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APPLICATION OF SIMULATION MODELLING IN COMPUTER AIDED SELECTION OF EQUIPMENT FOR TUNNELLING

by

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Abstract

The conventional drill and blast method of tunnelling is still accepted as the most versatile technique in excavating underground openings in hard rock. With the advent of new technologies and equipment, this centuries old method has been improved to a highly efficient process. In the pre-planning stage of a tunnelling project, selection of appropriate methods and equipment is of great importance for efficient execution.

A computer based iterative method employing simulation technique was developed to aid in the selection of equipment for hard rock full face drill and blast method of tunnelling. The research mainly converged on the identification and categorization of different operations involved, with alternative methods of execution and modelling of these on a time basis. The objective was to generate the required cycle times with different methods and equipment for a given tunnelling condition. Specifications on a wide range of equipment available in different categories and sizes were obtained and stored with standardized formats in several databases. Formats were standardized based on their relevance in depicting equipment characteristics and requirements of the simulation program.

A preliminary equipment selection program was developed to generate filtering conditions to access equipment databases. Options generated by databases are applied to the simulation program which provides total cycle time and individual activity times for a given tunnel segment. This program generates times for individual operations through random accession of appropriate probability distributions. Simulation is carried out with these generated time values. Statistical analysis of the total cycle time indicates the level of confidence with which it will lie within a specified time interval, which is kept as an indicator to optimize the selection of equipment. By changing equipment, methods and advance per round iterations are used to arrive at the optimum tunnelling advance rate compatible with the system layout.

1.0 Introduction

Tunnel construction is one of the most difficult, expensive and important segments in the field of construction. Excavation process plays the most dominant part and project duration is generally governed by the progress of excavation which makes it the most important segment of the project. Tunnels are driven in diverse ground conditions ranging from soft clays to hard rock. Ground conditions covering the geology of the area dictate the method of excavation to be adopted in a particular tunnelling venture. Majority of transportation and hydraulic conveyance tunnels are excavated through medium to hard rock.

Hard rock tunnelling can thus be taken as the most important area in tunnel construction. Further it has vital applicability in subsurface mining operations. In present construction practice, two major methods of excavation are adopted in hard rock tunnelling. These are drill and blast method and utilization of tunnel boring machines. Though the latter has gained a considerable popularity in present times, former is still the most adaptable, versatile and economical method in conditions of diverse geological characteristics. Drill and blast method is used in different configurations based on the tunnel size and length. For small to medium size tunnels full face excavation technique is generally adopted.

Pre-planning is of utmost importance for any project but more so for a tunnelling project which has to be carried out in a constricted space. In order to expedite tunnel excavation it has to be mechanized and therefore

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the planning for equipment becomes a crucial factor. The selection of equipment is based on construction method to be employed, ground conditions and tunnel dimensions. Hence this selection becomes one of the major considerations in the pre-planning stage.

This study was carried out to employ system techniques such as modelling and simulation in the selection of equipment fleet for a given tunnelling job. A simulation model was developed to depict the operations on a time basis with options of different construction methods and different types and sizes of equipment. This model can be used as an iterative tool in identifying the optimum equipment fleet based on the total cycle time for a drill and blast round.

2.0 Formulation of the model

The concept behind the formulation of the model for this study is the derivation of operation times of various activities associated with hard rock full face drill and blast method of tunnelling. This conventional tunnelling method essentially involves a cyclic set of operations which should be carried out for each round of advance. The derived time values are used to estimate the cycle time for a round. For the tunnel size range adopted for this study, which is 2.00 m - 8.00 m (representative cross-sectional dimension), cycle time for a round should generally coincide with the working shifts. One or more cycles may fit into one shift. Tunnel size range was selected based on the maximum size for economical full face drill and blast method as the upper limit and minimum feasible dimension for mechanized operations, as the lower limit. For larger tunnels using heading and benching method of excavation, the concept remains valid for heading operation provided that no appreciable influence is imposed upon this by the benching operation.

Drill and blast tunnelling process cycle is assumed to consist of the following operations.

