COMPUTER SIMULATION
OF
MATERIALS HANDLING IN OPEN PIT MINING

by

THOMAS J. O'NEIL

and

C.B. MANULA

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STATEMENT OF TRANSMITTAL

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William Spackman, Director
Coal Research Section
SUMMATION OF RESULTS

This report undertakes to describe a truck haulage simulation model and how it may be applied to aid management in evaluating alternative pit haulage schemes and to reduce the risk involved in the selection and assignment of equipment in open-pit mining systems. Details are presented of the distribution scheme, formulation and interpretation of simulation model, and method of solution.

The model using a computer, cycles trucks between their assigned shovel and discharge points over measured haulage routes. Required input parameters for model operation include the number of shifts to be simulated, operating time per shift, number and type of operating trucks and shovels, maximum truck acceleration and velocity, a vehicular deceleration rate, and the ratio of coal to total material loaded at each shovel. Equipment performance characteristics, system profile characteristics, and service time distributions are also necessary. Records are kept of all waiting times at loading and dumping points and of any interference on the haul roads, and a current journal of ore and waste production is maintained.

The truck haulage simulator presented here was developed primarily to evaluate and assign equipment optimally in an open pit mine. However, three related problems of current interest to the mining industry are ammenable to solution by the model. These are: haulage road construction; load weights; and haul road maintenance.
ACKNOWLEDGEMENTS

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INTRODUCTION

General Introduction

The American mining industry is charged with the responsibility of supplying the mineral raw materials required to sustain the high rate of economic growth of today's metal-based society. Certain metals and non-metals must be available not only to satisfy this nation's demands, but also to supply the future needs of an exploding world population. At the expected 1.55% annual increase, the population of the United States will exceed 330 million by the year 2000 (Landsberg, 1964); and at the present annual growth rate of 1.8%, the world population will be between seven and eight billion in the same year (Stamp, 1963). Obviously, the demand for mineral commodities in the next generation will intensify greatly; and consequently, the production of these products must increase manyfold. Given adequate mineral resources, the task of expanding production by a factor of three or four offers no small challenge.

The pressing demand for mineral raw materials is further harassed by the fact that mining, unlike the other basic industries, markets a wasting asset. Consumed mineral resources cannot be replenished, and most of the high-grade, easily-mined deposits have been exhausted. Technological advancements in mining engineering and mineral processing are helping to alleviate supply shortages, but deposit sizes and grades still place certain economic limitations on the amount of ore produced. The problem of accelerated demand for mineral commodities with diminishing resources is alarming and indicates the
increasing importance of large, low-grade mineral deposits.

An apparent solution to the problem of satisfying public demand for minerals from low-grade, low-profit ores is found in the mining and processing of enormous quantities of material. To mining companies, this means a larger enterprise with regard to plant and equipment, the reduction of high labor costs through mechanization and automation, and finally the development of scientific methods to minimize management's risk in making decisions. Because of the large capital investments and narrow profit margins in mining low-grade ores, little margin for error can be tolerated in the design of these large systems. Subjective conclusions which so often influence managerial decisions must be scrutinized closely when financial commitments are so high. At the same time, the problem of designing the most profitable system, or assigning equipment optimally in an existing system, varies in difficulty with size of the operation. Management is, therefore, required to make more accurate decisions with more complex problems and less certain information.

Operations research, a loosely used term implying a scientific approach to decision making, was developed during World War II to assist Allied commanders in removing much of the uncertainty from complex, weighty wartime decisions. These same techniques are now gaining favor in industry; as the consequences of high level decisions are far-reaching, with the overall effect on corporate health often unknown. This dissertation is concerned with the application of one O.R. technique, systems simulation, to the problem of optimal selection and assignment of equipment in an open pit truck haulage system.
Simulation is one of the most versatile operations research techniques and is especially well suited to the study of complex materials handling problems.

Large truck haulage operations are unusually vulnerable to faulty operating and planning decisions for the following reasons:

1. Rapid mining rates create new and complex assignment problems almost daily.

2. Capital expenditures are exceptionally high when large new equipment is purchased.

3. Rapid obsolescence and depreciation of off-highway haulage trucks cause vehicle purchase decisions to arise with surprising frequency.

4. Due to the extreme complexity of large haulage systems, productivity effects can seldom be predicted when operating procedures are changed.

Demand for scientific aids to decision making in the mining industry can only increase. It is difficult to name a major open pit mine that is not either undergoing expansion or planning a production increase. Mine planners all too often feel greater production can be realized simply by adding another shovel and a few more trucks to the operation and are perplexed when the system suddenly becomes overloaded and produces bottlenecks in unexpected places. With increasingly complex systems, it will be imperative that management receive adequate quantitative information to fully appraise the possible alternatives in major decisions.

Systems simulators cannot cure bad managerial judgement, or even give numerically exact answers in most cases. However, simulation can often identify some of the obscure problem areas and provide management with previously unobtainable data to minimize risks in making
decisions. Simulation permits management to test ideas experimentally on paper thereby avoiding costly trial-and-error analysis with the real system.

**Historical Background**

The growth of truck haulage as a primary transportation method in open pit mining closely parallels the progress made by manufacturers in developing large, reliable, automotive prime movers. In recent years, mine management has been eager to assimilate new proven developments in off-highway haulage trucks into mine production. Truck manufacturers have responded vigorously to the challenge and now market a vast and varied line of vehicles.

Historically, open pit mines have employed rail haulage almost exclusively, it being the only reliable high-volume method available early in the 20th century. Inflexibility, however, hindered rail haulage from the beginning, as track relining at both the shovel and the waste dumps proved very costly and time consuming. Also as the pits deepened, the locomotives' maximum gradability of about 4 per cent became critical. The required long lengths of graded track became excessively expensive to maintain, and cycle times were uneconomically long.

The debut of trucks as primary haulage units in open pit mining can be traced back to about 1937 on the Mesabi Iron Range (Whitney and Holt, 1939). Prior to that date, small experimental units had been tested but did not contribute significantly to mine production. Maximum truck capacity during this period was 15 to 20 tons with power units up to 150 hp. Although both diesel and gasoline engines
were used, the advantages of diesels were readily apparent; and gasoline engines soon disappeared in heavy duty, off-highway units. Truck haulage immediately showed promise, and one article in 1939 made the bold conclusion that "trucks are here to stay" (Whitney and Holt, 1939).

By 1955, trucks up to 50-ton capacities were common with both truck and shovel sizes increasing rapidly. In late 1959, R. G. LeTourneau introduced the first large electric powered haulage truck, an experimental, 75-ton, trolley driven unit tested at the Anaconda Company in Butte, Montana (Thomte, 1960). Unit Rig and Equipment Company unveiled the first self-contained diesel-electric unit in April, 1960. This 55-ton capacity truck was powered by a 600 hp diesel engine that drove d.c. traction motors in the vehicle's drive wheels. Shovels up to 11 cubic yards and trucks in the 50 to 60-ton range were popular in 1960. In 1965, shovels in 12 to 15-yard sizes were commonly found working in connection with 85 to 100-ton trucks (Wamsley, 1965). A large percentage of new trucks were diesel-electrics, and diesel automotive engines were available up to 1000 hp. Sixty-five-ton haulage trucks sold for nearly $100,000 each with diesel-electric units costing about 20% more. Larger vehicles are in development—a 240-ton coal hauler has been constructed by the Caterpillar Tractor Company (Kress, 1965)—with considerable effort being devoted to the application of gas turbine engines in off-highway haulage trucks. Figure 1 demonstrates vividly the enormous size of modern haulage trucks.

Although the capacity of haulage trucks has increased greatly, rapid mine expansion has demanded increased numbers of units also.
Figure 1

85-TON CAPACITY OFF-HIGHWAY REAR DUMP TRUCK
(Courtesy Unit Rig and Equipment Company)
At one western copper mine, a truck fleet of 97 vehicles was reported in 1964, and another copper mine required a fleet of 80 trucks when a large portion of the mine was converted from rail to truck haulage. It is evident that complex traffic patterns arise in modern surface mines, and an equipment assignment problem with a fantastically large number of alternatives presents itself to management.

In recent years very few new open pit mines have selected rail haulage for primary transportation of raw materials. Conversely, truck haulage has been chosen for most new mines, and at least two older mines have greatly reduced rail haulage in favor of truck haulage. Trucks offer several advantages over rail haulage in off-highway transportation of raw materials. Common among these are:

1. Trucks offer greater flexibility and versatility. Closer control of ore grade is possible, and shovel loading is not restricted by track location.

2. Trucks operate easily on 8 to 12% grades, and can negotiate much steeper ramps if necessary.

3. Improvements in truck chassis and component design have reduced operator fatigue while increasing vehicle safety, speed, and reliability.

Although the recent trend in mine materials handling is toward larger equipment, mine operators are faced with a complex management problem where new trucks or shovels are being considered. Smaller equipment leads to higher operating labor costs and heavier traffic intensities since more units are needed to satisfy the required production. Larger equipment requires a sizeable capital investment, is less maneuverable, and may create excessive maintenance and lost production costs when a unit breaks down. Operators of small and medium
sized mines would do well to examine their particular haulage requirements and limitations closely and realize that larger equipment is not a panacea to materials handling problems in open pit mining.

Statement of the Problem

In 1963 over 89% of the nearly five billion tons of material excavated in U. S. mining operations came from surface mines, and most of these mines used truck haulage as the primary conveyor of raw materials. One mine shows 200,000 tons moved daily with trucks, while for several others, truck haulage is responsible for more than 20 million tons transported annually.

To efficiently mine and transport quantities of this magnitude, a premium must be placed on the optimum selection and assignment of equipment to achieve maximum profit for the company. At the mine site, corporate profit is most obviously and directly influenced by costs, so that mine managers are concerned with meeting production goals at a minimum cost-per-ton mining expense. Three particular problems confront management in pursuing reduced truck haulage costs. These are:

1. What is the best assignment of trucks to shovels in the system?
2. If new equipment is needed, which new shovels and trucks will operate most effectively in the system?
3. Are any other physical changes in the system warranted?

For small open pit mines the solution to these problems may be obvious. The larger enterprises combining vehicles of various types and performance capabilities, however, breed problems of great complexity, with production and system configuration relationships usually unknown.
The simulation model described in this report was used to help solve a specific problem—the determination of future truck haulage requirements for open pit mining. High costs, expanded production, and greater pit depths created the need for a more efficient haulage system. Various alternatives were evaluated with aid of the simulator.

**Purpose and Scope**

The only absolutely certain way management can determine cost and productivity of any mining system is to install and operate the system. Although some assignment problems with existing equipment might be solved in this manner, system changes involving large capital expenditures can seldom be evaluated economically by such experimentation. Indeed, the probabilistic nature of mine production would necessitate a lengthy experiment for each alternative to locate the optimum system.

The most extensively used method for determining truck haulage requirements is based on the classic publication of the Euclid Division of General Motors* entitled "Estimating Production and Costs of Material Movement with Euclids" (1952). A later booklet produced by KW-Dart Truck Company is very similar in scope.

