The Simulation of Underground Stoping and Transport Operations in Gold Mining

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SYNOPSIS

Simulation is a technique for studying the operation of systems by synthetic experimentation. With digital computers it is possible to simulate even the complex production processes in gold mining. This has great potential in that it enables the investigation, analysis and comparison of mining systems to be done accurately, rapidly and at low cost. Two programs have been developed to simulate the principal underground production processes in gold mining.

These are the simulation of any stope contract and the simulation of underground transport operations. The programs synthesize these mining activities from a large number of small unit operations. The stope contract program simulates rockbreaking by drilling and blasting and the cleaning of the panels by face and gully scraping. The transport program simulates the functions and movements of all vehicles running on rails on one underground level. The simulation programs provide an effective means for experimenting with mining activities.

INTRODUCTION

In planning or running a mine, engineers are faced with both technical and organizational problems.

The technical problems concern the performance and design of machinery, techniques for carrying out operations, and the use of sciences such as rock mechanics and heat mechanics. Most of the technical aspects of mining are amenable to analysis and are now receiving attention, with the result that new equipment and techniques are being developed.

The organizational problems concern the utilization of these facilities, such as the selection of equipment, planning the layout of a mine and the sequence of operations. The organizational problems are so large and complex that the application of methods such as linear programming and queueing theory has been possible in only a limited number of simple cases. However, these complex organizational problems can be studied by simulation.

In simulation a model of the mining activity is constructed in the form of a computer program. In accordance with this program, the computer proceeds by arithmetical and logical steps to follow in proper sequence and order the unit operations constituting the activity and so reproduce its behaviour for virtually any specified conditions.

Simulation provides the engineer with an effective means for experimenting with any mining activity to gain a synoptic view of its behaviour. In this way, engineers can quickly and easily gain experience of a variety of situations to arrive at good practical answers to the design of mines and the planning of mining operations.

Any development, if it is to find profitable application in mining, must finally be proved in use underground. Simulation enables such underground experiments to be based on a much more thorough evaluation of the problem, and avoids much work which might otherwise have to be done in difficult circumstances underground.

Of the many mining operations to which simulation can be applied underground, production processes appear to demand the most attention, since they incur the greatest proportion of the costs, employ most labour, and have been least amenable to precise analysis.

There are several advantages in subdividing a complete mine operation into a number of subsystems. A simulation program for such a subsystem can be developed more rapidly than can one for the mine as a whole, and it can be put to use while other programs are being developed. A special-purpose program requires less preparation, saves computer time and can be used on smaller computers. Judicious subdivision of the mining system can make it possible for the output of one computer program to form the input to another program, so that ultimately the entire mining system can be simulated.

The production process in a gold mine can be divided into two distinct subsystems, namely, the stoping system and the transport system. Fundamentally, stoping is a source function while transport is a transmission function.

A stope system consists of many contracts, each of which is relatively independent of its neighbours, so that only one contract need be simulated.

By treating the transport system on an open-ended basis, it can be subdivided such that the rail transport on only one level need be simulated.

This paper deals with these two simulation programs, neither of which has made direct use of any previously published material. Consequently no references are quoted in the text, but Emshoff *et al* (1970) is the best general reference on the subject which the authors have found so far.

METHOD OF SIMULATION

Since there exist many different types and methods of simulation, a short description of the method used in the construction of the stoping and transport models follows.

Computer simulation is effected by synthesising a process from a large number of small representative unit operations.

Initially, a careful study of the actual process is made so as to define accurately those features and operations essential to the process. From this, a computer program is written in accordance with which the computer assembles the unit operations in proper order and sequence, taking into account the characteristics of these operations important to the result.

The size and number of the unit operations used are selected according to the purpose of the model. On the one hand, a detailed model may be unnecessarily expensive to construct

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and run in relation to the information sought. On the other hand, sufficient detail must be included to ensure that the simulator is sensitive to the variables which it is desired to study.