Surveying and setting out
Drilling preparations
Drilling the rounds
Charging and wiring the blast
Blasting and defuming
Scaling and mucking preparations
Muck loading and transporting
Provision of temporary supports.

Temporary support provision is an optional activity governed by the ground conditions encountered.

Operations listed above are carried out in many ways in practice, utilizing different equipment and methods. For the purpose of this study, several of the more popular and widely used methods were modelled. Durations of the operations involving variations in equipment productivity should be estimated by considering the uncertainty. This could best be done by adopting a probabilistic distribution for the purpose. Then the model can access these distributions, which is known as the Monte-Carlo method to generate activity times and equipment productivity values.

3.0 Type of the probability distribution adopted

Nesargi (6) has adopted a triangular distribution for modelling operations in hard rock drill and blast tunnelling process. He has supported his selection by data obtained from actual tunnelling projects. Also the project planning technique PERT (Program Evaluation and Review Technique) uses beta distribution to model activity durations, which closely approximates triangular distribution. Triangular distribution itself is a statistically viable probability distribution with three governing parameters which are optimistic, most probable and pessimistic estimates. Hence triangular distribution has been selected to model tunnel operation times. This distribution can be mathematically expressed as follows,

$$
\begin{aligned}
f(x) &= 0 && -x < a,\ x > c \\
&= 2(x-a)/(b-c)(c-a) && -a \leq x \leq b \\
&= 2(c-x)/(c-b)(c-a) && -b \leq x \leq c
\end{aligned}
$$

Where a, b and c are the lower, most probable and the upper estimates of the distribution respectively. Based on research by Chauhan (1), the advance per round was also modelled as a triangular distribution.

Total cycle time is generated by summing up the operation times for various activities generated by random accession of appropriate triangular distributions. Hence according to the Central Limit Theorem, the total cycle time will be normally distributed. This enables the normal distribution to be used in statistical analysis of the total cycle time values to predict the reliability of simulated durations.

4.0 Evaluation of parameters for probability distributions

Parameters required to define a triangular distribution are the three estimates namely; optimistic, most probable and pessimistic. For distributions depicting production rates of equipment, these estimates are derived from ideal production rates by the application of job and management conditions prevalent at the site. As adopted by previous researchers these conditions were categorised as good, fair and poor based on subjective interpretations.

With the above considerations in view, optimistic estimate was considered as the ideal rate while pessimistic estimate was given 40% of the ideal rate for production rates of equipment. Factors for the derivation of the most probable estimate from the ideal production rate were extracted from the matrix of job and management factors(7).

Table 1

Factor matrix based on job and management conditions

Job \ Management	Good	Fair	Poor
Good	0.75	0.71	0.65
Fair	0.69	0.65	0.60
Poor	0.61	0.57	0.52

Other activities which do not involve equipment were also modelled by using triangular distributions. Some examples are the drilling preparation time, scaling and mucking preparation time, surveying time, charging and wiring time, etc. In these cases the user is expected to provide the model with average expected times for such activities based on his experience and judgement. This parameter thus provided will be reduced to the three time estimates by factors derived with consideration of the nature of the activity. As an example, if charging and wiring time in a drill and blast cycle is considered, the average time for charging and wiring of a drill hole is required from the user, which will be used as the most probable estimate. Based on previous case studies and job reports, the optimistic time is taken as 70% and pessimistic time as 125% of the most probable time estimate.

5.0 Modelling of operations

Operations are modelled on a real time basis so as to depict the progress on a time scale. Activities within each operation have been accounted with their interrelations in this modelling.

Out of the eight operations modelled, only two operations dominantly utilise equipment. These two are drilling operation and muck loading and hauling operation. Modelling logic and block diagrams for only these two operations are presented in this paper.

