Simulation of Loading and Haulage of Fragmented Rock in a Typical Granite Quarry in Ondo State, Nigeria

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Abstract
This work analysed shovel-truck haulage system in surface mine using computer simulation method. Queueing models were used to approximate the real queueing situation, and the queueing behaviour analysed mathematically. Performance measures (average number in the queue, average time spent in the queue, probability that the queue is full or empty and probability of finding the system in a particular state) were determined. The queueing models developed were used to test the operation in a typical granite quarry for variation in the factors that affect production output. A spreadsheet (Microsoft Excel) was programmed to take in time measurements from the field and the data analysed. The various components (mean arrival rate, mean service rate and waiting times) that make up the total cycle time were established. It was discovered that the simulated values for the total cycle time were only slightly different from the actual values observed on the field. This confirmed the validity of the models. A program (LoadHaulPro 1.0) was also developed for use in calculations related to shovel-truck haulage systems in surface mines.

Keywords: rock haulage, simulation, modeling, programme, LoadHaulPro 1.0

INTRODUCTION
There is need for new policies and decision rules for operating a system to be tested on a model before running the risk of experimenting on the real system. It is therefore desirable to show how simulation of shovel-truck haulage system in a mine can yield valuable insight into important mine variables in optimizing results and profitability in the overall economic goal of the mining company. This may also lead to optimum utilization of mine transport machinery which may in turn bring about an increase in production.

Increased production at a minimum cost is the ultimate desire of any mining company. Excavation, loading and haulage are different aspects of production operations. The details of these aspects of production have to be looked into so that the operations can produce optimum results and profitability. It is very sad that productivity is often maintained at uneconomic levels at the expense of much needed revenue (Adedoyin, 1991).

In ore production, stripping which is excavation of the earth materials from the surface to the top of the deposit must first be carried out. Rock excavation can be classified as consolidated/solid rock excavation and unconsolidated/loose rock excavation. Consolidated or solid rock excavation involves solid bedrock or masses in its in situ which may be best removed by blasting. Unconsolidated or loose rock excavation on the other hand is the removal of detached masses of rock or stone or sand without blasting. After fragmentation of ore by blasting, loading and haulage come next. Loading is done by any of the bucket attached machines such as mechanical shovel, dragline and pay-loaders. Haulage is the transportation of the ore from the mine pit to the point of treatment. For long distance haulage, trucks are commonly used in open pit mines. All these operations are amenable to simulation

Simulation is defined as the process of designing a model of a real system and conducting experiment with the model for the purpose of either understanding the behavior of the system or for evaluating various strategies for the operation of the system. A system is defined as an aggregation or assemblage of objects joined in some regular interaction or interdependence (French et al, 1986).

STUDY AREA
Japaul Mines and Products Limited, a subsidiary of Japaul Oil and Maritime Services Plc, Ifon, Ondo State, Nigeria was used as study location. The present major operation of the company is the production of granite aggregates of various sizes for commercial purposes, mainly for road surfacing, structural works and other building/civil construction projects.

Increased Production
The overall economic goal in surface mining is to remove the least amount of material while gaining the greatest return on investment by processing the most
marketable mineral product. The higher the grade of the mineral deposit, the greater the value. To minimize capital investment while accessing the highest valued material within a mineral deposit, a mine plan is developed that precisely details the manner in which the ore body will be extracted and processed. Regardless of size, the mine plan includes provisions for pit development, infrastructure, (e.g., storage, offices and maintenance) transportation, equipment, mining ratios and rates. Mining rates and ratios influence the life of the mine which is defined by depletion of the ore body or realization of an economic limit (Hethmon and Dotson, 2010).

**Granite Rock**
Granite is a common and widely occurring type of intrusive, felsic, igneous rock. Granites usually have a medium to coarse grained texture. Occasionally some individual crystals (phenocrysts) are larger than the groundmass, in such a case, the texture is known as porphyritic. A granitic rock with a porphyritic texture is sometimes known as a porphyry. Granites can be pink to grey in color, depending on their chemistry and mineralogy. By definition, granite has a color index (i.e. the percentage of the rock made up of dark minerals) of less than 25%. Outcrops of granite tend to form tors, and rounded massifs. Granites sometimes occur in circular depressions surrounded by a range of hills, formed by the metamorphic aureole or hornfels, (Wikipedia, 2010a).

