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Analysis of Factors that Cause Drill Rig Breakdowns: A Case of Lubambe Copper Mine, Chililabombwe, Zambia

Dr. Dyson Galatia, PhD

Abstract: ***Mining is the key sector to Zambia's economic development. The sector is a major contributor to national export earnings and employment. Nevertheless, the importance of the mining industry to the economy depends on sustained high levels of production output. As such, Lubambe Copper Mine (LCM) under Konkola North Project, owned by Vale and ARM was commissioned in 2010 with the view of producing 200,000 tonnes of Ore per month by 2014. However, this target could not be achieved due to the high rate of drill rig breakdowns. Despite several attempts to address the problem of equipment breakdown, the situation still remained unresolved.This study therefore, sought to investigate the cause of the frequent drill rig breakdowns at the mine. A multimethod approach was adopted withqualitative data providing deeper insights and explanations of the problem. NVivo and SPSS software packages were used to determine association between variables, while the Z-Test was carried out to test the hypothesis and to validate the Chi-Square results.The findings from the study reviewed that human, environmental, maintenance and Supply Chain related factors were the cause of drill rig breakdowns at LCM. However, human related factors were identified as the major cause. These human factors include low motivation, fatigue, inadequate training and development for drill rig operators. Maintenance personnel were mainly affected by fatigue. The study however, proposed a Framework which could assist Executive Management to identify potential causes of drill Rig breakdowns and further recommended that management at LCM should establish measures to improve and monitor the motivation of employees through appropriate compensation, reward systems and job design with a maintenance culture based on precision.***

Keywords: Productivity, Break down, Reliability, Maintenance, Availability

1. Introduction

Mining is the key sector to Zambia's economic development and the sector is a major contributor to national export earnings and employment. Nevertheless, the importance of the mining industry to the economy depends on sustained high level of production. According to the Press Information Sheet 1 (2018:4), mining is the major income generating industry in the country and it plays an important role in contributing to the country's Gross Domestic Product (GDP).

Therefore, to sustain the high level of production, new mine projects are required and the existing mines need to be operated efficiently for sustainability.

In line with sustaining the mining industry in Zambia,LCM under KonkolaNorth Project was commissioned in 2010 with the view of producing 200,000 tonnes of copper ore per month by 2014.However, this production budget could not be achieved due to various challenges in mining operationsof which the numerous drill rig breakdowns formed part.

The drill rig availability budget was set at 83% and the expected tonnage from one drill rig was determined at 40,338 tonnes per month, however, this capacity could not be achieved and the data in Table 1 show how the mine planning department derived the expected production budget per month from a single rig.

Table 1: Drill Rig Productivity Analysis**Source:** Author, 2018

Item	Input	Unit
Equipment Availability (at full utilisation)	83.00	%
No. of Days in a Month	31.00	Days
Productive days in a month	27.00	Days
Metres/Rig/Shift	150.00	Metres
Shifts/Rig	2.00	Shifts
Tonnes/metre	6	Tonnes/metre
Effective Operating time/shift	8.00	Hours
Number of shifts/day	2.00	
Effective Operating time/day	16.00	Hours
Productivity	15.56	Metres/hour
Productivity	124.50	Metres/shift
Productivity	249.00	Metres/day
Drilled Reserves/day/rig	1,494.00	Tonnes/day
Drilled Reserves/Month/rig	40,338.00	Tonnes/month
Expected Production/month/5 Rigs	201,690.00	Tonnes/month
No. of rigs required (Sandvik DL320)	5.00	Drill Rigs

Further, the drill rig availability budget was driven from the concept:

1) Total week hours excluding Sunday – 144
2) Daily inspection 2hours by 6 days – 12 (to be added to maintenance hours)
3) Maintenance hours (MH) – 12
4) Scheduled Week hours (SSH) - 120
5) Breakdown hours (BH) – not allowed for

Therefore, the weekly availability target was:

(i) $$A = \frac{SSH-(MH+BH)}{SSH} x\ 100$$

Where **A** is the equipment availability; SSH is the total time allowed for the operation of the drill rig in a week also referred to as Actual Available Time by Akande et al (2013), it excludes break times, change over times, safety and production meeting time and other inevitable delays within the shift which may be referred to as management downtime; **MH** is the maintenance hours and **BH** is the breakdown hours.

(ii) $A = \frac{144-(24+0)}{144} \times 100 = 83.33$ rounded off to 83%

Thus, 83% was set as machine availability budget and 17% as maintenance time. Figure 1 diagrammatically illustrates this concept.

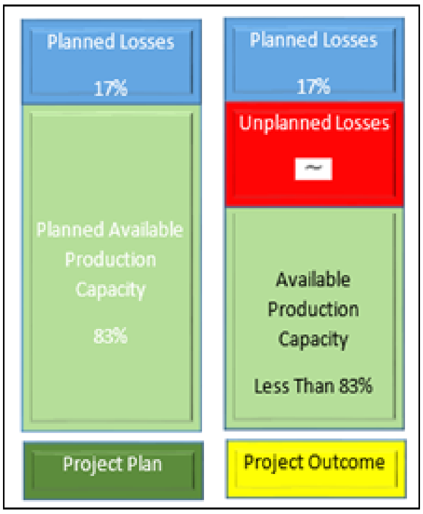

Figure 1: Drill Rig Availability Plan
Source: Author, 2020

Planned downtime was allocated 17% of the total calendar time and 83% as projected equipment availability time. However, the budgeted machine availability of 83% could not be achievedconsistently due to frequent breakdowns. Figure 2 shows the drill rig availability at LCM for the period 2014 to 2017.

