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Establishment of a mathematical relationship to correlate fleet size with equipment availability in open pit mine, using curve-fitting techniques: A case study of Mashamba copper deposit in the Democratic Republic of Congo)

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ABSTRACT: Mashamba open pit mine is located 10 km southeast of Kolwezi town, in one of the richest copper areas of the Democratic Republic of Congo. The copper deposit block model has been run through mine optimization and provided a life of mine (LOM) of 6 years within four major pushbacks. The optimization process involved the use of NPV scheduler Datamine software (Lersch-Grossman algorithm). The ultimate pit and pushback designs have been executed using Minesight software. The haulage analysis has been conducted for the entire LOM of the deposit using the Minesight Haulage tool. Initial simulation of truck fleet size was done assuming a truck availability of 85%. However, it has since been observed that in practice, 85% availability over the entire life of the mine will be an unrealistic target it was therefore interesting to conduct a set of scenarios using the Minesight haulage tool to vary the availability and to compare the fleet size variation. In this paper, curve-fitting techniques have been used to observe, analyse, and establish a mathematical relationship to correlate dump truck availability and fleet size data, and to determine how strongly the two variables are correlated. Despite the fact that the mathematical equation and correlation factor calculated in this case study are not expected to lead to a replacement of haulage software packages, they were found to be helpful tools for quickly predicting the fleet size (number of trucks required for the entire mine life) based on a given set of truck availabilities at Mashamba open pit.

KEYWORDS: Ordinary linear regression, analysis of variance, haulage, open pit mine, correlation factor.

1 INTRODUCTION

Load and haul plays an important role among the four fundamentals mining operations (drilling, blasting, load and haul). In some cases, haulage may represent a substantial proportion of the total mining cost. Existing mine planning processes and techniques, (mine optimization, pushback analysis, and mine scheduling) calculate the size of the fleet from the quantities of ore and waste required to be moved in in terms of the mine plan. Mashamba East open pit mine has been optimized and developed to produce approximately 3 Mt of ore and 30 Mt of waste per year during a life of mine (LOM) of 6 years. The investor (Katanga Mining Limited) intends to use the Caterpillar 777F dump truck series and diesel CAT 6030 FS front-end shovels. Both trucks and shovels were assumed to be running at 85% equipment availability. From experience in the neighbouring open pit mines(KOV pit, T-17 pit), concerns have been raised that such a high availability over the entire life of the mine is over-optimistic, taking into account factors such as in-pit groundwater, mud, and ground conditions that affect tyres, radiators, suspensions, *etc*. and contribute strongly to lower the availability. A multiple scenario fleet size data-set has been compiled using the Minesight Haulage Tool, in which, truck availabilities were varied from 85% to 65% along the life of the mine, and its appears that there is a certain correlation between fleet size and truck availabilities. This paper discusses the approach that has been implemented to calculate the correlation.

1.1 SITE LOCATION

Mashamba open pit is located in the Kolwezi area in the south of the Democratic Republic of Congo (DRC), close to the border with Zambia (Figures 1 and 2), and forms part of a larger sedimentary deposit located in the Central African Copperbelt. The geological settings are summarized in Figure 3.

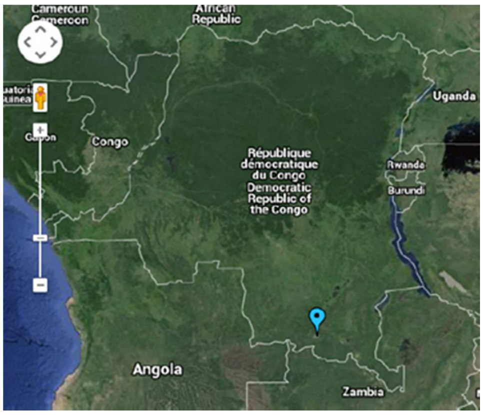

Fig. 1.Kolwezi town location.