6.0 Model for drilling the rounds

Two of the most popular types of equipment, viz. decked jumbo and hydraulic boomed rigs are considered in the model. The model allows two sizes of holes to be drilled using the same drills in order to accommodate parallel hole cuts which have gained much acceptance in the recent times for mechanized drilling. Governing factors for the duration of this operation is the penetration rate of drills. This rate depends on the rock type, type of drill and type of drill bit among other things. Hence the most reliable estimate of this value could be obtained by conducting field tests on the rock type with the type of drill and drill bit in question. In the absence of such data, the drilling rate for percussive drills can be estimated by an empirical relation presented by Hibbard et al. (4).

$$R = P/(A*E)$$

for

$$35 < C < 345 \Rightarrow E = 1.0344 \times 10^{-4} \times e^{0.00497*C} \qquad (kJ/mm^3)$$

$$C > 345 \Rightarrow E = 4.1835 \times 10^{-4} \qquad (kJ/mm^3)$$

Where;

- R = Rate of penetration (mm/s)
- P = Power output of the drill (kW)
- A = Cross sectional area of the hole (mm^2)
- E = Energy per rock volume disintegrated (kJ/mm^3)
- C = Compressive strength of rock (N/mm^2)

The model provides for both these options. A block diagram indicating the flow and the logic of the model for drilling with a decked jumbo is illustrated in Fig. 1. For hydraulic boom mounted rigs the model is very close to the above. In the proposed model drilling with multipe drills is considered. Time requirements for steel extension, collaring, positioning, together with the option for drilling two sized holes with the same drill are also incorporated.

7.0 Muck loading and transportation

Muck transportation is divided into two main modes: (i) rail mounted and (ii) tired transport. Inturn the rail transport is subdivided into single and double track configurations. Muck loading systems are then selected to match these transport modes.

8.0 Single track system

Since the loading of muck cars at the face is done one by one, a switching arrangement should be provided at the face to present each muck car to the loading device. This car switching arrangement can be a straight forward method such as Cherry picker, Side switch, Spur track or a California switch. Also the same purpose can be achieved by an indirect method conveying the muck along the track such as overhead conveyer or a shuttle train. Shuttle train is a new innovation which has a conveyer for the bottom of muck cars. For passing of trains along the track, separate train switches are provided. Single train operation does not require train switches while two and three train operations are modelled with two train switches, one at the portal and the other near the face (Fig. 2).

A block diagram is presented in Fig. 3 illustrating the logic used in the modelling of operations with only two trains, for simplicity.

9.0 Double track system

This system is more favorable in terms of movement efficiency since one track each, can be reserved for inward and outward traffic. Intermediate switching between tracks is normally achieved by using a Diamond switch. Muck loading is governed by the cleanup reach of the loader. For a loader capable of loading over the full tunnel width when placed centrally, a half California switch can be used to unify the rail tracks at the face. In the case of a loader which has the reach of only half tunnel width both tracks should extend to the loading point and switching of cars and trains is achieved by a diamond switch in the vicinity of the face. Track configurations are illustrated in Fig. 4. Model block diagram for this mode is presented in Fig. 5.

Train speeds are calculated based on characteristic curves of tractive effort versus speed of travel for locomotives which can be readily converted to an exponential regression equation. Tractive effort requirement is evaluated by consideration of weight and number of muck cars as well as grade along the track.

10.0 Tired transportation system

Generally in this mode, pneumatic tired trucks are used for muck haulage, while pneumatic tired or crawler tracked loaders are utilised for muck loading. Two different loading conditions were considered in developing the model. First type of loading condition is with a loader such as side dump, overhead throw or conveyer type which can carry out the operation without changing its orientation. The second type is with a loader such as front end dump which has to turn to discharge the bucket into the haulage vehicle. Load haul dump (LHD) machines also fall in to this category. These loading configurations are illustrated in Fig. 6. Travel speeds for haulage vehicles are evaluated using grade versus speed curves for trucks in loaded and empty travel. A block diagram of the model for the LHD machine or front end loading mode is given in Fig. 7.

11.0 Total simulation model

Total simulation model is made up of all contributing operation models linked by the simulation control, with data input and output facilities. Result of the highest interest arising out of the simulation study is the total cycle time required when a given set of conditions are applied. It is the intention of the tunnel constructor to have the total cycle time fit the shift time or any other convenient time duration. Though exact time prediction is not feasible, the concept of statistical confidence can be adopted to indicate the certainty with which the probable cycle time is generated. By the types of distributions used in the derivation of operation times it is evident that the total cycle time is normally distributed. By statistically analyzing the cycle time values for several simulation runs the level of confidence with which the cycle time falls within a time range specified by the user can be estimated.