The characteristics of each unit operation should be independent of every other unit operation, and the contribution of each to the overall result should be small. It must be possible to describe the required characteristics of each unit operation, which include:

(i) the duration of the unit operation, that is, the time taken to complete the operation without mishap,

(ii) the probability of failure or interruption while the operation is in progress,

(iii) the duration of the interruptions, and

(iv) the outcome or result of the operation.

The characteristics for the duration of the unit operation, the duration of the interruptions and the outcome of the operation may be specified by means of a fixed value, a formula, or, most frequently, by a range of values in a measured or a theoretical distribution. The probability of failure may be a series of probabilities for many types of failure. These characteristics and probabilities are determined from the analysis of actual underground observations.

During the simulation of every unit operation the duration of the event without mishap is determined first. If the duration of a unit operation has to be calculated from a distribution of values, a random number is generated which is used to select a value from the distribution. Therefore, when the calculation is repeated a different value is likely to be obtained; however, all the calculated values have the same distribution as those from which they are derived.

The probability of a failure is determined by generating another random number; if the random number is less than the probability of the occurrence of the failure, the failure is deemed to have occurred. The duration of the interruption due to the failure is then determined, and again random number generation may be used to select a value from a distribution.

The durations of the operation and of all the interruptions are then added together to determine the time to complete the unit operation. If the outcome of the unit operation is given by a distribution, a random number is generated and a value for the outcome is determined from the distribution.

The abovementioned operations are illustrated by Fig. 1, which is a simplified flow chart of a section of a program used to simulate the drilling of a single hole.

The procedure of using random numbers to select a value of a variable from a distribution of values makes it possible to use all the information contained in the distribution and thus provide an essential degree of realism by using values which differ from one another as they do in practice.

In synthesising the unit operations to form the complete model of the subsystem, the simulation program reassembles the unit operations by a sequence of calculations, the sequence being similar to the sequence of events in the mining process being simulated. This sequence of events is largely programmed into the model such that events are executed either in a pre-defined order according to some type of flow chart or, alternatively, on an outcome or result basis according to some