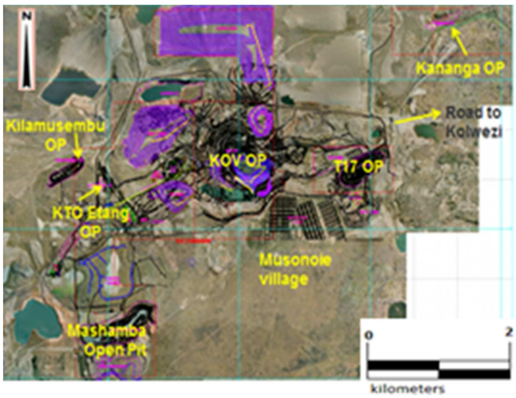

Fig 2. Mashamba open pit mine location in the Kolwezi district

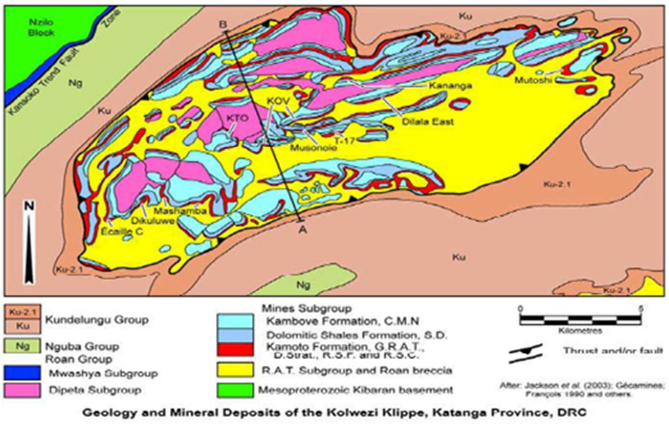

Fig 3. Mashamba open pit geological settings

1.2 Historical Context and Ownership

Kamoto Copper Company SA (KCC) has owned the material assets since 2006, including the mining and exploitation rights related to the mining assets. Katanga Mining Limited (KML) holds a 75% stake in KCC. La Generale des Carrieres ET des Mines (GCM) and La Société Immobilière du Congo (SIMCO), state-owned mining companies in the DRC, own the other 25% of KCC. Table I summarizes the different permits that the company acquired in order to operate legally in the DRC.

Table 1. Kamoto Copper Company permits that include the Mashamba open pit mine

Property	Exploitation permit number no.	Rights granted	Holder	Area of title	Valid until
Kamoto underground mine and Mashamba East open pit	PE525	Cu, Co and associated minerals	KCC	13 blocks, 11.04 km^2	03/04/2024 Renewable
T-17 open pit	PE11602	Cu, Co, nickel and gold	KCC	2 blocks, 1.698 km^2	03/04/2024 Renewable
Extension of Kananga	PE11601	Cu, Co, nickel and gold	KCC	1 block, 0.849 km^2	07/05/2022 Renewable
KOV open pit	PE4961	Cu, Co and associated minerals + use of surface	KCC	10 blocks, 8.49 km^2	03/04/2024 Renewable
Tilwezembe open pit	PE4963	Cu, Co and associated minerals + use of surface	KCC	9 blocks, 7.64 km^2	03/04/2024 Renewable
Kananga Mine	PE4960	Cu, Co and associated minerals + use of surface	KCC	13 blocks, 11.04 km^2	03/04/2024 Renewable

2 METHODOLOGY

Haulage data per year was generated using a yearly-defined haulage network. The haulage network consists of a bench centroid or a source point, a tie node, and destination nodes (ore stockpile or waste dump locations). In this analysis, a different haulage network was used for every year, because bench centroids locations are variable due to the annual mining schedule. Figure 4 and 5 illustrates an example haulage network per year. To accommodate severe ground conditions, a 7% rolling resistance and a maximum haul speed of 40 km/h were applied. A 5% variation range was applied every year to simulate a realistic drop in availability, as shown in Tables 2–5. Years 5 and 6 had to be omitted from this experiment due to the small amount of data generated by the Minesight Haulage tool (requires only three trucks, all of them allocated mostly to ore mining). An optimal equipment utilization of 90% was assumed.

The Minesight Haulage tool uses an SQL database to link the haulage network to the block model via an ODBC (open database connectivity) connection, to determine which material (ore or waste) goes where (mill or waste dump). The rolling resistance, ramp gradient, and equipment availability are added as constrains while the number of required trucks is calculated. The amount of material to be hauled is then evaluated, based on the pit design contained quantities; at the same time, equipment hours required to achieve production are determined. Every year, based on the 5% variation in the availability, it is possible to predict the fleet size. The correlation factor and a regression equation are calculated to help formulate the analysis as a mathematical relationship.

