International Journal of Engineering Innovation & Research
Volume 7, Issue 3, ISSN: 2277 – 5668

Using Run-of-mine Tonnage and Grade to Predict Cost and Categorize Gold Mines

Karim Rajabu Baruti
Corresponding author email id: karimbaruti@udsm.ac.tz, karim_baruti@yahoo.com

Date of publication (dd/mm/yyyy): 02/05/2018

***Abstract* – This paper focuses on establishing logistic model of cost effect of run-of-mine tonnage and grade in the justification of categorization of gold mines. Gold mines could be categorized based on the abilities of rom-grade and rom-tonnage to predict cost. The data used in the generation of the logistic model were cash-cost as dependent variable vs. rom-grade, rom-tonnage as independent variables together with the type of mine obtained from 160 gold mines selected from the top 20 gold rich countries in the period of 7 years from 2002 to 2008. Logistic Regression Analysis using SPSS software was carried out to determine the probability of occurrence of low cost given rom-grade and rom-tonnage for either an open pit, underground or both mines together. The results indicated that only rom-grade with a cut-off value 5.385 g/t can be used to categorize gold mines as low and high grade while there was not enough evidence to categorize gold mines based on their rom-tonnage. The full model established in this study has a percentage correct of 62.9 compared to 57.9 percent by guess. The relationship between cost vs. rom-grade and rom-tonnage indicated that only 6.9 percent of the cost is accounted by rom-grade and rom-tonnage. This is a weak relation indicating that rom-grade and rom-tonnage are not the only determinants and therefore on their own must be used with precaution. Validation of the model agrees well with the actual results.**

***Keywords* – Cost, Gold Mine Category, Rom-Grade, Rom-Tonnage.**

I. Introduction

Run-of-mine (ROM) grade and tonnage of any gold mine in any gold rich country are normally considered as the main criteria in determining cost of gold mining and used by many investors to categorize gold mines worldwide [1]. Using these criteria, for example, investors would categorize gold mine as low tonnage high grade underground mine or high tonnage low grade open pit mine [2]. High rom-tonnage and grade of a mine are considered by many investors as low cost mine and attractive for investments while low rom-tonnage and grade are considered as high cost and less attractive for investments [2], [3]. While this approach is useful, the categorization method used seems to be fragile since it is not built from any statistical mathematical model. Consequently, such categorization does not provide comparative results for all gold mines globally. The effective and desired rom-tonnage and rom-grade based category should be established based on statistical model to enhance prediction of cost. Such rom-grade and tonnage based categorization has not been established since the mathematical models fit on the rom-grade and rom-tonnage given type of mine has not been established.

This study has developed a mathematical model of cost vs. rom-grade and rom-tonnage in open pit or underground conditions that can be used to predict low or high cost in the categorization of gold mines using Logistic Regression Analysis.

II. Existing Grade-Tonnage based Categorization of Gold Mines and Models

A. Rom-Grade and Rom-Tonnage based Categories

Average grade of a rom expressed in ounce per tonne (Oz/t) or gram per tonne (g/t or gpt) of any mine is the concentration of valuable mineral gold [4]. A higher rom-grade implies that more gold per tonne of ore can be mined and processed which lowers the unit cost. On the other side, lower rom-grade implies that less gold per tonne could be mined and processed thus raising unit cost [5]. Average annual rom-tonnage expressed in million tonne (Mt/y) is the annual size or capacity of a mine. Higher rom-tonnage allows higher annual production of gold (ounce, oz). Company operates large rom- tonnage enjoys economies of scale which brings down the unit cost [6]. Rom-tonnage varies inversely with grade as ore tonnage does with the ore grade [7] - [9].

Categorization of mines based on rom-grade and rom-tonnage has increasingly been used over time [10] – [12]. However, rom-grade and rom-tonnage based categories are not well developed and categorization is still fragile. Consequently, mining institutions tend to categorize their mines with several limitations. For example, World Gold Council categorizes underground gold mines as high grade mines if they have grade between 8 and 10 g/t and low grade between 1 and 8 g/t. Acacia Mining PLC in Tanzania categorized Bulyanhulu - a high-grade underground mine, Buzwagi a low-grade bulk deposit mine and North Mara a high-grade open pit mine [13]. Reference [14] ranked open pit and underground gold mines based on their grades only. In these rankings, Fire Creek mine of USA with a grade of 44.1 g/t was ranked first in the list of underground mines while Avlayakan of Russia with a grade of 18.2 g/t was ranked first in the list of open pit gold mines. In some occasions, for example, Turquoise Ridge Mine was classified using both grade and tonnage as high-grade and high tonnage underground mine.

