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Effects of Machine Parameter and Natural Factors on the Productivity of Loading and Haulage Equipment

Martin Itoolwa Kulula, Jide Muili Akande

Department of Mining and Metallurgical Engineering, University of Namibia, Windhoek, Namibia
Email: jakande@unam.na

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Abstract

The purpose of this research is to investigate the factors which affect the performance of the loading and hauling equipment at Skorpion zinc mine, Namibia and also to find possible solutions to eliminate them, so that the weekly Zinc Oxide and ex-pit waste tonnages required could be produced. This is due to the high demand of Zinc on the market. The investigation on road conditions was focused on the effects of rolling resistance, grade resistance and road widths from the road between bench 540 in pit 103 to the Zinc oxide medium grade stockpile. Cycle time data were obtained by time and motion study of the load/haul/dump cycle from bench 540 loading site to the stockpile. The data used for equipment matching by queuing theory (excel modelling) was obtained when the loaders where loading Arkose at different loading sites. The effects of different weather conditions *i.e.* mist, rain and wind on production where determined by collecting actual shift production tonnages and comparing with target shift production targets during this conditions. The results produced from time and motion studies show that the haul trucks have an average availability of 80.4% and utilization at 49.7% which are very low when compared to the benchmark value of 89% and 69% for availability and utilization respectively. Decline in performance time is caused by factors such as daily safety meetings, lunch breaks, blasting, tools break down and the daily machine service. Rolling resistance is also one of the factors affecting production time at the mine. The rolling resistance of different segments was determined by roughness defect scores (RDS). From calculations, it is clearly seen that if the RR could be reduced to 2% on every road segment, then each cycle period per truck can be reduced by 1.24 minutes. This will increase the production of the haulers and decrease the operating cost. It was recommended that the wearing course of the road surface be treated with a bitumen based dust suppression product in order to keep the surface's rolling resistance to an absolute minimum (*i.e.* RR = 2%) [1]. The current average hauling road width is 15.987 m while the correct road width at Skorpion Zinc Mine must be 21.35 m to prevent bunching of trucks. It is therefore recommended that the haul roads be widened to 21.35 m width per segment.

Keywords

Utilization, Rolling Resistance, Productivity, Equipment Matching, Uniaxial Compressive Strength, Weather Conditions

1. Introduction

Skorpion Zinc Mine is an integrated world-class mining and refinery operation situated 25 km north of Rosh Pinah in southern Namibia. Zinc oxide ore is mined from a pit 190 meters deep, 1300 meters wide and 1900 meters long. The pit consists of 10 meter-high benches and about 1.6 Megaton of material is mined from it every month. Ore is made accessible by continuous drilling and blasting of selected ore and waste blocks. Designed loading plans are then used for selective mining to allow ore material to be assigned to the correct stockpiles [2]. Blending of stockpiles with various grades allows for a constant grade of 10% Zn to be fed to the refinery every day. The loading equipment used at Skorpion zinc are 2 PC2000 Komatsu hydraulic excavators, a Caterpillar 6030 FS hydraulic excavator, a Komatsu PC800 hydraulic excavator, 2992 K Caterpillar Wheel loaders, CAT 6015 BH, 2 Komatsu WA800-2 wheel loader and 1992 G Caterpillar wheel loader. The hauling equipments used are 26 Caterpillar 777 D and 6 Komatsu haul trucks with rated 90 tons payload each. According to the literature, material transportation represents 50 percent of the operating costs for an open pit mine [3], therefore ineffective management of loading and hauling equipment can cause significant increase in operating cost and inadequate productivity of equipment. The objectives of this study are to determine the selected rock properties(compressive strength and densities), the effects of selected machine parameters(bucket capacities and truck widths) and road conditions on productivity, effect of different climatic conditions on the productivity of equipment, productivity of loading and hauling equipment in the area of study.

2. Proposed Methodology and Discussion

2.1. Determination of Haul Road Width

During the investigation, as seen in **Figure 1**, the road width was measured on every 100 m interval from pit 103, bench 540, to the Chalcophanite (Zinc Oxide) medium grade stockpile. Measurements were taken using a 25 m long measuring tape.