These bulletins contain hundreds of averages of haulage cycle element times based on the companies' vast experiences in truck haulage. The procedure outlined for the determination of haulage fleet requirements involves the selection of appropriate averages and fac-

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* Formerly the Euclid Road Machinery Company, Form No. 355-R
tors to calculate an average haulage cycle time for one unit. Fleet requirements are then found by calculating the number of vehicles needed to sustain a specified production, and then estimating future equipment availability so that necessary spare units can be added. The above estimation procedures are still widely used by mining companies, equipment manufacturers, and are even taught in universities to underclass mining engineering students. While these procedures have some value as rough indicators when applied to small operations, their value in optimizing large complex layouts is questionable. It is common knowledge that haulage systems are combinations of various cycle elements, the duration of each element being a random variable that obeys some underlying probability distribution. On the other hand, probabilistic techniques, using simulation or queueing methods, and viewing the system in its entirety, would reflect reality much more closely.

Widespread availability of high-speed digital computers has encouraged the use of simulation in solving certain mine materials handling problems. The bookkeeping operations, the mass of data, and the huge number of calculations associated with simulation methods demand the use of digital computers to obtain a solution. Another reason for widespread use of simulation is the lack of reliable analytical methods of solution for complex systems, particularly in a finitely populated cyclic queueing problem such as that analyzed in this report.
This dissertation represents an attempt to develop mathematical relationships which accurately describe the sequence of operations for a general truck haulage system. These relationships have been programmed into the memory of a computer to aid management in rapidly assessing the relative effectiveness of proposed changes in a given haulage system. Essentially, the program permits management to evaluate many potential ideas without changing the actual operation. This eliminates costly trial-and-error methods which cannot be tolerated in present-day mining.

Systems simulation is one of the most widely used and versatile operations research techniques. The model described herein duplicates the production characteristics of the actual haulage systems and computes the production totals for each shift for any desired equipment assignment. System bottlenecks can also be identified, as queueing delay times for each element of the haulage cycle are accumulated and listed for the programmer.

As with all project and system evaluation techniques, the final effectiveness of the simulation model depends heavily on accurate cost information. Cost per shovel-shift and cost per truck-shift figures vary considerably from mine to mine. The analyst may find the optimum haulage system of one mine to be significantly sub-optimum for another operation. Therefore, the high degree of accuracy of the simulator is wasted if unreliable cost data are used.

Previous Related Studies

Many investigators, equipped with digital computers, have recognized the value of simulation in mining operations and developed simu-
lators to study complex materials handling problems. Discussed below are two previously structured truck haulage models and several other studies in the general area of simulated raw materials transportation.

Madge (1964) described a Monte Carlo simulation model developed to analyze truck requirements at a new mine. The model simulated production from two separate pits feeding a common crusher via truck haulage over separate haul roads. One shovel was assigned to each pit, and only ore was hauled. Considerable effort was devoted to accurately simulating shovel loading, but haulage times were considered constant. Queues were studied at the crusher and at the shovels to determine the truck fleet required and to delineate congested areas for further study. An interesting result of the study was that optimum truck fleet size as determined by simulation was in all cases at least two units less than the manufacturer's recommendation. A preliminary savings to the company of $180,000 resulted.

Waring and Calder (1965) programmed a similar but more complex truck haulage system. Empirical probability distribution functions for each haulage cycle element were developed from time study data and were the basis for randomly generated model element times. Only one shovel type and one truck type could be tolerated in the model, and again only ore movements were simulated. Although haul road queues as well as loading and dumping queues were studied, the haulage system layout used was inflexible and unusual. System interdependencies were studied to optimize production with particular emphasis placed on rock fragmentation as a production parameter.
Application of simulation to other types of materials handling systems has been described extensively in the technical literature. A rail haulage simulation model described by Achttien and Stine (1964) was used to determine if a new haulage adit was necessary with an increased level of production at an underground metal mine. Manula (1963) determined optimum loading station car storage to handle randomly fluctuating production in an underground coal mine. Sanford (1965) used a full simulation model to select the optimum conveyor belt size for an underground coal producer. The last two references and Falkie (1961) offer extensive bibliographies on simulation and other operations research topics pertaining to materials handling.

All of the work reviewed above used probabilistic simulation, known also as full, Monte Carlo, or random simulation. Two notable references (Nelson, 1964; and Kim and Manula, 1966) describe the standard simulation of a mine locomotive. In this variety of simulation, the model is controlled by some physical or scientific law other than the laws of chance. The locomotive in the above referenced works travelled over a known haulage profile according to its mechanical capability as outlined by the manufacturer's performance characteristic curves. The truck haulage model described in this thesis uses a modified version of this standard simulator to move trucks over haulage road profiles.
II METHOD OF ANALYSIS

A study concerned with maximizing the effectiveness of a truck haulage system should examine closely the production rates of the system under various operating conditions and also determine how productivity can be increased with fixed equipment resources. Unfortunately, operating characteristics vary considerably from mine to mine so that a successful optimizing technique at one operation may be completely unworkable at another property. Consequently, the need for a versatile and accurate production model to aid management in controlling truck haulage costs is readily apparent.

A Waiting Line Problem

Given a specified truck fleet, productivity can be most easily increased by reducing non-productive waiting line delay in the system. Waiting lines are usually minimized by equipment re-distribution, or by altering the storage aspects of the haulage system, or both. In truck operations, waiting lines can form at various stages in the haulage cycle. Typical locations are: (a) at the loading shovel, when the preceding truck is waiting or being loaded; (b) at the crusher, when the preceding truck is waiting or discharging; (c) at the waste dump, if operating practice requires a dump man; and (d) on the haul roads, when passing is not permitted. Figures 2 and 3 show typical open pit queueing situations.

Queueing Theory

An operations research technique called queueing theory was specially developed to resolve waiting line problems. Queueing models
Figure 2

TYPICAL WAITING LINE FORMING AT CRUSHER STATION
Figure 3
MOVING QUEUE
FORMING ON STEEP (12%) UPHILL GRADE
have been developed for many theoretical and practical situations, and queueing theory remains the only analytical optimization process available for waiting line problems. If arrival rates and service times can be approximated by one of several standard probability distributions, queueing theory may offer a rapid mathematical solution to the problem. However, as the system becomes increasingly complex with additional servicing channels, a finite customer population, and multistage or cyclical queueing is encountered, queueing theory analysis may become unsolvable or subject to such simplifying assumptions that the results are meaningless. Since these characteristics are common to all truck operations, a waiting line analysis usually precludes the use of queueing theory. More specifically, the reasons for rejecting a queueing model are listed in the following:

(1) Queueing theory requires traffic intensity parameters to approximate particular standard probability distributions. Customer arrival and service rates are usually assumed to be Poisson, and arrival intervals and service times must be constant, Erlang, or exponentially distributed. These are often prohibitive restrictions in truck haulage, as recorded data seldom can be accurately described by a standard probability distribution.

(2) Truck haulage presents a multistage cyclical queueing problem where customers proceed from one servicing station to the next in a prescribed cycle. Queues form at the shovel, at the dump, and moving queues are found on the haul roads. Multistage cyclical queues may be amenable to analytical solution, but intermediate queues found on haul roads are out of the realm of queueing theory analysis.
Complex truck haulage systems involving vehicles of different makes and models from several loaders and traversing a common haul road require many internal decisions to maintain the prescribed flow of traffic. Trucks must also be guided to specified destinations over a measured haul road profile. Queueing theory does not allow internal decision making and considers only the effects experienced at the servicing channels.

Generally speaking, queueing theory is only applicable to the study of servicing procedures. The effect of a different number of servicing channels, various service times, splitting a queue, or joining several queues can be determined with a waiting line model. Unfortunately, effects of physical changes in the system other than the service channel are ignored. Many excellent applications of queueing theory to telephone conversations, airport traffic control, and the operation and timing of traffic lights (Saaty, 1961) have been reported in technical publications. However, the gross assumptions necessary to thoroughly analyze an open pit truck haulage system with these methods would render the results nearly worthless.

Systems Simulation

All mine managers face the eternal problem of producing raw materials safely and more economically. Experience, scientific training, and educated guesses have been the manager's primary weapons in this endless battle. However, new, larger, more complex mining operations attach great import to management decisions. Educated guesses are no longer acceptable. Systems that can be described fully and accurately by mathematical formulae can usually be optimized directly
using calculus; but again, growing complexity of mining systems usually prevents solution by such straightforward means.

An OR activity referred to as simulation, strives to bridge the gap between theory and useful design procedures found in complex queueing problems. This method employs certain testing criteria which act as the counterpart to scale-model testing in physical research and design. The trend toward this method of analysis has been accelerated rapidly by the widespread availability of high-speed digital computers, which drastically reduce the time required for computation and can also generate the necessary random numbers required for simulation.

Systems simulation has been described as management's laboratory in that it offers decision makers a unique opportunity to experiment with proposed operational changes without altering the actual production system itself (Cragin, 1959). Simulation provides the indispensable tool of scientific research, experimentation with a representative model, to management. On a broader scale, simulation along with the other operations research disciplines demonstrates a significant trend toward quantified decision making by elevating the process from an intuitive art to a science.

For many investigations, systems simulation was selected because parameters describing the transfer of material could not be approximated by standard probability distributions. In other studies, simulation was the only method which enabled the changes in production due to alterations in physical elements of the system to be evaluated. Systems simulation was used in this thesis for both of the above reasons.
Both of the previously cited investigators in truck haulage optimization used the Monte Carlo technique for generating random cycle element times in their simulation models. Both studies were financed by industrial concerns to solve particular problems. Consequently, the models developed are applicable to only one mine under a given set of operating conditions. Not only are these models inflexible, but they make grand assumptions such as constant haul times, only one type of truck, or the haulage of only one type of material. These constraints further restrict the field of application of the models and raise considerable doubt as to the validity of the results.

Other investigators (Sanford, 1965; and Manula, 1963) have described the procedure of systems simulation rather thoroughly; but a review of technique and terminology is in order here, for a simulation model is the basis for this thesis.

**Simulation - A Definition.** The term "systems simulation" is something of a paradox. In a general sense it is a self-explanatory term, and yet it is not quite clear what characteristics of the system are being simulated or even how a system could be simulated. In operations research usage, systems simulation is a method used to reproduce and manipulate the production properties of a real world system in the reduced form of a model. Production need not be interpreted strictly as industrial output, but simply as the primary function of the system--usually the processing of units through a predetermined service plan.

**Selecting a Model.** The basis for a systems simulation study then is a factual model of the actual system. Three general types of
models available to the systems simulation analyst are:

(1) **Physical model** - a scaled down replica of the prototype as typified by model airplanes or plant layout models common in building construction.

(2) **Conceptual model** - a model employing the production concepts of the real system but not a visually apparent facsimile. Scientific experimental test apparatus quite often are conceptual models of real world situations.

(3) **Analytical model** - a mathematical representation of the prototype bearing no visual or conceptual resemblance to the actual system.

Physical models have little value in scientific investigation, for meaningful performance similitude cannot be attained. Conceptual models have considerable merit in some laboratory research, but to a degree are inflexible; and usually the time scale cannot be compressed sufficiently to be of value in dynamic decision making. Conversely, analytical models used in conjunction with high speed computers are extremely powerful tools in decision making. Management needs answers and needs them fast. Visual recognition and conceptual reproduction are unimportant model properties; only fast, accurate results are needed. Analytical models are ideally suited to such applications and have been almost universally selected for systems simulation studies.

