OPEN PIT MINE DISPATCHING:

A SIMULATION STUDY

by

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A Thesis Submitted to the Faculty of the

DEPARTMENT OF SYSTEMS ENGINEERING

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

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ACKNOWLEDGMENTS

I would like to thank Dr. Robert L. Baker for his advice and guidance in the development of this thesis, and to thank Drs. A. Wayne Wymore and Jerry L. Sanders for their suggestions and for serving on my committee.

I would also like to thank Mrs. J. L. Cude for her capable assistance and for the final typing of this manuscript.

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ABSTRACT

This study explores the feasibility of continuously reassigning or "dispatching" trucks to shovels in an open pit mine. A typical model for a truck-shovel haulage system is defined. The various configurations of the model incorporated 2, 4, and 6 shovels. Digital computer simulation is used to determine the effect of dispatching. It is found that, in general, dispatching does increase mine production to some extent. However, each mine should be evaluated for its specific conditions before a definite decision is made.

CHAPTER 1

INTRODUCTION

Open pit or surface mining has become increasingly prevalent in recent years. The decline in grade and quantity of crude ores, combined with the increased demand for more mineral commodities, has forced the mineral industry to increase vastly the amount of material handled. Because of this need, the trend has been toward open pit mining where economies of size and increased mechanization may be realized. The effect of this trend is particularly noticeable in Southern Arizona with its large open pit copper mines.

Eighty-two percent of all metallic and nonmetallic ores and coal was mined from the surface in the United States in 1964 (Allsman 1968). A recent government report (U. S. Bureau of Mines 1970) indicates that the demand of domestic resources is expected to increase at 3.4 to 5.5% per year.

The Role of Trucks

The emphasis toward surface mining was also enhanced by the introduction of large off-highway trucks for haulage. Prior to 1955, most material from surface mines was hauled by rail. This technique required slight grades, electric and rail lines, and switching stations. In 1955, the acceptance of truck haulage became apparent (Allsman 1968). Trucks can negotiate grades ten to fifteen times as steep as rail lines and require little peripheral equipment.

For many years the increase in productivity of trucks kept pace with the needs of open pit mining (Allsman 1968). Today, trucks with a carrying capacity of 240 tons are operating (White 1972). This is approximately eight times the size of earlier truck haulage units and more than double the size of the rail cars previously used. Nevertheless, there is some question as to whether or not these large vehicles have enough capability for the tremendous amounts of overburden that must be removed at some mines (Kress 1971).

Although the size of the trucks and shovels has increased, the operating and management techniques in the mines have changed little. This thesis will explore a means of obtaining increased production from a truck fleet in an open pit mine.

Problem Definition

The basic characteristics of the haul roads for open pit mines are presented schematically in Figure 1. Generally, there are at least two dump locations for receiving waste and ore. The ore is dumped at a crusher which pulverizes the ore before further processing. It is not uncommon for the haul roads to merge between the dumps and the shovels. This area is usually near the top of the pit and is called a "throat." Passing is frequently allowed on the uphill portion of a haul road.

The standard practice in truck shovel systems is for mine managers to assign a portion of the truck fleet to a particular shovel. These trucks will then return to this shovel throughout the duration of the operating shift. For maximum production, a shovel should operate continuously. While the shovel is loading one truck, the other trucks

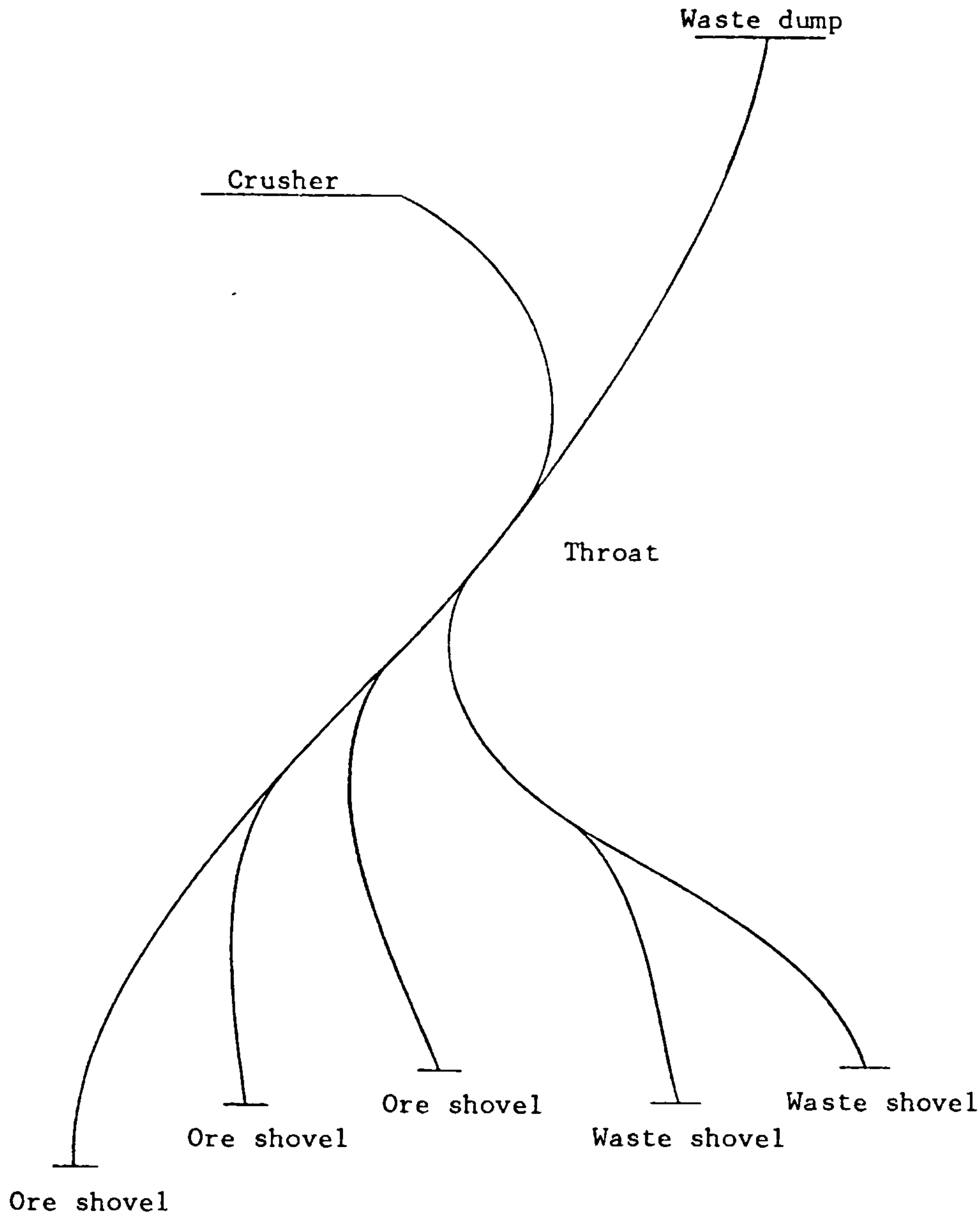


Figure 1. Schematic of haul roads.

are traveling to and from the dump location. Because the trucks are a major item of expense, the system seldom contains enough trucks to achieve maximum production.

Inefficiencies occur because the trucks and shovels do not operate at constant production rates. Variation in the load and travel times is to be expected. The interactions of the trucks on the roads, at the intersections, and at the dumps also has a disturbing effect.

Moreover, the operations of both trucks and shovels are interrupted for maintenance and servicing. Shovels are required to move to a new location every few hours. Unpredicted breakdowns may occur. Under present operating policies, it is not uncommon to observe several trucks waiting in line at an inoperative shovel while a neighborhing shovel has been idle for several minutes due to a lack of trucks.

Such observations are disturbing to mine management, but there is little that can be done if the trucks must arbitrarily return to the same shovel throughout the shift.

This thesis explores the concept of continuously dispatching the trucks to the shovels. As each truck returns from the dump, the current status of the mine is observed and the truck is sent to the most appropriate shovel at that moment. One question that immediately arises is the definition of "most appropriate." This is not obvious. Several dispatching schemes will be explored later in this thesis.

The dispatching of trucks may seem of benefit when the procedure is initially suggested. Further thought reveals that this might not be so. If one shovel is idle while a second shovel has trucks waiting in line while it is repaired, it might seem reasonable to reassign the trucks to the idle shovel. However, this merely saturates the second shovel with trucks and most of these will remain idle for a period of time. Further, when the first shovel is repaired, it will then have to wait for trucks. It is sufficient to say that the problem needs more than a cursory analysis.

Previous Efforts

The term "dispatching" does not have a standard definition within the mineral industry. For some mines it implies production scheduling which is the plan of ore removal over several months of time. In effect, this would be the reassigning of trucks to shovels on a weekly or monthly basis. Other mines suggest reassigning the trucks every several hours or on a shift basis (Korski 1969). It is sometimes mentioned in casual conversation that some mines have implemented dispatching but that it has not met with success. The lack of a common definition for the word probably explains some of the failures.

Dr. Lucien Duckstein (1968) presented a theoretical paper showing the mathematical framework that could be used in the analysis of traffic flow in an open pit mine. Due to the difficulty of this approach, simplifying assumptions were made. No failure of equipment was allowed and only two shovels were incorporated. Discrete load and travel distributions were utilized.

On the basis of this analysis, it was reported that dispatching would reduce the range of variation in arrivals at the shovel. The effect of a breakdown was expected to be less severe. No attempt was made to quantify the effect of dispatching.

Cross and Williamson (1969) presented the results of a case study. By using simulation they determined that in the mine evaluated, increased production could be obtained by using dispatching. They concluded that at this particular mine more production could be obtained with dispatching using one less truck than could be obtained without dispatching using a greater number of trucks. However, this paper did not discuss the specific technique of dispatching to be used.

The only other reference that utilizes dispatching was published by Deshmukh (1970). After determining a reasonable number of trucks for a nondispatched operation, simulation was used to determine the optimum number of trucks for use with dispatching. In this model he sends trucks to the next idle shovel or to the shovel which has been idle the longest. With a shovel availability of 95%, Deshmukh reports that a slight reduction in unit operating cost may be achieved by using dispatching.

Problem Approach

A study of the techniques and corresponding effects of dispatching is needed. This thesis will determine the expected performance of example mines under conditions of no dispatching. These results will then be compared to the performance achieved with various dispatching criteria.

Digital computer simulation was used to predict the production of mine operations. Simulation should not be used in the analysis of a problem if more realistic or more precise techniques are available. A real system can only be imitated by a simulation model. Some critical aspects could be missed in such a procedure. If possible, the real system should be used as an integral part of the analysis.

If a mathematical solution to a problem exists, an exact answer will be produced. Simulation is a statistical technique which relies on the composite results of a large number of samples. This means that the answers obtained from simulation are not as precise, although accuracy will increase as the expected number of samples increases.

In this truck-shovel system, various types of dispatching could be implemented in the mine but the expense would be prohibitive. The interactions of the mine components make it difficult to model a mine by mathematical means.

The components of the system are not independent and any action on one element has a definite effect on the others. Intuition in such a situation is often unreliable and not enough experience has been gained in actual situations that the knowledge may be extrapolated.

Thus, digital computer simulation is an appropriate tool for use on the truck-shovel problem. Simulation is in essence a technique for conducting experiments on a model of a real system. Several models of truck-shovel systems are developed in this thesis. Simulation is then used to produce the experimental data necessary to evaluate the different operating policies of the mines.

CHAPTER 2

DESCRIPTION OF THE MODEL

The technique of simulation involves defining a system in terms of its components and the rules governing interactions among the components. This set of rules and components is called the model of the system. In this model, the components are the trucks and shovels. The rules govern operations at the dumps, shovels, and on the roads.

The components of the system have characteristics or "attributes" associated with them. For the trucks and shovels, some of the necessary attributes are the number of loads hauled, the amount of idle time, and the current operating status.

The type of simulation used for this thesis is called Next Event Simulation. An event is defined as any operation that changes at least one attribute of at least one component. Since the state of the system is defined by its components and their attributes, this is equivalent to saying that an event changes the state of the system.

The Clock

The remaining item necessary in a simulation model is the clock. The events in the simulation occur at different points on the simulated time scale. The clock advances over the time scale and establishes the sequence of events.

Two decisions must be made with respect to the clock: One, by what increment does the clock advance over the simulated time scale; and two, what is the smallest unit of time that will be considered.

In Next Event Simulation, no concern is given to the model between changes of state. The only points that are of interest are those at which an event occurs. The clock is advanced from one event time to the next, regardless of the amount of the time between events. That is, the simulated clock is advanced on an event-by-event basis. This procedure gives Next Event Simulation its name.

Utilizing this technique means that the increment of advance on the simulated time scale is irregular. If three events occur at times 108, 109, and 129, the clock would be incremented by one time unit after the first event, and by twenty units after the second event.

In this type of simulation, time is often measured with the maximum accuracy available in the computer. However, too many digits may be difficult to interpret and this practice also introduces some programming difficulties. For these reasons, an integer time scale was established for this model. The smallest possible increment of time is one second.

A function of the clock was earlier defined as establishing the sequence of events. In addition to keeping track of the simulated time, the clock determines which event is to occur. This does not mean that the times of all events in the simulation are predetermined. When some particular event occurs, it has the possibility of generating new events. This technique is sometimes referred to as "bootstrapping" (Gordon 1969).

For example, the event of a load completion may be simulated. Two new events are then created. A new event of the truck arriving at an intersection is established, and the event of a shovel ready to load is created. The old event is "forgotten." When the clock advances to a new event time, this event will in turn generate another new event.

The open pit mine model may now be defined by the events of the model. Events may occur at the intersections, the dump, the shovel, and the dispatcher. The technique of starting and stopping the simulation must also be defined. Chapter 3 presents a discussion of the mine configurations that were studied and describes the parameters of the model.

Intersection Events

Some provision must be made to allow for the trucks to yield to one another at an intersection. In traveling to an intersection, one loaded truck may pass another on a dual lane haul road. This is particularly possible if one truck is of a different type. Empty trucks must yield to loaded trucks at an intersection. Generally, empty trucks are restricted to single lane haul roads and cannot pass. Tailgating is not allowed. When merging at an intersection, trucks in the left lane have priority.