2.2. Determination of Uniaxial Compression Strength

Six core samples of two different rocks namely Limestone and Arkose were col-

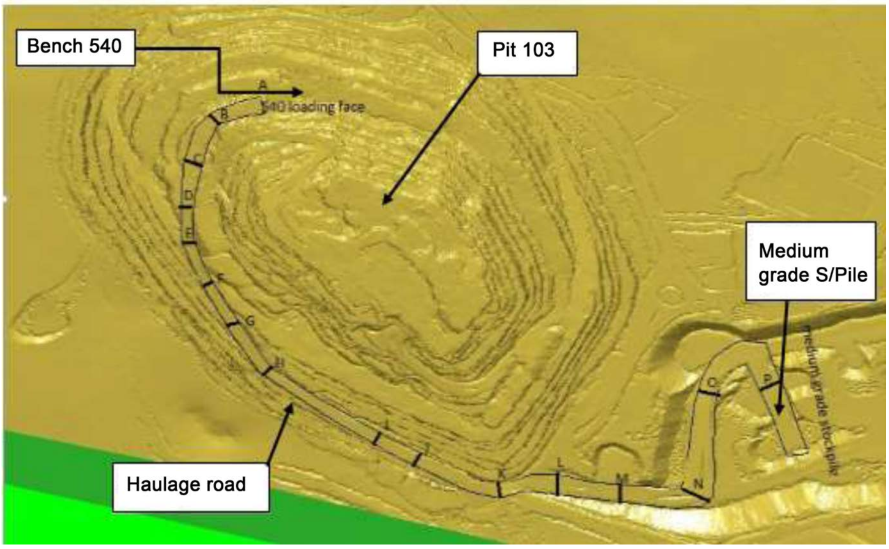

Figure 1. Haulage road used by the trucks from the loading site (bench 540) to the Zinc Oxide medium grade stockpile.

lected from the Geology department at Skorpion zinc mine, failure load (N) was determined from the point load strength index test and the uniaxial compressive strength (UCS) determined using Equations ((1) and (2)) [4].

$$I_{S50} = \frac{P}{De^2} \tag{1}$$

where P is the Failure Load in (N), De is the equivalent diameter in (mm).

The uniaxial compressive strength (UCS) is therefore given by Formula (2):

$$UCS = I_S k \tag{2}$$

k—Size correction factor.

2.3. Data Collection

The trucks and loaders cycle time periods were studied from August 3 to August 9, 2015. The cycle times periods were analyzed when the Loading and hauling (L&H) team was loading material from bench 540 to the dump area (stockpile), with the researcher and 4 operators doing the time motion study. It was also carried out when the loaders were loading waste material for equipment matching purposes The studies were performed during both the day and night shifts each shift being 12 hours, with the researcher and the operators each sitting on a caterpillar 777D haul truck with a stopwatch and recording the data. Data collection consists of two components namely time motion studies and existing data [5]. Data including in-pit road segment gradients and some tested rock properties were obtained from existing data at the mine.

2.4. Determining Equipment Availability and Utilization

Haul trucks and loaders Availability and utilization were determined under different weather conditions by formulas given below. According to Akande [5]

Availability and Utilization of loading and hauling equipment are determined by the following formulas:

$$\text{Availability} = \frac{\text{Available Hours}}{\text{Scheduled Calendar Hours}} \times 100 \quad (3)$$

$$\text{Utilization} = \frac{\text{Utilised Hours}}{\text{Available hours}} \times 100 \quad (4)$$

where:

$$\text{Available hours} = \text{Scheduled Calendar Hours} - \text{downtime hours} \quad (5)$$

$$\text{Utilized Hours} = \text{Available hours} - \text{Standby Hours} \quad (6)$$

2.5. Qualitative Rolling Resistance Assessments

Rolling resistance was estimated from a qualitative visual evaluation. A road defect classification system was applied in which the key defects influencing rolling resistance were identified and the product of defect degree and extent, measured on a scale of 1 to 5 each, were scored for each of these defects. The sum of the individual defect scores thus rated equivalent to the roughness defect score (RDS) can be converted using the scoring sheet and rolling resistance graph to give a rolling resistance for the segment of haul road under consideration [6].

2.6. Equipment Matching

For the purpose of this study equipment matching was done with Queuing Theory by Excel simulations. Data for loaders and haulers cycle time component were collected from the field and entered into an excel simulation to determine the maximum number of trucks that can be dispatched per loader to maximize production.