It is evident that gold mines could be categorized based on rom-grade and rom-tonnage, however, the cut-off values which distinguish low grade from high grade and low tonnage from high tonnage have not clearly been established. Further, categorization of gold mine on one or two criteria is not justifiable.

B. Existing Model

In the study of the modeling the impact of mine and country variations of cash-cost and country-benefit using

Multiple Linear Regression Analysis, [15] established that rom-grade was a significant determinant of cash-cost among others while rom-tonnage was not. The main determinants of cash-cost were the parameters of rock-mass, mine design and country variations. Rom-grade ranked fourth among the significant parameters based on their contributions. While a model provides a good insight in terms of relation between cost and rom-grade, it cannot be used to predict cost in the justification of rom-grade and rom-tonnage based category since both dependent variable which is cost and independent variables which are rom-grade and rom-tonnage were not categorical but rather continuous. Using such a model to predict low or high cost in the justification of rom-grade and rom-tonnage based category would be difficult. However, logistic model relating cost vs. rom-grade and rom-tonnage using categorical data would provide good estimates of the probability of occurrence of low cost by fitting data to a logistic curve.

III. Methodology

Observational study was found to be appropriate approach for this kind of research. The Raw Materials Group database used to develop cash-cost model in [15] were used in the development of the logistic model of cost fits on rom-grade, rom-tonnage and type of mine. The dataset include 160 gold mines from the top 20 gold rich countries. The main characteristics of the mines in the dataset were that the mine is in operation, the type of deposit mined is primary deposit and gold is produced as main product.

The main variables that were considered in the model were cash-cost as dependent variable and rom-grade and rom-tonnage as independent variables together with type of mine such as open pit, underground or both open pit and underground. For each variable considered in the model, analysis was carried out to divide them into two categories low or high based on their mean values. Those values higher than mean were considered as high while those values below the mean were considered low. Thus, cash-cost was categorized as low and high cost based on the mean $ 324.44 /oz, the rom-grade was also categorized as low rom-grade or high rom-grade based on its mean value 5.385 g/t. However, categorization of rom-tonnage in the form of low and high tonnage based on its mean value 7.37 Mt/y provided insignificant results and therefore the non-categorical data were used in the analysis.

The desired outcome was selected as low cost and assigned 1 in the SPSS while high cost was assigned 0. Low grade and high grade were assigned 0 and 1, respectively while open pit mine was given 0, underground mine 1 and both open pit and underground mine 2. SPSS software was used in the whole analysis beginning from characterization of variables to the logistic regression. Scatterplot and cross-tabulation were used in the preliminary examination of the relationship between and among the variables and Chi square (χ^2) values were obtained and thereafter Logistic Regression Analysis was carried out. In the SPSS, the method of enter was selected, cash-cost was selected in the dependent variable, the independent variables rom-tonnage was in the continuous variable while rom-grade and type of mine were in the categorical variables.

In predicting low or high cost, it was agreed to accept a cut-off value of 0.5 as suggested by SPSS software. This is a mean value of a probability which normally ranges from 0 to 1. All predicted values of probability above 0.5 were regarded as high cost and conversely all predicted values of probability below 0.5 were considered as low cost.

IV. Mathematical Model Development

In this section, mathematical relationships between and among the main variables in the model were established first. Thereafter, logistic model was established based SPSS outputs.

A. Assessment of Relationships between and Among Variables

Rom-grade and Rom-tonnage

The relationship between rom-grade and rom-tonnage was explored using scatterplot and results presented in Fig. 1. The figure indicates a negative correlation between rom-grade and rom-tonnage. This may be interpreted that gold mines with large rom-tonnage tend to have lower rom-grade and vice versa. Fig. 1, further, shows that majority of mines were characterized as low rom-grade and rom-tonnage.