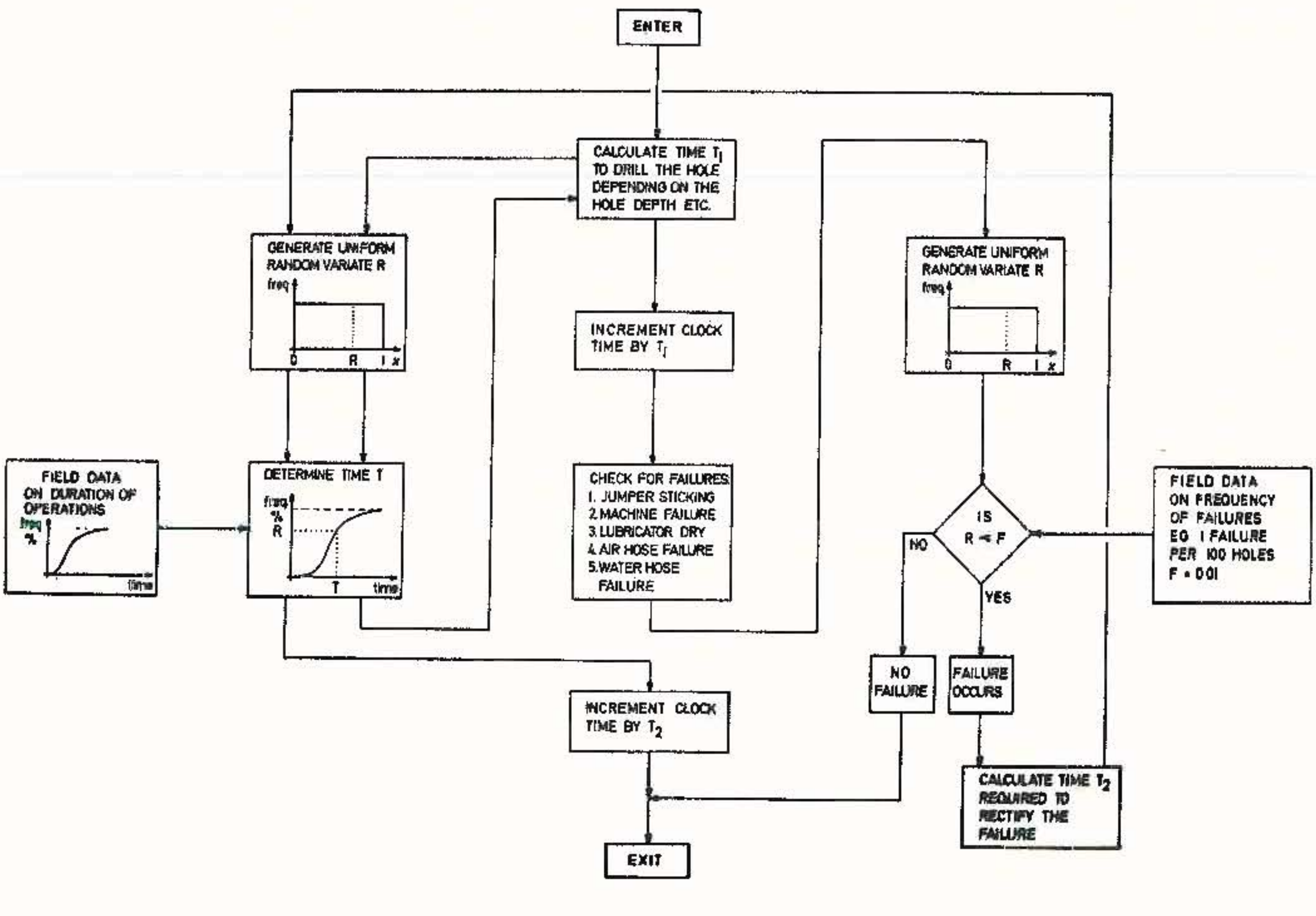

Fig. 1. Simplified example of a section of program used to simulate the drilling of a single hole.

type of decision table. Thus, the simulation programs are procedural models which express the dynamic relationships of the real system by means of a series of elementary operations on the appropriate variables and unit operations. In using the simulation models the prediction of outcomes is made by actually executing the procedural steps with appropriate initial data and parameters.

The programs are next-event type models in which one operation or event is dealt with at a time. For each operation, the duration and outcome are calculated and recorded on a list called the *calendar*. The calendar is scanned to find the earliest time recorded on it. The attention of the program is then switched to the operation corresponding to this earliest time and calculations for this operation are performed. The duration of this operation is added to the time on the calendar, that is, the time at which the operation was started, so that the time at which the operation is completed is obtained. The starting time is then removed from the calendar and replaced by the time of completion, which becomes the new starting time for the next event associated with that operation. The calendar is then scanned to determine the next earliest event, which may be the same operation or a different one. The computer then carries out the cycle of calculations for the relevant operation and repeats the process. Thus, the program switches from one operation or event to the other, making it possible for one event to interfere with subsequent events, so that the sequence of events progresses realistically in time. This method is suitable for simulating systems where dissimilar operations with widely differing durations are found and is particularly powerful for studying the interactions between interfering operations.

DESCRIPTION OF THE STOPE SIMULATION PROGRAM

The model simulates the rockbreaking, cleaning and support operations for one stope contract in a gold mine. A variety of combinations of panels making up a contract can be simulated with or without night shift cleaning. Rock is broken by drilling and blasting and the panel is cleaned by face and gully scraping. Any of the common types of support can be installed. The labour quota can be varied. The stope area covered by the simulator extends from the unmined rock to the centre gully.

Apart from the basic panel configuration, there are about 150 parameters which may be varied by the person running the simulation so as to alter the conditions of the experiment. The variable parameters extend from overall geometrical variables, such as the panel length and stope width, down to items such as winch speeds and scraper capacities. A data bank of the time distribution of operations and the probabilities of failures for unit operations has been built up from actual observations made underground. These data have been analyzed and provide the bulk of the input information. Thus, it is normally necessary to specify only about 20 input parameters to simulate a desired stope configuration.