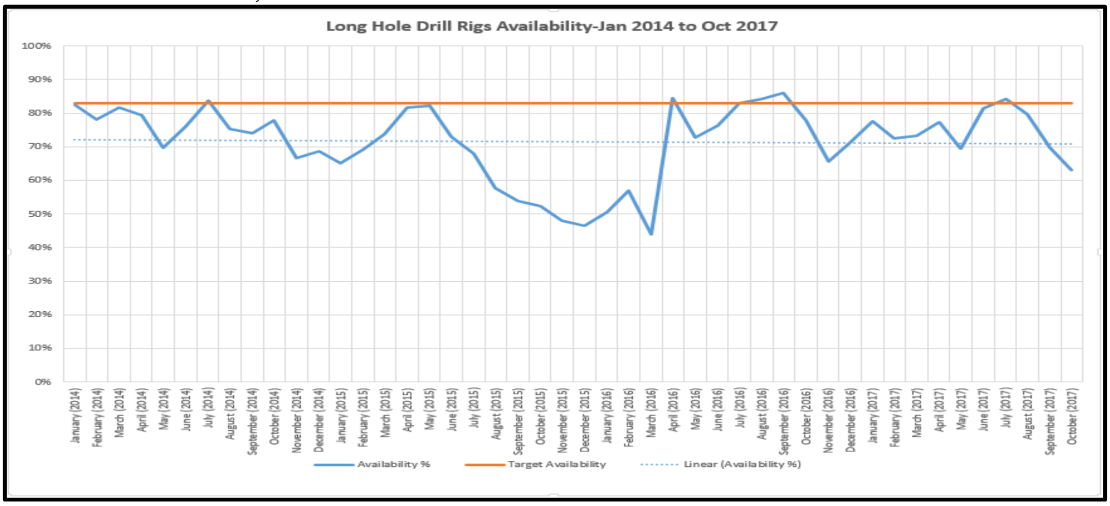

Figure 2: Drill Rigs Availability 2014 – 2017 **Source:** Author, 2017

The availability of the rigs was generally below budget throughout the reviewed period except for July 2014, April 2016, August 2016 and September 2016.On the hand, the production profile was equally below budget for the same period. This is expressed in Figure 3.

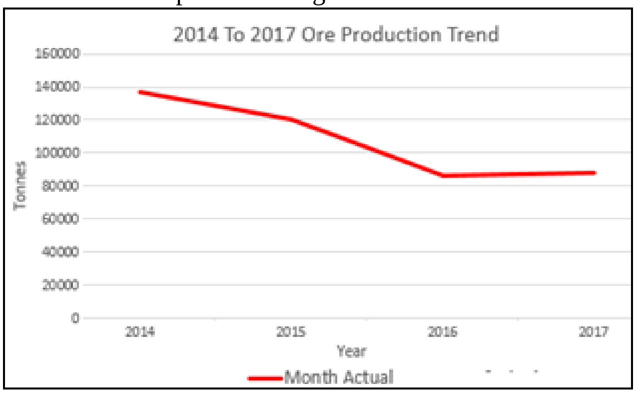

Figure 3: Ore Production Profile 2014 – 2017
Source: Author, 2017

Therefore, from Figure 3, it can be seen that the forecast production of 200,000tonnes of ore per month was not achieved, the average monthly production for 2014 was 136,845 and declining to 88,094 by 2017.

Drilling is very important to the ore extraction process underground and the drill rig dominates a mine's production rate, since drilling is the first process of a typical mining cycle.Al-Chalabi et al (2014:307) indicated that, since the drill rig machine is key to production, it is important to find solutions to reduce breakdowns and further commented that, more than 15 per cent of unplanned downtime (breakdowns) of underground mobile equipment is related to the drilling machine.This study therefore, sought to identify the major causes of the numerous drill rig breakdowns at LCM and develop a Framework for proactively identifying potential causes of breakdowns.

It is however, worth noting that, breakdowns of underground drill rigs may not only be unique to LCM, but have been experienced in other mines too. The study conducted by

Kansake and Suglo (2010) at Konjole Minerals in Ghana suggests that there were numerous drill rig breakdowns at the mine and it was established from the findings of the study that the major causes of the numerous drill rig breakdowns were hose bursts, overheating, shank adapter breakage and rod breakage, low flushing, percussion and rotation pressure, track removal and breakage and drilling rope breakage.

Similarly, Song (2012:61) analysed the failure behaviour of the critical sub-asset groups of four drill rigs at Granny Smith Mine in Australia where the reliability of drill rigs was low. To improve the drill rig reliability, he conducted a study and suggested changes in maintenance tactics which reduced the number of drill rig breakdowns and improved availability. By implementing these changes, the drill rig monthly productivity increased from 108,000 tonnes to 132,000 tonnes.

It should also be noted that this study only takes into consideration the time the mine was run by ARM of South Africa and Vale of Brazil.

2. Methodology

The overall objective of the study was to identify the main causes of the numerous drill rig breakdowns at LCM and construct a Framework which could assist Executive Management to identify potential causes of drill rig breakdowns. The study sought to answer the general research question:What were the major causes of the numerous drill rig breakdowns at LCM? The study was therefore, underpinned on a pragmatic view point and applied a multi-methods approach. The target population consisted of 207 LCM employees and sample size of 137 was analysed and for collecting the data a question was administered to selected employees. Further, an interview guide was used to collect information from key informants who were selected using a purposive sampling technique.

NVivo and SPSS software packages were used to determine association between variables, while the Z-Test was carried out to test the hypothesis and to validate the Chi-Square results. Additionally,Construct validity was conducted through a pilot study where the questionnairewas tested on a different mine before being issued to the intended respondents at LCM. This was carried out to ensure credibility and accuracy of the tool used in the study.To uphold consistency, the study used instruments that have already been used and tested and these instruments were drawn from the literature review and among others included questionnaires and interviews. Questionnaires were used to collect data from the selected respondents and interviews were conducted with the key informants who had expert knowledge on the subject under study.