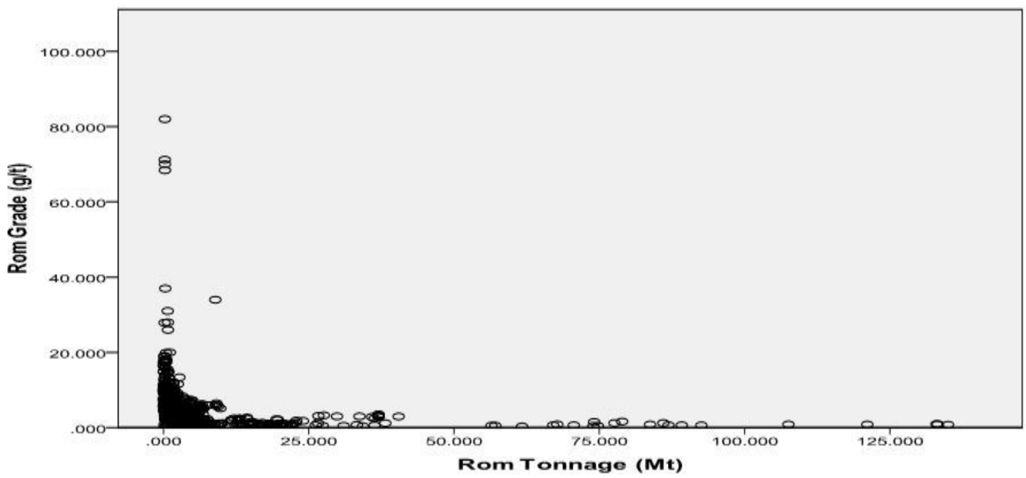

Fig. 1. Negative correlation between rom-grade and rom-tonnage

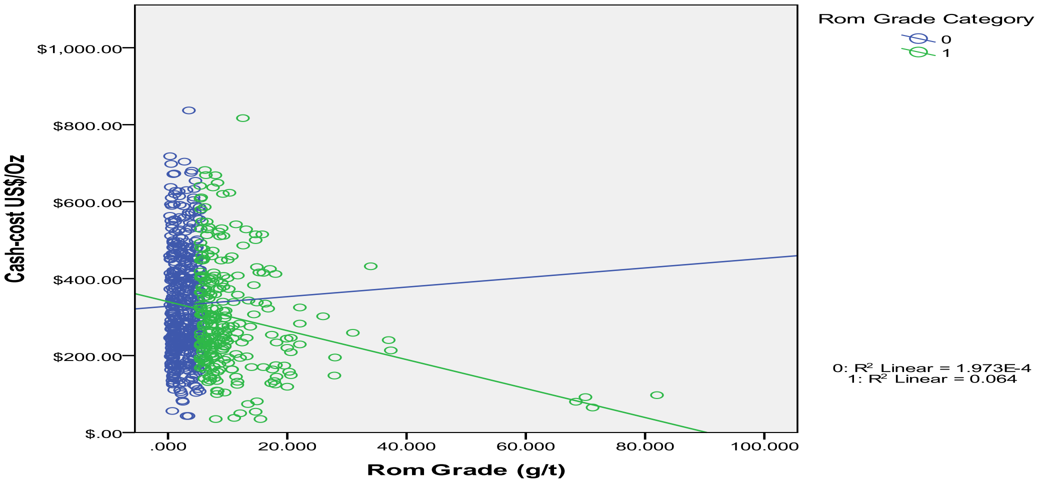

Fig. 2. Relationship between cost and rom-grade category

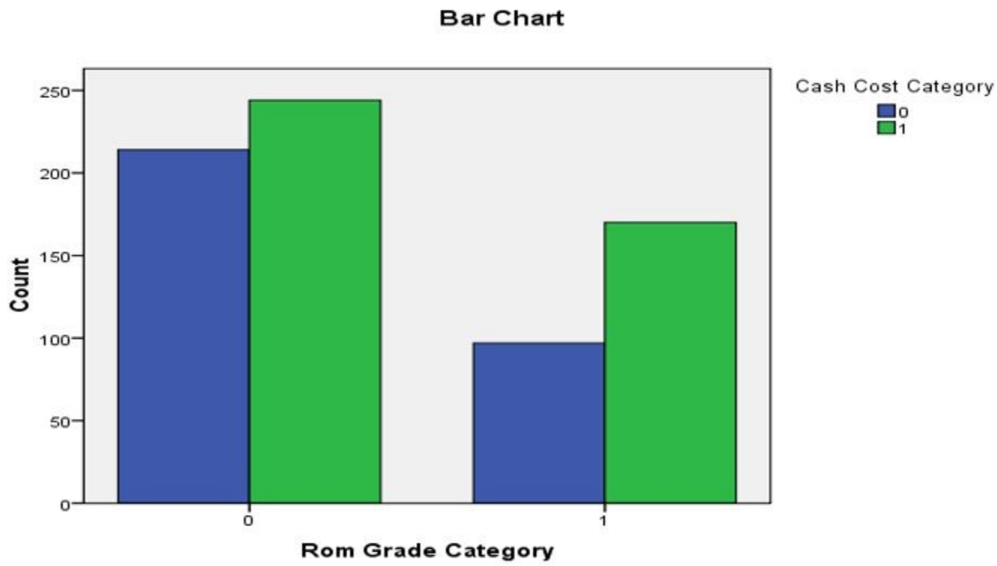

Fig. 3. Cost and rom-grade categories

Cost and Rom-grade

Scatterplot of cost and rom-grade category provided mixed results as shown in Fig. 2. The figure shows that in the low rom-grade category, cash-cost tends to increase with grade while decreases with grade in high rom-grade. The rate of decrease seems to be higher than the rate of increase.

Fig. 3 and cross tabulation of cash-cost and rom-grade category in Appendix 1 indicate that the proportion of low rom-grade with low cost was slightly higher than the proportion of low rom-grade with high cost. Low cost being (244) 53.3% while high cost being (214) 46.7%. The proportion of high rom-grade with low cost was much higher than the proportion of high rom-grade with high cost. Low cost being 63.7% (170) and high cost being 36.3% (97). In total, 57.1% of the mines were in low cost while the remaining 42.9% were in high cost.