Analytical models can further be described as either deterministic or probabilistic. If production parameters are known with certainty, a deterministic model can be formulated. Management has direct control of variables in a deterministic system, and interrelationships among variables are constant. Probabilistic models often reflect reality more closely than deterministic models in that system parameters are described by probability distributions. This is commonly the case in the real world.
Structuring the Model. After selecting a model type, the analyst's next concern is the formulation of a logical sequence of mathematical relationships which duplicate production characteristics of the real system. A flow diagram of the prototype is often helpful in visualizing the various paths through the system, probable congestion areas, and other critical spots requiring special attention. The structured analytical model is a sequence of computations that moves a unit through all the necessary elements of the system over a specified route. As most systems simulation problems are solved with the aid of a computer the formulated model is usually in the form of a computer program, assigning to the computer the tedious tasks of calculating and bookkeeping.

Generating Information. Although the program places the proper sequence of system events in the computer's memory, input data representative of the prototype are required to operate the model, much as quality fuel is needed to properly drive a machine. Numerical data are used to assign values to system components for particular units in the system. Consequently, the position, direction and production status of each unit is discernible at every instant in time.

Rather than enter enormous quantities of observed data into the computer memory, normally only data distribution parameters or mechanical performance characteristics are needed to imitate production qualities of the prototype. The computer uses this information to generate representative numerical values for system elements. Two general types of information generating methods are available for systems simulation.
(1) **Full Simulation.** Full simulation is a random sampling routine governed jointly by input probability distribution parameters and by the laws of chance. Because of its random nature, full simulation is more commonly and colorfully called Monte Carlo simulation. Either empirical or standard probability distribution functions may be sampled. Within the limits of the function, component values occur randomly, but in the same proportions as element values in the real system. An obvious result of Monte Carlo simulation is that model performance is completely controlled by the input information. Therefore, if historical time study data from the system are used, the analyst is assuming that past and future performances of the system are identical. It also becomes immediately apparent that unreliable data will give unreliable answers, regardless of the degree of sophistication in the model formulation.

(2) **Standard Simulation.** Standard simulation may be employed when a mechanical apparatus is to be simulated. Most machines can be described by a deterministic model, as a given quantity of input energy usually produces a constant work output. If input parameters are known with certainty, the machine's performance can be determined by examining its mechanical capabilities under the given conditions. The production rate of the machine, therefore, need not be selected randomly from past operating data, but calculated directly by mathematical formulae.

In comparison, full simulation reproduces the variable human factor in operations because past production data are used in predicting future performance. Inherently, this compels the analyst to
collect a mass of historical data, usually an expensive and lengthy process. Standard simulation requires no historical operating data, but yields only theoretical machine performance for the designated conditions. This is not an entirely objectionable result, for a correlation between theoretical and actual production may be feasible. Also, management may wish to know how close to peak performance their system is operating. A significant advantage of standard over random simulation is the ability of the former to readily accept new units of various capabilities into the system. Performance characteristics are the only information needed.

A more complete technical discussion of both full and standard simulation is presented under a separate heading in the following chapter.

*Applied Simulation.* Although high-speed digital computers have greatly enhanced simulation as a system optimization procedure, the method is not without disadvantages. Generally speaking, direct analytical methods are always preferred over systems simulation if both procedures are capable of solving the problem. Simulation models usually take longer to formulate, are more expensive to execute, and most important, do not determine optimum system inputs directly. It cannot be emphasized too strongly that simulation models can merely ascertain the effectiveness of a system, usually in terms of production, for a given set of input data. An absolute optimum condition can be found with certainty only after all possible combinations of input parameters are tested in the model. If a large number of alternatives confront management, a correspondingly large number of simulation
trials must be performed to ensure an optimal solution. Often prohibitive computation costs can be incurred when an attempt is made to examine all possibilities. Fortunately, in practice, experience and logic can usually eliminate a great many alternatives as being obviously sub-optimum resulting in a reasonable number of choices to be tested with the simulator.

Mathematicians often dismiss systems simulation lightly as being an unsophisticated, inefficient approach to optimization problems. Engineers, however, need solutions to problems and are not at all embarassed by a lack of ostentatious mathematical exercises in the solution method. Simulation is the most flexible, universally applicable, and in many cases, the only method capable of doing the job. While it is not recommended that simulation be used when a more direct method is available, a competent analyst with a thorough knowledge of simulation can probably solve more system optimization problems than an equally competent person possessing an equally thorough knowledge of any one other operations research technique.
III MODEL FORMULATION

The central idea embodied in this dissertation is the development and application of an analytical simulation model to maximize the effectiveness of truck operations in the open pit mining and construction industries. In this section some details are presented of the distribution system, formulation and interpretation of the simulation model, and basic statistical criteria for data and model testing.

There are two fundamental differences between this model and other truck haulage simulators— one a difference of degree, the other a difference of kind. The model described herein can simulate more complex systems than previous models by allowing transportation of material from multiple mine faces to multiple mine destinations and by being readily adaptable to a wide variety of mine layouts. The second difference that characterizes the model is the standard simulation of truck movements. This technique enables each vehicle to perform according to its mechanical capabilities and the physical profile of the haul road.

Among the similarities between other truck haulage simulators and this model are the recognition of the probabilistic nature of certain service times in the system and the use of a digital computer to operate the model. The computer inherits the staggering computational and bookkeeping work loads and provides a means for compressing the time scale by allowing several days' operations to be simulated in a matter of minutes.
Distribution System

Basic aspects of the system analyzed here may be brought into focus by referring to Figure 4, a schematic of a typical open pit truck-shovel operation. A single stage materials handling scheme is employed to transport both ore and waste. Loaded trucks are directed to a crusher or stockpile if ore is being mined, while overburden is conveyed to a waste dump.

Essentially, the model, using a computer, cycles trucks between their assigned shovels and the proper discharge points over measured haulage routes. Required input parameters for model operation include the number of shifts to be simulated, operating time per shift, number and type of operating trucks and shovels, maximum truck acceleration and velocity, a realistic vehicular deceleration rate, and the ratio of ore to total material loaded at each shovel. Equipment performance characteristics, system profile characteristics, and service time distributions are also necessary. Records are kept of all waiting times at loading and dumping points and of any interference on the haul roads, and a current journal of ore and waste production is maintained.

Generating Information

Both full and standard simulation techniques were adopted to generate system component information in the model. By formulating a hybrid model the best features of each technique are combined to produce a unique production simulator. Full or probabilistic simulation is used where system fluctuations due to random behavior are most likely
Figure 4

Schematic of Open Pit Truck-Shovel System Programmed into Mining Simulator
to occur, and standard or deterministic simulation is employed where
the different mechanical capabilities of truck types can cause sig-
nificant variations in production. Loading times, dumping times, and
load weights were regarded as random variables from independent prob-
ability distributions, whereas truck movements were governed by indi-
vidual vehicle performance abilities.

Standard simulation is employed to expedite the testing of any
truck in the system for which the manufacturer's performance curves
are available. As many as fifty trucks of five different types can
be operated simultaneously. Truck movements are consistent with
each vehicle's mechanical capabilities as determined by the manu-
facturer.

Full Simulation

To accurately simulate the operating prototype, data represen-
tative of the actual system were gathered. Empirical information
needed to operate the model includes truck loading and dumping times
and truck load weights. Note that separate distributions must be
defined for each truck size or shovel size-truck size combination.

Various statistical techniques were then employed to analyze
and screen the raw data to obtain useful information. The more
important statistical criteria are discussed below in detail while
comprehensive coverage of the more basic procedures may be found
in several excellent references (Spiegel, 1961; Dixon and Massey,
1957; Miller and Freund, 1965).

Loading and dumping times are random variables that can obviously
affect system productivity considerably. The effect of variable
load weights is more obscure, but truck performance is directly related to gross vehicle weight. Depending upon the nature of the material moved, truck load weights have been known to vary by 25% in either direction from their rated capacities. Most mines operate their trucks near rated capacities, but noticeable weight variations still exist.

Data Presentation. A sampled observation is a chance occurrence of a random variable that ranges over either a discreet or continuous spectrum of values. Sample measurements are vital only as representatives of the parent population. The analyst must examine and manipulate the raw data, applying sound engineering practicality to rationalize anomalous readings and reduce the information to the few descriptive sample statistics necessary to fully describe the actual process. Methods are available for determining the required number of observations to achieve a given level of confidence (Price, 1961) and to evaluate the relevance of extreme values found in the data (Manula, 1963).

Rapid insight into the general form of probability distributions can be gained by constructing a frequency distribution and a histogram. A frequency distribution of the data is formed by dividing the range of readings into classes, usually of equal size, and tallying the sample population of each class. Class width may be arbitrarily chosen, but it is advisable to form from 5 to 20 classes. By grouping the data in this manner, individual measurement identities are lost, but the reduction in information is compensated for by a better visual organization of the data. Additional information about the
data distribution form can be secured by plotting a histogram from the grouped class frequencies. If the random variable being studied can be considered continuous, a frequency polygon, formed by connecting the mid-points of the tops of the histogram rectangles, will approximate the probability density function of the statistic. The general shape of the frequency polygon may suggest a standard probability density function in which case a chi-square goodness of fit test should be conducted.

If empirical data are to be used for the computer Monte Carlo sampling routine, arrays must be defined containing the abscissa and ordinate projections of each discontinuity on the cumulative frequency polygon for each distribution used. If several probability distributions affect system performance, computer data storage capacity may prove insufficient. If, however, the data can be described accurately by a standard probability distribution, only characteristic parameters of the distribution indicating a degree of central tendency such as the mean and a degree of dispersion such as the standard deviation are needed by the computer. Random element times can then be computed directly with an algebraic equation. This not only frees a sizeable block of computer storage for other work, but the number of calculations performed is considerably reduced improving model efficiency and economy.

**Goodness of Fit Test.** When it is desirable to substitute a standard probability distribution for empirical data, the chi-square ($\chi^2$) goodness of fit test is commonly used to statistically evaluate the similarity between the two distributions. This test uses the sample
mean and variance as the best estimates of the population parameters
\( \mu \) and \( \sigma^2 \), so that theoretical class populations, \( e_1, e_2, \ldots, e_k \),
for the standard distribution being tested can be compared with
actual class frequencies, \( o_1, o_2, \ldots, o_k \). The \( \chi^2 \) statistic is then
calculated as follows:

\[
\chi^2 = \sum_{j=1}^{k} \frac{(o_j - e_j)^2}{e_j}
\]

The closer \( \chi^2 \) is to zero, the better the empirical data "fits" the
standard distribution. Values of \( \chi^2 \) for varying degrees of freedom
and different levels of significance are tabulated in most statistics
books. To accept the hypothesis that the observed and theoretical
distributions are the same, the calculated \( \chi^2 \) must be less than the
listed value for the same degrees of freedom and the desired signifi-
cance level.

Degrees of freedom, \( v \), can be found for a given test of \( k \) classes
by:

\[
v = k - 1 - m
\]

where \( m \) is the number of estimated population parameters necessary
for the test. For example, to fit empirical data to the normal dis-
tribution requires the estimation of two parameters, the mean and the
variance. Hence, there would be \( v = k - 3 \) degrees of freedom.

If the computed \( \chi^2 \) statistic is less than \( \chi^2_{.75} \) but greater
than \( \chi^2_{.05} \) for identical degrees of freedom, the empirical data can
be replaced by the standard distribution with little resulting error.
\( \chi^2 \) values less than \( \chi^2_{.05} \) are suspect, for observed data seldom fit
theoretical distributions so well.