3. Experimental Results

The results obtained from cycle times studies of the 10 CAT 777D haul trucks carried out are presented in Figure 2 & Figure 3. Table 1 indicates the rolling

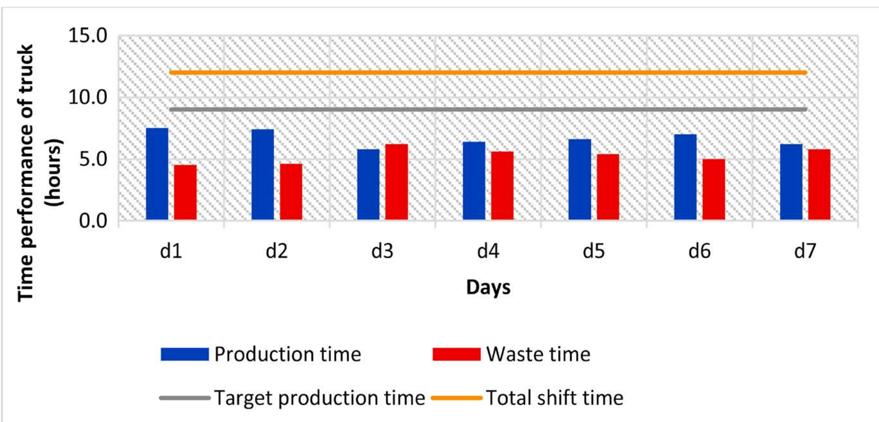

Figure 2. Average production and waste times of CAT 777D haul trucks during the day shift.

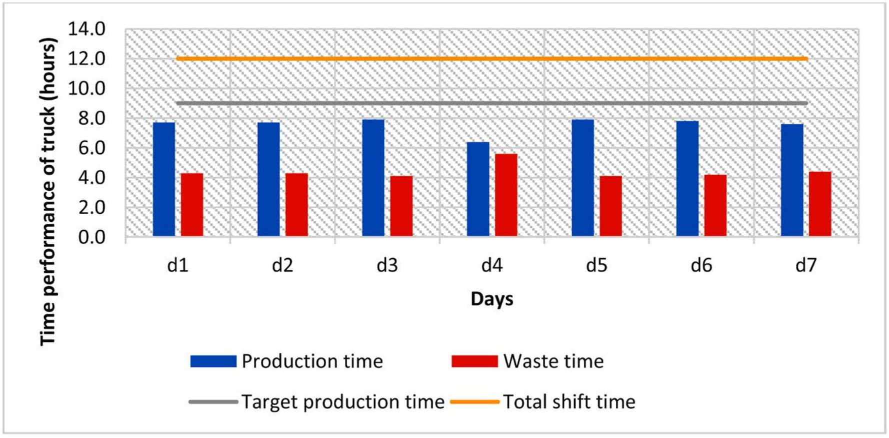

Figure 3. Average production and waste times of CAT 777D haul trucks during the night.

Table 1. Average Rolling Resistance and gradients in each segment from the pit to the Zinc oxide medium grade stockpile. Grade resistance values were obtained from existing data at the mine.

Road segments	Rolling Resistance (%)	Grade resistance (%)
A-B	3	6
B-C	8	3
C-D	4.5	5
D-E	2	7
E-F	4	5
F-G	2.5	3
G-H	3	2
H-I	2	3
I-J	4	4
J-K	5	3
K-L	3.5	2
L-M	3.5	3
M-N	6	5
N-O	4	5
O-P	3	2

resistance and gradient of the road. While Table 2 shows measured road width from the pit to the stock pile. Table 3 also shows the data for equipment matching.

3.1. Rock Properties

Uniaxial compressive strength of the overburden material loaded to expose the ore (Zinc Oxide) in pit 103 in Figure 1, was determined in the laboratory, the test results are presented in Table 4 The rock densities are determined and indicated in Table 5.

Table 2. Measured road width from pit to Zinc Oxide medium grade stockpile.

Road segments	Measured road width (m)
A-B	16.9
B-C	15.7
C-D	15.5
D-E	22.1
E-F	13.9
F-G	15.2
G-H	15.2
H-I	23
I-J	13.3
J-K	12.6
K-L	14.7
L-M	15.5
M-N	18.5
N-O	14.1
O-P	13.6

Table 3. Data to be used for equipment matching using queuing theory-excel simulations.