To model these criteria in a manner that exactly imitates real life is too complicated for the benefit gained. Therefore, the intersection model was simplified.

Empty trucks must travel to an intersection in the order of their departure for that intersection. The trucks are separated by a spacing factor from the previous arrival. Delays encountered by empty trucks yielding at intersections are ignored. This has an insignificant effect on the total travel time because of the rapid acceleration of an empty truck on a downhill slope.

For loaded trucks, the trucks leaving an intersection must be separated by a spacing factor. The order of the trucks departure is determined by their arrival times. One truck may pass another by leaving a departure point after some truck, but arriving at the next intersection ahead of it. This analysis also applies to the merging of trucks at an intersection.

When an intersection event is processed, an event specifying the arrival of the truck at the next location is created.

Dump Event

There are at least three types of dumps with somewhat different characteristics at a surface mine. The simplest is a waste dump where the truck backs up and empties the load. This may be done at any point along a stretch of the dump and no delays are encountered from other trucks.

A stockpile dump is similar except that more accurate placing of the load is usually desired. A small queue may form and delay some of the trucks.

When a truck is dumping ore at a crusher, the load must be precisely placed at the crusher bin. The crusher must be clear before dumping proceeds. Crushers are frequently designed to receive ore from two sides. In either case, queues may form due to a crusher delay. If such a situation occurs, the decision to form a small stockpile may be made.

In this truck-shovel model, a crusher dump with a stockpile was modeled. Delays corresponding to an inoperative crusher or a brief difficulty with the truck will be encountered. The occurrence of these delays is assumed to be uniformly distributed throughout the day.

At the time of the dump event, the simulation checks to see if the operational status of the truck was changed during its haul cycle. If the truck has an attribute indicating a need for maintenance, it dumps the load and is sent for repairs before returning to service. This assumes that the breakdown of one truck does not directly affect the operation of others by causing a road obstruction. Such breakdowns might occur for electrical problems, low tires, or the need for fuel.

After the dump event is completed, the event of the truck arriving at the dispatcher is generated.

Truck Loading Event

A truck has to be backed into position for loading when it arrives at the shovel. This is called "spotting." The truck should be spotted just as the shovel has completed one-half of its load swing and is ready for discharge. If either operation is delayed, idle time will result for the truck or the shovel.

A shovel only loads one truck at a time but it can load from two sides. While one truck is being loaded, the next truck may arrive and be spotted without waiting for the departure of the earlier truck. A truck may exit the shovel immediately after the discharge of the last shovel load. The truck does not have to wait for the shovel to complete its return swing.

After a truck has been loaded, it is sent to the next intersection on the return to the dump. At this time, the operational status of the shovel is checked to determine if a breakdown has occurred. If so, no more trucks are loaded until after repairs are completed. Any trucks traveling to this shovel or waiting at it will accumulate idle time. Shovel breakdown might occur for repair of cables or bucket teeth, electrical difficulties, or movement to a new location.

Dispatching Event

The dispatcher is located between the dump and the shovels. In defining the criteria by which the dispatcher would assign the trucks to the shovels, it was felt that the model should be capable of being readily implemented by human control, by a small process control type of computer, or by a combination of both.

No Dispatching

If no dispatching was to be used, the truck continued to the shovel assigned to it at the start of the shift.

Simple Counter

The first dispatching technique to be modeled was the most elementary. This procedure utilized a counter for each shovel that specified the number of trucks that were at the shovel or traveling to it.

When a truck arrived at the dispatcher, it was sent to the shovel with the smallest counter value. In the event of a tie, the truck was dispatched to the shovel with the lowest counter and the longest expected travel time.

This technique will be referred to as Type I dispatching or as the "Simple Counter" model.

Maximize Trucks, Maximize Shovels

Two additional types of dispatching were implemented. One method was to determine where a truck could probably be loaded next and assign it to this shovel. The other method was to determine which shovel would probably be idle next or had been idle the longest. The truck was then dispatched to this location. These techniques will be called "Maximize Trucks" and "Maximize Shovels," respectively. They may also be referred to as Type II and Type III dispatching.

The difference in these two techniques involves the travel time. The next idle shovel may not be the same as the earliest expected load location because of a longer travel time to the idle shovel. Both techniques must take into account the percent completion of the truck being loaded, the travel times to the shovels, and the expected completion time of any previous trucks sent to that shovel.

For example, shovel A may be ready to load at a time of 100 units while shovel B may not be ready until a time of 120. Assume that the current time is 90 and that the travel time from the dispatcher to shovel A is 40 units, while to shovel B it is 30 units. Then the next idle shovel is A, but the location where it is expected that the truck can be loaded earliest is shovel B.

In all types of dispatching, no trucks were sent to a shovel that was down for repairs or maintenance.

Predicted Maintenance Option

The need for services may be predicted in advance for many breakdowns. This is particularly true for such items as movement of the shovels and fueling of the trucks. Therefore, an additional criterion was modeled for use with the dispatching methods.

Before dispatching a truck to a shovel, the shovel status was interrogated to determine if the shovel would begin repairs within the next five minutes. In real life, this corresponds to checking the operation of the shovel or communicating with the shovel operator. If the shovel was scheduled for maintenance, no truck was dispatched to that particular shovel. Any trucks previously assigned to that shovel that were still empty had to be loaded before the shovel ceased operation.

Further, whenever a truck was at the dispatch location, the operational status of the truck was checked. If it was expected that the truck would need service within twenty minutes of the start of shovel maintenance, the truck was not dispatched to the shovel but was sent to the repair shops.

This technique will be referred to as the "Predicted Maintenance Option." Many mines currently utilize such an option--with or without dispatchers--by attempting to schedule all such maintenance for the lunch hours.

Start and End of a Shift

A truck begins a shift at the dump and travels to the dispatching location. It then advances to the shovel arbitrarily assigned to it or is dispatched to a shovel. Idle times are not accumulated for the trucks or shovels until after the first truck at the shovel has been loaded.

A truck terminates hauling when it is expected that it cannot leave the dispatching point, receive its load, and return to the dump before the end of the shift.

Computer Program

Programming this model is straightforward if the concept of Next Event Simulation is understood. Corresponding to each event there is a subroutine that changes the appropriate attributes. The attributes of the components are available to all subroutines in the program. A clock or monitor routine advances the clock from event to event and calls the proper subroutine in sequence.

The computer program for the truck-shovel model described here is listed in the Appendix. This was compiled and executed on a CDC 6400 computer at The University of Arizona Computer Center.

CHAPTER 3

THE CHOICE OF PARAMETERS

A model for a truck-shovel haulage system in an open pit mine was developed in the previous chapter. If this model is to be implemented the parameters of the model must be defined.

Unfortunately, there is no way in which this may be done so that the mine model becomes generally applicable. Basic differences such as the number and type of shovels, the make-up of the truck fleet, the length of the haul roads, and the number of dumps exist between mines. In fact, most mines have several types of shovels and at least two types of trucks. More subtle differences in operating policies aid in making the definition of a general mine impossible.

In this model, the parameters are defined so that a reasonable--although somewhat simplified--mine model is developed. Some of the results may be extrapolated to other situations. However, it appears that each mine is sufficiently unique to warrant a customized definition of the parameters if more specific results are needed.

Load and Travel Time Variates

Distributions for This Model

A truck loading is essentially a repetitious production process and as such could have a normal distribution (Gordon 1969, p. 114). However, the distribution for truck loadings cannot yield values below some minimum because of the physical limitations of the equipment.

The distribution must be truncated to the left of the mean to ensure that this minimum value is not exceeded.

A truck loading can take an indefinite amount of time. But once the duration of the loading has exceeded some limit, the process has in fact entered a new distribution of delay and breakdown times. Thus, the loading distribution should be truncated on the right.

A similar argument may be applied to the distribution of travel times. This distribution should be bell-shaped about the mean. It must be truncated on the side of low values because of the speed limits of the trucks. A truck will not require an extremely large travel time unless it is delayed or broken. Breakdowns should be considered independent of the travel times.

In this thesis, a truncated normal distribution will be used for the load and travel times.

The technique of sampling from a truncated normal distribution does raise one question. The mean of the samples from the truncated distribution will be different from the original mean unless the truncations are symmetric about the mean. In the load and travel time distributions, the left truncation will be closer to the mean than the right. This will increase the mean value of the samples.

If it is felt that the difference is critical, a transformed mean may be defined such that the truncated distribution will yield a mean corresponding to the mean desired (Johnson and Leone 1964, Vol. I, pp. 126-129).

In a simulation model, any theoretical, empirical, or imaginable distribution may be readily implemented. The most appropriate distribution should be chosen. If the precision suggested by the above paragraph is needed and if the empirical distribution is available, it would be better and easier to implement the empirical distribution.

Distributions from Other Models

For the distribution of load and travel times Deshmukh (1970) and Douglas (1971) used the log-normal curve. This is something of a standard practice in mathematical mine modeling. There is little doubt that empirical data that included delays and down times could be made to fit this theoretical distribution. However, the log-normal is appropriate for a variate that is the result of the product of independent variates (Hahn and Shapiro 1967, p. 100). This is apparently not the case for either load times or travel times.

Some of the models using the log-normal distribution apparently sample from this distribution to obtain the entire travel time for a truck without respect to the other trucks. This is invalid. The travel times are not independent.

The slowing down of one truck will delay all trucks immediately following unless passing is allowed. The trucks must be processed sequentially on an individual basis. In the model for this thesis, the possible travel time is determined independently of other trucks. The effect of the other trucks is then determined. If the truck should be delayed, the appropriate amount of time is added to the travel time to obtain the true time. This results in an occasional build-up of truck convoys on the return from the dump. This possibility has been confirmed by Schneider (1971) and from personal observation.

Rychkun (1971) rejects the log-normal distribution in his simulation study. For the load distribution he used empirical data. The variation in travel times about a mean was determined from a step function that approximated a truncated normal.

Shovel Parameters

Loading Times

Loading times for different types of shovels and for various trucks may vary from a low of 1.5 min to a high of 6 to 8 min. Most modern equipment is designed to load a truck in four cycles of the shovel. Each cycle has a duration of approximately one-half minute.

The model used in this thesis will generate random variates for load times from a truncated normal distribution. The mean load time is 2.0 min with a standard deviation of 0.30 min. The distribution is truncated at 1.0 deviation to the left and at 3.0 deviations to the right of the mean.

This is consistent with the load times reported by Schneider (1971), Rychkun (1971), Deshmukh (1970), and Cross and Williamson (1969).

Down Times

Each shovel will break down twice a day. The length of the times is determined from an exponential distribution with a mean of 22 min.

The frequency of down times and the duration is established by the above references with the exception of Rychkun (1971) who did not have data available on the duration of shovel down times.

Truck Parameters

Dump Times

The operation of dumping a load has very little variation if no delay is encountered. The dump time was therefore constant at 1.0 min (Schneider 1971). Delays at the dump were incorporated separately.

Spotting Time

This is defined as a constant of 40 sec. This value was determined from the survey by Schneider (1971).

Tailgating Distance

Each truck must remain separated from the previous truck by a time duration of 10 sec. This is double the factor used by Cross and Williamson (1969). At 20 miles per hour, this corresponds to 29.4 feet or approximately one truck length.

This is not unreasonable as the trucks often travel close together. Loaded trucks traveling uphill have no difficulty in stopping in a short distance. Empty trucks traveling downhill can brake easily.

Truck Delays at the Dump

The delays that a truck may encounter at a dump are limited to two per truck per shift. The delays are assumed to be uniformly distributed throughout the shift. The duration of the delays is determined from an exponential distribution with a mean of 3.0 min. This corresponds to approximately 10% of the total loads which was reported by Schneider (1971).

Truck Down Times

The length of time for truck maintenance is difficult to generalize. Some mines attempt to perform all maintenance during the lunch hour. Others have rapid fueling stations next to the roads. Probably the most common practice is the location of the maintenance yard at some distance from the haul roads.

Pastika (1972) reports a fueling time of 8 min by using roadside service. The Cross and Williamson study (1969) indicates that 30 min is possible.

In the present model the service or down times will be exponentially distributed with a mean of 22 min. This includes all travel time to and from the maintenance yard. The down times are uniformly distributed throughout the day.

Travel Times

The mean travel times are given in Table 1 and refer to the locations labeled in Figure 2. Individual travel times will be determined from a truncated normal distribution. The standard deviation is 15% of the mean value. The distribution is truncated at 1.0 deviations to the left and at 4.0 deviations to the right.

Table 1. Mean travel times.

Point to point	Empty (minutes)	Loaded (minutes)
Dump - Dispatcher	1.5	-
Dispatcher - I14	1.0	-
I14 - I13	0.1	0.3
I13 - I12	0.1	0.3
I12 - I11	0.1	0.3
I11 - I10	0.1	0.3
I10 - SA	1.1	2.8
I10 - SB	1.0	2.5
I11 - SC	1.0	2.5
I12 - SD	1.0	2.5
I13 - SE	1.0	2.5
I14 - SF	1.0	2.5
I14 - DUMP	-	4.0

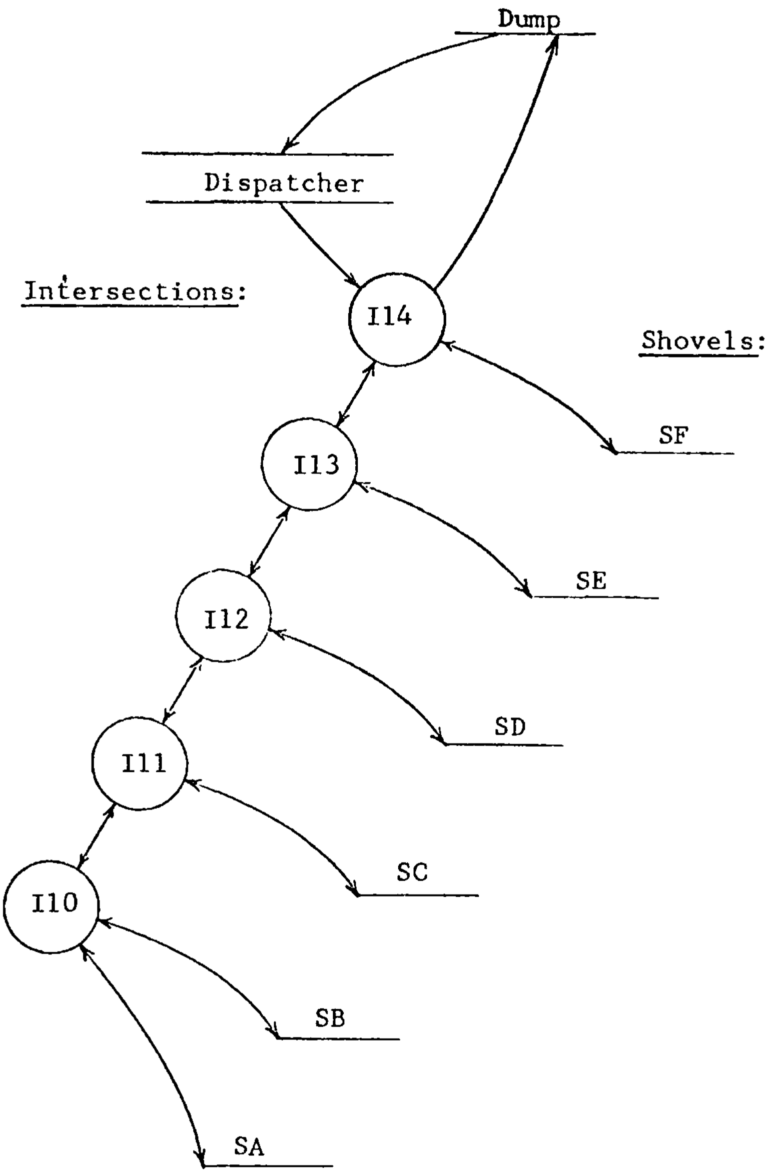


Figure 2. Schematic of general mine models.