Special points of interest in chi-square testing are:

(1) Expected frequencies of all classes must be greater than five, usually requiring the consolidation of several original classes into one.

(2) Should an amalgamation of classes be necessary, a corresponding reduction of degrees of freedom results.

(3) A close fit can often become a good fit by changing class boundaries or class intervals slightly. This is not statistical malpractice, but merely a judicious reorganization of the data.

Programming Distribution Functions. When a good fit was obtained between actual and theoretical measurements only parameters of the standard distribution were needed by the computer to conduct random sampling experiments. However, Monte Carlo sampling is performed on the cumulative distribution function, \( F(x) \), not on the density function, \( f(x) \), where:

\[
F(t) = \int_{-\infty}^{t} f(x) \, dx
\]

Therefore, each program subroutine that uses full simulation contains the relevant integrated form or distribution function for the random variable being sampled. Input parameters then merely define one particular function from a general family of distributions. For example, the integrated form of the exponential density function, \( f(x) = ae^{-ax} \), used to generate truck dumping times, is:

\[
F(t) = \left[ -e^{-ax} \right]_0^t
\]

where the value assigned to "a" defines the particular distribution. Consequently, all random variables governed by the same general dis-
tribution, e.g. exponential, can be randomly sampled via this same program subroutine. Actual random sampling processes are discussed in the next section.

If the empirical data could not have been described with accuracy by a theoretical distribution, a set of statistics fully delineating the observed data would have been furnished to the computer. As Monte Carlo sampling requires the relative cumulative distribution function of the random variable, the corresponding ordinate intercept for each histogram class boundary would be needed to reproduce the necessary distribution function. A linear interpolation between these points could then be easily made by the computer.

**Random Sampling.** Essentially, the problem involved in Monte Carlo sampling is how to relate a random number obeying a uniform distribution to a specific value of the component random variable described by a different distribution. The relative cumulative distribution function for the random variable provides this relationship. By entering the chart at the ordinate intercept of the random number between 0.0 and 1.0, projecting horizontally to the distribution function and then vertically to the abscissa, the value of the random variable is determined. For proof of this random sampling technique, the reader is directed to either Sasieni, Yaspan, and Friedman (1959) or Manula (1963).

This graphical procedure may be interpreted mathematically as determining the upper limit of integration for which the relative area under the density function equals the random number, i.e., the solution of the following equation for $t$: 
\[ F(t) = \int_{-\infty}^{t} f(x) \, dx \]

For illustration, again consider \( f(x) \) to be the exponential distribution describing dumping times

\[ f(x) = ae^{-ax} \]

then

\[ F(t) = [e^{-ax}]_0^t \]

or

\[ F(t) = -e^{-at} + 1, \quad 1 - F(t) = e^{-at} \]

and solving for \( t \)

\[-at = \ln [1 - F(t)]\]

and

\[ t = \frac{-\ln [1 - F(t)]}{a} \]

where \( F(t) \) is the random number between 0.0 and 1.0.

Random sampling a distribution function is fairly simple in concept and is performed rapidly by the computer. To sample the theoretical loading and dumping distributions, population parameters and a random number between 0.0 and 1.0 are placed in the proper distribution function, and the desired value is calculated.

If empirical data are used, the relative cumulative frequency polygon should be interrogated at each class boundary until the class containing the projection of the random number is located. Linear interpolation then can define the value of the random variable.

**Standard Simulation**

Standard simulation is used for only one operation in the model—
the movement of trucks along haul roads. This one application, though, adds considerable power and flexibility to the model by realistically duplicating actual truck performance. Indeed, deterministic simulation is one of the primary concepts that distinguishes this treatise from previous work in the field.

The performance of an automotive vehicle can be calculated by the equation of Newton's Second Law of Motion,

$$\sum F_\theta = ma_\theta$$

In rearranged form it states that the acceleration of a body in any direction, \( \theta \), is directly proportional to the algebraic sum of forces acting upon the body in that direction and inversely proportional to the mass of the body.

If rate of acceleration is constant, rectilinear motion formulae can be reduced to the following familiar relationships:

$$V_1 = V_0 + at$$
$$S_1 = S_0 + V_0 t + \frac{1}{2}at^2$$
$$V_1^2 = V_0^2 + 2aS_1 - 2aS_0$$

where \( V = \) velocity

\( t = \) time

\( S = \) distance

Figure 5 displays typical truck performance curves as supplied by manufacturers of all off-highway haulage trucks. These curves relate vehicle speed and rimpull, or propelling force available at the drive wheels. It is evident that rimpull and, consequently, acceleration vary greatly with vehicle speed so that the constant acceleration
Figure 5

Rimpull vs. Speed Plot for Model 65A Haulpak Haulage Truck (Courtesy LeTourneau-Westinghouse Co.)
equations are seemingly inapplicable. To circumvent this impasse, consider vehicle motion during any short period of time. If the selected period is short enough, acceleration during the period is approximately constant; and constant acceleration formulae are applicable.

This suggests the iterative procedure used in this thesis where, during a short period of time, a constant acceleration is assumed to compute a terminal velocity which, in turn, determines vehicular rimpull from truck performance curves. This rimpull fixes a new acceleration rate for the next incremental time period and the procedure is repeated. Distance traveled is continuously recorded providing current information on the position of the vehicle in the system.

If the haulage road profile remains unchanged, a maximum velocity is soon achieved where the truck has no surplus power for acceleration. When the profile changes, a new set of retarding forces is encountered; and a new acceleration rate, either positive or negative, is computed. The iterative travel process then commences for the new haul road section.

**Required Data.** To operate the standard simulator, two sets of data that must be supplied are:

(a) rimpull produced by each truck type at various vehicle velocities; and

(b) the physical retarding forces identified by the haulage profile.

**Mechanical Capabilities.** To furnish necessary truck performance data to the computer, the vehicles' characteristic curves were first approximated by a piecewise linear function. Two arrays were con-
structured containing the ordinate (rimpull) and abscissa (velocity) projections of the discontinuities in the approximating function. Linear interpolation by the computer then allows a rapid and accurate conversion between speed and rimpull. By establishing arrays for each truck type, every vehicle in the system can be operated realistically.

An alternative method of placing truck performance characteristics in the computer's memory is to fit the performance curves to a standard equation using the method of least squares. If an acceptable fit is attained, only the equation parameters are needed by the computer. The general appearance of most truck performance curves suggests an exponential curve so that a good fit might be readily obtained.

Haulage Profile. Although many resisting forces influence rail haulage operations (Staley, 1949), only two—rolling resistance and grade resistance—are relevant to truck haulage (Euclid, 1952).

1. Rolling resistance - This resisting force includes friction in wheel bearings, tire flexing, and tire penetration into the haul road surface. The value of this force is estimated according to road surface conditions and is usually expressed as a percentage of gross vehicle weight.

2. Grade resistance - Grade resistance is merely gravitational force influencing truck performance on grades. This also is expressed as a percentage and must be prefixed by a plus or minus sign to identify slope direction.

These forces are added algebraically to truck rimpull to obtain the resultant propelling force. A positive value accelerates the truck, and a negative one causes deceleration. Rimpull may vary continuously over a haul road section, but profile resistances are constant for any given section. In fact, constant haul road retardation forces partially de-
fine a haul road section. In the model, three criteria are used to define a haul road section:

(a) changes in rolling resistance and/or grade resistance;
(b) changes in maximum allowable velocity, as might occur at sharp corners; and
(c) intersections.

Travel Constraints. Every mine has peculiar operating conditions and practices that distinguish it from other operations. Vastly different rock types, deposit geometries, production requirements, and even weather conditions contribute to the diverse operating schemes developed in open pit mining. Effort has been made in constructing the simulator to permit the user to quantify pertinent travel constraints which affect production and might vary from mine to mine. Listed below are the constraints that must be defined for the model.

(1) **maximum speed** - Normally, for safety reasons, trucks are not allowed to exceed a certain maximum speed even though they are capable of doing so.

(2) **deceleration** - A deceleration rate, considered constant, is needed to stop trucks.

(3) **maximum acceleration** - Spinning wheels in rapid acceleration is a costly practice and usually is not tolerated by management. The establishment of a maximum acceleration rate is, therefore, advisable.

(4) **maximum downhill speeds** - Safe truck speeds decrease as downhill grades become steeper. For each downhill grade, a maximum allowable speed must be specified.

(5) **maximum cornering speeds** - Sharp corners often occur in real haulage systems forcing reduced truck speeds. If the prototype contains such corners, the model can limit vehicle cornering speed to any desired value.

(6) **type of material** - The simulator will load ore and waste at each shovel in any given ratio. An input ratio value of 0.0 permits only waste production, while a value of 1.0 is used if only ore is loaded.
Computer Program

Simulation of all but the most trivial systems demands the use of a high speed digital computer. Even moderately complex systems can easily exhaust storage capacity in the small computers popular in industry. This situation plagued one of the previous investigators in truck haulage simulation (Madge, 1964) and forced him to make dubious simplifying assumptions.

The truck haulage simulator developed for this study generates an enormous computational and bookkeeping work load that makes machine processing an absolute necessity. A flow diagram for the computer program is shown in Appendix A, and the program procedures are discussed below.

Simulation Procedures. The simulation program consists of four program units—three subroutines and a main program. Bookkeeping, sorting, comparing, and recording vehicle status in addition to standard input-output functions are performed in the main program. One subroutine computes truck loading times and load weights; one determines dumping times; and the third calculates vehicle travel time for a specified haul road segment.

The computer is programmed to execute a series of instructions based on a Gantt chart simulation of the operation. As described previously, the haulage cycle is separated into an operational series of elements through which each vehicle must be processed in a predetermined sequence. A current log of elapsed shift operating time is maintained for each truck, and the unit with the minimum value is selected for movement by assigning a value to its next cycle element. After
incrementing the proper vehicle’s time status and placing it in a new system location, cumulative shift times are again examined; the new minimum value found; and the movement process repeated.

Waiting lines are detected on particular cycle elements by comparing element completion times for the present and preceding trucks. At the loading shovels, the absence of trucks to load is also noted; and shovel waiting time is tabulated for the shift.

Shift production terminates when the elapsed shift time of a truck exceeds a specific input value. Production forecasts for the real world system analyzed in this thesis were based on an operating shift of seven hours.

**Output Information.** Shift operating statistics supplied by the computer that usually suffice for system analysis are:

1. **production** - the number of loads and tons of ore and waste hauled by each truck from each shovel

2. **shovel idle time** - cumulative shift idle time for each shovel

3. **truck wait time** - cumulative shift waiting time for trucks at each shovel

4. **cycle queueing delays** - cumulative truck delay time accrued for each cycle element except loading

If necessary, however, proper manipulation of program output statements can provide the status of each vehicle in the system at any instant for the entire shift.

**Program Execution.** The computer program was written in DAFT, a dialect of basic IBM FORTRAN developed by the Computation Center at The Pennsylvania State University for use with its IBM 7074 computer system. DAFT was developed to reduce compilation time and extend the
Testing the Model

After a simulation model has been structured, it must be tested to determine how accurately it imitates the real world. Normally, the ability of the model to approximately reproduce past operating data serves to evaluate its usefulness. Statistical hypotheses correlating model and prototype output are then tested at a predetermined risk level and the model is either accepted or rejected as an accurate production forecaster.