Loading and hauling of waste material (Arkose)	
Loose material density	2.0 g/cm^3
Loading by hydraulic excavator Komatsu PC2000	
Rated bucket fill factor, SAE 2:1	11 m^3
consider bucket fill factor	0.9
Loading cycle	
First bucket	0.17 min
Each additional bucket	0.5 min
Truck exchange time	0.5 min
Loader maximum hourly utilization	50 min
Hourly internal charge for shovel	1866 N$/hr
Hauling by off highway rigid frame truck CAT 777D	
Rated truck payload	92.2 tons
Travel time loaded	9.70 min
Dump time	0.7 min
Return time	7.20 min
Hourly charge per truck	1335 N$/hr
Hourly production required	1212.2 tons

Table 4. Failure loads and UCS of different rock core samples.

Rock type	Core sample diameter (mm)	Failure load (kN)	UCS (MPa)
Arkose	50	1.35	12.96
Arkose	50	1.63	15.65
Arkose	50	1.96	18.82
Limestone-east	50	10.88	104.44
Limestone-east	50	11.73	112.61
Limestone-east	50	10.54	101.18

Table 5. Rock densities.

Rock type	Density (g/cm^3)
Arkose	2
Limestone west	2.7

Table 6. Actual production tonnages obtained.

Weather condition	Actual total production (t)	Target total production (t)	Date
Mist	41,849	87,275	19-Jul
	60,502	87,275	18-Aug
Rain	74,656	87,275	16-Jul
	82,322	87,275	11-Aug
Wind	64,620	87,275	1-Aug
	66,584	87,275	2-Aug
Clear (Normal)	90,107	87,275	8-Aug
	84,115	87,275	9-Aug

3.2. Weather Conditions

Daily total production tonnages were collected for 8 days between July and August 2015 under different weather conditions at Skorpion zinc mine. Table 6 shows the results obtained for tonnages of material moved per day. 24 CAT 777D Haul trucks, 2 PC2000 Komatsu hydraulic excavators, 1 Caterpillar 6030FS hydraulic excavator and 1 Komatsu PC800 hydraulic excavator were used to load and haul the waste material tonnages presented in Table 6. Their utilization values were calculated and the averages are presented in Figures 4-6.

4. Data Analysis and Discussion

4.1. Availability and Utilization

Haul trucks availability and utilization were calculated from the cycle time data for the 777D haul trucks obtained from the field study. First the availability of each truck was calculated then the average for all the truck was determined, similarly was done for utilization. The results are presented in Figure 7.

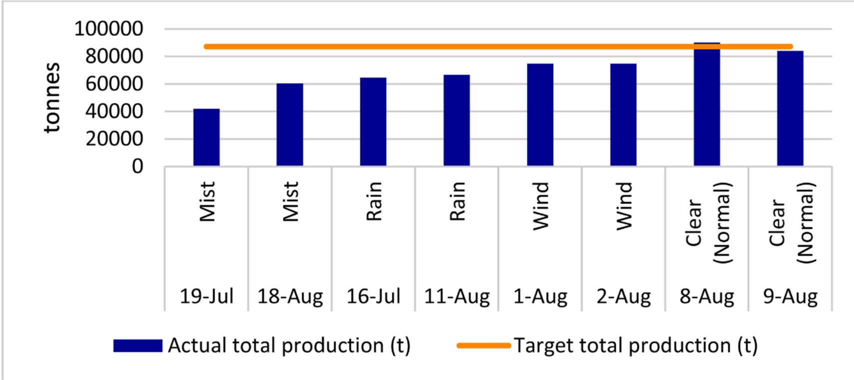

Figure 4. Actual production against target production in different weather conditions.

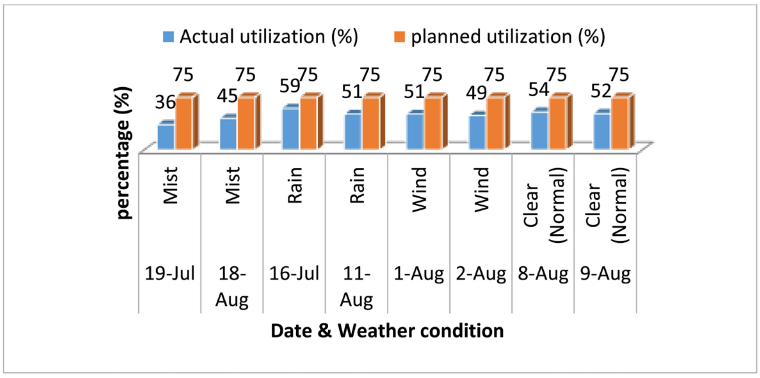

Figure 5. 24 CAT Haul trucks Average utilization.