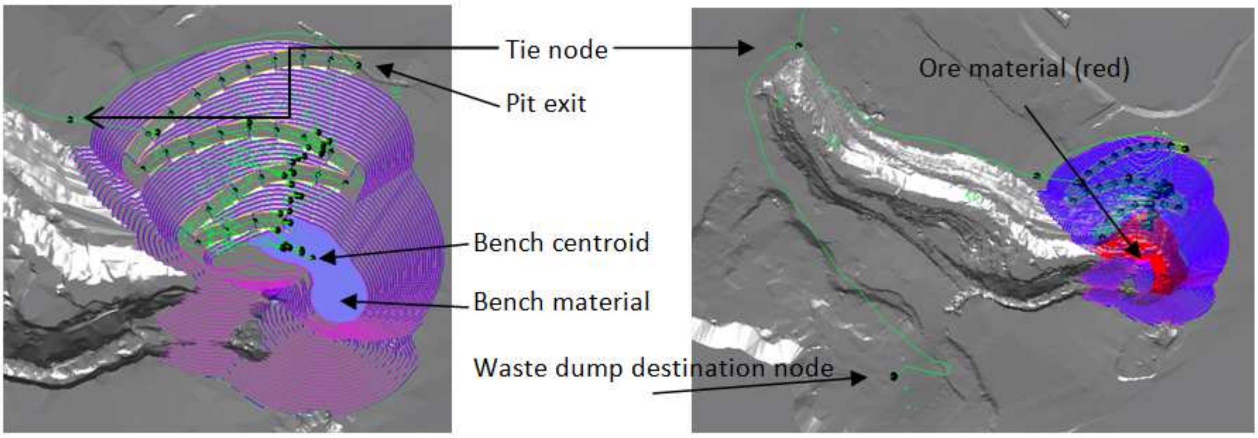

Fig 4. Mashamba open pit mine haulage network example *Fig 5.Detailed haul network*

2.1 STATISTICAL APPROACH

As stated previously, data was gathered yearly to obtain a clear context or variation domain of the availability and the fleet size.

2.2 DATA DISTRIBUTION

This study is based on the principle that availability is an input (X), and the fleet size is an output (Y). From a statistical point of view, this is termed a single-response variable analysis. Before making any calculation, it is good to know whether the data is distributed linearly or not. Tables 2–5 and Figures 6–9 summarize the data.

Table 2. Year1 data distribution

Year1	Truck availability	#Haulers
Observation 1	85	13.40
Observation 2	84	13.56
Observation 3	83	13.73
Observation 4	82	13.89
Observation 5	81	14.07
Observation 6	80	14.24

Table 3. Year2 data distribution

Year2	Truck availability	#Haulers
Observation 1	79	13.99
Observation 2	78	14.17
Observation 3	77	14.35
Observation 4	76	14.54
Observation 5	75	14.74

Table 4. Year3 data distribution

Year3	Truck availability	#Haulers
Observation 1	74	12.66
Observation 2	73	12.83
Observation 3	72	13.01
Observation 4	71	13.19
Observation 5	70	13.38

Table 5. Year4 data distribution

Year4	Truck availability	#Haulers
Observation 1	69	17.31
Observation 2	68	17.56
Observation 3	67	17.83
Observation 4	66	18.10
Observation 5	65	18.37

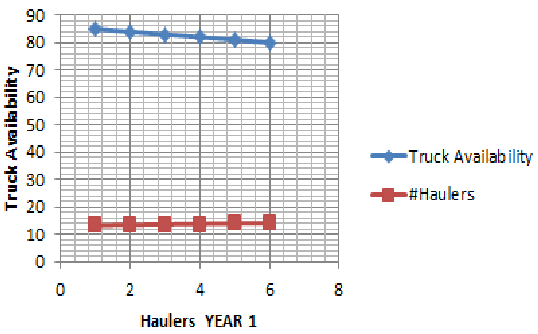

Fig 6.Year1 graphical data distribution.

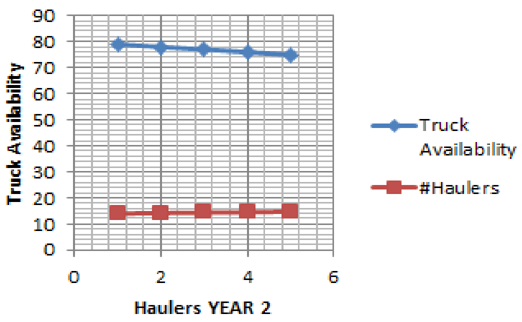

Fig 7.Year2 graphical data distribution.

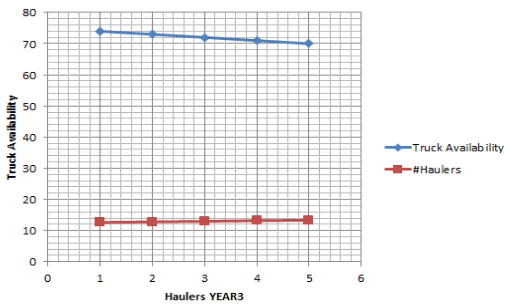

Fig 8.Year3 graphical data distribution.