12.0 Equipment databases

For tunnel construction planner to understand the capabilities, limitations and adaptability of the diverse range of equipment available, an efficient method of categorizing and storing of data should be available. The requirement of an equipment database system becomes even more important when equipment selection is based on simulation results.

With the above objective in mind several databases were created to store equipment data under different categories. Specifications of equipment were obtained from leading tunnelling equipment manufacturers around the world. The databases developed through a commercial database package could be constantly updated. Fields under which relevant data was stored were selected mainly to suit the required inputs to the main simulation model, although other important parameters were also stored where necessary.

Databases developed were on;

1.	Rock drills	25 cases
2.	Rock drill feeds	23 cases
3.	Hydraulic boom mounted drilling rigs	30 cases
4.	Muck loaders	65 cases
5.	Haulage locomotives	70 cases
6.	Rail mounted muck cars	36 cases
7.	Pneumatic tired muck trucks	6 cases
8.	Shotcrete spraying machines	9 cases

In order to access these databases, a preliminary selection of equipment options is required based on the size of the tunnel and methods to be utilised in the construction. To cater for this purpose a preliminary equipment selection criteria was identified. This criteria, developed into a computer program is capable of proposing equipment dimension and capacity ranges based on the tunnel size. These ranges are inturn used to access the databases in the initial selection of equipment for a particular job. After this initial filtering several equipment combinations can be tried on the simulation model to iteratively arrive at the optimum selection of equipment fleet based on performance and cycle time.

13.0 Computer simulation program

Previously discussed model of the logic of operations involved in tunnelling operations were developed into a computer program with the aid of Basic language to run on IBM compatible micro computers. Modular structuring adopted throughout the programming enables edition and enhancement of the program relatively without complication. The main structure of the program is illustrated in the form of a block diagram in Fig. 8.

14.0 Conclusions

The simulation model program and other peripherals supporting it could be used very effectively in the planning stage of a tunnel construction job as an aid in optimizing the selection of equipment fleet. The equipment databases developed could be constantly updated to reflect new additions and improvements of equipment in the currently vast array available in the market. The adaptability of the model to many different methods of operations makes it possible for the planner to evaluate the feasibility of different combinations of methods and equipment. Most importantly this model can assist the planner to select equipment fleet to suit a particular cycle time and advance per round. Further it could be used as a tool to evaluate the effect of advance per round on the total cycle time.