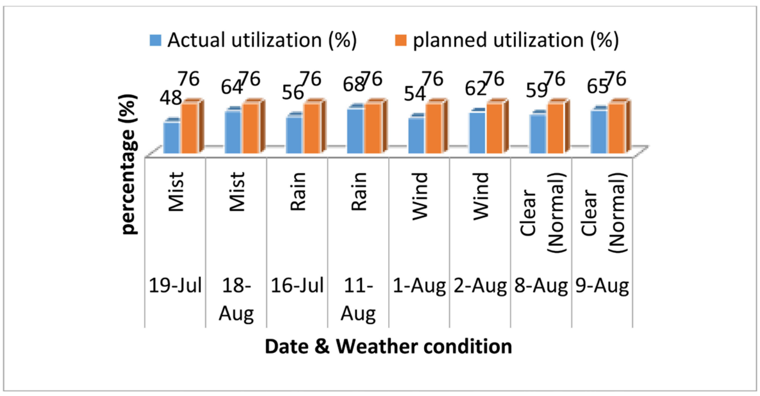

Figure 6. Excavators Average utilization.

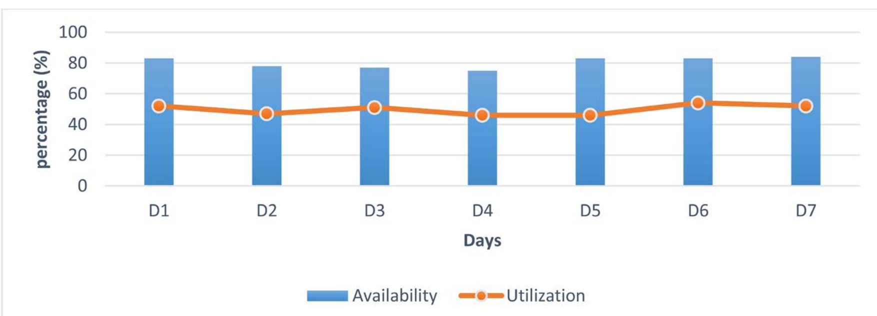

Figure 7. Average Haul trucks availability and utilization in study area.

4.2. Rolling Resistance

CAT 777D truck Rimpull-Speed-Gradeability curve was used to analyze the results gathered from rolling resistance and grade resistance. These calculations were carried out in order to compare and present the time performance for trucks within the current road conditions, with those of less rolling resistance which is required for a good haul road design indicated in Table 7.

According to Mkhatshwa [7] travel time between two points is given by equation 5.1

$$
\begin{aligned}
t = & \left(\frac{\left(\frac{D_{A-B}}{1000}\right)}{V_{A-B}}\right)\times 60+\left(\frac{\left(\frac{D_{B-C}}{1000}\right)}{V_{B-C}}\right)\times 60+\left(\frac{\left(\frac{D_{C-D}}{1000}\right)}{V_{C-D}}\right)\times 60+\left(\frac{\left(\frac{D_{D-E}}{1000}\right)}{V_{D-E}}\right)\times 60 \\
& +\left(\frac{\left(\frac{D_{E-F}}{1000}\right)}{V_{E-F}}\right)\times 60+\left(\frac{\left(\frac{D_{F-G}}{1000}\right)}{V_{F-G}}\right)\times 60+\left(\frac{\left(\frac{D_{G-H}}{1000}\right)}{V_{G-H}}\right)\times 60+\left(\frac{\left(\frac{D_{H-I}}{1000}\right)}{V_{H-I}}\right)\times 60 \\
& +\left(\frac{\left(\frac{D_{I-J}}{1000}\right)}{V_{I-J}}\right)\times 60+\left(\frac{\left(\frac{D_{J-K}}{1000}\right)}{V_{J-K}}\right)\times 60+\left(\frac{\left(\frac{D_{K-L}}{1000}\right)}{V_{K-L}}\right)\times 60+\left(\frac{\left(\frac{D_{L-M}}{1000}\right)}{V_{L-M}}\right)\times 60 \\
& +\left(\frac{\left(\frac{D_{M-N}}{1000}\right)}{V_{M-N}}\right)\times 60+\left(\frac{\left(\frac{D_{N-O}}{1000}\right)}{V_{N-O}}\right)\times 60+\left(\frac{\left(\frac{D_{O-P}}{1000}\right)}{V_{O-P}}\right)\times 60
\end{aligned}
\tag{7}
$$