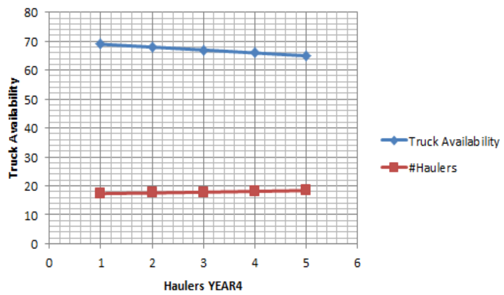

Fig 9.Year4 graphical data distribution

2.3 ORDINARY LEAST-SQUARES REGRESSION (OLS)

Based on the preceding observations, the mathematical relationship was established using an ordinary least-squares regression (OLS) approach, since according to the graphical distributions, the linear approach was the best to apply.

2.4 LINEAR REGRESSION APPROACH (LR)

In order to apply the LR approach to the data, the variable (X) will be the availability, which is supposed to vary in one single year by 5% (yearly variation domain), and the number of required trucks (haulers), will be the function (Y). The aim in this analysis is to generate a straight-line mathematical relationship using the general formula Y = ax + b, where 'a' is the slope of the line of best fit and represents the regression coefficient. The regression coefficient describes how the number of trucks varies when the availability varies by a single unit (here the unit is 1% increase inside the variation domain).

2.5 THE DATA ANALYSIS ADD-IN IN EXCEL

The compiled data-set was processed using the Excel data analysis tool to produce the linear regression equation for a single variable response.

2.6 DATA OUTPUT NAMING CONVENTION

Several papers, courses, tutorials are available to explain the details, but the discussion here is restricted to the output section in order to make the findings easy to understand by the reader. In the ANOVA (analysis of variance) section, the calculator determines the best set of the coefficients that will be applied to the equation and evaluates the standard error related to the determination of those coefficients (a and b in the linear equation Y = ax + b). The ANOVA determines quantities like the degree of freedom (df) associated with the mean square (MS), and also the sum of squares (SS). In addition, the ANOVA also conducts a test of significance and determines the so-called F-numbers (F). The regression statistics spreadsheet provides the adjusted R-square factor, the correlation factor between X (truck availability) and Y (trucks required).

2.7 YEARLY RESULTS FOR THE REGRESSION CALCULATION

- Year 1 Results

The regression results for the first year are shown in Tables 6–8.

Table 6. Year 1 regression results summary.

Regression statistics	
Multiple R	0.9998
R-square	0.9997
Adjusted R-square	0.9996
Standard error	0.0062
Observations	6.0000

Table 7. Year1 ANOVA results summary.

	df	SS	MS	F	Significance F			
Regression	1	0.4911	0.4911	12,749.7	3.68915E-08			
Residual	4	0.0002	0.0000					
Total	5	0.4913						
	Coefficients	Standard error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	27.6369	0.1224	225.745	0.0000	27.2970	27.976	27.297	27.976
TruckAvail	-0.1675	0.0015	-112.91	0.0000	-0.1716	-0.163	-0.1716	-0.1634

Table 8. Year1 residual results summary

Residual output				Probability output	
Observation	**Predicted #haulers**	**Residuals**	**Standard residuals**	**Percentile**	**#Haulers (rounded)**
1	13.40	0.01	1.21	8.33	14
2	13.57	0.00	-0.23	25.00	14
3	13.73	-0.01	-0.97	41.67	14
4	13.90	-0.01	-0.99	58.33	14
5	14.07	0.00	-0.26	75.00	14
6	14.24	0.01	1.23	91.67	15

- Year 2 Results

The regression results for the year 2 are shown in Tables 9–11.

Table 9. Year 2 regression results summary.

Regression statistics	
Multiple R	0.9998
R-square	0.9997
Adjusted R-square	0.9996
Standard error	0.0052
Observations	5.0000

Table 10. Year2 ANOVA results summary.

	df	**SS**	**MS**	**F**	**Significance F**			
Regression	1	0.3479	0.3479	12,697.65	1.54086E-06			
Residual	3	8.22E-05	2.74E-05					
Total	4	0.34800						
	Coefficients	Standard error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	28.7218	0.1274	225.3033	1.92E-07	28.3161	29.127	28.32	29.127
TruckAvail	-0.1865	0.0016	-112.684	1.54E-06	-0.19179	-0.181	-0.191	-0.181

Table 11. Year2 residual results summary

Residual output				Probability output	
Observation	**Predicted #haulers**	**Residuals**	**Standard residuals**	**Percentile**	**#Haulers (rounded)**
1	13.98	0.004808	1.060	10	14
2	14.17	-0.00234	-0.51762	30	14
3	14.36	-0.00484	-1.06943	50	15
4	14.54	-0.00249	-0.55071	70	15
5	14.73	0.004883	1.077147	90	15

- Year 3 Results

The regression results for the year3 are shown in Tables 12–14.