15.0 References

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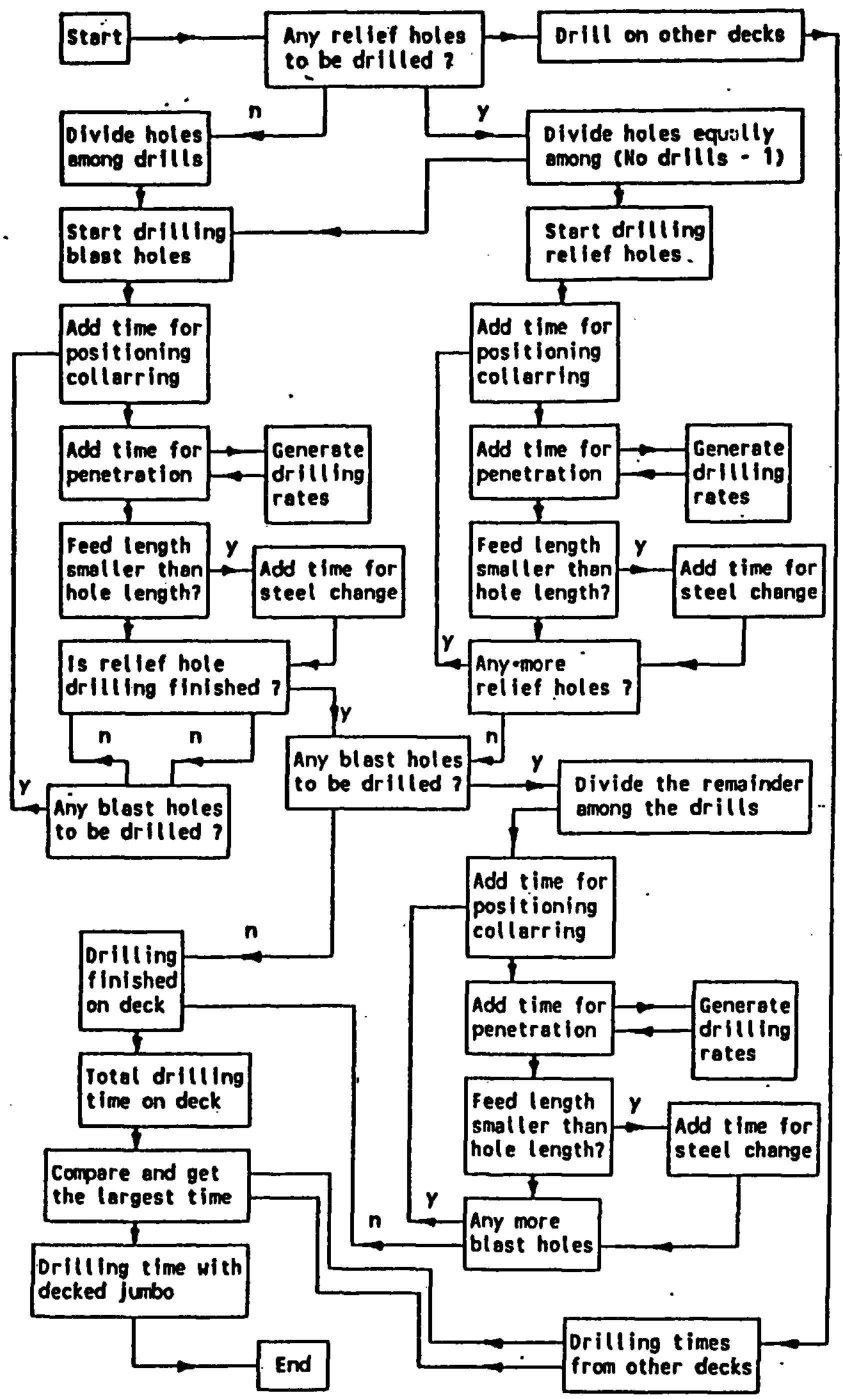