Table 7. Comparison of truck speed (obtained from Rimpull curve) due to the effect of rolling resistance and that of less rolling resistance required for good haul road design.

Road segments	Target speed (RR = 2%) km/h	Actual speed (km/h)
A-B	18	16
B-C	28	13
C-D	21	15
D-E	16	16
E-F	22	16
F-G	25	24
G-H	34	25
H-I	25	25
I-J	23	18
J-K	25	18
K-L	33	26
L-M	34	23
M-N	22	13
N-O	24	16
O-P	32	25

t = Travelling time from point A to P when loaded

D = segment distance (each segment is 100 m)

V = speed per segment (km/h)

Travelling time due to the effect of rolling resistance:

t = 4.951 minutes (**calculated from formula**)

Assume waiting time of 3.5 minutes

Total travel time = (4.951 + 3.5) minutes = 8.451 minutes

Target travel time with RR = 2%:

t = 3.707 minutes (**calculated from formula**)

Assume waiting time of 3.5 minutes

Total target travel time = (3.707 + 3.5) minutes = 7.207 minutes

The total production time the mine loses per truck cycle due to rolling resistance:

(8.451 − 7.207) minutes = 1.24 minutes.

4.3. Road Width

Table 8 was used to calculate the target road width for the haul road from the pit (bench 540) to the Zinc Oxide medium grade stockpile (SPRo).

The hauling roads at Skorpion zinc mine are two-way lanes and the caterpillar 777D truck is the widest hauling equipment used with the width of 6.1 m. Using the correct haul road design, Skorpion zinc hauling roads are supposed to be:

$$\text{Targeted Road width} = \text{Factor} \times \text{Width of Largest Truck on Road}$$
$$= 6.1\text{m} \times 3.5 = 21.35\text{m}.$$

Target road width is compared to the actual road widths measured for each segment as show in Figure 8.

Table 8. Minimum haul road width required for an open pit mine [6].

Number of lanes	Factor × Width of Largest Truck on Road
1	2
2	3.5
3	5
4	6

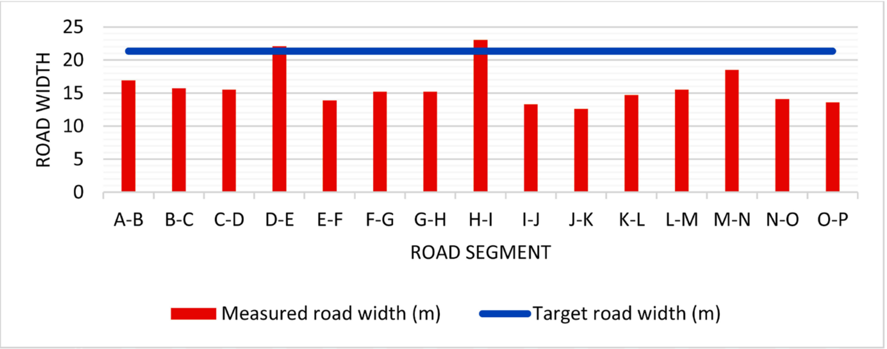

Figure 8. Differences in the targeted road width and the actual measured road widths measured on SPARo (access roads to the S/Piles) from the pit.

As it can be observed from the data in Figure 8 the data collected show that planning of the haul roads at Skorpion zinc mine is very poor which will result in bunching of haul trucks at the ramps causing an increase in production cycle times thus decreasing production.

