# COMPUTER SIMULATION OF DRILL-RIG/SHOVEL OPERATIONS IN OPEN-PIT MINES

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Abstract

In open-pit mining, there are four main operations: drilling, blasting, loading, and haulage. In the past years, several studies have been made on the shoval-truck systems. However, the drilling-blasting-loading system was neglected in spite of the fact that it takes 30-40% of the total expenditure in production. In order to cover this gap, a computer simulation program was developed and the relationship between the drill-rigs and shovels was investigated. It is discovered that the advance of faces for each cycle plays a dominant role in meeting the requirements of a balance production. The simulation program can be used to calculate the optimum advance for different combination of machines.

## INTRODUCTION

Drill-rigs, shovels and trucks are the three main elements of production in open pit mining. The problem of selecting the best combination of trucks and shovels in open pits has been the subject of several studies (1, 2) in recent years. The problem of matching the shovels and the drill-rigs, however, has been neglected in spite of the fact that 30-40 percent of the total direct mining cost is attributable to drilling, blasting and loading (3, 4). In order to cover this gap, this paper presents a computer simulation method to deal with this problem.

In this paper, the relationship between the equipment characteristics and the rate of advance at each mining face is used to formulate a parametric solution algorithm. This algorithm is particularly useful in existing operations where the dynamic nature of pit configuration and the variable performance of equipment require a periodic adjustment in dispatching equipment. An optimum solution for a given case can become even infeasible when circumstances change. By means of simulation, the algorithm tests several rates of advance at the mining faces and determines the optimum one that corresponds to the highest equipment efficiencies.

## BASIC CONCEPTION

To illustrate the matching problem clearly, let us consider a simple case with two drill-rigs and four truck-shovel systems. Suppose that at a given time the drill-rigs #1 and #2 are located at the faces where shovels #1 and #3 are operating respectively. Also suppose that each shovel has some known amount of broken material ready to load. Initially, drill-rigs #1 and #2 operate at #1 and #3 shovel-faces. After finishing their work, they are moved to shovels #2 and #4 respectively, and the shovel-faces #1 and #3 are blasted. Thus, an additional amount of broken material become available to load for shovels #1 and #3. Figure 1 illustrates graphically what happens at the faces where shovels #1 and #2 are assigned. The solid lines represent shovel #1 and the broken lines represent shovel #2. At time $t_A$ shovel #1 has $V_A$ amount of broken material to load, which will decrease in time. Thus, at time $t_B$ the shovel #1 will have $V_B$ amount of broken material remaining to load. Suppose that drill-rig #1 starts working at face #1 at time $t_A$ and completes its task at time $t_B$, then moves to face #2. The shovel #1, however, continues to operate until time $t_C$ while blasting is prepared. At time $t_C$ shovel #1 is stopped and moved some distance away for the blasting. At time $t_D$ the shovel #1 begins to operate again with $V_E$ amount of broken material in front of it. Thus, no loading and hauling takes place during the time period $(t_D - t_C)$ at face #1. Similarly at face #2, the shovel #2 starts at time $t_A$ with $V_m$ amount of broken material. At time $t_N$ the drill-rig #1 arrives at face #2 and begins to drill. At time $t_O$ drilling is completed and the drill-rig #1 moves to the next face. At time $t_Q$ blasting is completed at face #2 and shovel #2 begins to operate with $V_R$ amount of broken material in front of it.

Proceedings of the 1982
Winter Simulation Conference
Highland * Chao * Madrigal, Editors

82CH1844-0/82/0000-0463 $00.75 © 1982 IEEE

Simulation of Rig/Shovel (continued)

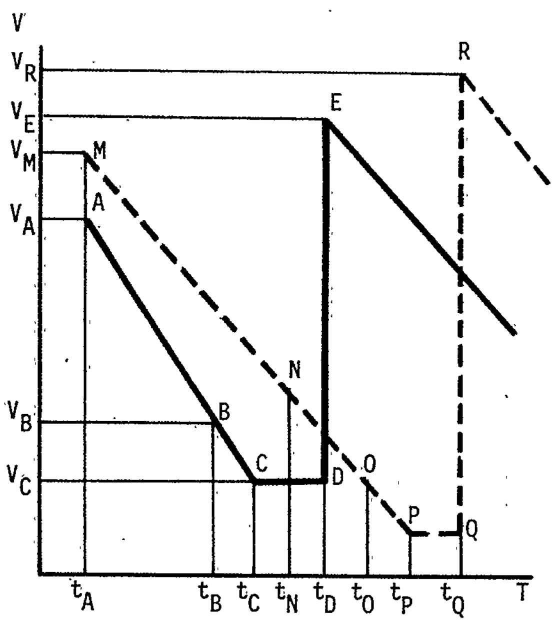
In this process, the slope of line AB depends upon the capacity of the truck-shovel system. The location of point B depends upon the capacity of the drill-rig and the size of the block to be drilled. The time $(t_B - t_A)$ is proportional to the size of the block and inversely proportional to the capacity of the drill-rig.