3. Discussion of Results

The study evaluated the human, maintenance, environmental and supply chain factors to identify the major cause of the numerous drill rig breakdowns at LCM during the period 2014 to 2017 and propose measure that could assist the mine management in minimising the number of breakdowns. These variables constitute the area in which the drill rigs are operated and were found to be significant to the study. Therefore, the discussion of the results was based on the following specific research objective:To identify the major causes of the numerous drill rig breakdowns and develop a Framework which could assist Executive Management at LCM to identify potential causes of breakdowns. As seen from Table 2, the majority of the respondents, 55.2% indicated that human factors were the major cause of breakdowns whereas 44.8% stated that human factors were not the major causes of breakdowns at LCM

Table 2: Cross tabulation on Human Factor Causes of Breakdowns

			YES	NO	TOTAL
Employment Category	Supervision	Count	30	25	55
		Expected Count	25.8	29.2	55.0
	Operatives	Count	31	48	79.0
		Expected Count	35.2	43.8	79.0
Total		Count	60	74	134
		Expected Count	60.0	74.0	134.0

Source: Field Data

Table 3: Human Factor Causing Breakdowns - Chi-Square Tests

	Value	df	Asymptotic Significance (2- Sided)	Exact Sig (2-Sided)	Exact Sig (1-Sided)
Pearson Chi-Square	2.670[a]	1	0.102		
Continuity Correction[b]	2.070	1	0.150		
Likelihood Ratio	2.665	1	0.103		
Fisher's Exact Test				0.121	0.075
Linear-by-Linear Association	2.647	1	0.104		
N of Valid Cases	134				

a) 0 Cells (0%) have expected count less than 5. The minimum expected count is 17.82
b) Computed only for a 2x2 Table

From the results obtained, there was no difference in responses between managers and operatives and the Chi-Square results indicate ($x^2(1, N = 134) = 2.67, p = .102$). This showed that both supervisors and operatives believed that human related factors were the main causes of drill rig breakdowns. Further, to augment the Chi-Square test, the Z-test analysis was carried out so as to confirm the results obtained.

Z- Test Analysis

- **Hypotheses**

Ho:$\pi 1 - \pi 2 = 0$*:* Human related factors were the main cause of drill rig breakdown at LCM.

Há:$\pi 1 - \pi 2 \neq 0$*:* Human related factors were not the main cause of drill rig breakdown at LCM.

- **Significance Level α= 0.01**
- **Rejection Region**

Reject the null hypothesis if p-value ≤ 0.05.

- **Test Statistic**

From the relationship of Z-Test is equal to the square root of the Chi-Square static, the Z-Test static can be calculated as: $Z = \sqrt{\text{Pearson Chi-Square}} = \sqrt{2.670} = 1.634$ (Z score is the same as square root of Pearson Chi-Square)
p-value = Asymp. Sig. (2-tailed) = 0.102

- **Conclusion**

Since p-value $= 0.102 > 0.05 = \alpha$, we accept the null hypothesis. Therefore, at the level $\alpha = 0.01$ level of significance, there was enough evidence to conclude that Human factors were the major cause of drill rig breakdown at LCM. Therefore, the Z-Test static verifies the results obtained from the Chi-Square test. Maintenance factors were also considered to be one of the causes of drill rig breakdown at LCM. Therefore, the data in Table 5.19 show respondent's views on whether maintenance factors contributed to drill rig breakdown at LCM.

Additionally, Table 4 show that 61.2%of the respondents stated that maintenance factors did not contribute significantly to drill rig breakdown at LCM, while on the other hand, 38.8% of the respondents believed that the maintenance factors contributed to the numerous drill rig breakdowns.

Table 4: Maintenance Factors

			NO	YES	TOTAL
Employment category	Supervision	Count	19	25	44
		Expected Count	17.1	26.9	44.0
	Operatives	Count	33	57	90
		Expected Count	34.9	55.1	90.0
Total		Count	52	82	134
		Expected Count	52.0	82.0	134.0

Source: Field Data

Table 5: Maintenance Factors - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2sided)	Exact Sig. (1sided)
Pearson Chi-Square	.528ª	1	0.467		
Continuity Correctionᵇ	0.290	1	0.591		
Likelihood Ratio	0.525	1	0.469		
Fisher's Exact Test				0.572	0.294
Linear-by-Linear Association	0.524	1	0.469		
N of Valid Cases	134				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 17.07.
b. Computed only for a 2x2 table

From the results obtained, these responses were not dependant on the position that the respondent held in the organisation and the Chi-Square results indicate (x2(1, N = 134) = 0.528, p = .467) signifying that all respondents believed that the maintenance factors contribute to drill rig breakdown at LCM. Further, to augment the Chi-Square test, the Z-test analysis was conducted so as to validate the results obtained.

Z- Test Analysis

- **Hypotheses**

Ho:$\pi 1 - \pi 2 = 0$: Maintenance factors contributed to drill rig breakdowns at LCM
Há:$\pi 1 - \pi 2 \neq 0$: Maintenance factors did not contribute to drill rig breakdowns at LCM

- **Significance Level α= 0.01**
- **Rejection Region**

Reject the null hypothesis if p-value ≤ 0.05.

- **Test Statistic**

From the relationship of Z-Test is equal to the square root of the Chi-Square static, the Z-Test static can be calculated as: $Z = \sqrt{\text{Pearson Chi-Square}} = \sqrt{0.528} = 0.726$ (Z score is the same as square root of Pearson Chi-Square)
p-value = Asymp. Sig. (2-tailed) = 0.467

- **Conclusion**

Since p-value $= 0.467 > 0.05 = \alpha$, we accept the null hypothesis. Therefore, at the level $\alpha = 0.01$ level of significance, there is enough evidence to conclude that maintenance factors contribute to breakdown of drill rigs at LCM. Therefore, the Z-Test static confirms with the results obtained from the Chi-Square test. Environmental conditions were equally identified as one of the factor contributing to the numerous drill rig breakdowns at LCM. The data in Table 6 show how respondents perceived environmental conditions in relation to drill rig breakdowns at LCM. The data presented in Table 6 show that, 43.2% of the respondents indicated that the underground environmental conditions contributed to the numerous drill rig breakdowns whereas the majority, 56.7% believed that environmental conditions did not contribute to the numerous drill rig breakdowns at the mine.