Figure 1 <u>Model for drilling with a jumbo (Single deck)</u>

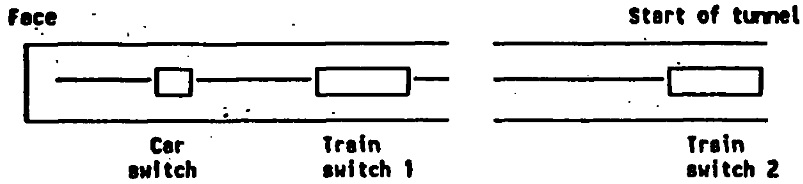


Figure 2 Single rail track configuration

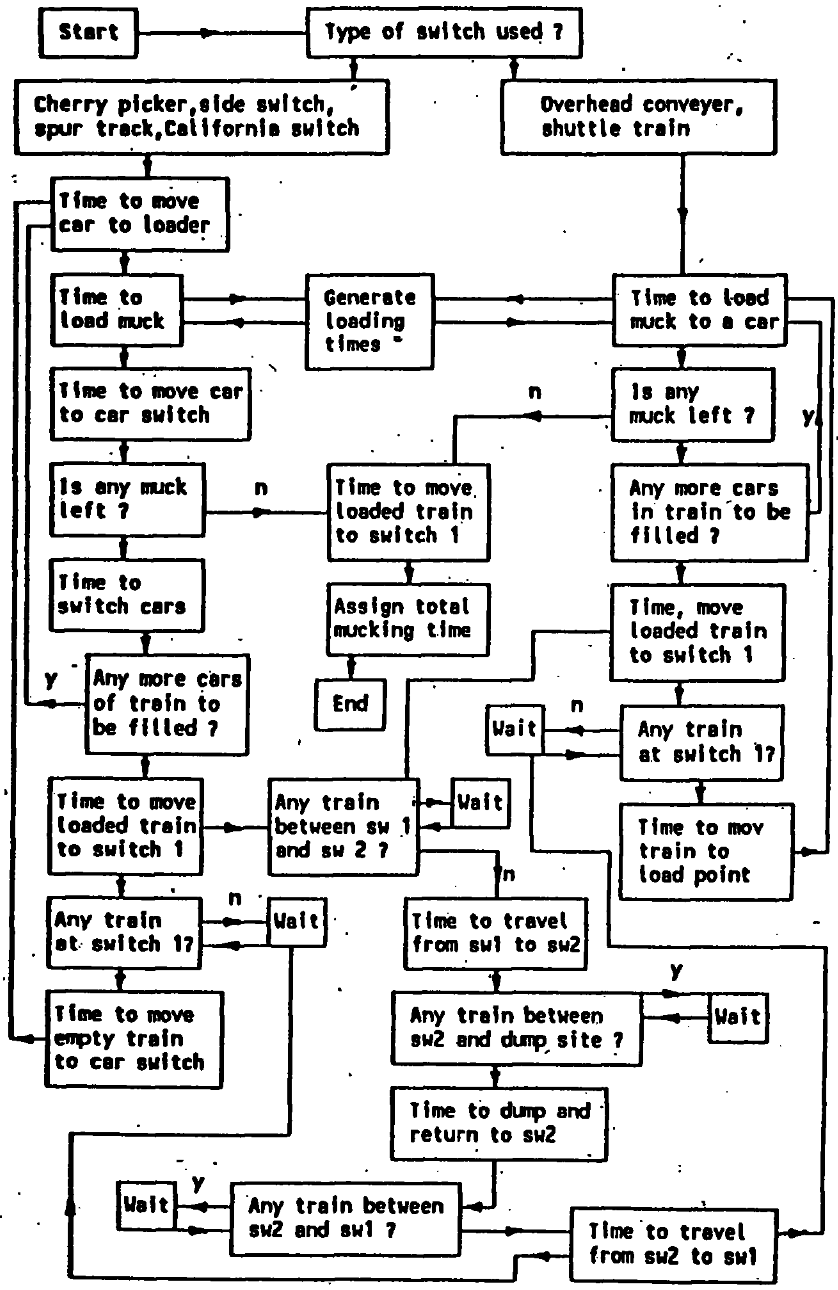
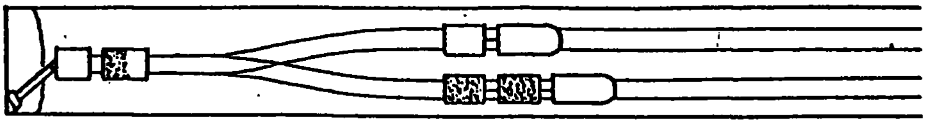
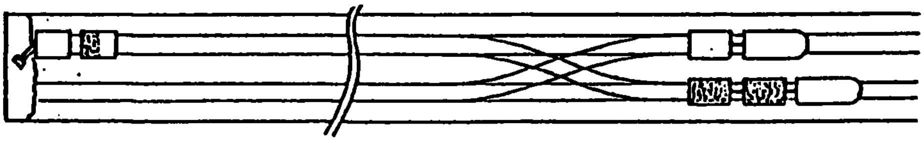


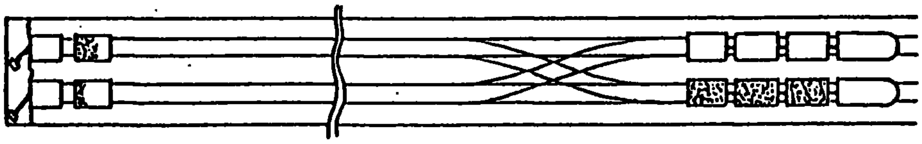
Figure 3 Model for muck haulage with single rail track



a) Loader with full tunnel width cleanup reach
Car switching by half California switch



b) Single loader with half tunnel width cleanup reach
Car switching by Diamond switch



c) Two loaders with half tunnel width cleanup reach
Car switching by Diamond switch