A vast amount of historical data is usually available for the prototype allowing parametric testing to be employed. Sample (model) production statistics can be compared with population parameters or other sample statistics to determine if there is reason to doubt that the two groups of observations came from the same population. Parametric tests, such as the z, t, and F tests, are widely used and can be studied in depth in nearly any statistics text.

Two substantial problems were encountered when the truck haulage model was tested. These problems and their respective solutions are listed below.

(a) Standard simulation of truck movements generates theoretical maximum production as trucks are operated near the limit of their abilities. Model production will, therefore, be invariably higher than actual production. For testing purposes it was then necessary to modify model production toward reality by making allowances for the
inherent human and conditional work components which cause real world performance to be sub-optimum. A subjective estimate of the combined effects of these components was set at 10 per cent of model production. The credibility of this figure was enhanced by comparing observed and theoretical truck cycle times for a particular haulage route. Measured cycle times were found to average nearly 12.1 minutes, while simulator values were about 10.8 minutes. This difference approximates the above-mentioned 10 per cent, and model production statistics were accordingly reduced by 10 per cent prior to statistical testing.

(b) Owing to the large number of system variables considered by the simulator, it was difficult to find a sufficient number of actual production shifts performed under identical conditions. Consequently, statistical inference based on a rather small sample size with an unknown parent population was necessary. This problem was circumvented by utilizing nonparametric testing methods to prove the model.

Nonparametric Testing. If the form of the parent population is not known, comparisons of sample and universe parameters are impossible; and distribution comparison, or nonparametric testing, must be employed. Recent advances in statistics have resulted in the definition of test statistics that compare distributions without specifying the form of the distributions. One nonparametric relationship, the chi-square goodness of fit test, was discussed previously; several others are described briefly below.

(1) **Sign Test** When two materials or treatments are compared under a variety of test conditions, several sets of paired observations (one for each set of conditions), are generated; and the sign
test can be used to determine if one material or treatment created significantly different results. If $X_i$ and $Y_i$ represent the $i^{th}$ set of measurements of two populations, only the algebraic sign of each difference, e.g., $X_i - Y_i$, is needed for this test. The number of times the less frequent sign occurs and the number of paired readings are used to compare test results to table values to determine if there is reason to doubt the equality of the distributions.

(2) **Runs** Difference signs may again be used here; and the number of runs, or sets of differences having the same sign and occurring in a row, are tabulated. Two identical populations will have neither too few nor too many runs from several randomly selected pairs of readings. The number of runs in a given set of observations is compared to standard values for statistical decision. The theory of runs can be extended to a numerically ordered list of observations from two samples, thereby obviating the computation of differences.

(3) **Rank-Sum Test** If several observations of two or more populations are combined in a single list according to size, each value can be assigned a rank, such as one for the smallest value, two for the second smallest, etc. In the comparison of two populations with both sample sizes, $n_1$ and $n_2$, being greater than eight, the Mann-Whitney $U$ test can be used. If $R_1$ is the sum of ranks of the first sample, the $U$ statistic can be computed as follows:

$$U = n_1 n_2 + \frac{n_1(n_1 + 1)}{2} - R_1$$
where

\[
\mu_u = \frac{n_1 n_2}{2} \quad \text{and} \quad \sigma_u^2 = \frac{n_1 n_2(n_1 + n_2 + 1)}{12}
\]

This statistic is approximately normally distributed so that the test can be based on the familiar z statistic, where

\[
z = \frac{U - \mu_u}{\sigma_u}
\]

Dixon and Massey (1957) discuss a nearly identical test with the T' statistic, and the Kruskal-Wallis H test (Miller and Freund, 1965) is an extension of rank sum testing to multiple sample comparison.

Rank sum tests are among the most powerful nonparametric methods and are only slightly less effective than some parametric tests.

(4) **Median Test** Median testing employs the chi-square distribu-
tion. In the test of two samples, the number of measurements occurring above and below the median of the combined samples is tabulated for both groups. The results can be shown as follows:

<table>
<thead>
<tr>
<th>Sample</th>
<th>Group</th>
<th>Number</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>above median</td>
<td>a</td>
<td>b</td>
<td>a + b</td>
</tr>
<tr>
<td>below median</td>
<td>c</td>
<td>d</td>
<td>c + d</td>
</tr>
<tr>
<td>TOTAL</td>
<td>a + c</td>
<td>b + d</td>
<td>a + b + c + d = N</td>
</tr>
</tbody>
</table>

Only one degree of freedom exists for the 2x2 contingency table so that a continuity correction must be applied during the calculation.
The new formula for $\chi^2$ is:

$$\chi^2 = \frac{(|ad-bc| - \frac{kN}{2})^2 N}{(a+b)(a+c)(b+d)(c+d)}$$

The hypothesis in median testing is the equivalence of parent populations, and the theoretical frequencies for both classes are one-half of each sample size.

Although nonparametric tests are generally simple to perform and are universally applicable whether or not population parameters are known, classical tests must not be discarded from further consideration. If the assumptions can approximately be fulfilled, parametric tests usually require fewer measurements and are more powerful in detecting false hypotheses than nonparametric tests (Dixon and Massey, 1957). If a choice is available, classical parametric tests will usually supply more reliable results. As mentioned previously, however, the scarcity of reliable production data from the real system resulted in small samples necessitating nonparametric testing of the truck haulage model.

Test Results. The simulator was tested with data obtained in the case study described in the following chapter, for that study was the first practical application of the model. Subsequent use of the model will not require retesting unless simulator assumptions apparently violate some fundamental operating practice employed at the mine being studied.

Prototype production statistics available for testing the model consisted of the number of truck loads from both operating shovels for each day in an eight-day period. The simulator was then used to
reproduce each shift's production constraints and compute the potential system output. Each model production statistic was then reduced by 10 per cent to approximate the inefficient human element inherent in actual operations. Figure 6 shows the model results in comparison with actual production.

Test data comprised a series of paired values, one each for the model and the prototype, with each pair resulting from a unique set of operating conditions. In nonparametric testing, the sign test is specifically designed to test the equality of distributions using paired observations obtained under a variety of operating conditions.

After subtracting adjusted model output from prototype production for each pair of values, \( P_i - M_i \) for \( i = 1, 2, \ldots, 8 \), a tally was made of plus and minus signs of calculated differences. Results showed that the less frequent plus signs occurred 3 times. Testing the hypothesis that the plus or minus signs are described by a binomial distribution with \( p = \frac{1}{4} \), a 10 per cent level of significance finds the critical value \( = 1 \). With the sample statistic equal to 3, the hypothesis is accepted. Therefore, after adjusting model production downward by 10 per cent, prototype and model output were judged to be samples from the same parent population.
<table>
<thead>
<tr>
<th>Day</th>
<th>Actual Production</th>
<th>Unadjusted Simulator Output</th>
<th>Sign of Difference Col.2 - Col.3</th>
<th>Col.3 x 0.9</th>
<th>Sign of Difference Col.2 - Col.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>452</td>
<td>581</td>
<td>-</td>
<td>523</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>597</td>
<td>483</td>
<td>+</td>
<td>435</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>497</td>
<td>507</td>
<td>-</td>
<td>457</td>
<td>+</td>
</tr>
<tr>
<td>4</td>
<td>468</td>
<td>679</td>
<td>-</td>
<td>611</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>642</td>
<td>657</td>
<td>-</td>
<td>591</td>
<td>+</td>
</tr>
<tr>
<td>6</td>
<td>550</td>
<td>616</td>
<td>-</td>
<td>554</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>446</td>
<td>503</td>
<td>-</td>
<td>453</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>601</td>
<td>678</td>
<td>-</td>
<td>610</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 6

Production Comparison for Model and Prototype

(Production in Truck Loads)
IV EXPERIMENTAL RESULTS

Ultimate effectiveness of scientific research can be measured only by successful practical applications. Industrial researchers may be particularly aware of the necessity for applied results, but all research must produce practical successes in the final analysis. Operations research analysts in mining must be unusually cognizant of the need to produce results, for O.R. to most mining men is a new, unknown discipline staffed by people speaking a strange technical language. O.R. analysts must be prepared to show tangible results quickly to justify their occupational existence.

Mining Plan

For the truck haulage model under consideration, the author was fortunate to be able to apply the simulator to a medium-sized open pit mine in the eastern United States. The mine operators were studying changes in the haulage system to combat increasing costs and to accommodate greater production. Management was receptive to simulation analysis and assisted greatly in collecting data and production information. Although the capacity of the model allows simulation of much more complex systems, the mine selected was large enough to permit the model to demonstrate its practical value.

The prototype is a typical open pit truck and shovel operation. Five benches are presently being mined with two 6 cubic yard electric shovels and a fleet of 32-ton capacity haulage trucks. The irregular nature of the ore deposit creates continually changing ore-to-waste loading ratios in most mine areas. Maximum haulage grades encountered
are 12% with one way haul distances being about 4,000 feet. A sketch of haul road profiles is shown in Figure 7. Normally, only overburden is mined at shovel location 1, thereby establishing a separate and independent sub-system within the main mining plan.

The particular problem facing management at this operation was the evaluation of new 65 and 75-ton haulage trucks as replacements for the existing units. Although the overall problem had many ramifications, including consideration of projected maintenance costs, the truck haulage simulator was used to compare production potentials of the existing and proposed systems.

Data Collection and Analysis

Three distributions—loading times, dumping times, and load weights—need to be delineated for proper utilization by the simulator. Field measurements were made to help determine most of these relationships for the mine studied. Adverse weather conditions and time limitations restricted the number of observations gathered, but realistic simulation was possible with the data obtained.

Dumping Times. Dumping operations with the 32-ton trucks were observed for both ore and waste production. Forty-four readings were made, the range being 0.56 min. to 1.35 min. Element timing commenced when the truck began backing to dump and ended when the empty truck started its return trip to the shovel. Operating practice requires a dump man to spot each truck, thereby creating a potential queueing situation by not allowing passing in dump areas. A mean, \( \mu = 0.74 \) min., and a standard deviation, \( S = 0.16 \) min., were computed for the sample.
Figure 7

General Layout of Prototype Mining System
The histogram, shown in Appendix C, formed from the sample data suggested an exponential probability distribution. Accordingly, after the ordinate axis was translated by subtracting 0.545 min. from every value so that the lower distribution limit could be considered zero, the sample data were fitted to the exponential curve,

\[ f(x) = ae^{-ax} \]

where

\[ a = \frac{1}{\bar{x}} = \frac{1}{.195} = 5.13 \]

The resulting sample value of the \( \chi^2 \) (df) statistic was:

\[ \chi^2_{s}(2) = 0.12 \]

Compared to table values

\[ \chi^2_{0.05}(2) = .103 < \chi^2_s < \chi^2_{0.75}(2) = 2.77 \]

Thus the exponential distribution provides an excellent approximation of the sample measurements allowing the theoretical distribution to be used for Monte Carlo sampling. Program input information, therefore, consists of only the mean of the translated distribution and the amount of translation.

Although the simulator can accommodate different dumping parameters for each truck type, it was assumed in this case study that dumping time is independent of truck size.

**Loading Times.** Similar data collection and analysis procedures were performed with truck loading times. Fortunately, the real system uses shovels of only one size and normally employs a single truck type. This greatly simplified data collection, for only one loading combination existed. In systems using equipment of several makes and sizes,
A distribution needs to be defined for every truck size-shovel size combination. Although, as will be shown later, statistical reproduction of sample data can be used to determine probability distributions of similar operations; multiple equipment combinations often mean extended periods of tedious time study.