An outline of the simulation program is shown in Fig. 2. The master control program performs the input and output operations and organizes all subsequent program flow depending upon the mining system that has been chosen.

Control is then passed to second-level control programs of which there is one for each of the three main types of operations, Fig. 2. These programs allocate the appropriate resources to the correct place at the correct time. For example, the rockbreaking control program would ensure that a certain panel is drilled only after cleaning operations have been concluded and drill crews have become available.

The actual mining operation subroutines are activated by the second-order control programs. These subroutines simulate the actual mining operations by calculating and sequencing their times. For example, at a certain stage in the simulation, the scraping program might be instructed by the cleaning control program that winch drivers have become available to clean a certain panel. The scraping subroutine then proceeds to simulate the cleaning of the panel until either the shift time elapses or all the rock has been cleaned from the panel, at which time program flow would pass back to the cleaning control program.

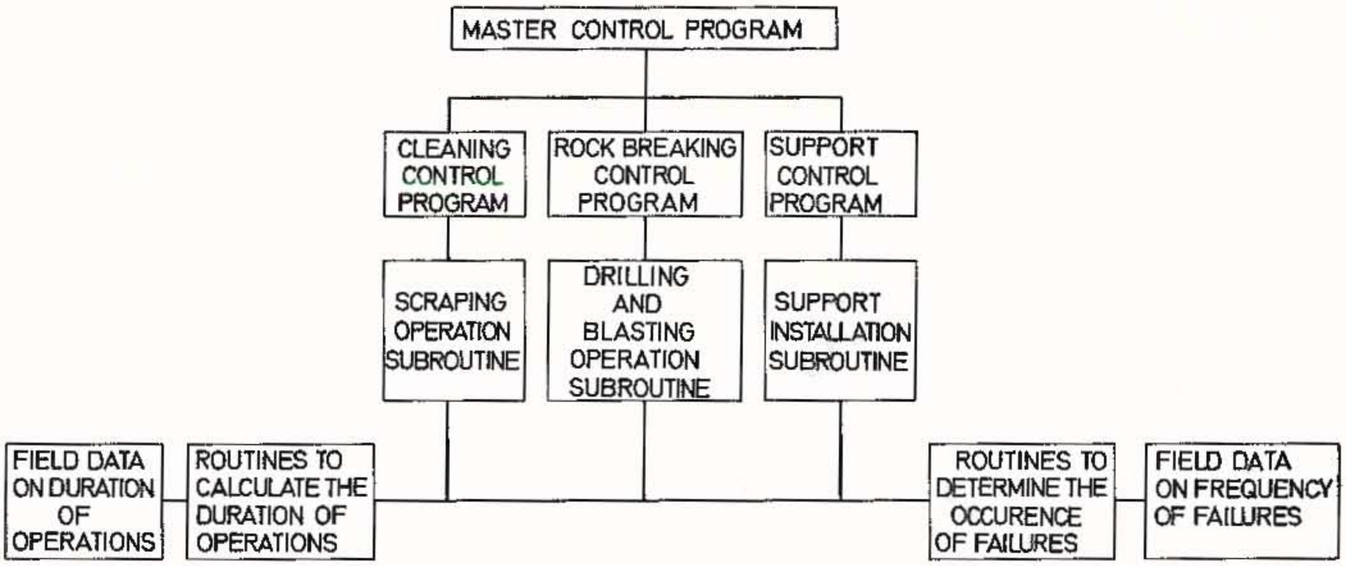

Fig. 2. Simplified flow diagram of a simulation model for rockbreaking, cleaning and support.

The mining operations are simulated at a high level of detail. For example, the drilling, charging and firing of each hole is simulated individually and the cleaning process is simulated on a scoop-by-scoop basis.

The three mining operation subroutines have access to programs which calculate the duration of operations and determine the occurrence of failures. These programs consist essentially of pseudo-random number generators which can select variates randomly from different pre-defined frequency distributions. Input to these programs consists of the field data which have been collected underground by actual observations.