Table 6: Environmental Conditions

			NO	YES	TOTAL
Employment category	Supervision	Count	23	21	44
		Expected Count	25.0	19.0	44.0
	Operatives	Count	53	37	90
		Expected Count	51.0	39.0	90.0
Total		Count	76	58	134
		Expected Count	76.0	58.0	134.0

Source: Field Data

Table 7: Environmental Conditions- Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	.527ª	1	0.468		
Continuity Correctionᵇ	0.292	1	0.589		
Likelihood Ratio	0.525	1	0.469		
Fisher's Exact Test				0.578	0.294
Linear-by- Linear Association	0.523	1	0.470		
N of Valid Cases	134				

a) 0 cells (0.0%) have expected count less than 5. The minimum expected count is 19.04.
b) Computed only for a 2x2 table

From the results obtained, these responses were not dependant on the position that the respondent held in the organisation and the Chi-Square results show (x2(1, N = 134) = 2.066, p = 0.151) stating that all respondents believed that environmental conditions were one of the contributing factors to the major breakdowns of drill rigs. Further, to augment the Chi-Square test, the Z-test analysis was conducted so as to validate the results obtained.

Z- Test Analysis

- **Hypotheses**

Ho:$\pi 1 - \pi 2 = 0$: Environmental factors caused drill rig breakdowns at LCM.
Há:$\pi 1 - \pi 2 \neq 0$: Environmental factors did not cause drill rig breakdowns at LCM.

- **Significance Level** α= 0.01

- **Rejection Region**

Reject the null hypothesis if *p*-value ≤ 0.05.

- **Test Statistic**

From the relationship of Z-Test is equal to the square root of the Chi-Square static, the Z-Test static can be calculated as:
$Z = \sqrt{\text{Pearson Chi-Square}} = \sqrt{0.527} = 0.725$ (Z score is the same as square root of Pearson Chi-Square)
p-value = Asymp. Sig. (2-tailed) = 0.468

- **Conclusion**

Since *p*-value = 0.468 > 0.05 = α, we accept the null hypothesis. Therefore, at the level α= 0.01 level of significance, there is enough evidence to conclude that environmental conditions cause breakdown of drill rig at LCM. Therefore, the Z-Test static confirms with the results obtained from the Chi-Square test.

Since materials used for the maintenance and repair of drill rigs were purchased through the Supply Chain Department, Supply Chain factors were considered as one factor that could contribute to drill breakdowns at LCM. The data in Table 8indicate that 68.7% of the respondents stated that Supply Chain factors did not contribute to the numerous drill rig breakdowns and only 31.3% believed that Supply Chain factors contributed to the numerous drill rig breakdowns at the mine.

Table 8: Supply Chain Factors

			NO	YES	TOTAL
Employment category	Supervision	Count	11	33	44
		Expected Count	13.8	30.2	44.0
	Operatives	Count	31	59	90
		Expected Count	28.2	61.8	90.0
Total		Count	42	92	134
		Expected Count	42.0	92.0	134.0

Source: Field Data

Table 9: Supply Chain Factors – Chi-Square Test

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	1.225[a]	1	0.268		
Continuity Correction[b]	0.825	1	0.364		
Likelihood Ratio	1.253	1	0.263		
Fisher's Exact Test				0.324	0.182
Linear-by-Linear Association	1.216	1	0.270		
Linear-by-Linear Association	134				

From the results obtained, these responses were not dependant on the position that the respondent held in the organisation and the Chi-Square results indicate (x^2(1, *N* = 134) = 1.225, *p* = 0.268) stating that all respondents believed that Supply Chain factors contributed to the numerous drill rig breakdowns at the mine. Further, to enhance the Chi-Square test, the Z-test analysis was conducted so as to validate the results obtained.

Z- Test Analysis

- **Hypotheses**

Ho:$\pi 1 - \pi 2 = 0$: Supply Chain factors at LCM caused drill rig breakdowns.
Há:$\pi 1 - \pi 2 \neq 0$: Supply Chain factors at LCM did not cause drill rig breakdowns.

- **Significance Level** α= 0.01

- **Rejection Region**

Reject the null hypothesis if *p*-value ≤ 0.05.

- **Test Statistic**

From the relationship of Z-Test is equal to the square root of the Chi-Square static, the Z-Test static can be calculated as:
$Z = \sqrt{\text{Pearson Chi-Square}} = \sqrt{1.225} = 1.106$ (Z score is the same as square root of Pearson Chi-Square)
p-value = Asymp. Sig. (2-tailed) = 0.268

- **Conclusion**

Since *p*-value = 0.268 > 0.05 = α, we accept the null hypothesis. Therefore, at the level α= 0.01 level of significance, there is enough evidence to conclude that Supply Chain factors contributed to breakdown of drill rig at LCM. Therefore, the Z-Test static confirms with the results obtained from the Chi-Square test.

Further,thirty five (35) key informants were purposively selected and interviewed on the bases of their expert knowledge on the topicand Table 10 shows the weight of responses.

Table 10: Key informants Responses

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Human Factors contribute to drill rig breakdowns	25	3	1	3	3
Environmental conditions contribute to drill rig breakdowns	10	5	8	15	2
Maintenance Factors contribute to drill rig breakdowns	9	2	12	11	1
Supply Chain factors contribute to drill rig breakdowns	9	1	8	12	5

Most key informants agree to the fact that human factors contributed significantly to drill rig breakdowns at LCM. Similar studies have been carried out on mining drill rigs and various results have obtained and presented (Kansake and Suglo, 2015; Song, 2012; Al-Chalabi, 2014; Pink 2011; Mohamad, 2011; Onwe and Abram, 2015).

4. Findings

The study reviewed that there were several related and unrelated causes that led to the numerous drill rig breakdowns at LCM and these causes were broadly classified as human, environmental, maintenance and Supply Chain factors.

Motivation

One of the key human related factors which was identified as a cause of drill rig breakdowns at LCM is lack of motivation among drill rig operators and maintenance personnel. It was noted that employees resorted to absenteeism through such means as unexplained and repeated sick leave. Repeated mistakes, negative behaviour and bad attitudes were observed from equipment maintenance reports and employee data files from Human Resources.