**Loading and Haulage**
Loading operation involves filling the dump trucks with rock fragments and haulage is the transportation from the mine face to either the stockpile or the crushing plant (Aladejare, 2008). Haulage in open-pit and strip mines is most commonly accomplished by haul trucks. The role of haul trucks in many surface mines is restricted to cycling between the loading zone and the transfer point such as an in-pit crushing station or conveyance system. Haul trucks are favoured based on their flexibility of operation relative to railroads, which were the preferred haulage method until the 1960s, (Hethmon and Dotson, 2010).

**Queueing Theory and Queueing Model**
Queueing theory is the mathematical study of waiting lines (or queues). The theory enables mathematical analysis of several related processes, including arriving at the (back of the) queue, waiting in the queue (essentially a storage process), and being served by the server(s) at the front of the queue (Wikipedia, 2010b). In queueing theory, a queueing model is used to approximate a real queueing situation or system, so the queueing behaviour can be analysed mathematically (Carmichael, 1987).

**MATERIALS AND METHODS**

**Summary of Operations at the Quarry**
After blasting is carried out, loading at the pit is then carried out using loaders or excavators. After loading, the loaded dump trucks then move the fragmented rocks to the crushing plants. The quarry has three working crushing plants with the following capacities (JMPL, 2009):

1) Plant - 1, with a capacity of 250 tons per hour, operated at 200 tons per hour.
2) Plant - 2, with a capacity of 250 tons per hour also operated at 200 tons per hour.
3) Plant - 3, with a capacity of 500 tons per hour, operated at 400 tons per hour.

It was noted that Plants 1 and 2 each needed one loading equipment (either an excavator or a loader) and two dump trucks (of 25 tonnes) to service them. Hence, they needed 8 dumpers each per hour, hence, 8 dump trucks with 25 tonnes each gives 200 tonnes per hour.

Plant 3 needed one loading equipment (an excavator, because of the size of the dump trucks) and two dump trucks (of 50 tonnes) to service it. It also need 8 of these dumpers per hour, hence, 8 dump trucks with 50 tonnes each gives 400 tonnes per hour. When the dump trucks get to the crushers, they are allowed to unload the granite rocks. Since each crushing plant needed 8 dumpers per hour, each load of granite rock was then crushed in 7.5 minutes when the systems are operating in a steady state.

Each crushing plant at the quarry needs one loading equipment and two dumpers. Hence, for the 3 plants working at the same time, three loading equipment and six dump trucks are needed, each working at the same time (parallel servers). The loading equipment serves the dump trucks which in turn serve the plants. In this study, one of the loading equipment, an excavator, servicing two 25 tonne dump trucks was studied during its steady state operation for over an hour.

**Field Investigations/Data Collection**
Table 1 shows a typical form used in the collection of field data, (Carmichael, 1987). The form is primarily intended for shovel-truck operations. The table shows the form completed for operations at the quarry with some typical field data. The data collected is for one excavator and two dump trucks at the quarry. From the field data in Table 1, a complete set of system parameters for a typical loader-truck operation were deduced as shown in Table 2.

\[
\text{Backcycle time} = t_{1,icycle} + t - t_{3,icycle} \quad \text{(for truck i)} \tag{1}
\]

When the queue is empty and the server is not busy [\(n = 0\) represented as \((i)\)],

\[
\text{Service time} = t_{3,i} - t_{1i} \quad \text{(for truck i)} \tag{2}
\]
When a queue exists and/or the server is busy $[n > 0$ represented as (ii)],

\[ \text{Service time } = t_{3,i} - 13i - 1 \text{ (for truck i)} \] \hspace{1cm} (3)

Average backcycle time $b = \frac{\sum_{n=1}^{2} \mu_2}{n}$ \hspace{1cm} (4)

Hence, $b = 7:15$

\[ \lambda = \text{trucks/minute} = 8.27 \text{ trucks/hour} \] \hspace{1cm} (5)

Average service time $s = \frac{\mu_2}{\lambda}$ \hspace{1cm} (6)

Hence, $s = 6.48$

\[ \mu_3 = \text{trucks/minute} = 9.87 \text{ trucks/hour} \] \hspace{1cm} (7)

Standard Deviation of the backcycle time $= \sqrt{\frac{\sum (s - \mu_2^2)}{n}} = 0.83$ \hspace{1cm} (8)

The Variance of the backcycle time $= (0.83)^2$ \hspace{1cm} (9)

Standard Deviation of the service time $= \sqrt{\frac{\sum (s - \mu_2)^2}{n}} = 2.67$ \hspace{1cm} (10)

The Variance of the service time $= (2.67)^2$ \hspace{1cm} (11)

The Servicing factor, $\rho = \frac{\lambda}{\mu_2} = 0.84$ \hspace{1cm} (12)

**Steady State Probabilities**

The mean service rates for the various phases measured in the field are indicated in Figure 1 and have units of trucks/minute.