It is important to note that the amount of material to be blasted during each cycle* at a given face plays an important role. For a given drill-rig capacity, if this amount increases the point $t_B$ moves to the right, which in turn moves the point $t_N$ also to the right by the same amount. This situation eventually reduces the working time of drill-rig $(t_O - t_N)$ at face #2, therefore, drill-rig may not provide enough broken material for shovel #2 and the loading operation is forced to stop, which is a serious accident in mining. On the other hand, if one decides to reduce the amount of material to be blasted at face #1, this results in moving point $t_B$ to the left, thus allowing more drilling time at face #2. The consequence of this action will be more frequent drilling and blasting at faces, and also more frequent movements of equipment, hance the available time for actual operation is reduced.

It is clear from this simple illustration that for a given number of shovels and drill-rigs a "good" match requires an optimum balance between the capacities of equipment and the amount of material to be blasted at each face. As the amount of broken material increases, the idle time associated with the mining operations decreases and the efficiencies of equipment increase. Therefore, the optimum solution is the maximum feasible amount of material to be blasted at each face meanwhile the truck-shovel system can keep on working without waiting.

Figure 1

THE GENERAL RELATIONSHIP BETWEEN DRILL-RIGS AND SHOVELS




*A cycle means the time period between two successive blasting at the same face.

## FORMULATION OF THE PROBLEM

As we have illustrated in the example above, the amount of material to be blasted in each face is an important factor in production scheduling. This factor can be expressed as a function of bench dimensions, the production rate of truck-shovel system, the density of the material to be mined and the available working time. The amount of broken material generated during one cycle must be at least as much as the total production capacity of the truck-shovel system available at the face. This condition can be expressed as:

$$A' \cdot P_{SE}(j) \leq W(j) \cdot H \cdot L \cdot D = V_S(j) \qquad (1)$$

or,

$$W(j) \geq \frac{A' \cdot P_{SE}(j)}{H \cdot L \cdot D}$$

where, $W(j)$ = the rate of advance of the face $j$ (m/cycle),
$H$ = the height of the bench (m),
$L$ = the length of the bench (m),
$P_{SE}(j)$ = the expected production rate of the truck-shovel system at face $j$ (tons/shift),
$A'$ = the available working time of the truck-shovel system (shifts/cycle),
$D$ = the average density of material to be mined,
$V_S(j)$ = the amount of broken material generated at face $j$ (tons/cycle).

In view of above requirement, let us consider the problem of matching the drill-rigs and truck-shovel systems. The problem becomes feasible if one can utilize some kind of dispatching policies that satisfy the condition (1) for all faces during a sufficiently large number of cycles. A feasible dispatching policy must not allow the truck-shovel system to run out of broken material at any face. Thus, instead of testing the feasibility of arbitrarily selected dispatching policies by means of simulation, we shall limit our search to those cases when the following principles are satisfied:

(1) The amount of broken material generated per cycle at any face should be proportional to the production rate of the truck-shovel system present at that face, i.e.,

$$\frac{V_S(j)}{V_S(k)} = \frac{P_{SE}(j)}{P_{SE}(k)} \quad \text{for all faces} \qquad (2)$$

where, $V_S(j)$ = the amount of broken material genereted at face $j$ (tons/cycle),
$P_{SE}(j)$ = the expected production rate of the truck-shovel system at face $j$ (tons/shift).

(2) Any drill-rig, upon completion of its task, should be dispatched to the face where the ratio of the remaining broken material to the production rate is minimum, i.e., the drill-rig must be dispatched to the face $j$ which needs the additional broken material the most. This principle can be expressed as:

Dispatch the drill-rig to face $j$

$$\text{where} \quad \frac{V'_S(j)}{P_{SE}(j)} \quad \text{is minimum} \tag{3}$$

where, $V'_S(j)$ = the amount of broken material remaining at face $j$ (tons),
$P_{SE}(j)$ = the expected production rate of the truck-shovel system at face $j$ (tons/shift).