Extensive analysis of loading times uncovered two distinct distributions as shown in Appendix C. One distribution reflects fairly easy digging conditions for the shovel, while the other apparently indicates more difficult conditions. This observation seems logical, as blocky, poorly blasted rock invariably causes increased loading times.

For hard digging conditions, a mean, $\bar{x} = 2.11$ min., and a standard deviation, $S = 0.43$ min., were computed; and the data were fitted to a normal distribution. The resulting $\chi^2$ (df) value, $\chi^2_S(4) = 1.57$, was compared to the following appropriate test values.

\[
\chi^2_{0.05}(4) = 0.711 < \chi^2_S < \chi^2_{0.75}(4) = 5.39
\]

Evidently the normal distribution describes the sample data for loading times under hard digging conditions very well.

A similar analysis with good digging conditions produced less favorable results. A mean, $\bar{x} = 1.60$ min., and a standard deviation, $S = 0.39$ min., were again computed from the measured observations, and the sample data were fitted to a normal distribution. The $\chi^2$ (df) value computed was $\chi^2_S(3) = 8.83$. The following comparison was made to test values:

\[
\chi^2_{0.95}(3) = 7.81 < \chi^2_S < \chi^2_{0.975} = 9.35
\]
This is obviously a poor fit, and further analysis of the data using Price's (1961) sample size indicator showed that an insufficient number of observations (59) had been made for a 95% confidence level.

\[ N = \left( \frac{t \cdot E}{\Phi} \right)^2 = \left[ \frac{1.96 \cdot .39}{.05 \cdot 1.60} \right]^2 = 93 \]

where

- \( N \) = required sample size
- \( t \) = no. of standard deviations required to encompass the desired confidence level
- \( E \) = confidence limits

However, as an underlying normal distribution of loading times is intuitively expected and was partially substantiated in the case of the hard digging conditions, loading times under good conditions were assumed to be normally distributed also.

**Load Weights.** Because of the lack of a rapid, inexpensive method of weighing large off-highway haulage trucks, no actual measurements were made of truck load weights. However, experienced mine employees estimated the average load weight for the 32-ton trucks to be 36 tons, subject to variations of ±4 tons. From this information a normal distribution with \( \mu = 36.0 \) tons, and \( 3\sigma = 4.0 \) tons or \( \sigma = 1.33 \) tons, was judged to be a realistic description of truck payloads.

**Distribution Reproduction.** One of the primary functions of the simulator is to test new equipment prior to purchase to determine its production effectiveness. Operating element time distributions for new equipment are seldom known, but can be reproduced statistically, if distributions are known for similar equipment.

In the particular problem analyzed, management wanted to know the effect on production of replacing the 32-ton haulage units by 65
or 75-ton trucks. Loading time and load weight distributions for these larger units were then derived from known distributions for the 32-ton trucks by increasing the parameters proportionately. A comparison of parameters for the three truck sizes are shown below.

<table>
<thead>
<tr>
<th>Truck</th>
<th>Loading Times</th>
<th>Load Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Easy Digging</td>
<td>Hard Digging</td>
</tr>
<tr>
<td></td>
<td>(minutes)</td>
<td>(minutes)</td>
</tr>
<tr>
<td>32T</td>
<td>1.60 0.15</td>
<td>2.11 0.18</td>
</tr>
<tr>
<td>65T</td>
<td>3.25 0.30</td>
<td>4.28 0.37</td>
</tr>
<tr>
<td>75T</td>
<td>3.74 0.36</td>
<td>4.94 0.44</td>
</tr>
</tbody>
</table>

Similar distributions can be established for other truck sizes and different shovel sizes when necessary.

The simulator is presently designed to accept only exponential dumping times and normally distributed loading times and truck load weights. However, the probability information generated in the program is developed exclusively in subroutines, so that any radical departure from assumed distributions can be accommodated with relatively minor changes to the main program.

Machine Performance. Mechanical capabilities for each truck type were used to accurately simulate vehicle movements. Performance curves for the 65-ton truck shown in Figure 5 are typical of those provided by manufacturers. The piecewise linear approximation programmed into the computer is also shown in that figure.

Haulage Profile. Figure 7 shows the haul road profiles used during simulation. The maximum grade encountered was 12%. All haul roads were in good condition, and a rolling resistance of 2% was
judged to be applicable. One way haul distances averaged 3500 to 4000 feet.

**Travel Constraints.** Operating personnel furnished the following estimations of variables influencing truck haulage operations:

- Maximum allowable velocity = 51.5 fps = 35.0 mph
- Maximum allowable acceleration = 3.67 fps$^2$ = 2.5 mph ps
- Deceleration = -2.94 fps$^2$ = -2.0 mph ps

Maximum allowable downhill speeds were specified as follows:

<table>
<thead>
<tr>
<th>Grade (%)</th>
<th>Speed (fps, mph)</th>
<th>Grade (%)</th>
<th>Speed (fps, mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>51.5, 35.0</td>
<td>-8</td>
<td>27.9, 19.0</td>
</tr>
<tr>
<td>-2</td>
<td>47.0, 32.0</td>
<td>-9</td>
<td>26.5, 18.0</td>
</tr>
<tr>
<td>-3</td>
<td>42.6, 29.0</td>
<td>-10</td>
<td>25.0, 17.0</td>
</tr>
<tr>
<td>-4</td>
<td>38.2, 26.0</td>
<td>-11</td>
<td>23.5, 16.0</td>
</tr>
<tr>
<td>-5</td>
<td>35.3, 24.0</td>
<td>-12</td>
<td>22.1, 15.0</td>
</tr>
<tr>
<td>-6</td>
<td>32.3, 22.0</td>
<td>-13</td>
<td>20.6, 14.0</td>
</tr>
<tr>
<td>-7</td>
<td>29.4, 20.0</td>
<td>-14</td>
<td>19.1, 13.0</td>
</tr>
</tbody>
</table>

Effective shift operating time was estimated to be 7 hours, with lunch break and shift change each accounting for one-half hour of lost production. Additionally, a 45-minute operating hour was assumed, as heavy, blocky ore created poorer than average mining conditions.

Trucks were forced to reduce speeds for safe travel around sharp corners and through dangerous intersections.

It is recognized that other mines operating under different conditions might find an entirely different set of constraints applicable. For this reason, travel constraints are variables that must be quantified by the program user.
Results

A complete analysis of truck haulage needs for the mine is continuing; preliminary results presented here represent initial evaluation information produced when the three truck types were operated under identical conditions.

The same eight-day production period used for model testing was the basis for comparing haulage schemes with the simulator. All truck assignment alternatives were evaluated under three variations of the operating conditions actually recorded for this period. Each set of operating conditions used is outlined below.

(a) All actual operating conditions were duplicated including 85% shovel availability and hard digging conditions, except that 100% truck availability was assumed.

(b) Same as (a), but assuming 100% shovel availability.

(c) Same as (b), with the addition of good loading conditions.

Critical shovel and truck delay time as well as production statistics were inspected for every system simulated.

The five basic truck assignment plans that were evaluated are described briefly below:

Plan I 32-ton trucks Nine (9) 32-ton trucks were used, assigning five to the shovel associated with the longer haulage cycle time. This is the schedule presently favored by management when truck availability permits.

Plan II 65-ton trucks Use four 65-ton trucks assigning two to each shovel.
Plan III  **65-ton trucks** Use six 65-ton trucks assigning three to each shovel.

Plan IV  **75-ton trucks** Use four 75-ton trucks assigning two to each shovel.

Plan V  **75-ton trucks** Use six 75-ton trucks assigning three to each shovel.

Eight-day simulation results for each alternative considered are shown in Figures 8, 9 and 10. Production statistics are daily averages using three shifts of seven 45-minute operating hours each. For convenience, truck and shovel delay figures are shift averages, again based on a shift of seven 45-minute operating hours. In every case, production was maximized by minimizing shovel idle time at the expense of abundant truck delay time.

As the physical system contained only two shovels and a maximum of nine trucks, significant waiting lines occurred only at the shovels. Maximum delay time noted at the waste dump was about 4.0 minutes, certainly not enough to warrant an additional service channel (dump man). Enough haul road delay time was recorded to indicate that the program was functioning properly, but there were no measurable effects on production.

This elimination of travel delay time permitted other equipment assignments to be studied without using the simulation model. For example, systems using five 65 and 75-ton trucks were analyzed by selecting pertinent values from simulation output for both the four and six-truck systems. In a similar manner, the value of having a spare vehicle available when a truck breakdown occurs can be deter-
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tons</td>
<td>Tons</td>
<td>Tons</td>
<td>Tons</td>
<td>Tons</td>
<td>Tons</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>270</td>
<td>9,720</td>
<td>325</td>
<td>11,700</td>
<td>130</td>
<td>9,503</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>235</td>
<td>8,460</td>
<td>313</td>
<td>11,268</td>
<td>101</td>
<td>7,383</td>
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<tr>
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<td>259</td>
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<td>305</td>
<td>10,980</td>
<td>131</td>
<td>9,576</td>
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<tr>
<td>5</td>
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<td>10,836</td>
<td>334</td>
<td>12,024</td>
<td>106</td>
<td>7,749</td>
</tr>
</tbody>
</table>

Figure 8

Daily Production Averages for Each Haulage Alternative

Based on Original Operating Conditions
### DAILY PRODUCTION

<table>
<thead>
<tr>
<th>Shovel Location</th>
<th>Ore-Waste Ratio</th>
<th>Plan I Loads</th>
<th>Tons</th>
<th>Plan II Loads</th>
<th>Tons</th>
<th>Plan III Loads</th>
<th>Tons</th>
<th>Plan IV Loads</th>
<th>Tons</th>
<th>Plan V Loads</th>
<th>Tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0</td>
<td>367</td>
<td>13,212</td>
<td>144</td>
<td>10,526</td>
<td>194</td>
<td>14,181</td>
<td>139</td>
<td>11,704</td>
<td>167</td>
<td>14,061</td>
</tr>
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<td>5</td>
<td>1.0</td>
<td>377</td>
<td>13,572</td>
<td>123</td>
<td>8,991</td>
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<td>165</td>
<td>13,893</td>
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<td>0.0</td>
<td>399</td>
<td>14,364</td>
<td>167</td>
<td>12,208</td>
<td>194</td>
<td>14,181</td>
<td>156</td>
<td>13,135</td>
<td>173</td>
<td>14,567</td>
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<tr>
<td>5</td>
<td>0.0</td>
<td>372</td>
<td>13,392</td>
<td>119</td>
<td>8,580</td>
<td>173</td>
<td>12,646</td>
<td>117</td>
<td>9,851</td>
<td>162</td>
<td>13,640</td>
</tr>
</tbody>
</table>