Duration of Shift

The mines operate on a 24-hr basis of 3 shifts of 8 hr each. Lunch periods are 30 min long. The duration of a shift is established as 7.5 hr for this model.

Mine Configuration

Most mines have haul cycles of between 10 and 20 min in duration. The number of trucks assigned to a shovel under ideal conditions may be calculated by the following equation:

$$\frac{\text{travel time} + \text{dump time} + \text{load time}}{\text{load time}} \tag{1}$$

Ideal conditions assume that there is no variation in the load and travel times and that the trucks and shovels never break down. This is never the case, but this equation is used as a general guide by the mines because it is felt that the discrepancies cancel each other out.

A haul cycle is a complete round trip for a truck that starts at some point, receives a load, dumps it, and returns to the starting point. The travel time is the time that a truck spends traveling on the roadways, either empty or loaded. The total time elapsed from the time a truck leaves a shovel until it returns to the same shovel is simply the dump time plus the travel time. The number of other trucks loaded at the shovel during this period is the elapsed time divided by the load time. Therefore, the total number of trucks assigned to the shovel is this number plus 1 for the truck that just returned. This is expressed by equation (1).

It is important to establish haul routes so that neither the dispatched nor the nondispatched operations have a definite advantage. This might be the case if each shovel required an additional one-half truck unit. The dispatcher could possibly exchange one truck between the shovels.

If the difference in travel times between two shovels is greater than the load time, the more distant shovel should have an additional truck or trucks assigned to it. The nondispatching model and the Simple Counter dispatching model would have to incorporate these additional trucks.

To make the model in this thesis easier to implement, the total difference in travel times between two shovels is 0.4 min. In the 6-shovel model, the difference between the near and far shovels is exactly 2.0 min or the expected duration of one load. If the trucks are arbitrarily assigned, all shovels will initially receive the same number of trucks. Any trucks left over are assigned consecutively, beginning with the shovels with the longer travel times.

Figure 2 and Table 1 present the general mine configuration. Case studies utilizing 2, 4, and 6 shovels were evaluated. The 2-shovel models incorporated shovels SB and SE with intersection 14. The 4-shovel configurations used shovels SB, SC, SD, and SE and the intersections between them. The entire schematic diagram shown in Figure 1 represents the 6-shovel model.

The results of the simulation runs are presented and discussed in the next chapter.

Reduction of Variation

To test the effects of dispatching under similar conditions, some of the variation in the model was identical for all shifts. In particular, the operation of the shovels was controlled.

Each shovel broke down twice during a shift. These down times were arbitrarily established so that two shovels would not be down simultaneously. The durations of the breakdowns were chosen at random but were the same for all shifts.

Each shift for a particular model was numbered consecutively. If two shifts under different models had the same number, then their sequences of load times were identical. That is, shift 1 of a non-dispatched model corresponded exactly to shift 1 of any dispatched model as far as the sequence of load times was concerned. Each shovel of each shift had a unique sequence of values.

In a manner similar to the shovel breakdowns, the truck breakdowns were controlled. The breakdown times and durations were established at random but were identical for all shifts.

This procedure helps to isolate the variation in the different models and reduces the number of runs. This is analogical to attempting to perform an experiment under identical conditions to reduce the residual variation. Differences can be detected with a much smaller sample size than would otherwise be required.

The production from 4 shifts was averaged to obtain each data point for the results presented in the next chapter. Specific examples from the 4-shovel configuration have shown that approximately 50 shifts would be required to obtain the same level of accuracy if the load and down times were allowed to vary. The means of the 50-shift runs with variation were within one standard error of estimate of the 4-shift runs.

CHAPTER 4

DISCUSSION OF RESULTS

A shovel is called "undertrucked" if it does not have enough trucks assigned to it. A system that is approaching saturation with trucks is called "overtrucked." Using the steady state equation for a reference, the 2-, 4-, and 6-shovel configurations were evaluated with a range of trucks extending from an undertrucked to an overtrucked environment. All types of dispatchers were considered. Four shifts were averaged to obtain each data point.

Analysis of Data

The frustration of trying to analyze simulation results makes one realize why simulation is often called a "tool of last resort" (Ockene 1970). Because the system simulated is usually complex and many of the distributions and parameters are unknown, advanced statistical techniques must be used. For example, in this truck-shovel model the distribution of loads hauled is unknown as is the real mean and variance of the distribution. It is to be expected that the shape of the distribution is dependent upon the number of trucks, the number of shovels, and the type of dispatching. There is no reason to expect that there is any consistency from one model to another.

Reitman (1971, pp. 361-362) describes the difficulty of analyzing simulation results:

> Simulation is a tool used after the analytical approaches have been abandoned. Therefore, statistical techniques which would have been valid for more conventional problems cannot automatically be transferred into the area of complex system design. . . . Under these circumstances the general rule for the designers of complex systems is to rely heavily on comparative results between alternative designs rather than on absolute results. . . . It appears better to err on the side of less statistical support for conclusions than to claim statistical inference which cannot be supported.

The data from the simulation study in this thesis will be analyzed by subjectively comparing the production of the various models. In this manner, insight and experience relating to the real situation may be gained. If this analysis was to be performed for a specific mine, then more extensive runs would have to be made to ensure greater accuracy and to perform statistical tests (see Procedure for Statistical Analysis section at the end of this chapter).

Simulation results can often be checked against field data but even this is most difficult in this problem. If the arbitrary constraint of all shifts working under identical conditions is released, it requires many runs to obtain accuracy in the sample values. This number of runs cannot be compared to a real mine because the mine is constantly undergoing a change in configuration. It is also affected by the additional factors of weather, day or night operations, and ore requirements.

The distribution of loads hauled does not appear to be normal. It terminates relatively near the mean on the right-hand side but is strongly skewed to the left or toward an occasional value that is much lower than the mean.

To help gain a feel for the dispersion of the data, the standard error of the mean for each data point has been calculated. This is defined as:

$$\sqrt{\frac{\text{variance}}{N}}$$

where

$$\text{variance} = \sum(x_i - u)^2/N,$$

x_i = the observation,

u = the mean,

N = the sample size.

General Results

Tables 2 through 5 give the output of the simulation runs. Figures 3, 4, and 5 show graphs of parts of the tables. The points on the plots are connected by straight line segments to aid in identification. A smooth curve does not pass through the points since the addition of a truck is not necessarily consistent from point to point.

Figure 3 illustrates production curves from the two shovel configuration. As is to be expected, the production increases steadily for all curves until the system becomes overtrucked. Production then begins to level off. When the shovels are operating at full capacity, no additional production may be gained regardless of the number of trucks.

Figure 4 presents some of the results from the 4-shovel model. Use of equation (1) for the assignment of the trucks revealed that the far shovel required 7.63 trucks while the near shovel required 7.03

Table 2. Production with two shovels.

Number of trucks	No dispatch	Dispatch without predicted maintenance			Dispatch with predicted maintenance		
		I	II	III	I	II	III
11	256.3	270.5	268.0	268.8	272.7	272.5	272.5
	(1.8)[a]	(1.9)	(1.6)	(1.2)	(1.8)	(1.3)	(1.3)
12	274.7	286.0	287.5	286.5	288.7	292.5	291.7
	(1.9)	(1.2)	(0.6)	(0.6)	(2.0)	(1.5)	(0.7)
13	293.5	302.7	302.7	304.0	305.5	309.0	309.7
	(1.5)	(2.4)	(0.4)	(0.9)	(2.2)	(1.2)	(1.6)
14	315.0	318.0	320.2	322.0	320.7	327.5	328.2
	(1.5)	(0.7)	(0.6)	(1.1)	(1.8)	(0.9)	(1.2)
15	329.5	326.2	335.5	334.7	333.0	342.0	341.5
	(1.1)	(1.0)	(1.3)	(2.3)	(1.7)	(0.8)	(1.9)
16	337.2	327.5	336.2	336.7	331.3	343.0	343.2
	(1.4)	(1.4)	(2.1)	(1.1)	(1.8)	(1.7)	(1.4)
17	345.2	327.0	344.7	343.0	335.5	351.0	349.5
	(1.3)	(2.6)	(2.7)	(1.5)	(1.5)	(1.5)	(0.8)
18	346.5	334.0	339.0	340.0	338.2	348.0	348.5
	(2.9)	(0.9)	(1.4)	(1.5)	(1.8)	(0.9)	(2.0)

a. Numbers in parentheses designate standard error of mean.

Table 3. Production with four shovels.

Number of trucks	No dispatch	Dispatch without predicted maintenance I	II	III	Dispatch with predicted maintenance I	II	III
26	546.5	568.5	581.5	582.5	570.7	589.0	592.5
	(2.7)[a]	(2.5)	(1.8)	(3.1)	(2.6)	(1.5)	(2.4)
27	550.7	568.0	583.5	586.5	578.0	594.5	598.7
	(2.1)	(0.8)	(3.8)	(4.7)	(1.1)	(3.6)	(4.4)
28	566.5	582.0	600.2	599.2	598.0	608.7	614.2
	(2.8)	(1.8)	(2.6)	(0.4)	(2.7)	(1.7)	(1.5)
29	581.3	596.0	618.0	611.0	606.3	625.0	620.7
	(1.1)	(4.6)	(1.6)	(1.1)	(2.7)	(4.7)	(2.2)
30	591.7	603.0	615.5	616.7	606.7	632.7	630.2
	(1.7)	(1.5)	(3.7)	(1.6)	(2.5)	(3.2)	(3.2)
31	604.5	614.2	629.0	630.5	623.5	643.5	640.2
	(1.7)	(3.1)	(2.8)	(2.3)	(2.0)	(3.5)	(3.8)
32	612.7	625.0	639.2	640.5	635.7	653.0	648.0
	(1.9)	(2.9)	(1.6)	(3.2)	(1.8)	(2.0)	(2.1)
33	626.7	637.2	647.2	648.7	643.0	664.2	662.2
	(1.1)	(1.9)	(2.3)	(1.3)	(3.7)	(2.8)	(1.4)

a. Numbers in parentheses designate standard error or mean.

Table 4. Four-shovel model with additional trucks.

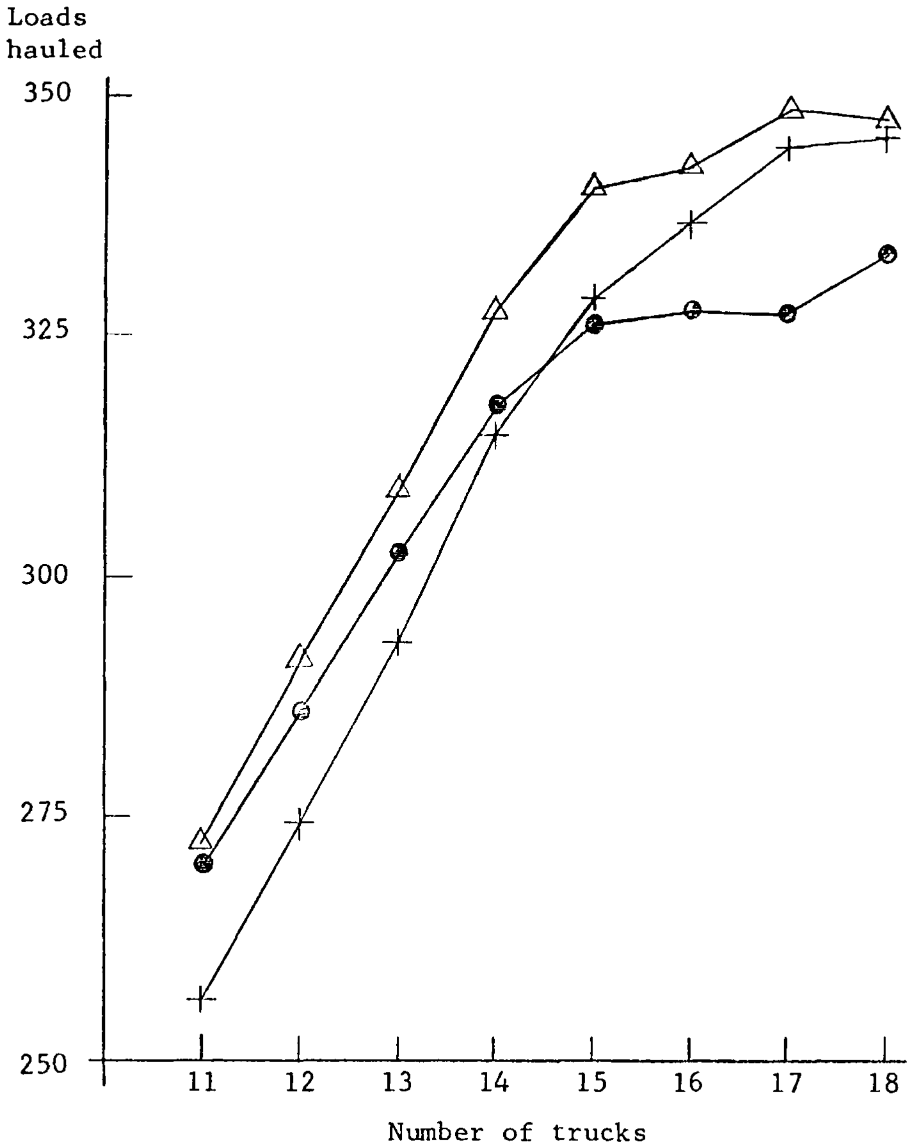
Number of trucks	No dispatch	Dispatch without predicted maintenance I	Dispatch with predicted maintenance II	Dispatch with predicted maintenance III
42	695.0 (1.1)[a]	685.5 (4.3)	718.2 (1.6)	722.2 (2.3)
43	702.5 (1.6)	687.0 (2.8)	725.5 (1.1)	727.2 (2.2)
44	707.2 (1.6)	696.0 (2.0)	730.2 (1.1)	728.0 (0.9)
45	713.2 (0.7)	695.2 (3.4)	731.7 (1.3)	730.7 (1.2)
46	715.2 (1.6)	697.5 (4.2)	732.2 (1.8)	732.2 (1.6)
47	718.0 (2.4)	703.2 (2.3)	732.7 (2.0)	733.0 (2.4)
48	721.7 (0.6)	709.0 (1.7)	734.5 (1.3)	734.5 (1.1)
49	726.2 (1.6)	713.0 (3.2)	733.0 (2.1)	734.0 (0.9)
50	726.7 (1.7)	711.2 (4.4)	734.2 (1.7)	734.5 (1.4)
51	729.0 (1.7)	724.2 (1.6)	733.5 (1.0)	733.7 (1.7)
52	733.0 (1.5)	718.0 (3.4)	734.0 (1.5)	734.2 (1.0)