Table 12. Year 3 regression results summary.

Regression statistics	
Multiple R	0.9998
R-square	0.9997
Adjusted R-square	0.9996
Standard error	0.0054
Observations	5.0000

Table 13. Year3 ANOVA results summary.

	df	SS	MS	F	Significance F			
Regression	1	0.3269	0.3479	11,099.72	1.8852E-06			
Residual	3	8.83E-05	2.94E-05					
Total	4	0.3270						
	Coefficients	Standard error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	26.035827	0.12360	210.6413	2.35E-07	25.6424	26.4291	25.642	26.429
TruckAvail	-0.1808	0.00171	-105.355	1.88E-06	-0.1862	-0.1753	-0.186	-0.175

Table 14. Year3 residual results summary.

Residual output				Probability output	
Observation	**Predicted #haulers**	**Residuals**	**Standard residuals**	**Percentile**	**#Haulers (rounded)**
1	12.65	0.004985	1.060	10	13
2	12.83	-0.00243	-0.51794	30	13
3	13.01	-0.00502	-1.06827	50	13
4	13.19	-0.00259	-0.55190	70	13
5	13.37	0.005065	1.077549	90	14

- Year 4 Results

The regression results for the year 4 are shown in Tables 15–17.

Table 15. Year 4 regression results summary.

Regression statistics	
Multiple R	0.9998
R-square	0.9997
Adjusted R-square	0.9996
Standard error	0.0086
Observations	5.0000

Table 16. Year4 ANOVA results summary

	df	SS	MS	F	Significance F			
Regression	1	0.70889	0.70889	9611.344	2.339E-06			
Residual	3	0.00022	7.37E-05					
Total	4	0.70911						
	Coefficients	Standard error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	35.67	0.1819	196.0008	2.93E-07	35.097	36.2511	35.09	36.25
TruckAvail	-0.266	0.0027	-98.037	2.34E-06	-0.2748	-0.2576	-0.274	-0.257

Table 17. Year 4 residual results summary

Residual output				Probability output	
Observation	**Predicted #haulers**	**Residuals**	**Standard residuals**	**Percentile**	**#Haulers (rounded)**
1	17.30	0.00787	1.05946	10	18
2	17.56	-0.0038	-0.5156	30	18
3	17.83	-0.00794	-1.0686	50	18
4	18.09	-0.00411	-0.5536	70	18
5	18.37	0.00802	1.07847	90	19

- Summary Equations from year1 to year4

Yearly equations are expressed as follow:

$$Y=-0.1675X+27.63 \quad (1)$$
$$Y=-0.1865X+28.72 \quad (2)$$
$$Y=-0.1808X+26.03 \quad (3)$$
$$Y=-0.2667X+35.67 \quad (4)$$

3 FINDINGS AND COMMENTS

The results show a strong linear relationship between equipment availability and fleet size and a correlation factor of r = 0.99 for the four years. This indicates that in 99% of cases, the fleet size variable (Y) is explained by the availability variable (X). Despite changes in bench centroid locations and occasional changes in the waste dumping location (from year 1 to year 2, for example), every year seems to carry with it a much stronger linear mathematical relationship that increases the fleet size by one truck every year when availability vary in a range of 5% yearly. The findings demonstrate that the fleet size variation equation or function is spatially independent, meaning that the haulage network 3D configuration does not affect the strong linear relationship between the availability and the fleet size.

4 CONCLUSION

For the Mashamba East open pit mine, there is a demonstrated linear correlation between equipment availability and fleet size. In the given 3D conditions, and in field conditions, despite geometric changes in the haulage network, the correlation seems to persist and to show a fleet size increase of one truck when availability drops by 5%. This analysis is not intended as a tool to be used as a substitute for a conventional mining haulage package, but the study has shown that this mathematical relationship is independent of a three-dimensional representation of a haul network that evolves spatially. This study is not complete; the findings are promising but the method needs to be applied to larger and more complex open pit mines with multiple waste dumping locations and ore stockpiles to check for a stronger validation of the findings.

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