4.4. Effects of Rock Uniaxial Compressive Strength on Loading Time

It was observed from field studies at the mine that when the Komatsu PC2000 hydraulic excavator was loading limestone east which has a very high uniaxial compressive strength (*i.e.* average = 112.02 MPa), the loading time was excessively high due to the large boulders that resulted from blasting. Blasting material with high uniaxial compressive strength results in large boulders after blasting if inappropriate powder factor is used or quality control is not being implemented on the blasting method at the mine [8]. The loader's operator had a hard time loading the boulders into the bucket or penetrating the loader's teeth into the waste material resulting in loader taking longer to fill up a truck thus increasing the loading time. When the same loader was loading Arkose (waste material) with a lower UCS the loading time was low and close to the target loading time since no large boulders are experienced and the bucket teeth could easily penetrate into the well fragmented material. The results of the loading times for both the limestone east and Arkose are presented in Table 9.

Table 9 shows that the loading time is very high when loading Limestone East at an average of 8:50 minutes compared to the target loading time of 3:00 minutes the production cycle time is increased by 5:50 minutes resulting in longer cycle times causing decreased production and productivity of both the excavator and the trucks its loading.

4.5. Excavator and Hauler Bucket Matching

Skorpion zinc mine is currently not reaching its target for moving the overburden to expose the Zinc Oxide. The purpose of this calculation is to find out, whether the loading buckets which are currently used by the mine are being correctly matched to the trucks [7]. This analysis focuses only on the loading of

Table 9. Shows Komatsu PC2000 hydraulic excavator's actual loading times when loading limestone east and Arkose.

Rock type	Average UCS (MPa)	Actual loading time (min)	Target loading time (min)	Number of Passes
Limestone east	106.1	10:30	3:00	16
		8:06	3:00	10
		7:53	3:00	11
Arkose	15.81	2:32	3:00	5
		2:49	3:00	5
		3:20	3:00	6

waste material. Equipment matching was carried out using queuing theory (Excel simulations) for 4 loaders loading waste material at different loading sites *i.e.* Komatsu PC2000 hydraulic excavator, 2 CAT 992K wheel loaders and a Komatsu WA800-2 wheel loader with a combined total hourly tonnage of 4848. The procedures and results for Komatsu PC2000 hydraulic excavator simulations are presented in Figure 9 and Figure 10. In order to use excel simulation, cycle time components were collected from field studies for all 4 excavators and the trucks. Hourly charge per truck, charge per excavator and hourly production required

7	Loading and hauling Arkose					
8	loose material density				2000	kg/m3
9	**Loading by Komatsu PC2000 hydraulic excavator**					
10		Rated bucket capacity, SAE 2:1			11.00	m3
11		consider bucket fill factor			0.90	
12		loading cycle				
13			first bucket		0.17	minutes
14			each additional bucket		0.50	minutes
15		truck exchange time			0.50	minutes
16		loader maximum hourly utilization			50.00	minutes
17		hourly internal charge for shovel			1866.00	N$/hr
18						
19	**hauling by Caterpillar 777D haul trucks**					
20		rated truck payload			92.20	ton
21		travel time loaded			9.70	minutes
22		dump time			0.70	minutes
23		return time			7.20	minutes
24		hourly charge per truck			1335.00	N$/hr
25						
26						
27	hourly production required			1212.2	ton	
28	to be calculated					
29	a	number of trucks in fleet to satisfy production requirement				
30	b	cost per ton at this point				
31	c	regardless of the production requirements, find the best match to yield the minimum cost per ton				
32	d	find the difference between the cost per ton which satisfies the production requirements				
33		and the cost per ton at the optimum trucks to loader match, in dollars and percents				
34	e	make any comment you find necessary				

Figure 9. Excel simulation Komatsu PC2000 hydraulic excavator being matched to Caterpillar 777D haul trucks (part A).

36	**suggested solution**						
37	bucket rated		11.00	Lm3		first bucket	0.17
38	fill factor		0.90			each additior	0.50
39	actual capacity		9.9	Lm3		load time	2.17
40	density		2000	kg/Lm3		exchange	0.50
41	ton per bucket		19.8	ton		total for L&T	2.67
42	truck load		92.20	ton			
43	bucket required		4.66	buckets		truck loaded	9.70
44	round		5.00	buckets		dump	0.70
45	actual truck load		99	ton		return	7.20
46						HDR	17.60
47							
48						R=L&T/HDR	0.15
49							
50	minutes/hr loader		50.00				
51	L&T		2.67				
52	max trucks delivered per hr		18.73				
53	truck actual payload		99				
54	max loader production		1853.9				
55			team	team cost	cost per		
56	trucks	Pt	prod, ton/h	$/hr	ton		
57	2	0.256	475	4536	9.56		
58	3	0.377	699	5871	8.40		
59	4	0.491	910	7206	7.92		
60	5	0.596	1105	8541	7.73		
61	6	0.69	1279	9876	7.72	requires to satisfy 1212.2 t/h and minimum cost	
62	7	0.772	1431	11211	7.83		
63							
64							
65		**reply**					
66	a	required	6	trucks			
67	b	at	7.72	dollar/ton			
68	c	optimum	6	trucks			
69	d	at	7.72	dollar/ton			
70		difference	0.00	dollar/ton			
71		percent	0.00				