Output from the program can be requested at three different levels of detail.

At the coarsest level of detail the program produces a summary showing the total number of blasts, the total area mined, the total tonnage extracted and the face advance for each panel over the period of time simulated. Labour efficiency figures such as the square metres per workman per month are also given.

A second summary indicates the type of activity conducted in each panel during every shift. Also listed are parameters such as the tonnage blasted or cleared, the number and type of delays which occurred and the amount of support installed.

At the finest level of detail a complete record is presented of the simulation, and it is possible to determine, for example, the exact time at which a particular hole was drilled and whether any delay was associated with it. Similarly, cleaning operations are listed for every pass of the scraper scoop with an inter-event time of about three seconds.

The program is written in FORTRAN IV language and requires 170 k of storage. It can simulate one month's mining in about five minutes on an IBM 360 mode 150 machine with a memory that has been uprated to that of a model 65. The program running time increases as the mining system is made more complex and also increases with the level of output detail required.

DESCRIPTION OF THE TRANSPORT SIMULATION PROGRAM

The transport simulation program simulates the functions and movements of all vehicles running on rails on one underground level, including the collection of ore from boxholes or ore passes, the tramming of the ore to the tips by locomotives pulling hoppers, and the transport of materials from shaft stations to the workings in cars moved by men or locomotives. The area covered by the program starts at the boxholes with rock entering the boxholes at a predetermined rate, or possibly varying at random, and ends at the shaft orepass, where the rock is dumped. The system is 'open' in the sense that there is a flux of some vehicles, materials and ore into and out of the system, with the result that it is sensitive to external influences and difficult to isolate.

The system effectively has two types of input and two types of output. The rock constitutes an input at the boxholes or development ends and an output at the shaft tips. Material cars form an input as they enter the system from the shaft. Empty material cars at the shaft are an output.

Although the methods of calculating operation times and the occurrence of failures are the same as in the stope simulator, there do exist some marked differences between the programs. In the stope simulation program the operations are cyclic, namely, a panel is drilled, then blasted, and finally cleaned. The program is structured accordingly. Even at a greater level of detail, such as in preparing the face and drilling, the operations are still largely sequential. Thus program flow is basically sequential and cyclic.

However, the rail transport system is characterized by the simultaneous functioning of a great number of independent vehicles. A large amount of interference may occur between the variables, such as a number of locomotives using one track. Hence the program is structured differently. It is shown in simplified form in Fig. 3.

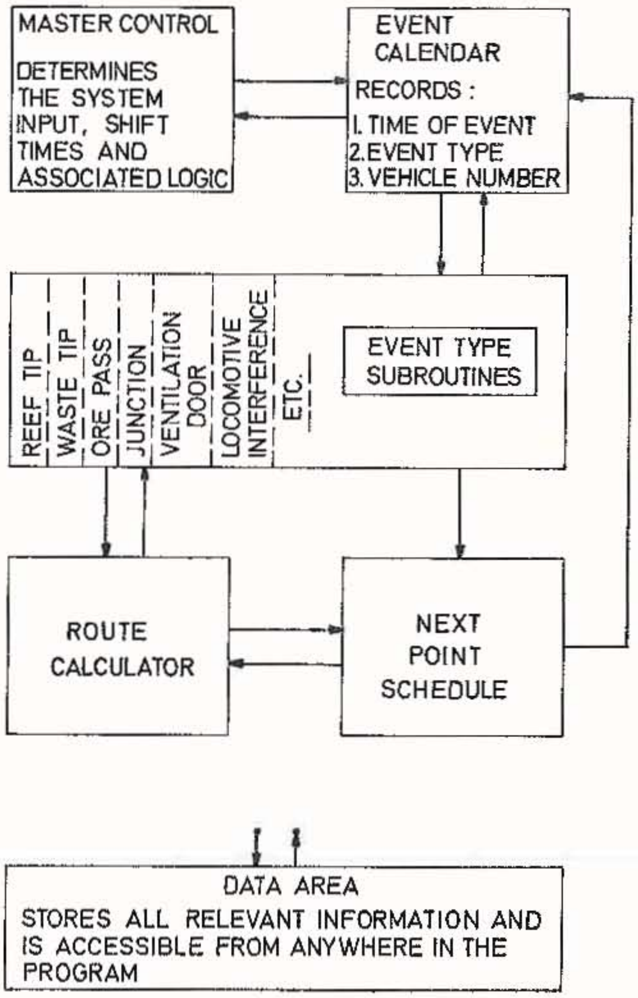

Fig. 3. Simplified flow diagram of the simulation model for transport.