### SHIFT DELAY TIME (minutes)

<table>
<thead>
<tr>
<th>Shovel Location</th>
<th>Ore-Waste Ratio</th>
<th>Plan I Shovel Truck Delay</th>
<th>Plan I Shovel Truck Delay</th>
<th>Plan II Shovel Truck Delay</th>
<th>Plan II Shovel Truck Delay</th>
<th>Plan III Shovel Truck Delay</th>
<th>Plan III Shovel Truck Delay</th>
<th>Plan IV Shovel Truck Delay</th>
<th>Plan IV Shovel Truck Delay</th>
<th>Plan V Shovel Truck Delay</th>
<th>Plan V Shovel Truck Delay</th>
</tr>
</thead>
<tbody>
<tr>
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<td>62.3</td>
<td>90.4</td>
<td>6.1</td>
<td>0.8</td>
<td>87.6</td>
<td>62.3</td>
<td>6.7</td>
<td>0.0</td>
<td>173.0</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>13.0</td>
<td>131.3</td>
<td>127.0</td>
<td>4.5</td>
<td>28.9</td>
<td>34.7</td>
<td>99.2</td>
<td>4.9</td>
<td>5.0</td>
<td>66.7</td>
</tr>
<tr>
<td>1</td>
<td>0.0</td>
<td>1.0</td>
<td>159.8</td>
<td>50.6</td>
<td>12.5</td>
<td>0.0</td>
<td>198.9</td>
<td>29.8</td>
<td>14.6</td>
<td>0.0</td>
<td>259.9</td>
</tr>
<tr>
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<td>0.0</td>
<td>17.8</td>
<td>70.0</td>
<td>137.9</td>
<td>1.1</td>
<td>35.2</td>
<td>20.3</td>
<td>110.7</td>
<td>2.5</td>
<td>6.2</td>
<td>46.4</td>
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</table>

**Figure 9**

**Average Production Statistics for Each Alternative**

Assuming 100% Shovel Availability and Hard Digging Conditions
### DAILY PRODUCTION

<table>
<thead>
<tr>
<th>Shovel Location</th>
<th>Ore-Waste Ratio</th>
<th>Plan I Loads</th>
<th>Tons</th>
<th>Plan II Loads</th>
<th>Tons</th>
<th>Plan III Loads</th>
<th>Tons</th>
<th>Plan IV Loads</th>
<th>Tons</th>
<th>Plan V Loads</th>
<th>Tons</th>
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<td>197</td>
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<tr>
<th>Shovel Location</th>
<th>Ore-Waste Ratio</th>
<th>Plan I Shovel Truck Delay</th>
<th>Tons</th>
<th>Plan II Shovel Truck Delay</th>
<th>Tons</th>
<th>Plan III Shovel Truck Delay</th>
<th>Tons</th>
<th>Plan IV Shovel Truck Delay</th>
<th>Tons</th>
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<tr>
<td>2</td>
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<td>32.0</td>
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<th>Tons</th>
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<th>Tons</th>
<th>Plan IV Shovel Truck Delay</th>
<th>Tons</th>
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<td>12.0</td>
<td>149.1</td>
<td>2.4</td>
<td>56.0</td>
<td>16.7</td>
</tr>
</tbody>
</table>

Figure 10

Average Production Statistics for Each Alternative

Assuming 100% Shovel Availability and Easy Digging Conditions
mined for the five or six-truck systems. Such an interpolation would not be valid for more complex mining systems where significant travel interference develops on haul roads.

The daily production goal in the actual mining system is approximately 25,000 tons of ore and waste. Haulage truck availability for the eight-day test period was unusually low causing actual production to fall far short of this target. However, further examination of the six 75-ton truck system which yielded practically no shovel delay time revealed that, with hard digging conditions and an 85% shovel availability, current shovel loading capacity is insufficient to maintain the desired production regardless of the number of haulage units used. Therefore, loading rather than haulage is the limiting production factor under certain conditions.

The utilization of a third loading shovel as a spare would create, in effect, a system with 100% shovel availability allowing alternative haulage systems to be appraised with information from Figure 9. Under these operating conditions, neither four-truck system can maintain the required 25,000 tpd production. In both cases, output from shovel location 5 is insufficient, as shovel delay time becomes excessive. Considering the larger units only, either six 65-ton or five 75-ton trucks are needed to supply adequate haulage capacity for all mining situations.

If, however, blasting operations provide good loading conditions, the statistics in Figure 10 are applicable. Again, the four 65-ton truck system is unable to transport the necessary tonnage; and the four 75-ton truck fleet is marginal. Further examination of the
latter system shows sufficient haulage capacity if two upper mine benches are worked but inadequate capacity to maintain 25,000 tpd when two lower levels, e.g., locations 4 and 5, are mined. Also permanently favorable loading conditions is an idealized situation never fully achieved in practice. Therefore, either five 65-ton or five 75-ton vehicles are needed to sustain the specified production level for all mining locations under these operating conditions.

**Recommendations**

Recommended operational changes and truck fleet size to maintain the 25,000 tpd production level are listed below.

1. Particular effort should be directed to the establishment of good loading conditions to improve any system's production potential.

2. The activation of a spare loading shovel to supplement production when a primary shovel breaks down would again improve the production capabilities of any system by achieving, in effect, greater shovel availability.

3. Given sufficient shovel loading capacity by employing (1), (2), or both of the above practices, either five 75-ton or six 65-ton trucks are needed to insure adequate output from all mining locations. The final decision in favor of either alternative would be influenced greatly by initial costs, operating costs, and reserve haulage capacities of each system.
Remarks

The mining configurations analyzed in the previous section represent only two of several possibilities. However, the shovel locations used depict extreme conditions, with loading area 5 associated with the longest haulage route; and locations 1 and 2, with the shortest cycle times. The most pessimistic case, working locations 4 and 5, can be approximated by considering two shovels mining at location 5. If adequate loading and haulage capacity exists for this hypothetical system, desired production can then be maintained for any actual mining configuration.

An interesting phenomenon was noticed while operating the standard simulator with a 32-ton truck on a 15% grade using a 3-second time increment. At low velocities, automotive vehicles exhibit steeply sloping performance curves; and available rimpull is quite sensitive to small changes in vehicle speed. Consequently, erratic truck behavior was recorded as the constant acceleration assumption proved invalid for a three-second interval on the steeply sloping portion of the performance curve. Although a two-second time increment smoothed out the speed oscillations somewhat, a constant velocity on the 15% grade was achieved only after reducing the time element to one second. This phenomenon is of more than academic interest, as total travel time for the haulage element was changed by several tenths of a minute when the time increment was varied. In future applications of the simulator, truck performance on steep grades should be scrutinized closely, for extended operation on the steeply sloping portion of the truck performance curve may produce erroneous
cycle times.

Economic justification of new haulage units in any mine depends to a large extent on how well matched truck cycle times and shovel loading times are. Naturally, the ideal situation is found when truck cycle times are approximately an even multiple of shovel loading times, thereby minimizing both truck and shovel loading delays. Small and medium-sized mines seldom employ large loading shovels and, due to the resulting lengthy loading times, are particularly vulnerable to truck-shovel mismatches when large haulage units are used. Consequently, management is often faced with the dilemma where a given number of trucks cannot sustain the necessary production, but the addition of one more truck creates excessive truck delay time. To enable operators of small and intermediate-sized mines to benefit from reduced costs and increased productivity of large haulage trucks when economic truck-shovel pairings cannot be attained, either of two methods may be feasible. For multiple shovel systems, these methods achieve, in effect, the assignment of fractional parts of a truck to individual shovels. A brief discussion of each method is presented below.

**Vehicle dispatching.** Some mines have installed truck dispatching systems where a central dispatcher directs empty trucks via two-way radio to the shovel with the smallest work backlog. Unfortunately, the dispatcher is forced to make many hurried judgments which too often result in little improvement over the basic assignment scheduling technique.
Gaming methods. In this method, one or several truck drivers are instructed to follow a particular loading sequence where they will service more than one shovel in a designated ratio. Alert drivers are necessary here to maintain the specified loading order. Gaming methods will create unique distributions of shovel and truck delay times that can only be analyzed by simulation.
Additional Applications

A production system simulator often appreciates in value with use for two reasons. First, familiarity with the model allows the user to manipulate and modify its internal formulae to solve a broad range of problems; and second, new uses for the simulator crop up unexpectedly from unsuspected sources.

Although the truck haulage simulator discussed here was developed primarily to assign equipment optimally in an open pit mine, three related problems of current interest to the mining industry are amenable to solution by the model. These problems, listed below, are attractive future applications for the model.

1. Haul Road Construction. For years, mine operators have studied the problem of minimizing truck cycle times by altering haul road grades. Although the current trend is toward short, steep grades and long, level hauls (Shilling, et al, 1966), the truck haulage simulator can be used to determine the best haulage route profile for a given mine.

2. Load Weights. A complete spectrum of opinions exists on the best load weight for a truck. The cause of these varied views is the reduction in performance with increased load weights which obscures the most productive alternative. The simulator can be used to determine the best load weight for a given truck type on a given haulage profile such that maximum productivity is achieved. Naturally, excessive maintenance costs sustained on grossly overloaded vehicles
will place an upper limit on any recommended load weight in management's final decision.

3. **Haul Road Maintenance.** It is common knowledge that reduced tire damage and increased production results from improved haul road maintenance. The simulator can evaluate quantitatively the effects on production by altering the rolling resistance of haul roads, thereby producing useful information to justify expenditures for better road maintenance.

**Future Refinements**

During formulation and application of this mining simulator, a number of refinements to the model and areas of further study became evident. Model modifications which appear advisable are listed below:

1. **Reduced Computer Execution Time.** The program execution time is disappointingly long, indicating that the program should be examined to minimize computational inefficiencies. New larger and faster computers will reduce machine processing costs, thereby attracting more potential users.

2. **Passing on Haul Roads.** A routine could easily be added to the main program to allow faster vehicles to overtake slower ones. Normally, however, haul roads are too narrow to permit passing.

3. **Other Considerations.** Future investigators in truck haulage simulation may find it advantageous to incorporate some of the following ideas into their models:

   (a) Rather than forming a piecewise linear approximation of the truck performance curves, fitting the data to an exponential curve might prove beneficial. This would be particularly desirable if com-
puter memory capacity is critical, for linear approximated curves require large arrays in storage.

(b) If extensive maintenance records are available for the operation, random breakdown generators for trucks and shovels may be feasible. An extension of this routine could reassign trucks to the remaining operating shovels if a shovel failure occurs.

(c) Mines located in severe climates may wish to make suitable adjustments for extreme weather conditions.

Future Research

Mine management's objective is to minimize total plant cost per unit of finished product. In addition to mining costs, concentration and occasionally smelting and refining affect total plant expense, suggesting that an analytical model of the entire mining enterprise would be extremely valuable. The formulation of such a model could begin by employing the truck haulage simulator to control actual mining operations and to help evaluate concentrator crusher, surge bin, and belt conveyor capacities. Integrated systems simulators open broad new horizons for scientific decision making. Future research efforts in this direction would be well-advised.

Summary

Because of its innate simplicity and ready applicability, systems simulation is the most engineering oriented operations research technique. Simulation continues to be a leader in bridging the gap between theory and practice in a profession where the gap remains regrettably wide. Sophisticated O.R. models allowing direct mathematical optimization are usually highly specialized and seldom are adaptable to
general industrial usage, leaving only systems simulation to solve the problem. Simulation can be used to analyze very complex systems by using certain testing criteria which act as the counterpart to scale model testing in physical research and design.

Although simulation has been widely acclaimed, there is obviously a need for a basic educational program, for few practicing engineers know how simulation can be applied. This is indeed unfortunate, as the unique methodology of simulation offers a tremendous advantage to the engineer who needs to solve a large variety of complex industrial and design problems. More specifically, the mining engineer is offered an effective means to plan and forecast long range objectives, to compare and evaluate capital investment alternatives, and to solve the many queueing and storage problems found in mining operations.