It was observed on the field that the average backcycle time was 14 minutes (7 minutes at the loader, 5 minutes for transit and 2 minutes to unload at the crusher).

At the loader, 5 minutes, $\mu_1 = \frac{1}{5} = 0.200$ trucks/minute

During transit, 2 minutes, $\mu_2 = \frac{1}{2} = 0.500$ trucks/minute.

At the crusher, 7 minutes, $\mu_3 = \frac{1}{7} = 0.143$ trucks/minute

The number of possible states $(n_1,n_2,n_3)$ in which $n_1 + n_2 + n_3 = 3$ (phases) is

\[ \binom{K + M - 2}{R} = \binom{1 + 2 - 2}{2} = \binom{0}{2} = 6 \] \hspace{1cm} (13)

Where $K =$ number of units in system = 2 trucks

$M =$ number of phases = 3 phases

The state probabilities may be calculated according to

\[ P(n_1,n_2,n_3) = \binom{K}{n_1} \binom{M-K}{n_2} \binom{M-K}{n_3} \] \hspace{1cm} (14)

when $n_1 \neq K$ and

\[ P(n_1,n_2,n_3) = P(K,0,0) \] \hspace{1cm} (15)

when $n_1 = K$

For Example, the state probability for $P(1,1,0) = P(2,0,0)$ \hspace{1cm} (16)

The coefficient 0.8000000 along with the coefficient for the other 5 state probabilities is given in Table 3.

<table>
<thead>
<tr>
<th>State No.</th>
<th>System State</th>
<th>Coefficient</th>
<th>Pr[State]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 0 0</td>
<td>2.0000000</td>
<td>0.1826775</td>
</tr>
<tr>
<td>2</td>
<td>0 2 0</td>
<td>0.3200000</td>
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<tr>
<td>6</td>
<td>0 1 1</td>
<td>1.1188811</td>
<td>0.1021972</td>
</tr>
</tbody>
</table>

The state probability $P(2,0,0)$ is found from the requirement that the sum of the state probabilities equals 1. From Table 4.2, the sum of the coefficients equals 10.9482556. Hence,

\[ P(2,0,0) = \frac{2.0000000}{10.9482556} = 0.1826775 \] and for example,

\[ P(1,0,1) = \frac{2.7972028}{10.9482556} = 0.2554930 \]

The other state probabilities follow similarly. Note as a check, that the sum of the values in the last column of Table 4.2 equals 1.

The utilization of the loader may now be evaluated. In particular,

\[ \eta_1 = 1 - \sum P(0,n_2,n_3) \] \hspace{1cm} (17)

That is,

\[ D_1 = 1 - \sum \text{probabilities of state 2, 3, 6} \] \hspace{1cm} (18)

\[ = 1 - 0.4887585 = 0.5112415 \]

That is, the loader is busy for 51.1% of the time or idle for 48.9% of the time.

For trucks of 25 tonne capacity, the production of the loader is then,

\[ \text{Production} = \eta_3 \mu_3 C = (0.5112415)(0.143)(25) = 1.83 \text{ tonnes/minute} \] \hspace{1cm} (19)

for $\mu_3$ in units of trucks/minute and the truck capacity, $C$, in tonnes/truck.

The production may also be calculated via the cycle time. The output from phase 3,
\[ \Theta = n_3 \mu_3 = (0.5112415)(0.143) = 0.0731075 \text{ trucks/minute.} \quad (20) \]

and this equals the output from all phases.