a. Numbers in parentheses designate standard error of mean.

Table 5. Production with six shovels.

Number of trucks	No dispatch	Dispatch without predicted maintenance			Dispatch with predicted maintenance		
		I	II	III	I	II	III
39	812.5	843.8	862.0	860.7	845.7	868.2	862.0
	(1.6)[a]	(4.6)	(2.7)	(4.4)	(1.6)	(2.3)	(5.1)
41	834.7	872.5	899.2	896.5	883.5	900.0	899.7
	(1.1)	(3.3)	(2.7)	(3.3)	(4.3)	(4.4)	(2.4)
43	854.7	903.0	911.2	910.7	908.7	914.0	914.2
	(3.0)	(2.4)	(1.7)	(1.5)	(2.4)	(2.6)	(3.8)
45	888.7	924.7	935.5	937.2	937.5	945.7	949.2
	(4.3)	(1.7)	(4.1)	(3.4)	(4.7)	(4.3)	(5.7)
47	908.5	937.2	962.0	961.5	954.2	963.0	967.0
	(3.1)	(5.6)	(3.0)	(2.3)	(6.6)	(3.6)	(3.4)
49	932.2	961.7	977.2	986.0	967.7	989.7	989.7
	(1.5)	(5.1)	(1.7)	(3.7)	(4.2)	(3.2)	(4.3)
51	959.7	973.2	999.2	1001.0	987.0	1012.5	1012.5
	(4.1)	(1.9)	(2.1)	(5.4)	(2.5)	(3.1)	(4.2)

a. Numbers in parentheses designate standard error of mean.



Key: + = No dispatching
O = Simple counter (Type I) without predicted maintenance
Δ = Maximize trucks (Type III) with predicted maintenance

Figure 3. Production with two shovels.

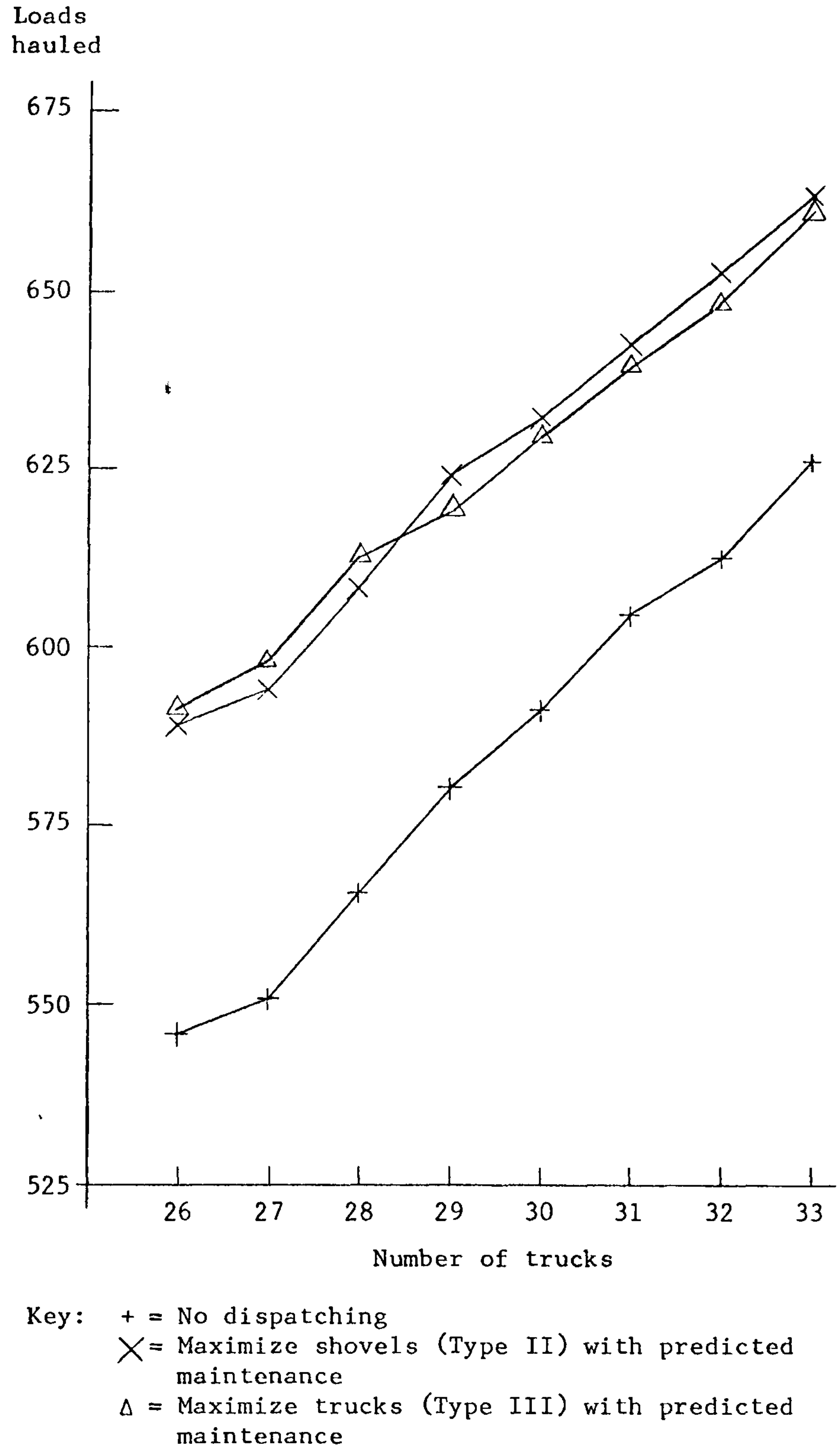
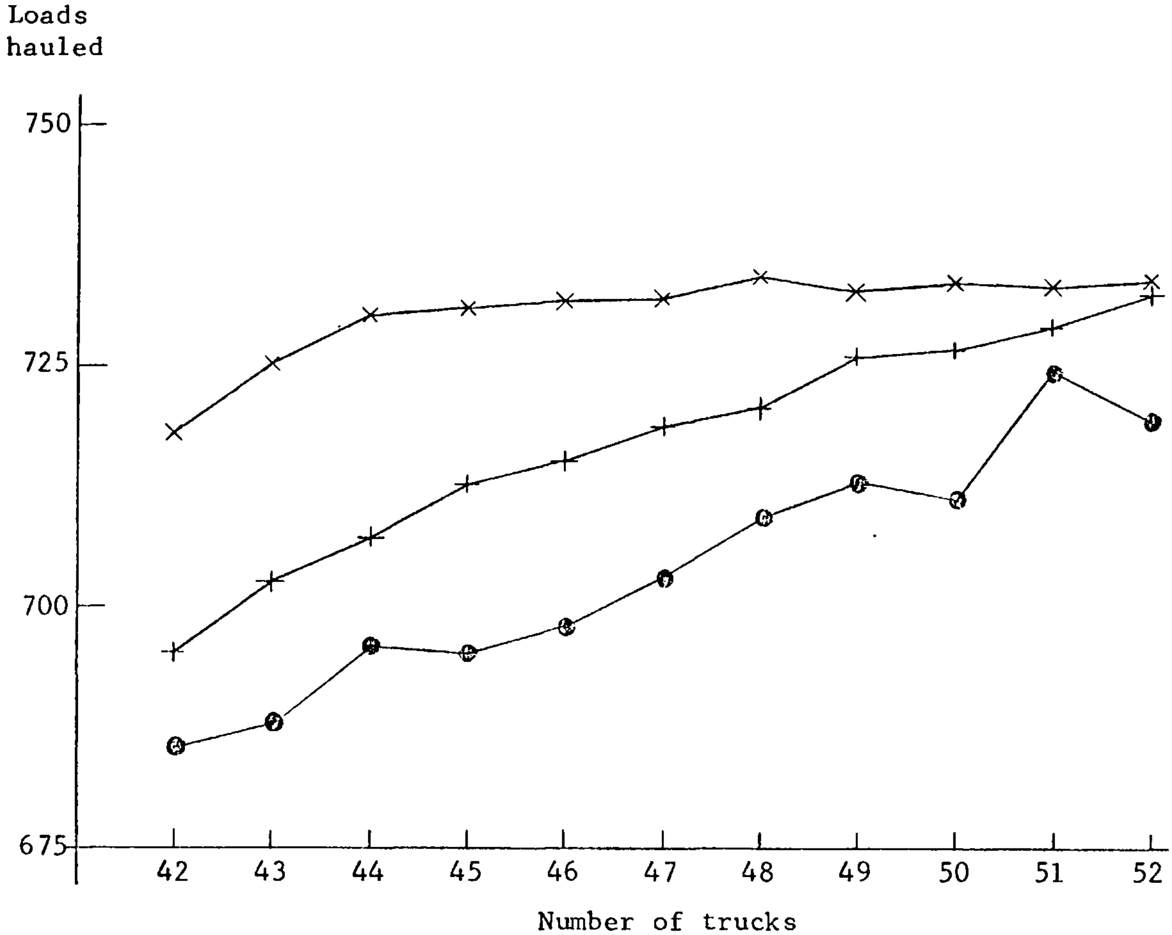


Figure 4. Production with four shovels.



Key: + = No dispatching
O = Simple counter (Type I) without predicted maintenance
X = Maximize shovels (Type II) with predicted maintenance

Figure 5. Four-shovel model with additional trucks.

trucks. The model was evaluated with 26 to 33 trucks. However, production did not seem to reach a limit.

The number of trucks was extended for selected dispatching techniques on this 4-shovel model. As may be seen from Figure 5 and Table 4, not until 52 trucks were assigned to the system did the production level off. The number of trucks under ideal conditions would be 30. This represents an increase of 5 to 6 trucks per shovel in order to overcome the variability of the operations.

The production limit for two shovels was about 350 loads while for four shovels it is 725 loads. Slightly more than double production may be obtained by the addition of two shovels. To achieve this, however, the number of trucks was almost trebled. A larger system does not automatically mean greater gains.

Comparison of Dispatchers

Figures 3 and 5 illustrate that the Simple Counter dispatcher is not adequate when the system approaches a normal or overtrucked condition. Since the counter cannot determine the percent completion of the truck being loaded or the expected travel time, it often dispatches trucks to the wrong shovel. This results in less efficiency than the no dispatching mode of operation. Only when a system is severely undertrucked should this method be considered.

Figure 4 shows characteristics of the Maximize Trucks and Maximize Shovels types of dispatching. When the system is undertrucked, the operation of the trucks should be maximized to yield the most production. With a greater number of trucks, it becomes more important to stress shovel utilization. Although Figure 4 serves to illustrate this, the results are not significant enough to confirm precisely where the crossover point occurs.

Of greater interest is the distribution of idle times for the different types of dispatching. This is shown in Figure 6 for the 6-shovel model. The Simple Counter assigns trucks to the most distant shovel in the event of a tie. The resulting idle time for the nearer shovels may be readily seen.

Conversely, maximizing truck production will cause the near shovels to be used more heavily. Hence, the rank of idle times is reversed. These distributions are more pronounced with fewer trucks.

Only the Maximize Shovel option tends to distribute the idle time evenly across the shovels. Mine management might make use of the skewness of one of the dispatching types, but in general it is considered more desirable to have all shovels working at the same rate. The Maximize Shovel type of dispatching will be considered in the following discussion.

Dispatching Versus Nondispatching

It has been seen that in general the Maximize Shovel is probably the best overall criterion for dispatching. The success of this technique will depend upon the number of trucks in the system.

