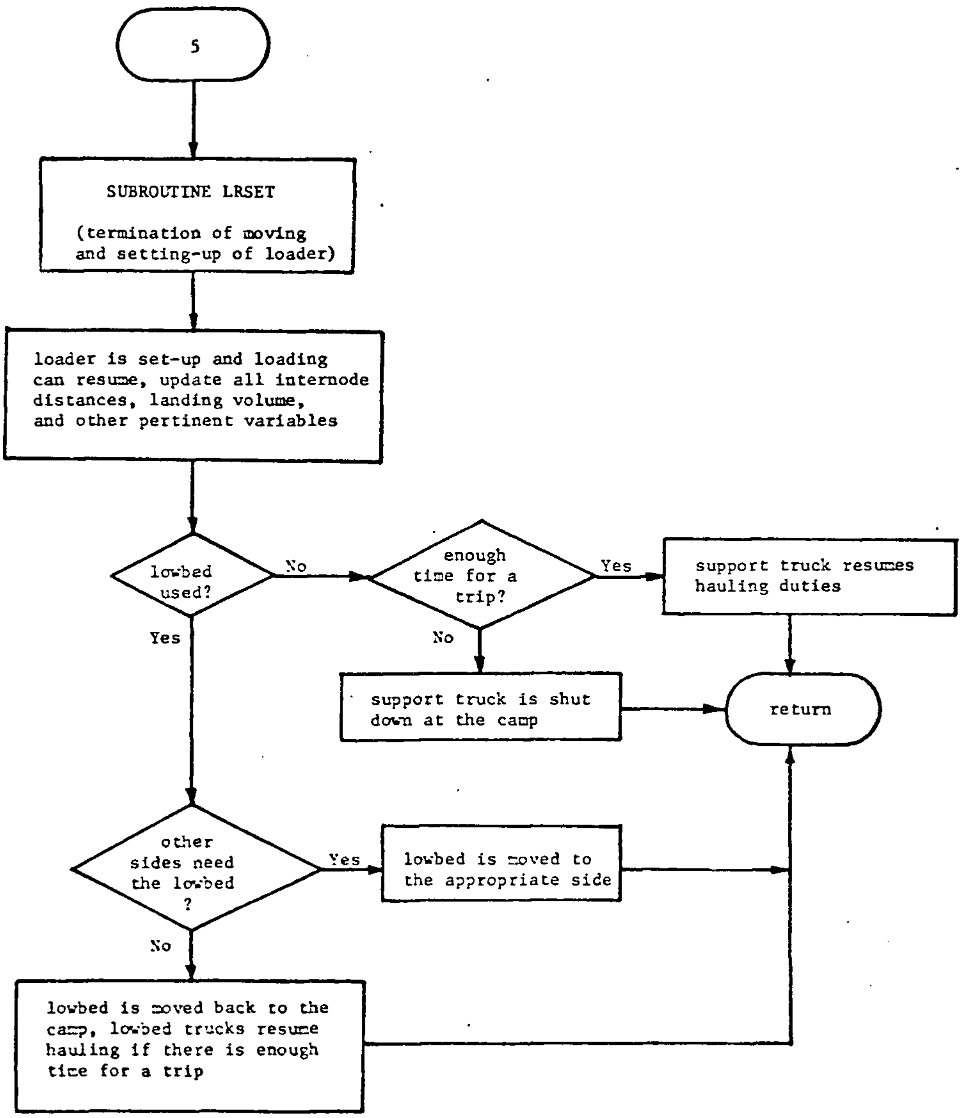

2 - 11
SUBROUTINE TRAVSD
(truck dispatching and travelling to the side)
end of std. shift?
Yes
overtime dispatching routine to send trucks to the sides
return
update volume at all landings
include for dispatching all empty trucks approaching the camp, generate camp delay if required
for each landing:
loader down?
Yes
are there trucks travelling to this side?
No
Yes
include these trucks for dispatching, update their "departure" from the camp
remove from the event list the old schedule of arrival of the trucks
No
yarder down?
Yes
enough logs at landing for a load ?
No
Yes
classify as class 2 landing
No
yarder moving ?
Yes
has enough trucks been dispatched to clear old landing?
Yes
if lowbed (or support truck) is required, enter landing into list of landings needing a lowbed (support truck)
No
No
classify landing as either class 1 or 2
No
all landings examined?
Yes
sort landing class 1 by volume(or by distance if after 1:00 P.M.) and landing class 2 by "waiting" time
enough landings?
No
re-check each landing for capability of supporting more loads (class 3 landings)
are there landings in class 3?
Yes
No
Yes
sort trucks first by capacity and next by time of departure
for each truck to be dispatched:
needed as lowbed or support truck ?
Yes
dispatch support truck (or the lowbed if ready) to the scheduled side
No
any landing available?
Yes
dispatch truck to the given landing
sufficient time for a load?
Yes
schedule arrival of truck at spar
No
No
truck stays overnight at the camp
all trucks checked?
No
Yes
return