The basis of this simulation is that a master program keeps an event list in the form of a *calendar*. This calendar is updated repeatedly as the master program switches from one event subroutine to another. For all vehicles it keeps a record of their position, occurrence of the previous event, occurrence of the next event and the vehicle attributes such as speed, direction, load and route.

Different event-type subroutines exist for all the different types of operations, such as loading at a boxhole, tipping at an ore pass and locomotive interference.

A powerful feature of the program is its route selector which scans the entire track layout to select a suitable route for each vehicle at appropriate times during the simulation. This feature makes it possible to simulate any track layout or changes in the layout, without re-programming the associated logic. The track layout is specified in the form of a number of interconnected points and the next point schedule governs the movement of vehicles from point to point on the track. In addition, a large number of data are kept in a data area which is accessible from anywhere in the program. All relevant information regarding the simulation is stored here and updated as simulation progresses.

The input to the simulator consists mainly of specifying the track layout, together with details regarding the position and capacity of ore passes, tips, shafts, development ends, ventilation doors, refuelling points, condition of track and visibility. In addition, it is possible to specify distributions for vehicle speeds, loading and tipping rates and all possible delays associated with tramming.

Output from the simulation program consists of summaries indicating items such as the total tonnage transported and details regarding the movement and interference of all vehicles. The amount of core storage required by the program and the program running time depend on the number of vehicles simulated and the complexity of the track layout. The program is written in FORTRAN IV language.

USE OF THE PROGRAMS

In essence, computer simulation is synthetic experimentation. It should be viewed as real experimentation and its use should follow exactly the same procedure. Initially, details regarding the mining situation, technique and specification of equipment must be defined. The experiment is then carried out and the results analyzed. Further experiments are then conducted in the light of the results. The purpose of simulation is for the engineer to gain experience rapidly so that he can arrive at a good solution to his problem by repeated experiments with the computer model.

Optimization by means of the computer models themselves is not an objective of the two simulation programs. 'Optimum' solutions are determined by the engineer using the programs on a trial and error basis. This approach provides much greater scope for innovation than could be achieved by making the computer seek the 'optimum solution'.

The mining engineer plays an essential role in the use of computer simulation. Before actually running computer experiments, he has to verify that the simulation model represents adequately the system which he wishes to analyze. The model can be verified easily by simulating an existing system similar or identical to the one being analyzed. The engineer must decide whether there is a sufficient degree of similarity between the results of the simulation and the existing system. He may need to provide additional data if the degree of similarity is not adequate. This procedure leads to the early identification of areas where more data may be needed and it gives the engineer confidence in the results that may emerge from the analysis. The engineer proceeds by making changes to the system and observing the results of the changes.

The sensitivity of the system to particular variables can be determined by changing these deliberately and examining the effect. Conversely, such a sensitivity analysis can be made to reveal the conditions to which a system is especially sensitive and then to modify the system so as to reduce its sensitivity to these conditions. Where artificial data have to be used, the importance of the accuracy of such data can be assessed by determining the sensitivity of the result to the data in question. Alternatively, those specifications important for a new system or item of equipment to yield some required result can be arrived at by repeated trials or a sensitivity analysis, using a range of specifications.

As an illustration of the use of simulation, Table I shows the results of a series of experiments utilizing the stope simulation program. In this series, four parameters were varied, namely, the number of panels per contract, the length of each panel, the depth of the holes drilled and the number of rockdrills used. The effective shift duration time was set at six and a half hours with the Saturday shifts shortened by one hour. Mining operations were carried out on day shifts only, night shift cleaning not being resorted to. The stoping width was one metre and two winch crews were allocated to the contract for cleaning. All other variables were assigned values typical of a normal underground stoping practice.