Table 6 gives the percentage gain over nondispatched conditions for all of the shovel configurations. In general, it may be concluded that Maximize Shovel Dispatching with the Predicted Maintenance Option

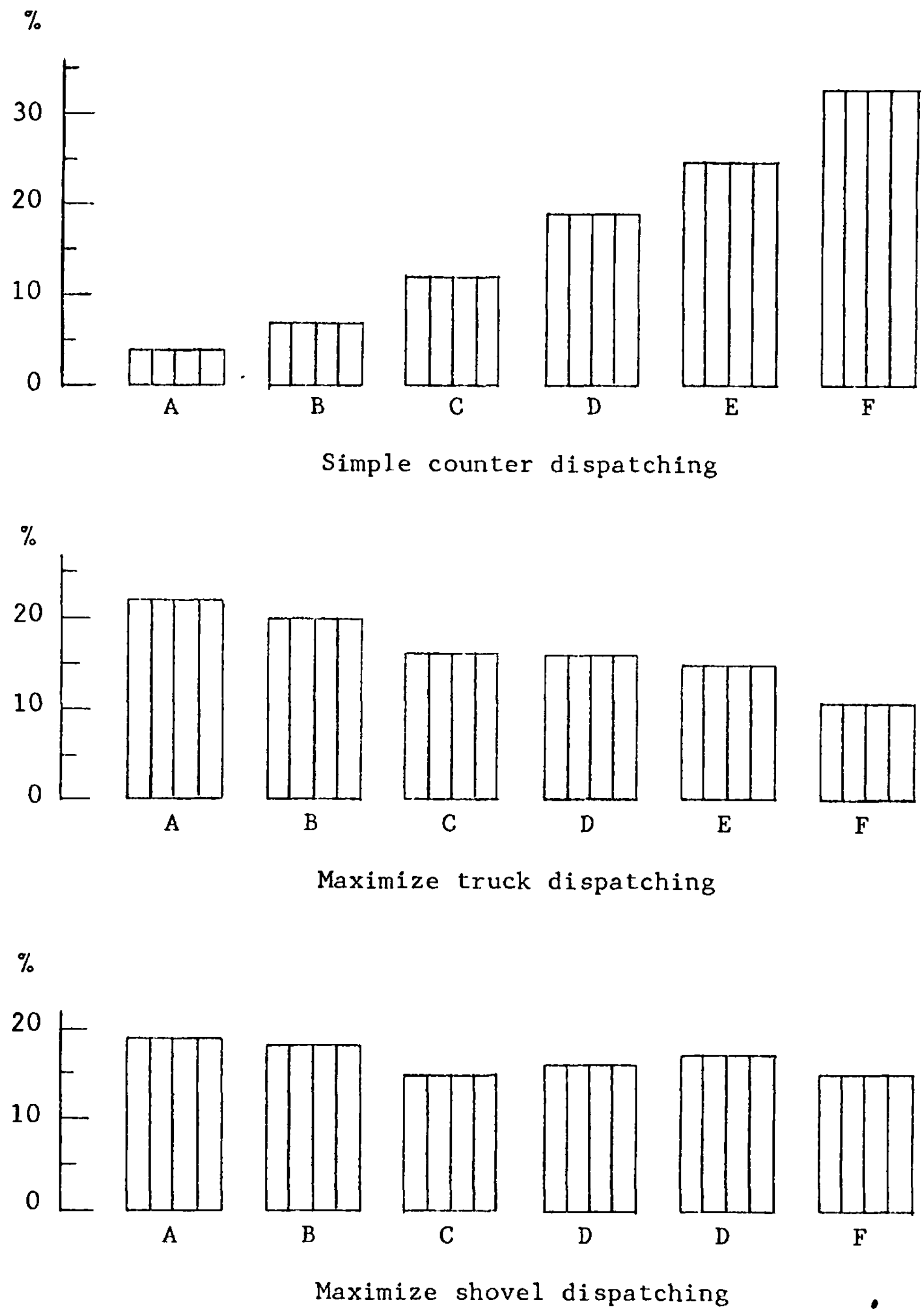


Figure 6. Distribution of shovel idle times.

Predictive maintenance, 45 trucks.

Table 6. Percent gained with maximize shovel dispatching with predicted maintenance.

Two Shovels

	Trucks							
	11	12	13	14	15	16	17	18
% Gain	6.3	6.2	5.2	4.2	3.6	1.8	1.2	0.6

Four Shovels

	Trucks							
	26	27	28	29	30	31	32	33
% Gain	8.4	8.7	8.4	6.8	6.5	5.9	5.8	5.2

Six Shovels

	Trucks						
	39	41	43	45	47	49	51
% Gain	6.1	7.8	7.0	6.8	6.4	6.2	5.5

will yield approximately a 5% increase in production. This is reduced if the system is approaching truck saturation.

Predicted Maintenance Option

The use of the Predicted Maintenance Option does give increased production. A scan of the production tables under columns of the same type of dispatching shows that in all cases the use of this option increases production.

An analysis of the percent of increase may be obtained by comparing the results of the 4-shovel model. As in other situations, there is no reason to suspect a uniform increase between the number of trucks or between types of dispatchers.

Table 7 gives the percentage increase when the Option is used. The attempt to serve both trucks and shovels concurrently is not as great as hoped for. In general, less than a 2% gain is seen.

Deterministic Versus Stochastic Simulation

In complex systems it is often possible to use the expected values for the stochastic variables and allow them to remain constant in the simulation. This is known as deterministic simulation (Emshoff 1970).

This procedure is not feasible in the truck-shovel model because the components are too interdependent. For example, in the Simple Counter dispatching, some oscillation or rhythm might occur which would be damped out by the introduction of variation. The effect of the oscillation might be good or bad.

Table 7. Percent gained by predicted maintenance with four-shovel configuration.

Number of trucks	Type of dispatching		
	I	II	III
26	3.9	1.3	1.7
27	1.8	1.9	2.1
28	2.7	1.4	2.5
29	1.7	1.1	1.6
30	0.6	2.8	2.2
31	1.5	2.3	1.5
32	1.7	2.2	1.2
33	0.9	2.6	2.1
Average	1.85	1.95	1.86

The Maximize Shovel dispatcher with the Predicted Maintenance Option was used to compare deterministic and stochastic simulations. For the deterministic runs, the 4-shovel configuration was used. No variation was allowed in the travel times, load times, truck down times, or delay times. As may be seen by Table 8, the stochastic model produces about 96% of the production of the deterministic model. Again, the detrimental effect of the variation introduced into the system is seen.

If the difference between these types of simulation were consistent, deterministic runs could be made and the output scaled accordingly. This would reduce the number of runs required. It is not felt that this is the case in this model.

Procedure for Statistical Analysis

A particular mine configuration might be analyzed by a multiway analysis of variance. For a particular configuration the number of shovels would be fixed, but the number of down times should be allowed to vary. A reasonable range would be from 2 to 4 down times per shovel per shift.

The number of trucks should be allowed to vary by a range of at least 2 trucks per shovel. The frequency of down times for each truck might also be allowed to vary but this factor will be assumed constant for this discussion.

A variety of travel times should be incorporated into the experiment. These should approximate long and short hauls as well as conditions favorable to dispatching and nondispatching.

Table 8. Stochastic versus deterministic simulation.[a]

Number of trucks	Production: Stochastic	Production: Deterministic	Ratio
26	592.5	617.0	96.03
27	598.7	621.0	96.41
28	614.2	644.0	95.37
29	620.7	646.0	96.08
30	630.2	656.0	96.07
31	640.2	661.0	96.85
32	648.0	677.0	95.72
33	662.2	688.0	96.25
Average			96.0975

a. 4 shovels, type III dispatching with maintenance option.

The Maximize Shovel type of dispatching should be compared to the nondispatching model. And finally, the dispatching would have to be evaluated both with and without the Predicted Maintenance Option.

If a 4-shovel mine model was experimented upon in this manner, 8 levels of trucks, 8 levels of down times, and 2 levels (yes or no) for the factors of dispatching and predicted maintenance would be required. In addition, the travel times and dispatching conditions would have to be evaluated for at least 2 levels.

To perform a factorial analysis, the population distributions must be normal with equal variances. The distribution of loads hauled does not appear to be normal nor do the variances of the distributions appear to be equal. The central limit theorem would allow the mean of the production to be treated as a normal variate for large sample sizes. The equality of variances is not critical so long as the sample size for each treatment is the same (Naylor, Wertz, and Wonnacott 1967). Nevertheless, the time and expense involved in this approach would be excessive.

This effort may be reduced by using Fractional Factorial Design (Johnson and Leone 1964, Vol. 2). This technique assumes that the significant factors can be determined by evaluating each factor at its upper and lower level. For the trucks and number of shovel down times, a maximum and minimum number would be established. Long and short travel times would be incorporated and there would be two levels for the favorability of the travel times to dispatching.

To simplify the procedure, we could apply the Predicted Maintenance Option to both the nondispatched and the dispatched models.

In summary, the factors and their levels are:

trucks (minimum and maximum number),

shovel downs (minimum and maximum number),

travel times (long and short),

favorable to dispatching (yes and no),

predicted maintenance (yes and no),

dispatching (yes and no).

Thus, there are 6 factors, each at 2 levels, which is a 2^6 experiment. This requires 64 treatments, each with many replications to overcome the normality and variance assumptions. A substantial reduction from the previous experiment has been obtained, but the effort is probably still excessive.

This effort may be halved by taking a balanced fraction of the 64 treatments. This "confounds" one of the interactions. That is, some interaction is divided among blocks so that it is not possible to determine if an observed difference is due to one factor or another or both. This results in "alias-pairs" of interactions which cannot be distinguished.

An example might help to clarify the situation at this point, where

N is the effect of the number of trucks,

S is the effect of shovel downs,

T is the travel time effect,

F is the favorable to dispatching effect,

P is the effect of predicted maintenance, and

D is the effect of dispatching.

Following the procedure of Johnson and Leone (1964, Vol. 2, p. 210), the highest order interaction, NSTFPD, may be confounded. The alias-pairs shown below would be determined. "I" is the total effect of the entire experiment.

Effect	Alias	Effect	Alias
I	NSTFPD	TF	NSPD
N	STFPD	TP	NSFD
S	NTFPD	TD	NSFP
T	NSTPD	FP	NSTD
F	NSTPD	FD	NSTP
P	NSTFD	PD	NSTF
D	NSTFP	NST	FPD
NS	TFPD	NSF	TPD
NT	SFPD	NSP	TFD
NF	STPD	NSD	TFP
NP	STFD	NTF	SPD
ND	STFP	NTP	SFD
ST	NFPD	NTD	SFP
SF	STPD	STF	NPD
SP	NTFD	STP	NFD
SD	NTFP	STD	NFP

These alias-pairs determine which interactions cannot be separated in this fractional experiment; for example, row 3 of the left side indicates that the effect of S (shovel downs) cannot be isolated from NTFPD (interaction of 5 factors).

When the alias-pairs are known, the principal block can be generated as described by Johnson and Leone (1964, Vol. 2, p. 193). Generating the blocks in this manner avoids having the blocks confounded with the main factors. The elements of the principal block for this experiment are shown below. Each lower case letter refers to the application of the high level of treatment for the corresponding capital letter (i.e., t represents a treatment with the maximum level of trucks). The absence of a letter indicates treatment at a low level. A 1 represents all low level treatments.

1	nstfpd	sp	ntfd
ns	tfpd	sd	ntfp
nt	sfpd	tf	nspd
nf	stpd	tp	nsfd
np	stfd	td	nsfp
nd	stfp	fp	nstd
st	nfpd	fd	nstp
sf	stpd	pd	nstf

The results from these treatments could then be analyzed by Yates technique. If further reductions are required, this procedure may be extended to one-fourth replications or smaller 2^{-r} replications. However, the amount of confounding increases with each reduction.

CHAPTER 5

EXTENSIONS AND CONCLUSIONS

The effect of dispatching trucks in an open pit mine has been explored in this thesis. The purpose was to gain a general evaluation of the feasibility of implementing dispatching under a variety of conditions. The needs of a mine are exactly the opposite. They need a specific evaluation for their unique operation. Additional study should be directed toward an actual operation.

Variability is a Detriment

Comparison of the deterministic and stochastic simulations, and comparison of the use and lack of use of the Predicted Maintenance Option indicates that variability in a truck-shovel system reduces production. Dispatching helps to reduce this variability.

This conclusion suggests that the mines should be more concerned about the variability of their operations. Work should be done to compare the operation of a mine under conditions of more and less variability. A factor that adds to variability is the use of mixed fleets and different shovels. Future models should incorporate this feature.

Other means of reducing variability should be explored by mine management. This is supported in part by White (1972) when he suggests that big trucks are needed if only to reduce the traffic jam at the shovels. On the other hand, the smaller the truck the less effect it has on the production when it is down. Kress (1971) indicates that side dumping trucks might increase production as much as 5%.

Implementation of Dispatching

In Chapter 2 it was established that any type of dispatching model should be able to be implemented by a small computer or by a human observer. The Simple Counter dispatcher would be the easiest to implement by a computer but this technique did not prove entirely satisfactory.

The human mind is probably the most capable in evaluating the next idle shovel in a system. A computer could be programmed to consider load times and travel times and make decisions according to a set of rules. Often it might make a better dispatching decision than a human mind. But more often the human mind would have a more complete picture of the situation plus the ability to anticipate events. This would be too difficult to program into a computer. Further, the feedback and correction procedures are far easier with a human being than with a computer. If dispatching is to be implemented, I feel that human capabilities reign over the computer.

Ideally, the dispatcher would need to see all of the dumps, roads, and shovels in the mine. This is seldom possible. In fact, it is often difficult to have a line of sight to all of the shovels at once. The best solution would depend upon the individual mine, but it might be satisfied by an observing station on the side of the pit opposite the roads or by remote TV cameras. Communications could be established by the use of numbered trucks for identification and by the use of radios which are already utilized in some mines.

Cost Analysis

The optimal number of trucks and the benefits of dispatching should be determined on a cost basis for a specific mine. This cannot be done on a general basis because of the discrepancy in cost of the equipment. Nevertheless, some general evaluations will be made.

The best dispatching technique with the Predicted Maintenance Option increased production by about 5%. The Maintenance Option alone accounts for almost a 2% gain. Thus, if the variability of the mine is similar to that given in the model, dispatching alone may increase production by 2 to 3%.

With a fleet of 40 to 50 trucks, it may be possible to save one or more trucks. If it is assumed that an equal or greater amount of production may be obtained with dispatching using one less truck, then the cost of dispatching may be compared to the cost of an additional truck.

The operating cost of a typical truck is \$15.00 to \$20.00 per hour (Nadzam and Beebower 1971, E/MJ 1969, Bishop 1968). This cost includes labor, tires, maintenance, and depreciation. Since dispatching increases truck use, tire wear and maintenance would increase somewhat. The cost of labor plus the remaining savings would probably be sufficient to pay the wages of the dispatcher. But this is close to the break-even point. Depreciation savings cannot necessarily be included because the dispatching system must be paid for.