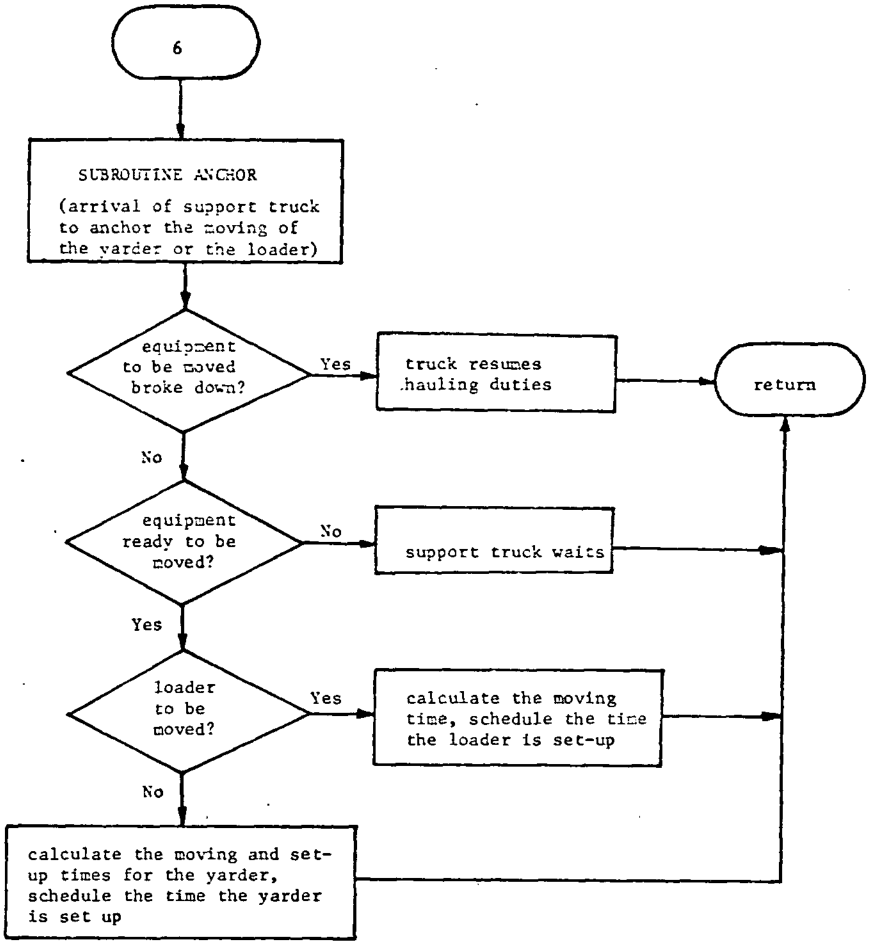

1 - 12
SUBROUTINE UNLOAD
(arrival at the dump)
dump closing time ?
Yes
truck needed for lowbed duty ?
No
truck is parked in its loaded state at the dump
Yes
No
dump busy?
Yes
truck joins the queue
return
No
generate unloading time, schedule the departure of the truck
return

