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

Yun Qing-xia
Xian Institute of Metallurgy and Construction Engineering
Xian, P.R.C.

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 shovel-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 t0, shovel #1 has V1 amount of broken material to load, which will decrease in time. Thus, at time t1 the shovel #1 will have V2 amount of broken material remaining to load. Suppose that drill-rig #1 starts working at face #1 at time t1 and completes its task at time t2, then moves to face #2. The shovel #1, however, continues to operate until time t3 while blasting is prepared. At time t3 shovel #1 is stopped and moved some distance away for the blasting. At time t4 the shovel #1 begins to operate again with V3 amount of broken material in front of it. Thus, no loading and hauling takes place during the time period (t3-t4) at face #1. Similarly at face #2, the shovel #2 starts at time t2 with V4 amount of broken material. At time t5 the drill-rig #1 arrives at face #2 and begins to drill. At time t6 drilling is completed and the drill-rig #1 moves to the next face. At time t7 blasting is completed at face #2 and shovel #2 begins to operate with V5 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
of broken material increases, the idle time associated with the mining operations decreases and the efficiencies of equipment increases. 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.

**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:

\[ A' \cdot P_{SE}(j) \leq W(j) \cdot H \cdot L \cdot D = V_S(j) \]  

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.,

\[ \frac{V_S(j)}{V_S(k)} = \frac{P_{SE}(j)}{P_{SE}(k)} \quad \text{for all faces} \]  

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

---

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

\[
V_S(j) = \text{amount of broken material remaining at face } j \text{ (tons)},
\]

\[
P_{SE}(j) = \text{the expected production rate of the truck-shovel system at face } j \text{ (tons/shift)}.
\]

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.,

\[
A = \frac{V_S(j)}{P_{SE}(j)} \quad (4)
\]

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 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 \( TD = t'(2) - t(2) \). 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 \( P_{A1}, P_{A2}, \ldots, P_{A1} \).
Simulation of Rig/Shovel (continued)

... $P_{AM}$. When the $P_{AM}$ 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.,

Null hypothesis $H_0$: $P = P_0$
against $H_1$: $P = P_1, P = P_0$.

where $P$ = the probability of success for a given $A$ after $N$ runs, $P_0 = the required probability of success, P_1 = a specified probability of success.$

For large $N$, the normal approximation to the binomial 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, we have:

$$N = \frac{Z_{1-\alpha}^2 P_0 q_0 - Z_{1-\beta}^2 P_0 q_0}{P_0 - P_1}$$

where, $Z_{1-\alpha}$ = the value of the standard normal variate at the $\alpha$ percentile, $Z_{1-\beta}$ = the value of the standard normal variate at the $1-\beta$ percentile, $q_0 = 1 - P_0$, $q_1 = 1 - P_1$.

As an illustration, when $P_0 = 0.9, P_1 = 0.8, \alpha = 0.05, \beta = 0.20$, then $N = 70$. If $P_0 = 0.9, P_1 = 0.7, \alpha = 0.05, \beta = 0.20$, then $N = 20$.

INPUT AN 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 $j$ (mm).
D(j): the density of material (rock or ore) at face $j$ (tons/m3).
PSE(j): the mean production rate of truck-shovel system $j$ (Kt/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 $j$ (Kt/shift).
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., $P_0$).
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 $j$ (Kt/shift).
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 $EEFD(i) = TTWD(i)/[TTWD(i)+TTMD(i)]$.
TTWS(j): the total loading time of shovel $j$ (shifts).
TMRS(j): the total idle time of shovel $j$ (shifts).
EFFS(j): the efficiency of shovel $j$, where $EFFS(j) = TTWS(j)/[TTWS(j)+TMRS(j)]$.

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 Kt/shift, the mean production rate of each drill-rig is 9 Kt/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/hour. 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.

466
### INITIAL SITUATION OF SIMULATION

**TABLE 1**

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

### RELATIONSHIP BETWEEN A AND EFFICIENCY

**TABLE 2**

<table>
<thead>
<tr>
<th>Factor of Advance</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>16</th>
<th>18</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency of Drill-Rigs, %</td>
<td>57.3</td>
<td>68.0</td>
<td>74.0</td>
<td>80.0</td>
<td>81.0</td>
<td>83.0</td>
<td>85.0</td>
<td>86.3</td>
<td>88.0</td>
</tr>
<tr>
<td>Efficiency of Shovels, %</td>
<td>84.7</td>
<td>87.3</td>
<td>89.8</td>
<td>91.7</td>
<td>92.8</td>
<td>93.8</td>
<td>94.0</td>
<td>94.8</td>
<td>95.0</td>
</tr>
</tbody>
</table>

### RELATIONSHIP BETWEEN THE CAPACITIES

**TABLE 3**

<table>
<thead>
<tr>
<th>Drill-Rigs</th>
<th>Truck-Shovel Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Groups</td>
<td>Total Capacity for Each Ktons/Shift</td>
</tr>
<tr>
<td>Total Number</td>
<td>Total Capacity Ktons/Shift</td>
</tr>
<tr>
<td>#1</td>
<td>3</td>
</tr>
<tr>
<td>#2</td>
<td>3</td>
</tr>
<tr>
<td>#3</td>
<td>3</td>
</tr>
<tr>
<td>#4</td>
<td>3</td>
</tr>
<tr>
<td>#5</td>
<td>3</td>
</tr>
<tr>
<td>#6</td>
<td>3</td>
</tr>
<tr>
<td>#7</td>
<td>3</td>
</tr>
</tbody>
</table>

### 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
Simulation of Rig/Shovel (continued)

<table>
<thead>
<tr>
<th>RELATION BETWEEN A AND BROKEN MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TABLE 4</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of Groups</th>
<th>The Amount of Broken Material in Front of Each Shovel Ktons</th>
<th>Factor of Advance A</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>30 80 32 82 34 84</td>
<td>15</td>
</tr>
<tr>
<td>#2</td>
<td>52 96 54 98 56 100</td>
<td>24</td>
</tr>
<tr>
<td>#3</td>
<td>100 160 102 162 104 164</td>
<td>42</td>
</tr>
</tbody>
</table>

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 commend.

REFERENCES