The implementation cost of a dispatching system may be compared to the purchase price of a truck. New trucks cost from approximately $80,000.00 for the smaller sizes up to $500,000.00 or more for the 200-ton capacity trucks (White 1972). This should be more than sufficient to implement and sustain a dispatching operation.

Final Remarks

Dispatching has been examined and found to be capable of increasing mine production in general situations. The benefits gained, however, are not substantial enough to ensure implementation of this procedure under all conditions. Each mine must be evaluated under its own unique circumstances.

Variability of the operations seems to be the largest cause of lost production. Quite possibly the mines can derive a greater benefit by controlling variability in a manner other than dispatching. Any such alternatives should be explored.

Simulation has been seen to be a powerful tool in the analysis of complex problems. Simulation will not solve problems nor make decisions. It merely produces data that say in effect: If the decision is made to operate as the model indicates, then the production and operating data are estimated to be that produced by the simulation.

APPENDIX

COMPUTER TRUCK-SHOVEL PROGRAM

```
      PROGRAM    TRUCKS
     1   ( INPUT, OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT )
C
C        PROGRAM TO SIMULATE DISPATCHING TECHNIQUES
C        IN AN OPEN PIT MINE.
C
C        MAIN PROGRAM ESTABLISHES PARAMETERS AND READS
C        A MINE CONFIGURATION.  CONTROL IS THEN PASSED
C        TO ROUTINE SHIFT TO SIMULATE A DAYS OPERATION.
C
C
C        THE KEY VARIABLES AND ARRAYS ARE DESCRIBED BELOW.
C
C        ARRAY ITEMS CONTAINS MISCELLANEOUS VARIABLES
C        THAT ARE USED THROUGHOUT THE PROGRAM.  THE
C        VARIABLES STORED AND THEIR LOCATIONS ARE AS
C        FOLLOWS..
C             1 =  IN         INPUT FILE
C             2 =  IOUT       OUTPUT FILE
C             3 =  NSHVL      NUMBER OF SHOVELS
C             7 =  IDSPH      TYPE OF DISPATCHER
C             8 =  INITR      INITIAL RANDOM NUMBER
C             9 =  IDBUG1     MINIMUM DEBUG TIME
C            10 =  IDBUG2     MAXIMUM DEBUG TIME
C            11 =  ISHFT      CURRENT SHIFT NUMBER
C            12 =  NTRCKS     CURRENT NUMBER OF TRUCKS
C            13 =  LOCE       POINTER TO LOCATION IN NEXTE
C            14 =  JTRCK      CURRENT TRUCK
C            15 =  NOWT       CURRENT TIME
C            16 =  ISPACE     TAILGATING PARAMETER
C            17 =  IQUIT      END OF SHIFT TIME
C            18 =  ISPOT      SPOT TIME
C            19 =  IDUMP      DUMP TIME
C            21 =  ISWING     SECONDS IN SHOVEL SWING
C            22 =  ISD2       VARIABLE 21 / 2
C            23 =  IPM        PREDICTED MAINTENANCE INDICATOR
C            24 =  IHSD       SHOVEL DOWN INDICATOR
C            25 =  IBS        FIRST SHIFT NUMBER
C            26 =  IES        LAST SHIFT NUMBER
C            27 =  JSHFT      SHIFT COUNTER
C
C        INFOS IS THE SHOVEL INFORMATION ARRAY.
C        NTIME IS THE NEXT EVENT ARRAY.
C        NODES DEFINES THE HAUL ROUTES.
C        MOVE GIVES THE NEXT LOCATION AFTER AN EVENT.
C        TRVL GIVES THE TRAVEL TIMES IN MINUTES.
C        RANDS STORES THE RANDOM NUMBER FOR THE SHOVELS.
C        HEAD IS THE HEADING.
C        IADD IS THE HANDICAP ASSIGNMENT OF TRUCKS.
C        IASSGN IS THE PRELIMINARY ASSIGNMENT OF TRUCKS.
C        INFOUT IS THE INFORMATION OUT ARRAY.
```

```
C
      COMMON / ALPHA /
     1  INFOT(14,60), INFOS(26,6), NTIME(60,3), NODES(15),
     2  MOVE(15), TRVL(15,15), RANDS(6), ITEMS(40),
     3  HEAD(7), IADD(6), IASSGN(2,6), INFOUT(51,9)
C
       EQUIVALENCE
     1   (IN,ITEMS(1)),  (IOUT,ITEMS(2)),  (NSHVL,ITEMS(3))
C
      ITEMS(1)  = 5
      ITEMS(2)  = 6
      ITEMS(16) = 10
      ITEMS(17) = 27000
      ITEMS(18) = 40
      ITEMS(19) = 60
      ITEMS(20) = 1200
      ITEMS(21) = 30
      ITEMS(22) = 15
C
C          READ IN NODE-TO-NODE CONFIGURATION
C          AND TRAVEL TIMES
C
  100 CONTINUE
      DO 112 J=1,15
      MOVE(J) = 9999
      DO 102 I=1,15
  102 TRVL(I,J) = 9.99
  112 CONTINUE
C
  114 READ (IN,901)  NSHVL, HEAD
      IF ( NSHVL .EQ. 0 )      GO TO 900
  115 READ (IN,902)  I, J
      IF ( I .EQ. 0 )      GO TO 120
      MOVE(I) = J
      GO TO 115
C
  120 CONTINUE
      READ ( IN, 903 )    I, J,    TIME
      IF ( I .EQ. 0 )    GO TO 130
      TRVL(I,J) = TIME
      GO TO 120
C
  130 CONTINUE
      CALL SHIFT
      GO TO 100
C
  900 STOP
  901 FORMAT ( I1, 9X, 7A10 )
  902 FORMAT ( I2, 1X, I2 )
  903 FORMAT ( 2(I2,1X),  F6.2 )
      END
```

```
      SUBROUTINE SHIFT
C
C         ROUTINE TO READ A RUN REQUEST CARD AND SIMULATE
C         THE REQUIRED NUMBER OF SHIFTS.
C
      COMMON / ALPHA /
     1  INFOT(14,60), INFOS(26,6), NTIME(60,3), NODES(15),
     2  MOVE(15), TRVL(15,15), RANDS(6), ITEMS(40),
     3  HEAD(7), IADD(6), IASSGN(2,6), INFOUT(51,9)
C
      EQUIVALENCE
     1    (IN,ITEMS(1)),(IOUT,ITEMS(2)),(ISHFT,ITEMS(11)),
     2    (NTRCKS,ITEMS(12)), (NOWT,ITEMS(15)),
     3    (INITR,ITEMS(8)),( IPM,ITEMS(23)),(IDSPH,ITEMS(7)),
     4    ( IBS,ITEMS(25)), ( IES,ITEMS(26)),
     5    (JTRCK,ITEMS(14)),   (JSHFT,ITEMS(27))
C
C         READ RUN REQUEST CARD
C             NTMIN = MINIMUM NUMBER OF TRUCKS
C             NTMAX = MAXIMUM NUMBER OF TRUCKS
C             NSTEP = STEP SIZE FOR TRUCK DO LOOP
C             REMAINING VARIABLES ARE AS DEFINED FOR ITEMS
C
  100 CONTINUE
      READ ( IN,901)  NTMIN, NTMAX, NSTEP, IBS, IES, IDSPH,
     1    IPM, T1, T2, INITR
      IF ( NTMIN .EQ. 0 )     GO TO 900
      ITEMS(9) = T1 * 60.
      ITEMS(10) = T2 * 60.
C
      WRITE (IOUT, 9900)
      DO 832 NTRCKS = NTMIN, NTMAX, NSTEP
      DO 102 I=1,51
      DO 102 J=1,9
  102 INFOUT(I,J) = 0
      JSHFT = 0
      DO 822 ISHFT = IBS, IES
C
      CALL RESET
C
C         CALL NEXTE TO DETERMINE THE NEXT EVENT.
C         JTRCK IDENTIFIES THE TRUCK.
C         IF JTRCK = 99, END OF SHIFT
C                    98, SHOVEL ENDS BREAKDOWN
C
C         IEVNT GIVES NODE WHERE EVENT OCCURS
C               = 1 TO 6 FOR SHOVELS
C               = 7 FOR DISPATCHER
C               = 8 FOR DUMP AND MAINTENANCE
C               = 9 TO 15 FOR INTERSECTION
C
```

```
  110 CONTINUE
      CALL NEXTE( 2, ITIME, JTRCK )
      NOWT = ITIME
      IF ( JTRCK .EQ. 99 )      GO TO 780
      IF ( JTRCK .EQ. 98 )      GO TO 770
      IEVNT = INFOT(3,JTRCK)
      IF ( IEVNT .LT. 9 )    GO TO 120
C
      CALL ATNODE
      GO TO 110
C
  120 CONTINUE
      IF ( IEVNT .GE. 7 )    GO TO 124
C
      CALL SHOVEL
      GO TO 110
C
  124 IF ( IEVNT .EQ. 8 )      GO TO 125
      CALL DSPTCH
      GO TO 110
C
  125 CALL DUMPLD
      GO TO 110
C
  770 CONTINUE
      CALL UPSHVL
      GO TO 110
C
  780 CONTINUE
      CALL OUTSHF
C
  822 CONTINUE
  832 CONTINUE
      GO TO 100
  900 RETURN
C
  901 FORMAT ( 2(I2,1X), 2(I1,1X), I2, 1X, 2(I1,1X) )
 9900 FORMAT ( 1H1 )
      END
```

```
      SUBROUTINE RESET
C
C         THIS ROUTINE HANDLES THE INITIALIZATION
C         FOR EACH SHIFT.
C
      COMMON / ALPHA /
     1  INFOT(14,60), INFOS(26,6), NTIME(60,3), NODES(15),
     2  MOVE(15), TRVL(15,15), RANDS(6), ITEMS(40),
     3  HEAD(7), IADD(6), IASSGN(2,6), INFOUT(51,9)
C
      EQUIVALENCE
     1    (ISHFT,ITEMS(11)), (LOCE,ITEMS(13)), (IN,ITEMS(1)),
     2    (NTRCKS,ITEMS(12)), (IOUT,ITEMS(2)),
     3    (INITR,ITEMS(8)), (NSHVL, ITEMS(3)),
     4    (IDSPH, ITEMS(7)),    (IHSD, ITEMS(24)),
     5    (IQUIT, ITEMS(17))
C
C         ESTABLISH INITIAL RANDOM NUMBER FOR EACH SHOVEL
C         SO THAT THE VARIOUS DISPATCHING TECHNIQUES
C         MAY BE REPEATED UNDER IDENTICAL LOAD TIMES.
C         EACH SHIFT WITHIN EACH TRUCK-SHOVEL SET IS
C         DIFFERENT.
C
      NSET = ISHFT * 10
      X = RANF(INITR)
      DO 102 I=1,NSET
  102 X = RANF(0.0)
      DO 112 I=1,6
  112 RANDS(I) = RANF(0.0)
C
C         ZERO OUT TIMES AND DATA ACCUMULATORS
C
      IHSD = -99999
      DO 122 I=1,15
  122 NODES(I) = 0
      DO 132 I=1,60
      INFOT(1,I) = 0
      INFOT(2,I) = 0
      INFOT(3,I) = 8
      INFOT(10,I) = 0
  132 CONTINUE
      DO 152 J=1,6
      DO 142 I=1,9
  142 INFOS(I,J) = 0
      INFOS(14,J) = 15
      INFOS(10,J) = -IADD(J)
  152 CONTINUE
C
C         ESTABLISH ARRAY NTIME
C
      NTIME(1,1) = 2
```

```
      NTIME(1,2) = -999999
      NTIME(1,3) = 0
      NTIME(2,1) = 999999
      NTIME(2,2) = 999999
      NTIME(2,3) = 99
      LOCE = 3
      DO 162 I=3,60
  162 NTIME(I,1) = 0
C
C        ESTABLISH TRUCK ASSIGNMENT IF NO
C        DISPATCHER IS TO BE USED.
C
      IF ( IDSPH .NE. 0 )    GO TO 190
      DO 182 I=1,NSHVL
      DO 172 J=I,NTRCKS, NSHVL
      INFOT(9,J) = I
  172 CONTINUE
  182 CONTINUE
  190 CONTINUE
      DO 192 I=1,NTRCKS
      INFOT(7,I) = 1
  192 INFOT(8,I) = 4
C
C        ENTER TRUCKS IN NEXT EVENT ARRAY
C
  250 CONTINUE
      DO 252 I=1,NTRCKS
  252 CALL NEXTE ( 1, 0, I )
C
C        ARBITRARILY ESTABLISH DOWN TIME FOR SHOVELS
C        AND TRUCKS.  IDENTICAL FOR ALL SHIFTS.
C
      DO 272 J=1,6
      INFOS(14,J) = 15
      DO 262 I=15,26
      INFOS(I,J) = 99999
  262 CONTINUE
  272 CONTINUE
      FEND = IQUIT
C
      INFOS(15,1) = 135 * 60
      INFOS(17,1) = 225 * 60
      INFOS(15,2) = 315 * 60
      INFOS(17,2) = 405 * 60