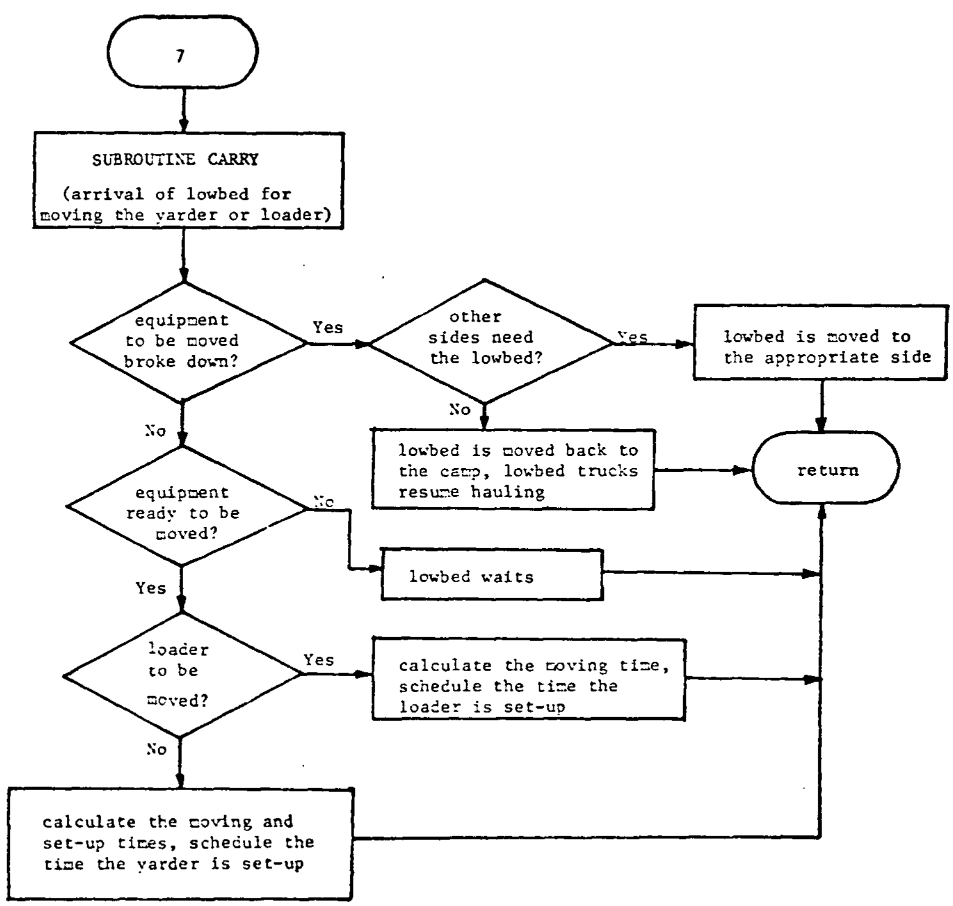

2 - 12
SUBROUTINE TRAVCP
(departure from dump, travel to camp)
truck broke down at dump ?
Yes
No
enough time for a load?
No
truck needed for overtime hauling ?
No
truck needed for lowbed duty ?
No
truck is parked empty overnight at the dump
Yes
Yes
Yes
generate travel time to camp, schedule the arrival of the truck at the camp
queue at the dump?
No
Yes
trucks in the queue advance forward, first truck is unloaded, schedule its departure from the dump
return