It was also discovered that most operators were discouraged by some human resource management practices which they deemed unfair. Most respondents indicated that workers were subjected to working as drill rig operators on an acting capacity without being confirmed in those roles within the stipulated time. Such practices caused employees to feel that they were not recognised for their work and being deprived of opportunities for advancement and career growth.

Other factors identified and linking to low motivation relate to low pay and the non-availability of a performance-based incentive schemes such as production bonus at the mine. Since production bonuses were widely used in the mining industry, LCM employees developed a feeling of inequity as they felt they were not adequately compensated.Such feelings resulted into low work performance, a condition that led to less care of equipment employees were assigned to.

Fatigue

Fatigue was cited as another cause leading to breakdowns of drill rigs at LCM. The results of this study showed that a number of drill rig operators worked long hours due to the inadequate number of operators. Additionally, if one of the operators was sick, then the one on shift was asked to work double shift to cover up the operator who did not turn up for work, as a result, operators got fatigued and failed to concentrate on their work. This contributed to the high number of operator absenteeism and in certain situations, equipment damage due to accidents as a result of operators going into a condition of circadian rhythm. Further, it was seen that the mine had a large number of inexperienced operators who did not complete their tasks within the stipulated time frame. Therefore, experienced operators were made to do extra work to cover for the lost time emanating from the use of inexperienced operators. As such, the experienced operators worked extended hours with inadequate rest periods. On the other hand, the inexperienced operators equally got exhausted due to repeated work in trying to correct the drilling mistakes. In addition, some experienced operators carried out duo roles, they worked as drill rig operators as well as supervising inexperienced drill rig operators. This practice made the experienced operators to rush in performing their duties and paid less attention to potential or developing faults on equipment.

Operator Training and Development

The other factor observed as a cause of the numerous drill rig breakdowns at LCM is the nature of operator training and development. It was seen that despite the training for drill rig operators being regarded as adequate, there were nevertheless some important aspects of training that were neglected. The scope of training did not cover most significant functionalities of the machine, the program was more focussed on the safety aspect of the machine rather than the primary operation of the equipment, the actual drilling process. Further, the operators lacked basic technical knowledge of the machine which could help them identify faults or failure indicators before a breakdown occurred and on the contrary, nopost training audits were conducted to assess the effectiveness of the training in actual job conditions.

The quality of training was also not satisfactory as the mine did not have specialised trainers. Additionally, the number of the available trainers was not adequate, a condition which made trainers rush through the training programme. As such, the poor quality of training was observed to be one of the factors contributing to low motivation and reduced job performance among operators. In line with the above narration, Kuhn (2012) said, research has shown that training and motivation have a positive impact on performance of employees and that when job performance is low as a result of lack of motivation caused by inappropriate training, employees wrongfully operate their equipment. Further, Mohammad (2011:149) explained that training of operating and maintenance personnel is key to reducing equipment breakdowns through proper identification and resolution of equipment faults. Figure 4 shows the factors behind employee's low morale, fatigue and a condition of low skills at LCM during the time of the study.

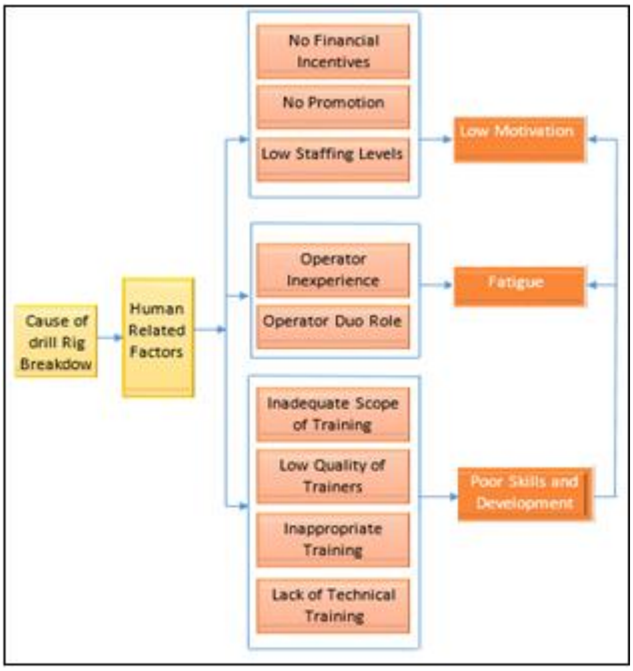

Figure 4: Human Factors Causes of Drill Rig Breakdowns
Source: Author, 2020

From Figure 4 it is noted that if there is no financial incentive, promotion and adequate staff, employees tend to be demotivated. On the other hand, inexperienced operators tend to overuse themselves in trying to carry out the assigned task correctly, this is mainly due to not having the full understanding of the functionality of the machine. Similarly, operators carrying out due roles end up in a state of fatigue as they do not have enough time to rest. Further, inadequate scope of training, low quality of trainers and lack of basictechnical machine concepts lead to poor operator skills and development. Therefore, poor skills and development lead to fatigue and low motivation of the employees. Finally, from this on-site observation, it can be concluded that human factors influence the performance of drill rig operators and maintenance personnel through negative behaviours exhibited by employees in responding to equipment issues. Therefore, human factors have a great influence on quality improvement practices and significantly influence organisational performance.