Figure 4 Track layouts and switching devices for double track

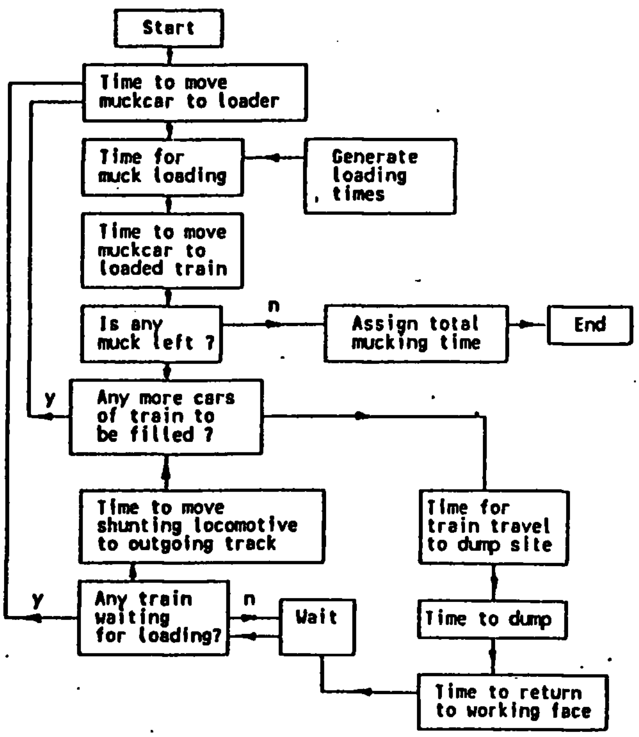


Figure 5 Model for muck haulage with double track rail system with full cleanup width loader