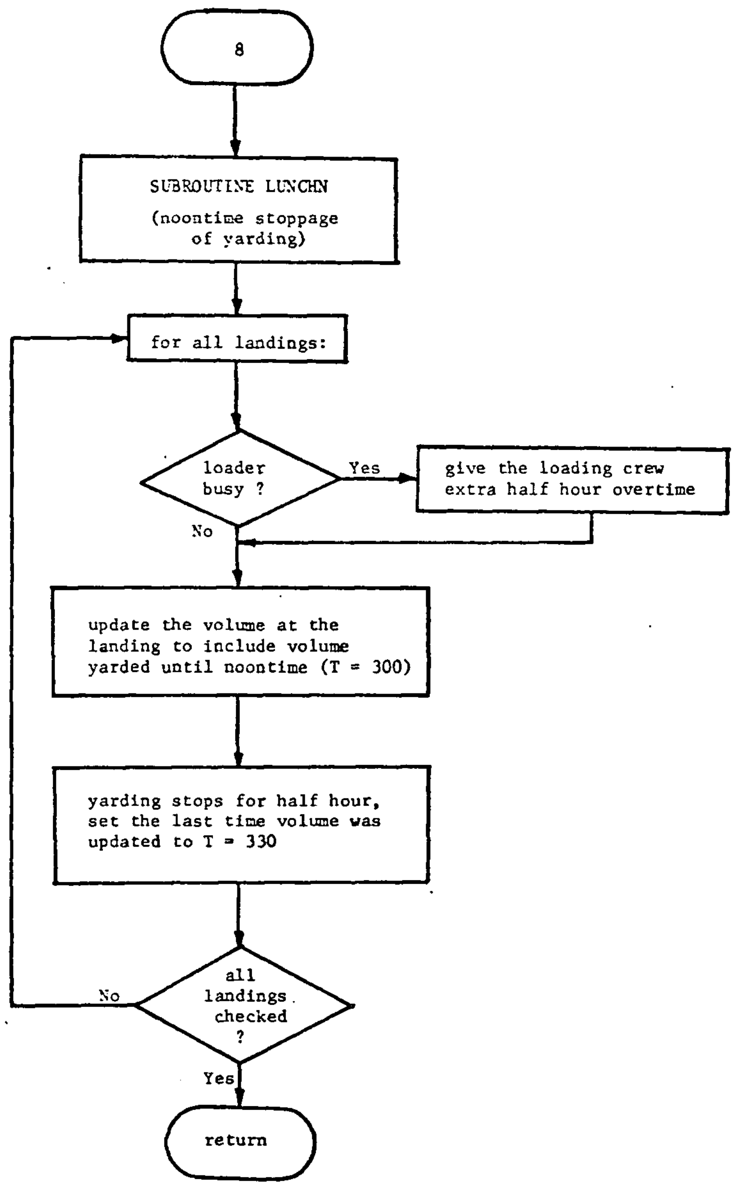

3
SUBROUTINE YRMOVE
(start of moving of yarder)
yarder down ?
Yes
moving is postponed, truck assigned to support the moving resumes hauling
return
No
update volume at the landing and at the setting
setting volume depleted ?
No
re-schedule the start of moving of the yarder
return
Yes
truck being loaded?
Yes
sufficient load?
Yes
trucks in queue ?
No
No
adjust load volume and loading time
Yes
re-dispatch trucks
No
yarder prepares to move
yarder to turn around ?
Yes
calculate rig-down, turn around, and rig-up times; schedule the time yarder is set-up
No
yarder type
1 Grapple (or track-type undercarriage)
2 High Lead (or tire-type undercarriage)
3 "Trakloader"
moving distance over a mile ?
No
support truck ready?
No
return
Yes
Yes
lowbed ready ?
Yes
calculate rig-down, travel, and rig-up times; schedule the time yarder terminates moving and the time the yarder is set-up
No
return

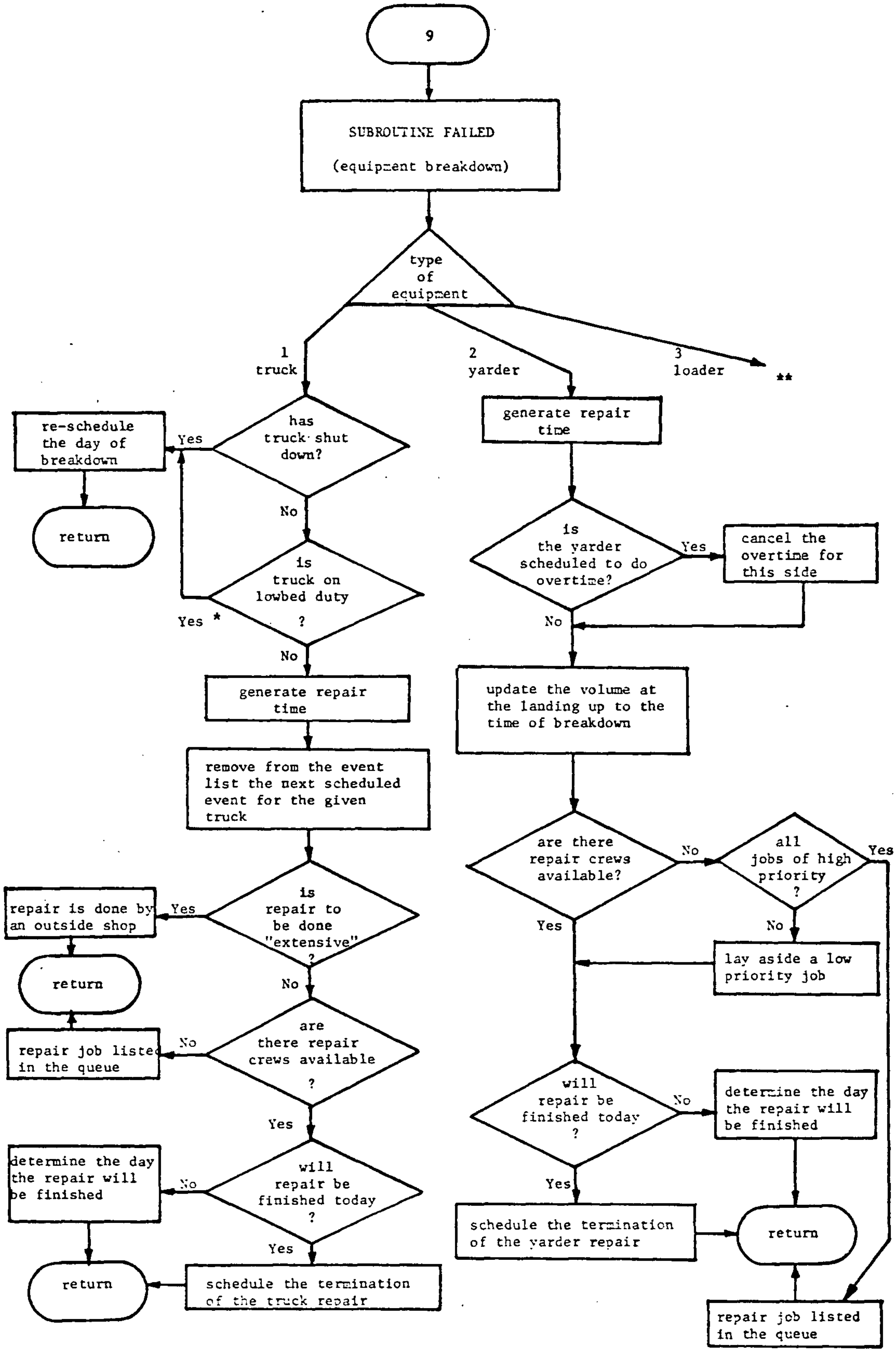

4
SUBROUTINE YRSET
(termination of setting-up of yarder)
yarder is set-up and yarding resumes, update the setting volume and the other setting status variables
yarder a "Trakloader" ?
No
return
Yes
exit 5