Environmental Factors

Tough environmental conditions were not cited as the major factor contributing to drill rig breakdowns, environmentalconditions have the potential to cause equipment breakdowns. Thestate of underground roadwaysin many places was steep, water logged and had rough terrain, rough terrain cause equipment to vibrate and this condition led to structural failure of the equipment as well as disturbance to electrical components.Other than just causing equipment structural failure as a result of rust, water is a good conductor of electricity and can act as a low resistance path on the insulation of electrical circuits causing insulation breakdown, change of dielectric and external electrical faults such as tracking or insulation flashover. All these conditions were experienced at the mine and affected equipment performance.The high temperature was believed to have been caused by poor ventilation in certain areas. This condition triggered the overheating of drill rig engines and hydraulic systems which eventually resulted into failure of such components. Excessive heat has the potential to cause physical or chemical change in equipment parts hence, creating variation in the characteristics of these components, the effect of embrittlement for example which occurs on both metallic and non-metallic equipment parts causes loss of material strength, cracking and fracture.Various writers have commented on the impact of environmental conditions on mining equipment; Thornburg (2016) indicated that, operating a drill rig in harsh environmental conditions can cause frequent breakdown of machines and associated subsystems and Barabady and Kumar (2008:647) implored that the performance of mining machines does not only depend on the reliability of the equipment, but also the environmental conditions where the equipment operate. Further, Sahu (2015:237) commented that proper design and maintenance of the roadways plays a significant role in reducing the breakdown frequency of equipment and thereby increasing production and productivity in a mine. Finally, Ray and Euler (2017:651) concluded that, environmental conditions such as temperature are required to be maintained within acceptable parameters in the mine working environment to minimise stress on equipment and personnel. Figure5 shows what led to poor roadway and worksite conditions at LCM.

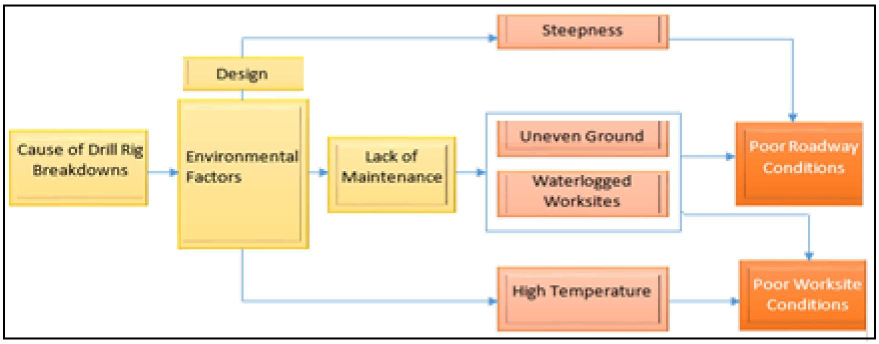

Figure 5: Operating Conditions
Source: Author, 2020

From Figure 5,it can be stated that poor roadway and worksite conditions are as a result of lack of maintenance, poor mine design and inadequate ventilation in work areas.

Maintenance Factors

Though maintenance factors did not come out prominently as the main contributing factor to drill rig breakdowns at the mine, certain areas or functions did not support maintenance processes. The number of maintenance personnel was not adequate and this resulted into some maintenance schedules being postponed or omitted all together. Further, the maintenance section did not have a reliability section to analyse equipment failureto enable maintenance personnel make informed decisions, this therefore made it difficult to carry out pre-failure studies which could help prevent incipient failures or breakdowns. This condition made the maintenance Technicians to operate without proper equipment failure history logs. Niklin (2013:93) indicated that failure causes of production systems need to be identified for effective solutions and root-cause failure analysis should be used to identify the failure causes.

Transport was another issue, the maintenance personnel did not have adequate transport to get to breakdown sites in time and had to walk to attend to the broken down equipment. The facilities in which the maintenance activities were designated to be undertaken were also inadequate. Additionally, the mine only had one maintenance workshop which was located on surface and catered for all mobile equipment at the mine, this workshop was always crowded as it compensated for breakdown repairs, planned maintenance and component change-out activities. The non-availability of an effective maintenance program (Enterprise Recourse Planning) made it difficult for the maintenance personnel to plan and schedule work, the tracking of component life-cycle and was through Excel spread sheets which had neither maintenance triggers nor automatic check sheets generation capabilities. Figure 6 shows the interrelationship of factors that caused maintenance constraints and non-adherence to OEM maintenance standards at the mine.

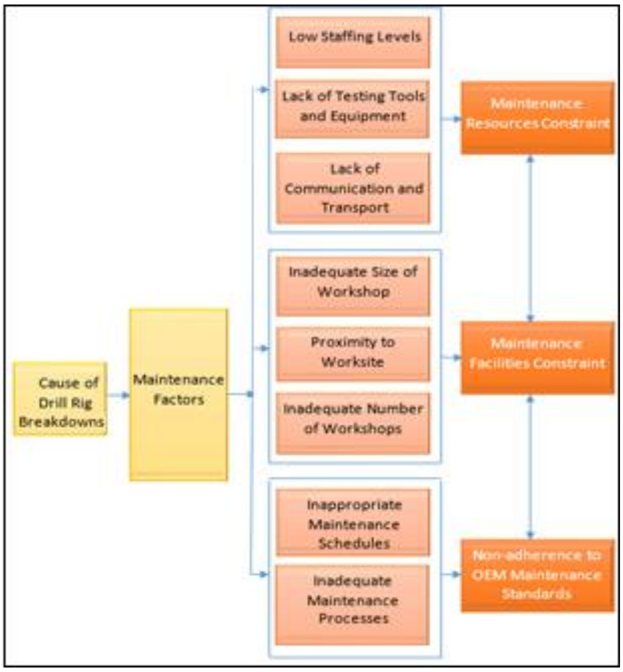

Figure 6: Maintenance Practices
Source: Author, 2020

From Figure 6, maintenance is mainly affected by inadequate resources such as staffing levels, testing equipment and communication. Other factors include, inadequate workshop capacity, proximity to the workshop from work areas and the inadequate number of workshops contribute to inappropriate maintenance standards. Finally, lack of proper maintenance processes and inappropriate schedules compromise maintenance standards and lead to poor quality maintenance which lowers equipment reliability.

Supply Chain Factors

Supply Chain is linked to the quality of parts since it is accountable for the procurement of parts for the mine. Though Supply Chain did not significantly contribute to the drill rig breakdowns, a number ofsubstantial observations were made. The supply department had an online material issuing and monitoring system to ensure quick and accurate provision of materials to user departments, however, in certain cases, part numbers did not match the requireditems. Further, the system did not trigger the reorder level and this contributed to stock out of major maintenance parts. Additionally, the supply department did not have a quality assurance section and depended on supplier’s test certificates and visual inspection by user departments to ascertain the integrity of received components or parts. At times, sub-standard parts were given priority owing to the cost factor.