Equation (1) can also be used to express the maximum working time $A$ required to load $V_S(j)$ amount of broken material of face $j$, i.e.,

$$A = \frac{V_S(j)}{P_{SE}(j)} \tag{4}$$

From equation (2), we can find out that $A$ is a constant. But the constant $A$ here does not represent the actual working time of the truck-shovel system at face $j$. The actual working time depends upon not only the value of $V_S(j)$ generated for this cycle, but also the amount of broken material left from previous cycles, and the actual production rate of the truck-shovel system at face $j$. However, the factor $A$ can be used as a decision parameter which leads to the calculation of $V_S(j)$ on the basis of expected production rate $P_{SE}(j)$. Since $A$ directly relates to $w(j)$, the rate of advance of the face $j$, we shall refer the parameter $A$ as the factor of advance.

It is clear from this argument that an arbitrarily selected value of $A$ does not necessarily lead to a feasible solution. The formulation of the simulation procedure presented below is based on a systematic search for feasible value of $A$. A series of simulation runs based on a range of $A$ can be used to study the dispatching policies outlined above.

## THE SIMULATOR MATCH

### GENERAL DESCRIPTION

This simulator is developed to study the relationship between the operational characteristics of drill-rigs and truck-shovel systems in open-pit mining operations. It can also be used to determine the optimum working time of truck-shovel systems or the rate of advance at each face.

The program is primarily based on event scheduling approach, in which events being modeled are the states of the drill-rigs. Drill-rigs are considered to be in one of two possible states at a given time $t$, namely (a) drilling at a face, (b) moving from one face to another.

Figure 2

THE CONCEPTION OF SIMULATOR MATCH

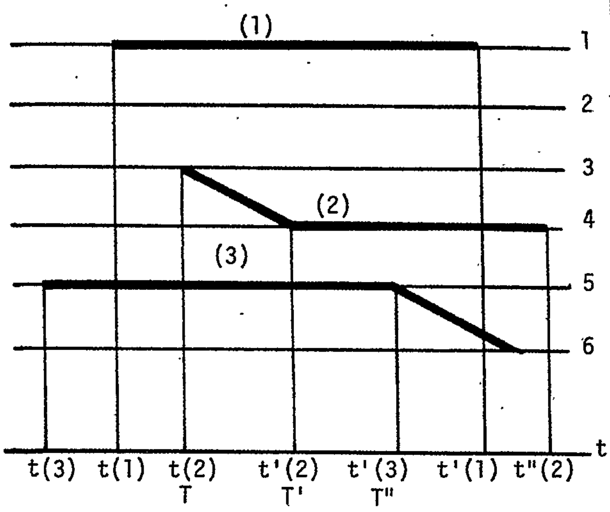



Figure 2 illustrates this concept graphically. Suppose there are six truck-shovel systems represented by fine line and three drill-rigs represented by heavy lines in Figure 2. The procedure starts with an initial test value of factor $A$. At a given time $T$, drill-rigs 1 and 3 are drilling for shovels 1 and 5. Their drilling times are $t'(1)-t(1)$ and $t'(3)-t(3)$ respectively. The drill-rig 2 completes its task for shovel 3 at time $t(2)$ and moves to shovel 4. Its moving time is $t'(2)-t(2)$. The comparison of the three completion times $t'(1)$, $t'(2)$ and $t'(3)$ indicates that the time $t'(2)$ is the smallest one, i.e., the next event is the event of the drill-rig 2 completing its move. The required time increment for this event is $TD = t'(2)-T$. During this period, drill-rigs 1 and 3 continue to drill as drill-rig 2 moves from shovel 3 to shovel 4. At the same time all the shovels are loading except the shovel 3, which moves out of the immediate face area for blasting. The broken material inventory of shovels 1, 2, 4, 5 and 6 are decreasing as they continue to load and shovel 3 gains an additional inventory. At $T'$, drill-rig 2 begins to drill for shovel 4, its time is $t''(2)-t'(2)$. Then by comparing $t'(1)$, $t''(2)$ and $t'(3)$, it is found that the next event is the event of drill-rig 3 finishing its drilling task for shovel 5 with the time increment of $TD = t'(3)-T'$. At the same time, the amount of broken material, total working time and idle time for each equipment are calculated. This procedure is allowed to continue as long as the amount of broken material remaining in front of each shovel is sufficient. When the amount is found to be short, the procedure is stopped and the value $A$ is declared to be unsuccessful. Otherwise, the procedure continues for a sufficiently long time (i.e., 200 working shifts). Thus in each simulation run for a given $A$, the selection of $A$ may turn out to be a failure or success. This experiment is repeated $N$ times (say 70). At the end an estimate of the probability $P_A$, i.e., the probability of success for a given $A$, is obtained. The program continues to repeat the same experiment for a range of $A$ to obtain the estimates $P_{A1}, P_{A2}, \ldots, P_{Ai},$

. . ., $P_{Am}$. When the $P_{Aj}$ is larger than a required probability $P_0$ (say 0.90), its $A$ is regarded as feasible, otherwise it is infeasible.