5
SUBROUTINE LRSET
(termination of moving and setting-up of loader)
loader is set-up and loading can resume, update all internode distances, landing volume, and other pertinent variables
lowbed used?
No
enough time for a trip?
Yes
support truck resumes hauling duties
No
support truck is shut down at the camp
return
Yes
other sides need the lowbed ?
Yes
lowbed is moved to the appropriate side
No
lowbed is moved back to the camp, lowbed trucks resume hauling if there is enough time for a trip


6
SUBROUTINE ANCHOR
(arrival of support truck to anchor the moving of the yarder or the loader)
equipment to be moved broke down?
Yes
truck resumes hauling duties
return
No
equipment ready to be moved?
No
support truck waits
Yes
loader to be moved?
Yes
calculate the moving time, schedule the time the loader is set-up
No
calculate the moving and set-up times for the yarder, schedule the time the yarder is set up

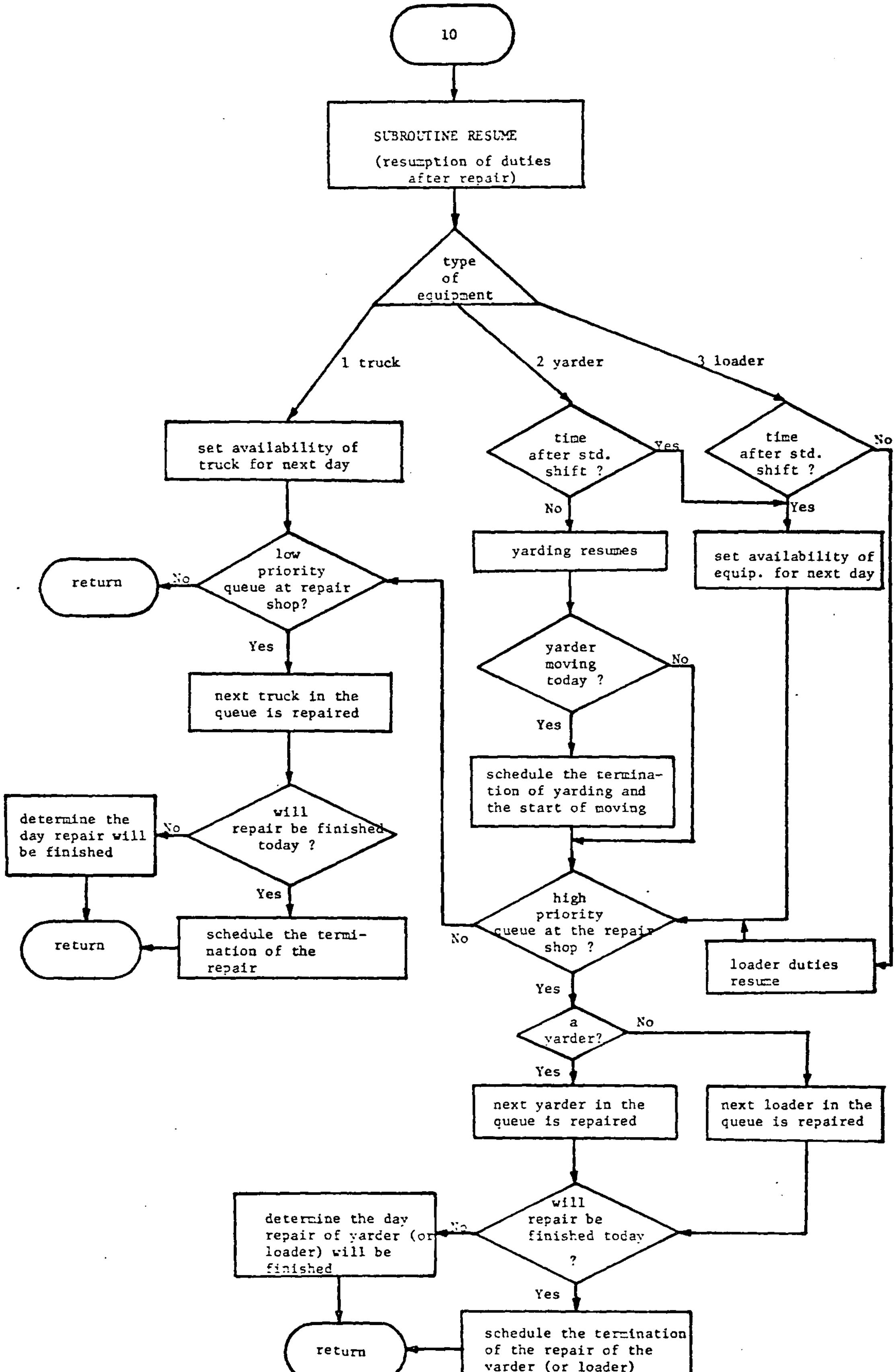

7
SUBROUTINE CARRY
(arrival of lowbed for moving the yarder or loader)
equipment to be moved broke down?
Yes
other sides need the lowbed?
Yes
lowbed is moved to the appropriate side
No
lowbed is moved back to the camp, lowbed trucks resume hauling
return
No
equipment ready to be moved?
No
lowbed waits
Yes
loader to be moved?
Yes
calculate the moving time, schedule the time the loader is set-up
No
calculate the moving and set-up times, schedule the time the yarder is set-up

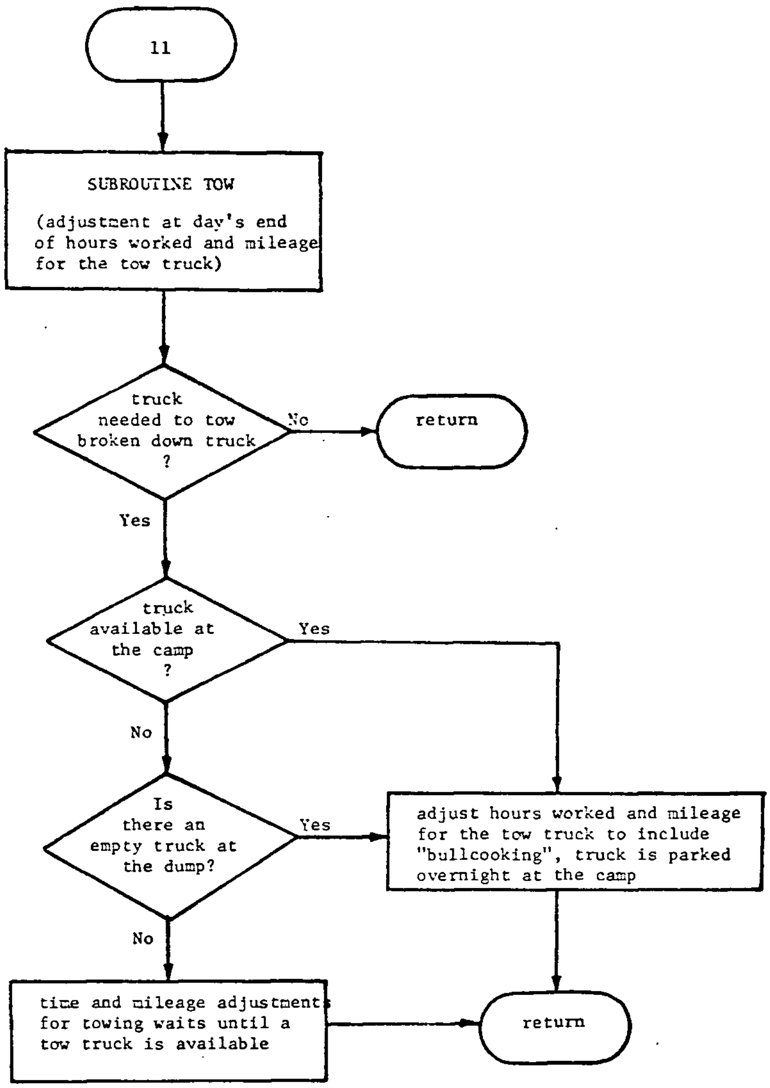

8
SUBROUTINE LUNCHN
(noontime stoppage of yarding)
for all landings:
loader busy ?
Yes
give the loading crew extra half hour overtime
No
update the volume at the landing to include volume yarded until noontime (T = 300)
yarding stops for half hour, set the last time volume was updated to T = 330
all landings checked ?
No
Yes
return