Figure 10. Excel simulation Komatsu PC2000 hydraulic excavator being matched to Caterpillar 777D haul trucks (part B).

were provided by the mine planning engineer.

For Komatsu PC2000 hydraulic excavator material density, hourly charge per truck and excavator and also cycle time components data were entered into excel and an R value *i.e.* R = 0.15 was generated. R as defined in chapter 2, is the ratio of hauler loading time t including the hauler spotting time to the total travelling time (including hauling, dumping and returning).

The R value was used to determine the probabilities (Pt) that one or more haulers is available for loading at loading site. The probability values are 0.256, 0.377, 0.491, 0.596, 0.69 and 0.772 for trucks 2 to 7 respectively. The Probability values (Pt < 1) obtained from Pt tables were entered into excel simulation and team production tons/hr and cost per ton values were generated.

As shown in Figure 10. 6 trucks satisfy the required hourly production of 1212.2 tons since they are able to move approximately 1279 tons of waste material in 1 hour at the minimum cost per ton. The CAT 777D trucks are well matched with the Komatsu PC2000 hydraulic excavator since it only takes 5 buckets to fill up the CAT 777D truck with Komatsu PC2000 hydraulic excavator.

5. Conclusions and Recommendation

5.1. Conclusions

From this research, based on the objectives, the following conclusions were drawn.

- Rolling resistance is also one of the factors affecting production time at the mine. The mine has sufficient road maintenance equipment which can reduce the RR to a desired value of 2%; clearly this equipment is not being utilized effectively.
- Weather conditions such as rain, mist and wind causes a huge loss in production and mist has the highest loss compared to the other two, because it lasted for a longer period of time (up to 3 hours) causing haulers to move slower on the roads or pull off from production (for periods up to 3 hours) due low visibility to prevent accidents. Mist is experienced quite often at Skorpion.
- Incorrect road width design also influences the production performance of the trucks at the mine by bunching. The correct road width at Skorpion Zinc Mine must be 21.35 m, but the current average hauling road width is 15.987 m.
- Rock mass properties considered in this study *i.e.* uniaxial compressive strength (UCS) and densities have significant impact on the blast fragmentation sizes in the sense that intact rocks with high UCS values have large boulders after blasting resulting in higher loading times of the haulers and loaders thus reduced their productivity.
- From the average cycle time data of the 2 different shifts that are being worked at the mine, it was calculated that the average working time per shift

is seven hours and eight minutes per twelve-hour shift. The decline in performance time is caused by factors such as daily safety meeting (on average one hour long), lunch breaks (one hour long), the daily machine service (which takes an average of one and a half hour) Leaving the pit about twenty minutes earlier, tools down and blasting.

- After blasting operations, operators spend on average 30 minutes more at the lunch room before returning to work which reduces production time.
- From calculations, it is clearly seen that if the RR could be reduced to 2% on every road segment, then each cycle period per truck can be reduced by 1.24 minutes. This will increase the production of the haulers and decrease the operating cost.
- Equipment buckets are being matched correctly at the mine and the number of trucks is sufficient to satisfy the need of the loaders.

5.2. Recommendations

The following are recommendations to be considered to improve productivity of loading and hauling equipment at Skorpion zinc mine:

- Treat the wearing course of the road surface with a bitumen based dust suppression product in order to keep the surface's rolling resistance to an absolute minimum [1].
- Utilizing the maintenance equipment more to keep rolling resistance at required 2%.
- The haul roads should be widened to 21.35 m to prevent bunching of trucks for maximum production
- Implement quality control on the blasting method and powder factor used at the mine to prevent large boulders after blasting.
- Lunch time, entry time, knock-off time, meeting and working time should be closely monitored.

Acknowledgements

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