As the value $A$ increases the frequency of idle time associated with the operations of truck-shovel systems and the drill-rigs decrease, hence their efficiencies increase. This trend continues so long as the value of $A$ is feasible. The best selection of $A$, therefore, is the largest feasible $A$.

THE NUMBER OF REPETITION N

In each simulation run for a given $A$, the result may be a failure or success. They obey a binomial distribution. In order to determine the number of repetition for the simulation, a hypothesis testing is used, i.e.,

$$\text{Null hypothesis } H_o: \; P = P_o$$
$$\text{against } H: \; P = P_1 < P_o$$

where $P$ = the probability of success for a given $A$ after $N$ runs,
$P_o$ = the required probability of success,
$P_1^o$ = a specified probability of success.

For large $N$, the normal approximation to the binomal can be utilized to simplify the computation. Let $\alpha$ be the level of the first type of error and $\beta$ for the second type of error, eventually we have:

$$N = \left(\frac{Z_{1-\beta}\sqrt{P_1 q_1} - Z_\alpha \sqrt{P_o q_o}}{P_o - P_1}\right)^2$$

where, $Z_\alpha$ = the value of the standard normal variant at the $\alpha$ percentile,
$Z_{1-\beta}$ = the value of the standard normal variant at the $1-\beta$ percentile,
$q_1 = 1-P_1$,
$q_o = 1-P_o$.

As an illustration, when $P_o = 0.9$, $P_1 = 0.8$, $\alpha = 0.05$, $\beta = 0.20$, then $N = 70$. If $P_o = 0.9$, $P_1 = 0.7$, $\alpha = 0.05$, $\beta = 0.20$, then $N = 20$.

INPUT ANT OUTPUT

The simulator MATCH accepts the following list of inputs representing a particular open-pit operation:

- PLE(i, j): the mean drilling rate of drill-rig i at face j (m/shift).
- PLS(i, j): the drilling rate variance of drill-rig i at face j.
- PAT(i, j): the drilling pattern assigned to drill-rig i at face j (mxm).
- D(j): the density of material (rock or ore) at face j (tons/m3).
- PSE(j): the mean production rate of truck-shovel system j (Ktons/shift).
- PSS(j): the production rate variance of truck-shovel system j.
- DIS(i, j): the distance from face i to face j (Km).
- VSO(j): the initial amount of broken material at face j (Ktons).
- TMSE(j): the mean idle time for shovel j (shifts).
- TODE(i): the mean idle time for drill-rig i (shifts).
- VD(i): the average moving velocity for drill-rig i (Km/shift).
- JSOO(i): the initial location of drill-rig i.
- TIME: the time period for each experiment (i.e., 200 shifts).
- CENT: the minimum probability of success required (i.e., $P_o$).
- KCYC: the number of repetition required for each selection of A (i.e., N).
- A: the factor of advance.

For a given value of $A$, the following information is obtained after a sufficient number of repetition:

- VS(j): the final amount of broken material at face j (Ktons).
- TTWD(i): the total drilling time of drill-rig i (shifts).
- TTMD(i): the total idle time of drill-rig i (shifts).
- EEFD(i): the efficiency of drill-rig i, where EFFD(i) = TTWD(i)/[TTWD(i)+TTMD(i)].
- TTWS(j): the total loading time of shovel j (shifts).
- TTMS(j): the total idle time of shovel j (shifts).
- EFFS(j): the efficiency of shovel j, where EFFS(j) = TTWS(j)/[TTWS(j)+TTMS(j)].

## TEST CASE

To demonstrate the use of the simulation MATCH, a series of equipment configuration have been used in a hypothetical open-pit, where three drill-rigs are matched against six truck-shovel systems. The mean production rate of each truck-shovel system is 4 Ktons/shift, the mean production rate of each drill-rig is 9 Ktons/shift. Table 1 shows the distances between the shovels, the initial amount of broken material and the initial locations of the drill-rigs. Each drill-rig is assumed to travel at a velocity of 5 km/shift. Shovels and drill-rigs are assumed to have one shift/cycle idle time due to failures.