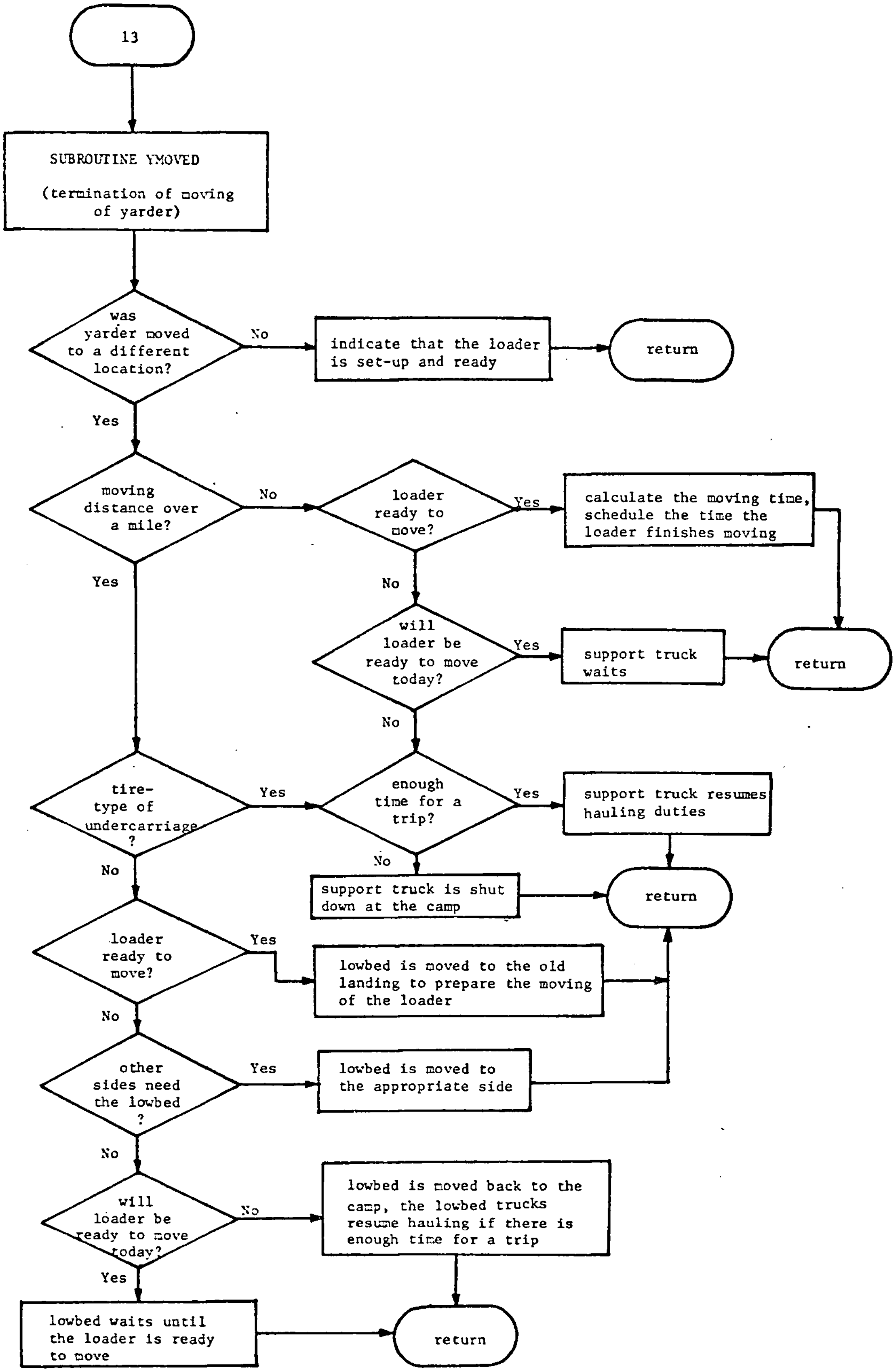


* It is assumed that truck failure never occurs when the truck is on lowbed duty.