It was also observed that,there was adequate storage facility for the small and medium items, however, bigger items were stored in open space subjected to water and dust. Paz and Leigh (1994:47) established that, the shortage of supplies directly or indirectly affect productivity and tend to make maintenance scheduling a dynamic and challenging process. Figure 7 shows how supply factors contributed to machine breakdown.

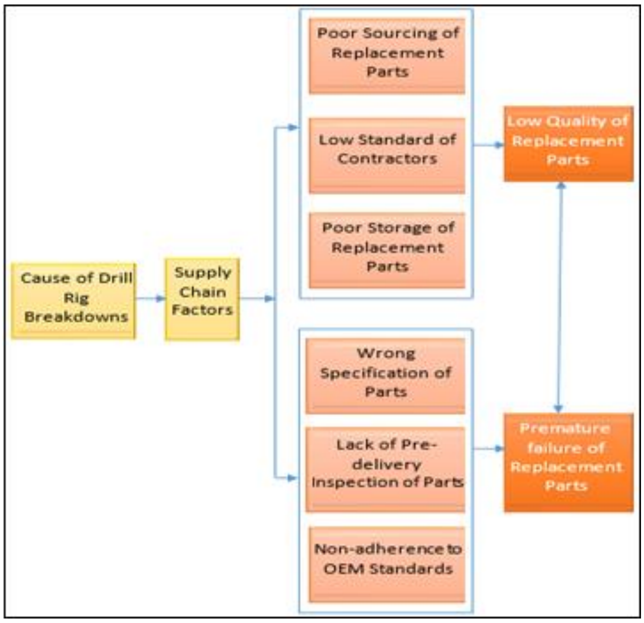

Figure 7: Supply Chain and Quality factors
Source: Author, 2020

From Figure 7, it can be seen that the low quality of replacement parts was caused by poor sourcing of replacement parts, where the vendor was not adequately inspected to ascertain the potential to carry out specific tasks. Further, premature failure of components and parts resulted from wrong specification of parts, lack of pre-delivery inspections and non-conformance to OEM standards.

Framework for Identifying Drill Rig Breakdowns

To minimise production time losses arising from equipment downtime, a Framework for identifying drill rig breakdown causes is developed. Thus, if the potential breakdown causes are anticipated correctly and prevented, the mine can experience less drill rig downtime and subsequently, improved productivity with reduced maintenance costs.It is a well-known fact that effective maintenance standards prevent catastrophic losses that endanger the operation's productive capacity. Figure 8 presents a network diagram of the proposed Framework.

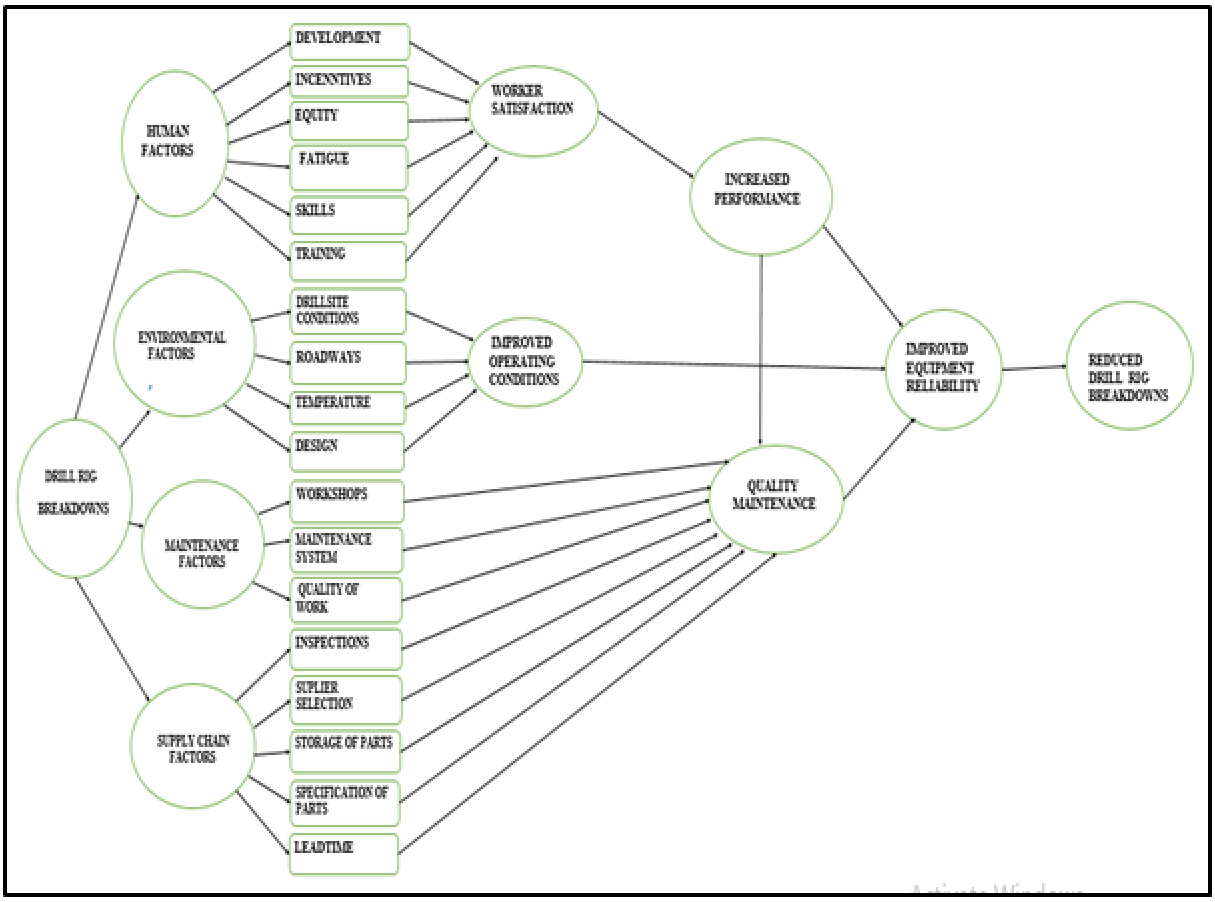

Figure 8: Drill RigBreakdown Framework
Source: Author, 2019

Operationalisation of the Framework

The developed drill rig breakdown Framework shown in Figure 8 follows the main dimensions of the analytical framework, addressing the human, environmental, maintenance and Supply Chain factors.