      INFOS(15,3) = 195 * 60
      INFOS(17,3) = 285 * 60
      INFOS(15,4) = 165 * 60
      INFOS(17,4) = 375 * 60
      INFOS(15,5) = 255 * 60
      INFOS(17,5) = 345 * 60
      INFOS(15,6) = 105 * 60
```

```
      INFOS(17,6) = 435 * 60
      INFOS(16,1) = 22.0 * 60.0
      INFOS(18,1) = 18.0 * 60.0
      INFOS(16,2) = 24.0 * 60.0
      INFOS(18,2) = 21.5 * 60.0
      INFOS(16,3) = 27.0 * 60.0
      INFOS(18,3) = 16.0 * 60.0
      INFOS(16,4) = 22.6 * 60.0
      INFOS(18,4) = 30.0 * 60.0
      INFOS(16,5) = 20.5 * 60.0
      INFOS(18,5) = 17.2 * 60.0
      INFOS(16,6) = 25.0 * 60.0
      INFOS(18,6) = 24.0 * 60.0
C
      X = RANF(6987027893)
      DO 312 I=1,60
      INFOT(4,I) = RANF(0.0) * FEND
      INFOT(5,I) = REXPN( 22.0 )  *  60.0
      INFOT(11,I) = RANF(0.0) * FEND
      INFOT(12,I) = REXPN ( 3.0 ) * 60.0
      INFOT(13,I) = RANF(0.0) * FEND
      INFOT(14,I) = REXPN( 3.0 ) * 60.0
  312 CONTINUE
C
      RETURN
C
      END




      SUBROUTINE ATNODE
C
C        ROUTINE TO ADVANCE TRUCKS FROM ONE NODE TO THE NEXT
C        TRUCK HAS ARRIVED AT THE NODE DESIGNATED IN ROW 3.
C
      COMMON / ALPHA /
     1  INFOT(14,60), INFOS(26,6), NTIME(60,3), NODES(15),
     2  MOVE(15), TRVL(15,15), RANDS(6), ITEMS(40),
     3  HEAD(7), IADD(6), IASSGN(2,6), INFOUT(51,9)
C
      EQUIVALENCE
     1   (JTRCK,ITEMS(14)), (ISPACE,ITEMS(16)),
     2   (IOUT,ITEMS(2)), (NOWT,ITEMS(15)),
     3   (IDBUG1,ITEMS(9)), (IDBUG2,ITEMS(10))
C
C        CHECK AGAINST TAILGATING
C
      LOC = INFOT(3,JTRCK)
```

```
      IF ( NOWT .LT. ISPACE+NODES(LOC))
     1                        NOWT = ISPACE + NODES(LOC)
      NODES(LOC) = NOWT
C
      NXTLOC = MOVE(LOC)
      TIME = TRVL(LOC,NXTLOC)
      NTRVL = NRML( TIME, TIME*0.15,  1.0,   4.0  )
      NEXT = NOWT + NTRVL
      INFOT(3,JTRCK) = NXTLOC
      CALL NEXTE ( 1, NEXT, JTRCK )
C
      IF ( NOWT .LT. IDBUG1 .OR. NOWT .GT. IDBUG2 )   RETURN
      WRITE (IOUT, 901)  NOWT, JTRCK, NEXT, LOC, NXTLOC,TIME
  901 FORMAT ( 10X, *ATNODE*  5I10, F10.2 )
      RETURN
      END
```

```
      SUBROUTINE DUMPLD
C
C        TRUCK HAS ARRIVED AT DUMP.  UNLOAD, CHECK FOR
C        MAINTENANCE, AND SEND IT TO THE DISPATCHER.
C
      COMMON / ALPHA /
     1  INFOT(14,60), INFOS(26,6), NTIME(60,3), NODES(15),
     2  MOVE(15), TRVL(15,15), RANDS(6), ITEMS(40),
     3  HEAD(7), IADD(6), IASSGN(2,6), INFOUT(51,9)
C
      EQUIVALENCE
     1   (IOUT,ITEMS(2)), (JTRCK,ITEMS(14)),
     2   (NOWT,ITEMS(15)), (IDUMP,ITEMS(19)),
     3   (IDBUG1,ITEMS(9)), (IDBUG2,ITEMS(10)),
     4   (ISPACE,ITEMS(16))
C
C        AVOID DUMP TIME IF START OF SHIFT
C
      NRDY = 0
      IF ( INFOT(1,JTRCK) .EQ. 0 )     GO TO 400
      NRDY = NOWT + IDUMP
      IF ( NRDY .LT. INFOT(4,JTRCK) )     GO TO 300
C
C        TRUCK BREAKDOWN
C
      NRDY = NRDY + INFOT(5,JTRCK)
      INFOT(4,JTRCK) = 99999
      NEXT = NRDY - IDUMP
      CALL NEXTE ( 1, NEXT, JTRCK )
```

```
      IFLAG = 777777
      GO TO 900
C
C        CHECK FOR DUMP SLOWDOWM
C
  300 IF ( NRDY .LT. INFOT(11,JTRCK) )    GO TO 350
      NRDY = NRDY + INFOT(12,JTRCK)
      INFOT(11,JTRCK) = 99999
      GO TO 400
  350 IF ( NRDY .LT. INFOT(13,JTRCK) )    GO TO 400
      NRDY = NRDY + INFOT(14,JTRCK)
      INFOT(13,JTRCK) = 99999
C
C        TO DISPATCHER
C
  400 CONTINUE
      TIME = TRVL( 8, 7 )
      ITRVL = NRML ( TIME, TIME*0.20,  1.0,  4.0  )
      NEXT = NRDY + ITRVL
      IF ( NEXT .LT. NODES(7) + ISPACE )
     1                          NEXT = NODES(7) + ISPACE
      NODES(7) = NEXT
      INFOT(3,JTRCK) = 7
      IFLAG = 0
      CALL NEXTE ( 1, NEXT, JTRCK )
C
  900 CONTINUE
      IF ( NOWT .LT. IDBUG1  .OR.  NOWT .GT. IDBUG2 )RETURN
      WRITE ( IOUT, 980 )    NOWT, JTRCK, NEXT, IFLAG
  980 FORMAT ( 10X, *DUMPLD*,  4I10 )
      RETURN
      END




      SUBROUTINE DSPTCH
C
C        ROUTINE TO DISPATCH TRUCK TO PROPER SHOVEL
C        ACCORDING TO REQUESTED CRITERIA.
C
C        IDSPH = 0 FOR ARBITRARY ASSIGNMENT
C              = 1 FOR SIMPLE COUNTER
C              = 2 FOR MAXIMIZE TRUCKS
C              = 3 FOR MAXIMIZE SHOVELS
C
      COMMON / ALPHA /
     1  INFOT(14,60), INFOS(26,6), NTIME(60,3), NODES(15),
     2  MOVE(15), TRVL(15,15), RANDS(6), ITEMS(40),
```

```
     3  HEAD(7), IADD(6), IASSGN(2,6), INFOUT(51,9)
C
      EQUIVALENCE
     1    (IOUT,ITEMS(2)),(JTRCK,ITEMS(14)),(NOWT,ITEMS(15)),
     2    (LKAHD, ITEMS(20)), (IDSPH,ITEMS(7)),
     3    (IDBUG1,ITEMS(9)), (IDBUG2,ITEMS(10)),
     4    (ISPACE, ITEMS(16)),  (ISWING, ITEMS(21)),
     5    (IHSD, ITEMS(24)),  ( ISPOT, ITEMS(18)),
     6    (NSHVL,ITEMS(3)), (IQUIT,ITEMS(17)),
     7    ( IPM, ITEMS(23))
C
  100 CONTINUE
      NPASS = INFOT(8,JTRCK)
      IF ( IDSPH .GT. 0 )    GO TO 1000
C
C         ARBITRARY ASSIGNMENT
C
      NXTS = INFOT(9,JTRCK)
      GO TO 8500
C
C         IF PREDICTED MAINTENANCE, CHECK FOR
C         TRUCK REPAIR WITHIN HALF HOUR OF SHOVEL DOWN.
C
 1000 CONTINUE
      IF ( IPM .EQ. 0 )     GO TO 1090
      IF ( INFOT(4,JTRCK) .GT. IHSD+1800 )    GO TO 1090
      NEXT = NOWT + INFOT(5,JTRCK)
      NXTS = 777777
      CALL NEXTE (1, NEXT, JTRCK )
      INFOT(4,JTRCK) = 99000
      GO TO 9800
C
C         DETERMINE TYPE OF DISPATCHING
C
 1090 CONTINUE
      GO TO ( 1100, 2000, 3000 ), IDSPH
C
C         SIMPLE COUNTER
C
 1100 CONTINUE
      NMIN = 99
      DO 1102 I=1,NSHVL
      IF ( INFOS(7,I) .EQ. 1 )    GO TO 1102
      IF ( NMIN .LE. INFOS(10,I))     GO TO 1102
      NMIN = INFOS(10,I)
      NXTS = I
 1102 CONTINUE
      GO TO 8500
C
C         DETERMINE NEXT EXPECTED IDLE SHOVEL
C
```

```
 2000 CONTINUE
      NMIN = 99999
      DO 2012 I=1,NSHVL
      IF ( INFOS(7,I) .EQ. 1 )      GO TO 2012
      IF ( NMIN .LE. INFOS(5,I) )      GO TO 2012
      NMIN = INFOS(5,I)
      NXTS = I
 2012 CONTINUE
      GO TO 8500
C
C         DETERMINE EXPECTED EARLIEST LOAD LOCATION
C
 3000 CONTINUE
      NMIN = 99999
      DO 3012 I=1,NSHVL
      IF ( INFOS(7,I) .EQ. 1 )      GO TO 3012
      ITRAV = TRVL(7,I)         * 60.0
      ITRAV = ITRAV + (ISWING-ISPOT)
      IEXBLD = NOWT + ITRAV
      IF ( IEXBLD .LT. INFOS(5,I) )     IEXBLD = INFOS(5,I)
      IF ( NMIN .LE. IEXBLD )      GO TO 3012
      NMIN = IEXBLD
      NXTS = I
 3012 CONTINUE
C
C         SEND THE TRUCK TO THE SHOVEL IF NOT QUITTING TIME
C
 8500 CONTINUE
      TIME = TRVL( 7,NXTS )
      ITT = TIME * 60.0
      ITT = ITT + (ISWING-ISPOT)
      IEXBLD = NOWT + ITT
      IF ( IEXBLD .LT. INFOS(5,NXTS) ) IEXBLD=INFOS(5,NXTS)
C
      IAHD = LKAHD - 30 * (NXTS-1)
      ICHKQ = IEXBLD
      IF ( IDSPH .EQ. 0 )     ICHKQ = ICHKQ + 300
      IF ( IDSPH .EQ. 1 ) ICHKQ = INFOS(10,NXTS)*120 + NOWT
      IF ( ICHKQ  + IAHD .GE. IQUIT )      GO TO 8700
      ITRVL = NRML ( TIME, TIME * 0.15,  1.0,   4.0  )
      NEXT = NOWT + ITRVL
      IF ( NEXT .LT. NODES(NXTS) + ISPACE)
     1                           NEXT = NODES(NXTS) + ISPACE
      NODES(NXTS) = NEXT
      INFOS(5,NXTS) = IEXBLD + NPASS*ISWING
      INFOS(10,NXTS) = INFOS(10,NXTS) + 1
      INFOT(3,JTRCK) = NXTS
      CALL NEXTE ( 1, NEXT, JTRCK )
      GO TO 9800
C
C         TIME TO CALL IT A DAY
```

```
C
 8700 CONTINUE
      NEXT = 99000
      CALL NEXTE(1,NEXT,99)
C
C
 9800 CONTINUE
      IF ( NOWT .LT. IDBUG1 .OR. NOWT .GT. IDBUG2 )   RETURN
      WRITE ( IOUT, 9881)  NOWT, JTRCK, NEXT, NXTS, ITRVL
 9881 FORMAT ( 10X, *DSPTCH*,  5I10 )
      RETURN
      END



      SUBROUTINE SHOVEL
C
C         ROUTINE TO PROCESS LOADING OF A TRUCK
C         ONCE IT HAS ARRIVED AT THE SHOVEL.
C
      COMMON / ALPHA /
     1  INFOT(14,60), INFOS(26,6), NTIME(60,3), NODES(15),
     2  MOVE(15), TRVL(15,15), RANDS(6), ITEMS(40),
     3  HEAD(7), IADD(6), IASSGN(2,6), INFOUT(51,9)
C
      EQUIVALENCE
     1    (JTRCK, ITEMS(14)), (NOWT,ITEMS(15)),
     2    (IOUT,ITEMS(2)),   (IDBUG1,ITEMS(9)),
     3    (NOWT, ITEMS(15)),   (ISWING, ITEMS(21)),
     4    (IHSD,ITEMS(24)),   (ISD2, ITEMS(22)),
     5    (ISPOT,ITEMS(18)), (IDBUG2,ITEMS10)),
     6    (IPM,ITEMS(23))
C
      JSHVL = INFOT(3,JTRCK)
      IRDY = INFOS(6,JSHVL)
      IWAIT = NOWT + ISPOT - (IRDY+15)
C
C         IS SHOVEL DOWN
C
      IF ( INFOS(7,JSHVL) .EQ. 1 .AND.  IPM .EQ. 0 )
     1                                           GO TO 700
      IF ( INFOT(10,JTRCK) .NE. 0 )     IWAIT = IWAIT - 20
C
C         TRUCK SHOULD ARRIVE AND BE IN POSITION(SPOTTED)
C         AS 1/2 OF SHOVEL SWING IS COMPLETED.
C         IWAIT IS SHOVEL WAIT TIME.
C
  100 IF ( IWAIT )   110, 110, 115
```

```
C
C         TRUCK WAS EARLY.  ADD TO TRUCK IDLE
C         TIME IF NOT THE FIRST LOAD FOR THE TRUCK.
C
  110 CONTINUE
      IF ( INFOT(1,JTRCK) .GE. 1 )
     1   INFOT(2,JTRCK) = INFOT(2,JTRCK) - IWAIT + INFOT(10,
      INFOT(10,JTRCK) = 0
      LDBGN = IRDY
      GO TO 120
C
C         TRUCK WAS LATE.  ADD TO SHOVEL IDLE TIME IF
C         NOT FIRST LOAD FOR THE SHOVEL.
C
  115 CONTINUE
      IF ( INFOS(1,JSHVL) .GE. 1 )
     1              INFOS(2,JSHVL) = INFOS(2,JSHVL) + IWAIT
      LDBGN = NOWT + ISPOT - ISD2
C
C         LOAD THE TRUCK AND SEND IT ON ITS WAY.
C
  120 CONTINUE
      RLAST = RANDS(JSHVL)
      LOADT = NRML ( 2.0, 0.3, 1.0, 3.0 )
      RANDS(JSHVL) = RANF(-9.0)
      NRDY = LDBGN + LOADT
      NXTLOC = MOVE(JSHVL)
      TIME = TRVL( JSHVL, NXTLOC)
      ITRVL = NRML ( TIME, TIME*0.15,  1.0, 4.0 )