Many mining companies have remained suspicious of operations research methods because of the traditional conservatism of mine management and also because of aloof and uncommunicative O.R. analysts. Simulation, however, is easily understood, removing much of the mystery that O.R. methods hold for laymen. Where management may be unreceptive to rigorous mathematical models, the practicality and comprehensibility of systems simulation make this method more attractive to managers.

Simulation models can be written in a variety of ways to study the same general problem. There are, however, certain concepts adopted in developing a simulator which are determined by problem characteristics. Probabilistic simulation is used when the system populace exhibit random behavior in causing complex delay and storage
phenomena in parallel or series networks. If the limiting variables or constraint equation coefficients are known with certainty, deterministic simulation is preferred. Here the problem is not to maximize a system's effectiveness from a series of possible results, but to compute directly the outcome from a given set of quantified variables.

In this thesis, the truck haulage problem dictated the need for both general model types in order to modify the simulator towards realism. The resulting model is capable of evaluating equipment assignment or purchase alternatives for complex truck and shovel open pit mining systems by computing the productivities of the various plans. A case study proved the value of the simulator, as a problem in limited shovel loading capacity was uncovered at the mine under study. Also, two truck models were evaluated with the simulator; and management was advised of the necessary fleet size and operating changes required to achieve production goals.

Although other problem areas in mining, where mechanized processes are affected by uncontrolled random elements, may be likewise suited to hybrid simulation, the final choice of a simulation model is controlled by economic considerations. While the most desirable highly refined model can seldom be financially justified in industry, certain requirements cannot be compromised. Oversimplified inexpensive models often produce unreliable information which could result in disastrous management decisions. The key to appropriate operations research expenditures lies not only in the potential savings of the projects but also in the recognition of minimum outlays necessary for producing valid results regardless of projected savings.
BIBLIOGRAPHY


BIBLIOGRAPHY


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COMPUTER PROGRAM FLOW DIAGRAM

START
READ DATA

INITIALIZE SHIFT PRODUCTION COUNTERS

LOAD ALL TRUCKS

DETERMINE ELAPSED SHIFT TIME (TM) FOR EACH TRUCK

LOCATE MINIMUM TM

IS TRUCK TRAVEL ELEMENT NEXT

YES

IS TRUCK LOADING ELEMENT NEXT

NO

GENERATE DUMP TIME

DID DUMPING DELAY OCCUR

NO

DETERMINE TYPE MATERIAL DUMPED

COUNT ONE LOAD ORE OR WASTE

COMPUTE NEW TM

WAS TRUCK DELAYED ON HAUL ROAD

NO

DETERMINE NEW VEHICLE POSITION

LOCATE MINIMUM TM

NO

IS SHIFT COMPLETE

YES

PRINT SHIFT PRODUCTION AND DELAY STATISTICS

IS RUN COMPLETE

NO

STOP

NO

DETERMINE MATERIAL TYPE

YES

DID SHOVEL WAIT FOR TRUCK

YES

CUMULATE SHOVEL IDLE TIME

NO

DID TRUCK WAIT FOR SHOVEL

YES

CUMULATE TRUCK LOADING DELAY TIME

NO

CUMULATE TRUCK DUMPING DELAY TIME

GENERATE LOAD TIME

GENERATE LOAD WEIGHT

DETERMINE NEW TM AND VEHICLE VELOCITY

CUMULATE TRUCK DELAY TIME FOR GIVEN SECTION
BEGIN MULTIPLE DECK COMPILE

DIMENSION TWA(5),SWAT(5),DECISION(10),CATCH(5,10),LOAD(5,10),GRADE(10),
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      TWAIN,LOADS,AXIS,LOADS,AXIS,LOADS,AXIS,LOADS,AXIS,LOADS,
Definition of Program Input Controls

System Size

N₁ - - - - - - - - - - - - - number of shovels in system
N₂ - - - - - - - - - - - - - number of different truck types in system
N₃ - - - - - - - - - - - - - number of different shovel types in system
JSHIFT - - - - - - - - - - number of shifts to be simulated
NN (I) - - - - - - - - - number of trucks assigned to Ith shovel
KINDT (I,J) - - - - - - - truck type of Jth truck from Ith shovel
KINDS (I) - - - - - - - shovel type of Ith shovel

Truck Performance

SPEED (I,J) - - - - - - - velocity in fps associated with Jth point on performance curves of Ith truck type
RP (I,J) - - - - - - - rimpull in lbs. associated with Jth point on performance curves of Ith truck
GVW (I) - - - - - - - empty vehicle weight in tons of Ith truck type

Haul Road Profile

SECTION (I,J) - - - - - - - number of haul road sections traversed with Ith material type (waste or ore) from the Jth shovel
NUMBER (I,J,K) - - - - - - - number of elements in Kth haul road section hauling Ith material (waste or ore) from the Jth shovel
GRADE (I,J,K,L) - - - - - - - grade in per cent of the Lth element on Kth haul road section hauling Ith material from Jth shovel
RORI (I,J,K,L) - - - - - - - rolling resistance in per cent of Lth element on Kth haul road section hauling Ith material from Jth shovel
DIST (I,J,K,L) - - - - - - - length in feet of Lth element on Kth haul road section hauling Ith material from Jth shovel
CURVE (I,J,K,L) - - - - - - - maximum allowable speed in fps at end of Lth element on Kth haul road section hauling Ith material from Jth shovel
Production Constraints

RATIO (I) - - - - - - - - - - - - ratio of ore to total material mined by Ith shovel
ACCELMAX- - - - - - - - - - - - maximum allowable truck acceleration in fps\(^2\)
VELMAX- - - - - - - - - - - - - - - maximum allowable truck velocity in fps
DECEL - - - - - - - - - - - - rate of truck deceleration in fps\(^2\), must be negative
DIG (I) - - - - - - - - - - - - digging conditions of Ith shovel
DNHILL (I)- - - - - - - - - - - - maximum allowable downhill truck velocity in fps on a grade of \(-I\) per cent

Probability Distribution Parameters

XBAR (I,J,K)- - - - - - - - - - - - mean of loading time in minutes for Ith digging conditions with Jth shovel type and Kth truck type
SIGMA (I,J,K) - - - - - - - - - - - - standard deviation for loading time in minutes for Ith digging conditions with Jth shovel type and Kth truck type
WTLOAD (I)- - - - - - - - - - - - mean of load weight in tons for Ith truck type
WONSIG (I)- - - - - - - - - - - - standard deviation of load weight in tons for Ith truck type
DMPMEAN (I) - - - - - - - - - - - - mean of dumping time in minutes after axis shift for Ith truck type
AXIS (I)- - - - - - - - - - - - amount in minutes of vertical axis shift for dumping times for Ith truck type


### Frequency Distribution

For Tyre Loading (300 Brakes)

<table>
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<th>Class Marks</th>
<th>Frequency</th>
</tr>
</thead>
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<td>1.25 min.</td>
<td>6</td>
</tr>
<tr>
<td>1.25</td>
<td>5</td>
</tr>
<tr>
<td>1.35</td>
<td>3</td>
</tr>
<tr>
<td>1.75</td>
<td>1</td>
</tr>
<tr>
<td>1.95</td>
<td>2</td>
</tr>
<tr>
<td>2.15</td>
<td>2</td>
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</tr>
<tr>
<td>2.75</td>
<td>0</td>
</tr>
<tr>
<td>2.95</td>
<td>1</td>
</tr>
</tbody>
</table>

Sample Size = 30
Mean = 1.69 min.
Standard Deviation = 0.38
Table 1

Frequency Distribution and Histogram
for Truck Loading Times - Easy Digging Conditions

<table>
<thead>
<tr>
<th>Class Mark</th>
<th>Frequency</th>
<th>Relative Frequency</th>
<th>Cumulative Relative Frequency</th>
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<tbody>
<tr>
<td>1.15 min.</td>
<td>8</td>
<td>.1356</td>
<td>.1356</td>
</tr>
<tr>
<td>1.35</td>
<td>16</td>
<td>.2712</td>
<td>.4068</td>
</tr>
<tr>
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<td>15</td>
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<td>.8645</td>
</tr>
<tr>
<td>2.15</td>
<td>4</td>
<td>.0678</td>
<td>.9323</td>
</tr>
<tr>
<td>2.35</td>
<td>2</td>
<td>.0339</td>
<td>.9662</td>
</tr>
<tr>
<td>2.55</td>
<td>1</td>
<td>.0170</td>
<td>.9832</td>
</tr>
<tr>
<td>2.75</td>
<td>0</td>
<td>.0000</td>
<td>.9832</td>
</tr>
<tr>
<td>2.95</td>
<td>1</td>
<td>.0170</td>
<td>1.0002</td>
</tr>
</tbody>
</table>

Sample Size = 59
Mean = 1.60 min.
Standard Deviation = 0.39

EQUIPMENT: 6 yd.³ shovel and 32-ton Trucks
Table 2

Frequency Distribution and Histogram

for Truck Loading Times - Hard Digging Conditions

<table>
<thead>
<tr>
<th>Class Mark</th>
<th>Frequency</th>
<th>Relative Frequency</th>
<th>Cumulative Relative Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.15 min.</td>
<td>1</td>
<td>.0172</td>
<td>.0172</td>
</tr>
<tr>
<td>1.35</td>
<td>1</td>
<td>.0172</td>
<td>.0344</td>
</tr>
<tr>
<td>1.55</td>
<td>7</td>
<td>.1207</td>
<td>.1551</td>
</tr>
<tr>
<td>1.75</td>
<td>8</td>
<td>.1379</td>
<td>.2930</td>
</tr>
<tr>
<td>1.95</td>
<td>11</td>
<td>.1896</td>
<td>.4826</td>
</tr>
<tr>
<td>2.15</td>
<td>9</td>
<td>.1552</td>
<td>.6378</td>
</tr>
<tr>
<td>2.35</td>
<td>7</td>
<td>.1207</td>
<td>.7585</td>
</tr>
<tr>
<td>2.55</td>
<td>6</td>
<td>.1034</td>
<td>.8619</td>
</tr>
<tr>
<td>2.75</td>
<td>5</td>
<td>.0862</td>
<td>.9481</td>
</tr>
<tr>
<td>2.95</td>
<td>2</td>
<td>.0345</td>
<td>.9826</td>
</tr>
<tr>
<td>3.15</td>
<td>1</td>
<td>.0172</td>
<td>.9998</td>
</tr>
</tbody>
</table>

Sample Size = 58
Mean = 2.11 min.
Standard Deviation = 0.43 min.
Table 3
Frequency Distribution and Histogram for Truck Dumping Times

EQUIPMENT: 32-ton Trucks

<table>
<thead>
<tr>
<th>Class Mark</th>
<th>Frequency</th>
<th>Relative Frequency</th>
<th>Cumulative Relative Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.645</td>
<td>27</td>
<td>.6137</td>
<td>.6137</td>
</tr>
<tr>
<td>0.845</td>
<td>11</td>
<td>.2500</td>
<td>.8637</td>
</tr>
<tr>
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<td>4</td>
<td>.0909</td>
<td>.9546</td>
</tr>
<tr>
<td>1.245</td>
<td>1</td>
<td>.0227</td>
<td>.9773</td>
</tr>
<tr>
<td>1.445</td>
<td>1</td>
<td>.0227</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

Sample Size = 44
Mean = 0.74 min.
Standard Deviation = 0.16 min.