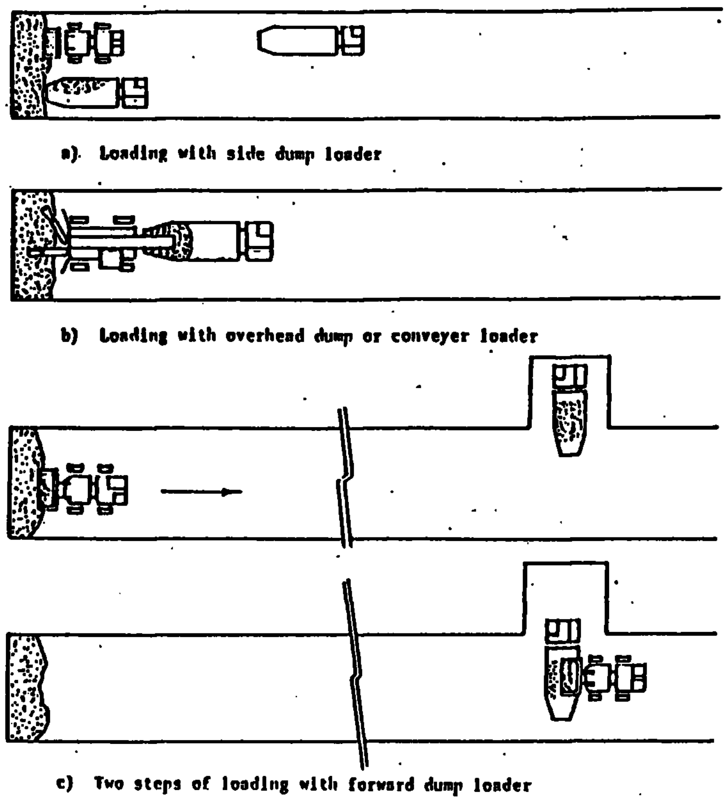


Figure 6 Loading methods with tired or crawler mounted vehicles

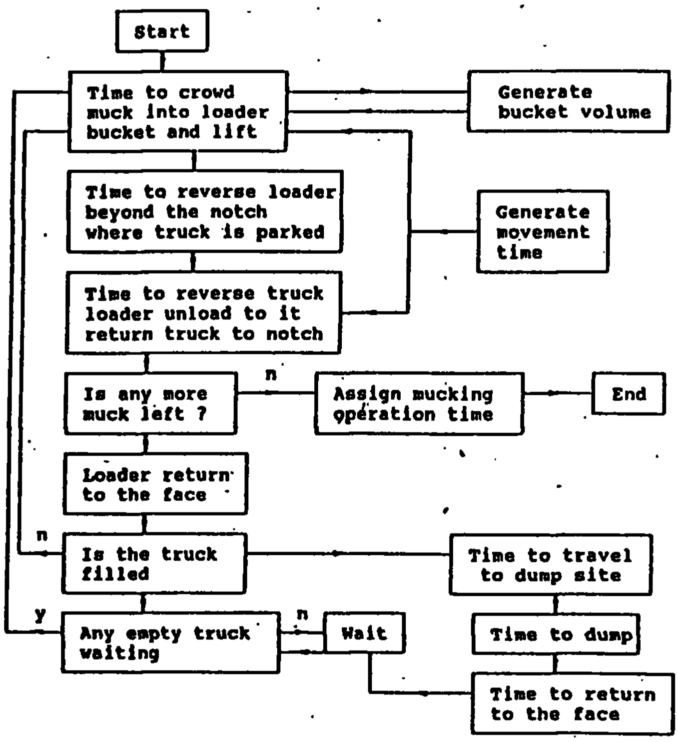


Figure 7 Mucking model for tired transport with a front end dump loader

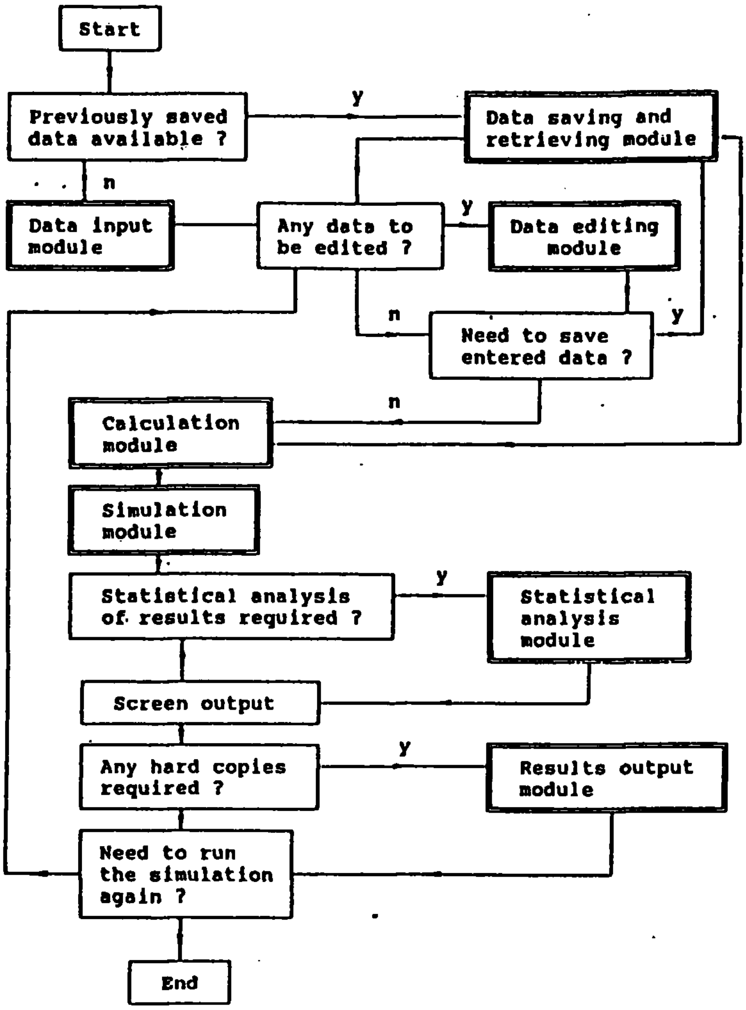


Figure 8 Structure of the total simulation program