      NEXT = NRDY + ITRVL - ISD2
      INFOT(3,JTRCK) = NXTLOC
      INFOT(1,JTRCK) = INFOT(1,JTRCK) + 1
      INFOS(1,JSHVL) = INFOS(1,JSHVL) + 1
      INFOS(10,JSHVL) = INFOS(10,JSHVL) - 1
      CALL NEXTE ( 1, NEXT, JTRCK )
C
C         IS IT SHOVEL BREAKDOWN TIME.
C         CHECK FOR DOWN TIME BEFORE REQDY WITH NO PREDICTIED
C         MAINTENANCE  --OR--  DOWN TIME WITHIN 6 MINUTES OF
C         READY AND PREDICTED MAINTENANCE.
C
      LOOK = INFOS(14,JSHVL)
      IF ( INFOS(LOOK,JSHVL) .GT. NRDY  .OR. IPM .EQ. 1 ) GO
     1                                                GO TO 127
      INFOS(7,JSHVL) = 1
      GO TO 128
  127 IF ( INFOS(LOOK,JSHVL) .GT. NRDY+360  .OR.
     1                            IPM .EQ. 0 )      GO TO 130
      IHSD = NRDY
      INFOS(7,JSHVL) = 1
      IF ( INFOS(10,JSHVL) .NE. 0 )      GO TO 130
```

```
      NRDY = NRDY + INFOS(LOOK+1,JSHVL) - 360
      GO TO 129
  128 CONTINUE
      NRDY = NRDY + INFOS(LOOK+1,JSHVL)
  129 INFOS(14,JSHVL) = LOOK + 2
      CALL NEXTE ( 1, NRDY, 98 )
  130 INFOS(6,JSHVL) = NRDY
C
C         DISPATCHING INFORMATION
C
      INFOS(5,JSHVL) = INFOS(5,JSHVL) + (LOADT - 120 )
      GO TO 890
C
C         SHOVEL IS DOWN.
C         REASSIGN TRUCK ARRIVAL TIME AS SHOVEL
C         READY TIME AND STORE DELAY IN ROW 10 OF TRUCK INFO.
C         DELAY TIME IS TIME UNTIL SHOVEL
C         IS READY AND INCLUDES SPOT TIME.
C
  700 CONTINUE
      NXTLOC = 98
      CALL NEXTE (1, IRDY, JTRCK )
      INFOT(10,JTRCK) = (-IWAIT) - IS02
C
  890 CONTINUE
      IF ( NOWT .LT. IDBUG1 .OR. NOWT .GT. IDBUG2 ) RETURN
      WRITE ( IOUT, 980 )  NOWT, JTRCK, NEXT, NXTLOC, JSHVL,
     1              IRDY, IWAIT, NRDY
      J = JSHVL
      WRITE (IOUT, 981) INFOS(1,J), INFOS(2,J), INFOS(5,J),
     1  INFOS(6,J), INFOS(7,J), INFOS(10,J), INFOS(14,J),
     2    ( INFOT(I,JTRCK), I=1,3)
  980 FORMAT ( 10X, *SHOVEL*,  8I10 )
  981 FORMAT ( 16X, 10I10 )
      RETURN
      END
```

```
      SUBROUTINE NEXTE ( IACT, ITIME, IEVNT )
C
C         ROUTINE TO UPDATE NEXT EVENT TIME TABLE
C
C         IACT = 1 FOR ADD AN EVENT
C                2 FOR DETERMINE NEXT EVENT AND DELETE IT
C
C         COLUMNS OF NTIME CONTAIN..
C                         1 = POINTERS
```

```
C                              2 = TIME
C                              3 = EVENT
C
      COMMON / ALPHA /
     1  INFOT(14,60), INFOS(26,6), NTIME(60,3), NODES(15),
     2  MOVE(15), TRVL(15,15), RANDS(6), ITEMS(40),
     3  HEAD(7), IADD(6), IASSGN(2,6), INFOUT(51,9)
C
      EQUIVALENCE
     1    (LOCE, ITEMS(13))
C
      IF ( IACT .EQ. 2 )      GO TO 500
      LOC = 1
  100 CONTINUE
      LOCO = LOC
      LOC = NTIME(LOC,1)
      IF ( ITIME .GE. NTIME(LOC,2) )     GO TO 100
C
C         ADD AN EVENT
C
      IF ( LOCE .NE. 0 )       GO TO 150
      DO 112 I=3,60
      IF ( NTIME(I,1) .GT. 0 )     GO TO 112
      LOCE = I
      GO TO 150
  112 CONTINUE
      CALL ERROR ( 101 )
C
  150 CONTINUE
      NTIME(LOCO,1) = LOCE
      NTIME(LOCE,1) = LOC
      NTIME(LOCE,2) = ITIME
      NTIME(LOCE,3) = IEVNT
      LOCE = 0
      RETURN
C
C         FIND NEXT EVENT AND DELETE
C
  500 CONTINUE
      LOC = NTIME(1,1)
      NTIME(1,1) = NTIME(LOC,1)
      ITIME = NTIME(LOC,2)
      IEVNT = NTIME(LOC,3)
      LOCE = LOC
      NTIME(LOC,1) = 0
      RETURN
      END
```

```
      SUBROUTINE UPSHVL
C
C         ROUTINE TO CHANGE DOWN SHOVEL INDICATOR WHEN
C         SHOVEL HAS BEEN REPAIRED.
C
      COMMON / ALPHA /
     1  INFOT(14,60), INFOS(26,6), NTIME(60,3), NODES(15),
     2  MOVE(15), TRVL(15,15), RANDS(6), ITEMS(40),
     3  HEAD(7), IADD(6), IASSGN(2,6), INFOUT(51,9)
C
      EQUIVALENCE
     1   ( NOWT, ITEMS(15)),  (NSHVL,ITEMS(3)),
     2   (IPM, ITEMS(23)),   (IHSD,ITEMS(24))
C
      DO 12 I=1,NSHVL
      IF ( INFOS(6,I) .NE. NOWT )     GO TO 12
      IF ( INFOS(7,I) .EQ. 0 )    GO TO 12
      INFOS(7,I) = 0
      LOC = INFOS(14,I) - 1
      INFOS(5,I) = INFOS(5,I) + INFOS(LOC,I)
      IF ( IPM .EQ. 0 )      RETURN
      INFOS(6,I) = INFOS(6,I) + 360
C
C         IS ANOTHER SHOVEL DOWN FOR PREDICTED MAINTENANCE
C
      IHSD = 0
      DO 2 J=1,NSHVL
      IF ( INFOS(7,J) .NE. 1 )    GO TO 2
      IHSD = INFOS(5,J)
      RETURN
    2 CONTINUE
      RETURN
   12 CONTINUE
      CALL ERROR ( 102 )
      RETURN
      END
```

```
      SUBROUTINE OUTSHF
C
C         ROUTINE TO OUTPUT INFORMATION AT END
C         OF SIMULATION OF SHIFT
C
      COMMON / ALPHA /
     1  INFOT(14,60), INFOS(26,6), NTIME(60,3), NODES(15),
     2  MOVE(15), TRVL(15,15), RANDS(6), ITEMS(40),
```

```
     3  HEAD(7), IADD(6), IASSGN(2,6), INFOUT(51,9)
C
      EQUIVALENCE
     1    (IOUT, ITEMS(2)),   (NSHVL,ITEMS(3)),
     2    ( IPM, ITEMS(23)),   (INITR, ITEMS(8)),
     3    (NTRCKS, ITEMS(12)),   (IBS,ITEMS(25)),
     4    (JSHFT, ITEMS(27)),   (IES,ITEMS(26)),
     5    (IDSPH,ITEMS(7)),   (ISHFT,ITEMS(11))
C
      JSHFT = JSHFT + 1
      IF ( ISHFT .NE. IBS )      GO TO 400
      WRITE (IOUT, 979)   HEAD
  979 FORMAT ( /// /// 40X, 7A10 )
      WRITE (IOUT, 980 )  NTRCKS, NSHVL, IDSPH, IPM, INITR
  980 FORMAT (  /       I3, * TRUCKS*, I5, * SHOVELS*, I5,
     1    * DISPATCH*, I5, * PREDICTED MAINTENANCE*, O25,
     2    * RANDOM NUMBER*    //  53X, *LOADS*, 5X,
     3    *A.T.I.*,  13X, *IDLE SHOVELS*, 18X, *TOTAL*   )
C
  400 CONTINUE
      IDLES = 0
      LOADS = 0
      DO 412 I=1,NSHVL
      LOADS = LOADS + INFOS(1,I)
      IDLES = IDLES + INFOS(2,I)
  412 CONTINUE
      IDLET = 0
      DO 414 I=1,NTRCKS
  414 IDLET = IDLET + INFOT(2,I)
      FN = IDLET
      FD = NTRCKS
      IDLET = FN / FD
      INFOUT(JSHFT,1) = LOADS
      INFOUT(JSHFT,2) = IDLET
      DO 424 I=1,6
      INFOUT(JSHFT,I+2) = INFOS(2,I)
  424 CONTINUE
      INFOUT(JSHFT,9) = IDLES
      WRITE (IOUT,982)  ISHFT, LOADS, IDLET,
     1    (INFOS(2,I), I=1,6), IDLES
  982 FORMAT ( 40X, *SHIFT*, I3, I9, I11, 4X, 6I6, I9 )
C
      IF ( ISHFT .NE. IES )       RETURN
      FD = JSHFT
      DO 522 JJ=1,9
      J = 10 - JJ
      DO 520 I=1,JSHFT
  520 INFOUT(51,J) = INFOUT(51,J) + INFOUT(I,J)
      FN = INFOUT(51,J)
      INFOUT(51,J) = FN / FD
  522 CONTINUE
```

```
      AVRG = FN / FD
C
      WRITE (IOUT, 984) AVRG,  (INFOUT(51,J),  J=2,9 )
  984 FORMAT ( / 40X, *AVERAGES*, F11.1, I9, 4X, 6I6, I9 )
      SUMSQ = 0.0
      DO 528 I=1,JSHFT
      FN = INFOUT(I,1)
      SUMSQ = SUMSQ + (FN-AVRG)**2
  528 CONTINUE
      SE = SQRT(SUMSQ) / FD
      WRITE (IOUT, 985 )   SE
  985 FORMAT ( 40X, *STANDARD ERROR LOADS =*,  F4.1 )
C
      RETURN
      END
```

```
      FUNCTION NRML ( EX, SD, SDL, SDR )
C
C        NORMAL TABLE LOOK-UP TRUNCATED.
C
C        TRUNCATED NORMAL DISTRIBUTION BY RECTANGULAR
C        APPROXIMATION.  DISTRIBUTION IS TRUNCATED AT SDL
C        DEVIATIONS TO THE LEFT AND AT SDR DEVIATIONS TO THE
C        RIGHT.  DISTRIBUTION IS DIVIDED INTO 26 SEGMENTS.
C
C        EX    = EXPECTED VALUE
C        SD    = STANDARD DEVIATION
C        SDL   = LEFT LIMIT IN UNITS OF STANDARD
C                   DEVIATIONS.  (GIVEN AS A POSITIVE VALUE.)
C        SDR   = RIGHT LIMIT
C
      DIMENSION CDI(26), CDIP1(26), XI(26), XIP1(26)
      DATA (CDI(I), I=1,26) /.5000, .4013, .5987, .3085,
      DATA (CDI(I), I=1,26) /.5000, .4013, .5987, .3085,
     1   .6915, .2266, .7734, .1587, .8413, .1056, .8944,
     2   .0668, .9332, .0401, .9599, .0228, .9772, .0122,
     3   .9878, .0062, .9938, .0030, .9970, .0013,
     4   .9987, .000 /
      DATA (CDIP1(I), I=1,26)/ .5987, .5000, .6915, .4013,
     1   .7734, .3085, .8413, .2266, .8944, .1587, .9332,
     2   .1056, .9599, .0668, .9772, .0401, .9878, .0228,
     3   .9938, .0122, .9970, .0062, .9987, .0030, 1.000,
     4   .0013 /
      DATA ( XI(I), I=1,26) / 0.0, -.25, .25, -.50, .50,
     1   -.75, .75, -1.00, 1.00, -1.25, 1.25, -1.50,
     2   1.50, -1.75, 1.75, -2.00, 2.00, -2.25, 2.25,
```

```
     3   -2.50, 2.50, -2.75, 2.75, -3.00, 3.00, -4.00 /
      DATA ( XIP1(I), I=1,26) / .25, 0.0, .50, -.25, .75,
     1   -.50, 1.00, -.75, 1.25, -1.00, 1.50, -1.25, 1.75,
     2   -1.50, 2.00, -1.75, 2.25, -2.00, 2.50, -2.25,
     3   2.75, -2.50, 3.00, -2.75, 4.00, -3.00 /
C
  100 CONTINUE
      R = RANF(0.0)
      DO 20 I=1,26
      IF ( R - CDI(I) )  20,300, 300
  300 IF ( CDIP1(I) - R )  20, 400, 400
  400 X = XI(I) + ((R-CDI(I)) / (CDIP1(I) - CDI(I))) *
     1   (XIP1(I) - XI(I))
      GO TO 90
   20 CONTINUE
C
   90 CONTINUE
      IF ( SDL + X )  100, 500, 500
  500 IF ( SDR - X )  100, 900, 900
  900 CONTINUE
      X = X * SD + EX
      NRML = X * 60.0
      RETURN
      END




      FUNCTION REXPN ( EX )
C
C        ROUTINE TO DETERMINE EXPONENTIAL RANDOM VARIATES
C
C        EX = EXPECTED VALUE = 1.0 / ALPHA
C                   WHERE ALPHA = RATE OF OCCURENCE
C
      R = RANF(0.0)
      REXPN = -EX * ALOG(R)
      RETURN
      END
```

```
      SUBROUTINE ERROR  ( IGOOF )
C
      COMMON / ALPHA /
     1  INFOT(14,60), INFOS(26,6), NTIME(60,3), NODES(15),
     2  MOVE(15), TRVL(15,15), RANDS(6), ITEMS(40),
     3  HEAD(7), IADD(6), IASSGN(2,6), INFOUT(51,9)
C
      EQUIVALENCE
     1   (IOUT, ITEMS(2))
C
      WRITE (IOUT,91)  IGOOF
   91 FORMAT ( /// /// 10X,  * FATAL ERROR *  I6  )
      CALL EXIT
      RETURN
      END
```

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