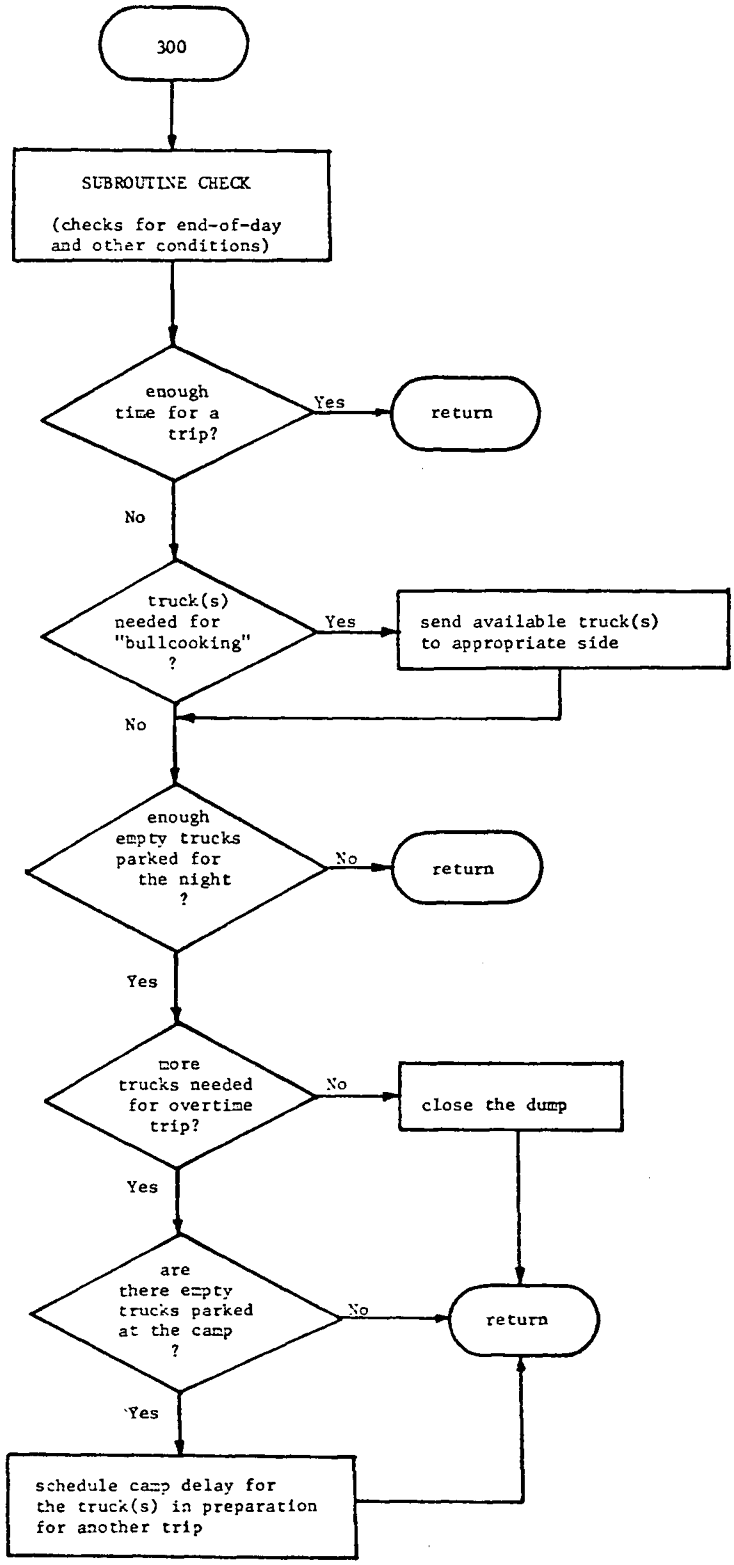
** The routine for loader breakdown is similar to the routine for yarder breakdown except that the landing volume is not updated in the case of a loader breakdown.


10
SUBROUTINE RESUME
(resumption of duties after repair)
type of equipment
1 truck
2 yarder
3 loader
set availability of truck for next day
time after std. shift ?
Yes
No
time after std. shift ?
No
Yes
low priority queue at repair shop?
return
No
Yes
yarding resumes
set availability of equip. for next day
next truck in the queue is repaired
yarder moving today ?
No
Yes
schedule the termination of yarding and the start of moving
will repair be finished today ?
determine the day repair will be finished
No
Yes
return
schedule the termination of the repair
high priority queue at the repair shop ?
No
Yes
loader duties resume
a yarder?
No
Yes
next yarder in the queue is repaired
next loader in the queue is repaired
will repair be finished today ?
determine the day repair of yarder (or loader) will be finished
No
Yes
return
schedule the termination of the repair of the yarder (or loader)


11
SUBROUTINE TOW
(adjustment at day's end of hours worked and mileage for the tow truck)
truck needed to tow broken down truck ?
No
return
Yes
truck available at the camp ?
Yes
No
Is there an empty truck at the dump?
Yes
adjust hours worked and mileage for the tow truck to include "bullcooking", truck is parked overnight at the camp
No
time and mileage adjustments for towing waits until a tow truck is available
return



Note: It is assumed that a support truck is needed to move any yarder with either a tire-type undercarriage regardless of moving distance or with a track-type of undercarriage for moving distances less than a mile. For longer distances, a lowbed is required.



300
SUBROUTINE CHECK
(checks for end-of-day and other conditions)
enough time for a trip?
Yes
return
No
truck(s) needed for "bullcooking" ?
Yes
send available truck(s) to appropriate side
No
enough empty trucks parked for the night ?
No
return
Yes
more trucks needed for overtime trip?
No
close the dump
Yes
are there empty trucks parked at the camp ?
No
return
Yes
schedule camp delay for the truck(s) in preparation for another trip