The average number of trucks waiting in the queues at the loader and the crusher are, respectively,

\[ L_q = \sum (n_i - 1)P(n_1...n_M) \quad (21) \]

Hence,

\[ L_q = 1 \times (\text{probabilities of state 1}) = 1 \times 0.1826775 = 0.1826775 \quad (22) \]

\[ L_q = 1 \times (\text{probabilities of state 3}) = 1 \times 0.4800414 = 0.4800414 \quad (23) \]

The associated average waiting times in the queues are,

\[ W_q = \frac{L_q}{\Theta} = \frac{0.1826775}{0.0731075} = 2.4987518 \text{ minutes.} \quad (24) \]

\[ W_q = \frac{L_q}{0.3573329} = 0.1826775 \quad (25) \]

Hence, the total cycle time is,

\[ \text{Cycle time} = \frac{1}{\mu_1 + \frac{1}{\mu_2} + \frac{1}{\mu_3} + W_q} = \frac{5.00 \times 0.200 + 2.00 \times 0.500 + 6.99 \times 0.143 + 2.4987518 + 4.8877353}{21.3795323} \text{ minutes,} \quad (26) \]

\[ \text{Cycle time} = \frac{2}{21.3795323} \text{ tonnes/minute.} \quad (27) \]

\[ \text{Cycle time} = 0.0731075 \text{ trucks/minute.} \quad (28) \]

\[ \text{Cycle time} = \frac{1}{\mu_1 + \mu_2 + \mu_3} \quad (29) \]

\[ \text{Cycle time} = \frac{1}{\mu_1 + \mu_2 + \mu_3} \quad (30) \]

The optimization may be carried out by searching for a value of C1/C2 at which the changeover from 2 to 3 hauling units occurs. Let’s consider our values from Figure 4.1 where \( \mu_1 = 0.200, \mu_2 = 0.500, \mu_3 = 0.143, \)

\[ C_1/C_2 = \frac{(0.5112415)2}{0.2613679} \quad (31) \]

\[ C_1/C_2 = (0.5112415)3 \quad (32) \]

Considering the numerical illustration of obtaining the value of C1/C2 at which the changeover from 2 to 3 hauling units occurs. Let’s consider our values from Figure 4.1 where \( \mu_1 = 0.200, \mu_2 = 0.500, \mu_3 = 0.143, \)

\[ \text{Figure 2: LoadHaulPro 1.0} \quad (33) \]

\[ \text{Figure 2: LoadHaulPro 1.0} \quad (34) \]

\[ \text{Figure 2: LoadHaulPro 1.0} \quad (35) \]

That is, for C1/C2 values greater than 4.05, use 3 hauling units. For C1/C2 values lesser than 4.05, use 2 hauling units. For C1/C2 value equal to 4.05, either 2 or 3 hauling units may be used.
CONCLUSION
This study showed that waiting time as a cycle time variable is a very natural component for a load-and-haul system and its inclusion is vital in completing the total cycle time calculation. Estimating cycle time is important as it estimates production which is necessary to estimate product revenue and cash flow. The various components that make up the total cycle time were established. These include the mean arrival rate, the mean service rate and the waiting times. It was also discovered that the simulated values for the total cycle time were only slightly different from the actual values observed on the field. This confirms the validity of the models. The servicing factor for the shovel-truck system at the quarry was also calculated. This also helped in the calculation of the utilization of the shovels and loaders.

LoadHaulPro 1.0, a programme was developed for use in shovel-truck haulage system analysis in a typical quarry.

ACKNOWLEDGEMENT
The authors wish to acknowledge the management of Japaul Mines and Products Limited for permission to use their quarry as a case study. Also the contribution of Engr. Dare Joshua (Asst. Production Manager) and Engr. Komolafe Kayode (Pit Engineer) of same company is highly appreciated.

REFERENCES


APPENDIX

Table 1: Time Study Typical Data

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<th>D</th>
<th>I</th>
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<th>O</th>
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<table>
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<tr>
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<th>ARRIVAL TIME</th>
<th>START MANOEUvre TIME</th>
<th>LOAD / UNLOAD</th>
<th>NO. OF BUCKETS</th>
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<td>1 2 3 0 3 1</td>
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<td>3 4 0 2</td>
<td>3 6 2 0</td>
<td>4 3 0 8</td>
<td>1 0</td>
</tr>
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</table>

Source: (JMPL, 2009)
Table 2: Reduced data

<table>
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<th>Cycle No.</th>
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<th>Time t2</th>
<th>Time t3</th>
<th>Backcycle Time (B)</th>
<th>Queue/Server Status</th>
<th>Service Time (S)</th>
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</table>

\[
\sum = 10.9482556 \quad \sum = 0.9999997
\]

Table 3: State Probabilities of the shovel-truck system

<table>
<thead>
<tr>
<th>State No.</th>
<th>System State</th>
<th>Coefficient</th>
<th>Pr[State]</th>
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