THE EFFICIENCIES OF EQUIPMENT

Table 2 shows the relationship between the advance and the efficiencies of equipment. It is certified that the efficiencies of equipment depend upon the factor of advance.

THE RELATIONSHIP BETWEEN THE CAPACITIES OF EQUIPMENT

Table 3 shows the relationship between the capacities of the drill-rigs and the truck-shovel systems. It is clear from Table 3 that the capacities of equipment should be selected properly in order to gain the highest efficiency.

INITIAL SITUATION OF SIMULATION

TABLE 1

| Number of Shovels | Distance Between Shovels, km #1 | #2 | #3 | #4 | #5 | #6 | Initial Amount of Broken Material Ktons | Initial Location of Drill-Rigs |
|---|---|---|---|---|---|---|---|---|
| #1 | 0.0 | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 52 | (1) |
| #2 | 1.5 | 0.0 | 1.0 | 2.0 | 3.0 | 4.0 | 96 | - |
| #3 | 2.5 | 1.5 | 0.0 | 1.0 | 2.0 | 3.0 | 54 | - |
| #4 | 3.5 | 2.5 | 1.5 | 0.0 | 1.0 | 2.0 | 98 | (2) |
| #5 | 4.5 | 3.5 | 2.5 | 1.5 | 0.0 | 1.0 | 56 | - |
| #6 | 5.5 | 4.5 | 3.5 | 2.5 | 1.5 | 0.0 | 100 | (3) |

RELATIONSHIP BETWEEN A AND EFFICIENCY

TABLE 2

| Factor of Advance | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
|---|---|---|---|---|---|---|---|---|---|
| Efficiency of Drill-Rigs, % | 57.3 | 68.0 | 74.0 | 80.0 | 81.0 | 83.0 | 85.0 | 86.3 | 88.0 |
| Efficiency of Shovels, % | 84.7 | 87.3 | 89.8 | 91.7 | 92.8 | 93.8 | 94.0 | 94.8 | 95.0 |

RELATIONSHIP BETWEEN THE CAPACITIES

TABLE 3

| Number of Groups | Drill-Rigs Total Number | Capacity For Each Ktons/ Shift | Total Capacity Ktons/ Shift | Truck-Shovel Systems Total Number | Capacity for Each Ktons/Shift | Total Capacity Ktons/ Shift | Factor of Advance A |
|---|---|---|---|---|---|---|---|
| #1 | 3 | 8-8-8 | 24 | 6 | 4-4-4-4-4-4 | 24 | 8 |
| #2 | 3 | 9-9-9 | 27 | 6 | 4-4-4-4-4-4 | 24 | 24 |
| #3 | 3 | 10-10-10 | 30 | 6 | 4-4-4-4-4-4 | 24 | 27 |
| #4 | 3 | 15-15-15 | 45 | 6 | 4-4-4-4-4-4 | 24 | 41 |
| #5 | 3 | 15-10-5 | 30 | 6 | 4-4-4-4-4-4 | 24 | 15 |
| #6 | 3 | 9-9-9 | 27 | 6 | 1-7-3-5-2-6 | 24 | 16 |
| #7 | 3 | 9-9-9 | 27 | 6 | 5-3-2-6-3-5 | 24 | 19 |

## THE AMOUNT OF BROKEN MATERIAL

Table 4 shows the relationship between the initial amount of broken material and the factor of advance. Obviously, the more the broken material is, the larger the A will be.

## CONCLUSION

The effective operation of an open-pit requires periodic adjustments in dispatching equipment. As the mining progresses, the pit configuration and the production rate of equipment change. An optimum match for a given static situation can eventually degenerate into a very inefficient operation. The simulator MATCH provides an effective and

RELATION BETWEEN A AND BROKEN MATERIAL

TABLE 4

| Number of Groups | The Amount of Broken Material in Front of Each Shovel Ktons | | | | | | Factor of Advance A |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | |
| #1 | 30 | 80 | 32 | 82 | 34 | 84 | 15 |
| #2 | 52 | 96 | 54 | 98 | 56 | 100 | 24 |
| #3 | 100 | 160 | 102 | 162 | 104 | 164 | 42 |

practical tool which can be used in making periodic adjustments to rate of advance in order to maintain a high level of equipment efficiency. Addition of a new equipment to the available set or reduction of the number of equipment due to long-term failure also require an adjustment in the operating policy of the open-pit. The simulator MATCH can also be used in this case to determine the most effective rate of advance under new circumstances.

ACKNOWLEDGEMENT

Special thanks are due to Prof. T. M. Yegulalp of Columbia University for his helpful commends.

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