Two values were given to each of the four parameters varied, and the resultant sixteen possible combinations were simulated. One month's mining was simulated in each case and the total number of blasts, the total tonnage extracted, the total area mined, the average face advance per panel and the labour productivity are shown in Table I.

By studying the output of the simulation runs, a decision can be made on, for instance, the advantage of using a longer hole or assigning extra rockdrills to a panel. The 'optimum' configuration will depend on whether the purpose of the simulation experiment is to determine the system producing the largest mined area, the highest face advance, the best labour efficiency or the highest face utilization.

It must be emphasized that the results apply only to the specific system being simulated and may not hold true for other systems. Values in the table, however, indicate how a large number of different configurations can be tested quickly and easily.

CONCLUSION

The stoping and transport simulation programs offer a method of overcoming one of the principal obstacles to innovation and development in mining, namely, the time, cost and risk involved in executing experiments, when these could be done only underground.

TABLE I

SUMMARY SHOWING THE GROSS RESULTS OF A SERIES OF EXPERIMENTS USING THE STOPE SIMULATION PROGRAM

INPUT	Panels/contract	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3
	Panel length (m)	40	40	40	40	60	60	60	60	40	40	40	40	60	60	60	60
	Hole depth (m)	1,0	1,0	1,5	1,5	1,0	1,0	1,5	1,5	1,0	1,0	1,5	1,5	1,0	1,0	1,5	1,5
	No. of rockdrills	3	5	3	5	3	5	3	5	3	5	3	5	3	5	3	5
RESULTS	Total blasts	18	22	15	17	15	15	10	12	25	31	21	25	20	22	13	18
	Total tonnage	1 349	1 760	1 659	1 899	1 660	1 667	1 779	2 113	2 003	2 244	2 353	2 937	2 214	2 638	2 206	3 056
	Area mined (m^2)	504	659	621	711	622	628	666	791	750	841	882	1 100	830	987	827	1 145
	Average face advance per panel (m)	6,3	8,2	8,8	8,9	5,2	5,3	5,6	6,6	6,3	7,0	7,4	9,2	4,6	5,5	4,6	6,3
	Productivity (m^2/man/month)	18,7	21,3	23,0	22,9	23,0	20,3	24,7	25,5	27,8	27,1	32,6	35,5	30,7	31,9	30,6	36,9

The time required for an experiment is reduced since it is possible to simulate a month's mining in a matter of minutes. Thus, meaningful experiments can be conducted at rates much faster than those required to conduct actual mining experiments underground. This enables a larger number of experiments, covering a much greater range of conditions, to be conducted than would be possible underground. Hence, the probability of finding a much improved solution is increased.

The cost of an experiment is reduced since the cost of analysis by simulation is trivial when compared with that of conducting real experiments, or with the savings that can result from its use.

When the simulation of several stope or transport systems has shown one of them to be particularly promising, it will still have to be tried and perfected underground. This, however, can be done with confidence and at the minimum of risk because of the experience already gained from the simulation experiments.

Comparisons between a number of different systems can be made under truly identical conditions, which is not the case in the mine. It is also possible to investigate hypothetical systems which may not yet be available in practice, to assess their potential before committing resources to constructing such systems and equipment for them.

The computer can be made to print a complete record of the simulated system, making it possible to relate cause and effect more easily than in the real system. This has advantages when investigating the potential of new equipment or, conversely, when determining equipment specifications to achieve a desired result. Often the full potential of new equipment is not attained because of the unforeseen bottlenecks created by its use. However, with simulation, it is possible to examine, in advance, exactly how a new machine affects the whole operation.

The two simulation programs are designed to reproduce the behaviour of an actual mining process as accurately as possible and few specialized techniques are needed in using them, so that engineers, with little additional training, can use them with confidence.

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