Human Factors

Human factor related causes have been identified in the study as the major dynamics contributing to the frequent drill rig breakdowns at the mine. The major areas highlighted within the human factor comprise employ training and development, the issue of incentives, equity within the work place, skills and workplace fatigue. As such, addressing these concerns could help reduce the impact of the human factor on drill rig breakdowns.

The demotivation arising from acting issues can be alleviated by ensuring that each acting role is acknowledged by human resources personnel and documented with the acting period and allowances clearly defined and paid. Further, the training department should formulate a training request form that the requesting department should complete and signed by senior officials and thereafter, the document may be sent to the Human Resources Department for final approval, filling and follow-up. This can create transparency and instil confidence in the operators in acting roles.

Further, incorporating an incentive scheme into the annual budget and reviewing it each year could motivate both the drill rig operators and maintenance personnel. This could equally be coupled with a benchmarking process which may be conducted within the Zambian mines to compare the conditions of employment. The results of such benchmarking audits could be given to management before the final approval of the budget for consideration. This may help management adjust the incentives in line with other mines within the country as the underground conditions are similar.

The training of drill rig operators needs to focus on the actual drilling activitiesand must encompass all aspects that are required for accurate and effective drilling. This should include selecting the drill rig operators on merit and avoid favouritism or other backhand methods. To enhance the skills of the drill rig operators, performance audits should be conducted on drill rig operators after completing their training in order to identify and address any skills gaps. Additionally, the issue of fatigue for the drill rig operators can be alleviated by carrying out a job analysis to arrive at the optimal number of qualified and competent operators. This action can equally relieve the experienced operators from carrying out more than one role and availing them ample time to rest.

Addressing the above issues adequately could lead to worker satisfaction and subsequently increased performance. However, this requires concerted effort from all levels of management.

Environmental Factors

Environmental factors equally have the potential to causeequipment breakdown. Continuous maintenance of roadways can help in lessening equipment components failures and to ensure continuity, a standalone road maintenance team is required which should be independent of the ore production section. There is usually a tendency of production taking preference when production and road maintenance teams are combined. Water runs along roadways when pipes burst along the decline, therefore, running dewatering pipes through raise boreholes (drilled holes) away from the decline (roadway) significantly assist in reducing damage to the roadways. On the other hand, this initiative keeps water line away from heavy mobile equipment. Where possible, drilling of drain holes in operating areas should be encouraged as this helps in draining stagnant water from operating areas.

The mine design is another aspect to be considered, in designing roadways, incline angles must be correctly outlined, however, in many cases, error occur during mining operations if grid line are not accurately followed. Steep inclines should be avoided as they pose a great challenge to mobile equipment. Ventilation into work areas must be adequate to ensure that temperatures are within acceptable limits as stipulated by the Mine Safety Department.

If operating conditions are maintained to acceptable standards, the damage to equipment is minimised resulting into equipment increased effective operating time and subsequently improved productivity.

Maintenance Factors

Maintenance factors such as adequacy of workshop infrastructure, maintenance systems, quality of maintenance and maintenance parts and staff skills contribute significantly to equipment performance or reliability. Therefore, it is imperativeto provide adequate workshop infrastructure equipped with special tools, maintenance parts must be procured from OEM or approved and certified dealers and all parts received must be inspected to ensure conformity to standard. It is also important to ensure that qualified maintenance personnel are hired and they must keep up with all the equipment technological advancement through further training which is usually provided by the OEM. A maintenance based Enterprise Resource Planning software is required to assist in planning and monitoring equipment life cycle activities.

It is also important to have available testing equipment on site for testing such major components as engines before fitting. This minimises rework through premature failure of parts and ensuring standard maintenance parts are purchased. On the other hand, to ensure effective labour utilisation, a job analysis/design should be conducted to ensure that the correct number of personnel is made available to the department.

Supply Chain Factors

Supply Chain is yet another area that contributes to equipment maintenancethrough procurement and storage of parts. This section should always ensure that correct and standard parts are purchased and within time. Runout of maintenance parts distort maintenance planning and in some instances introduced overrunning of parts and contributing to downtime when they fail unexpectedly.

Finally, the use of the proposed framework can generate worker satisfaction, improved environmental conditions and improved quality of maintenance, all of which if planned and executed accordingly can lead to improved equipment reliability and consequently, reduced number of equipment breakdown. However, since no framework or model is used on the mine to this effect, validation of the Framework may not be possible immediately on quantitative basis.

5. Conclusion

The main objective of this study was to explore the causes of the numerous drill rig breakdowns at LCM and thereafter develop a Framework for identifying potential sources of breakdowns.

The most important finding to emerge from this study is that, human factors contributed significantly to the numerous drill rig breakdown at LCM. The elements of human factor that contributed to these breakdowns at the mine include lack of motivation, high levels of fatigue among operators and maintenance personnel, and the low skills level of operators arising from inappropriate training and development program implemented at the mine.

Further, the other aspect coming out prominently as a contributing factor to the numerous drill rig breakdowns at LCM is the environmental factor. Lack of maintenance of the roadways and worksites as well as inappropriate mine design contributed significantly to the drill rig breakdowns experienced at the mine. Maintenance practices though not to a greater extent, equality contributed to the numerous drill rig breakdowns experienced at the mine. Finally, Supply Chain, though not a major contributing factor affected equipment reliability to some degree. Inadequate storage capacity for bigger components, the lack of redelivery inspection of parts and runout of maintenance parts all adversely affected maintenance of equipment.

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