The χ^2 test was conducted in order to test if there were any relationship between cost category and rom-grade category. The χ^2 test result indicated that the p - value (.006) was less than the chosen significant level (α = .05). Based on these results it could be concluded that there was evidence to suggest an association between cash-cost category and rom-grade category, $\chi^2(1) = 7.441$, $p = .006$.

Cost and Rom-tonnage

The scatterplot of cost and rom-tonnage provided mixed results similar to the scatterplot of cost and rom-grade. Fig. 4 shows that cost in low rom-tonnage tends to increase with tonnage but decreases with tonnage in high rom-tonnage. The rate of increase of cost in low rom-tonnage seems to be higher than the rate of decrease in high tonnage.

Figure 4 and cross tabulation of cash-cost and rom-tonnage category in Appendix 2 indicate that the proportion of low rom-tonnage with low cost was slightly higher than the proportion of low rom-tonnage with high cost. Low cost being (281) 5.1% while high cost being (220) 43.9%. The proportion of high rom-tonnage with low cost was much higher than the proportion of high rom-tonnage with high cost. Low cost being 61.3% (76) and high cost being 38.7% (48). In total, 57.1% of the mines were in low cost while the remaining 42.9% were in high cost.

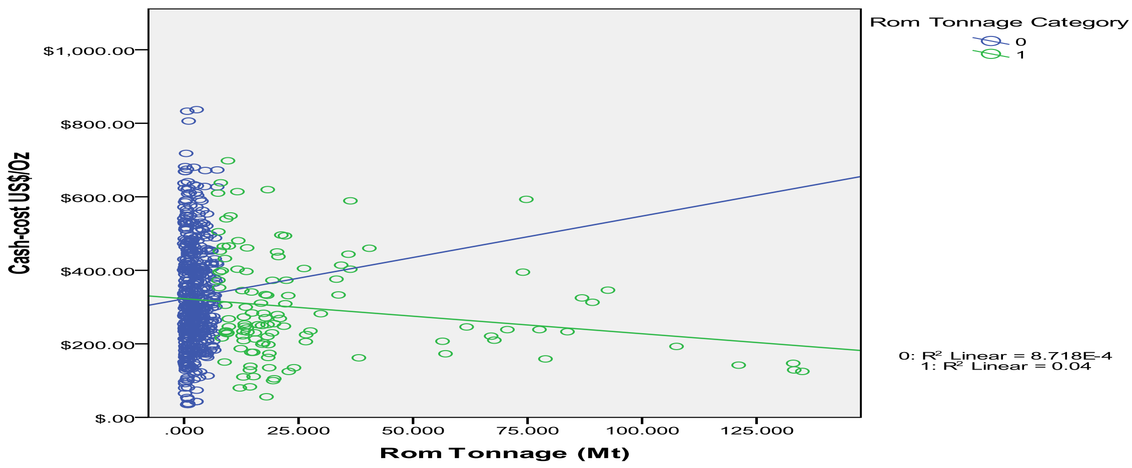

Fig. 4. Relationship between cost and rom-tonnage category

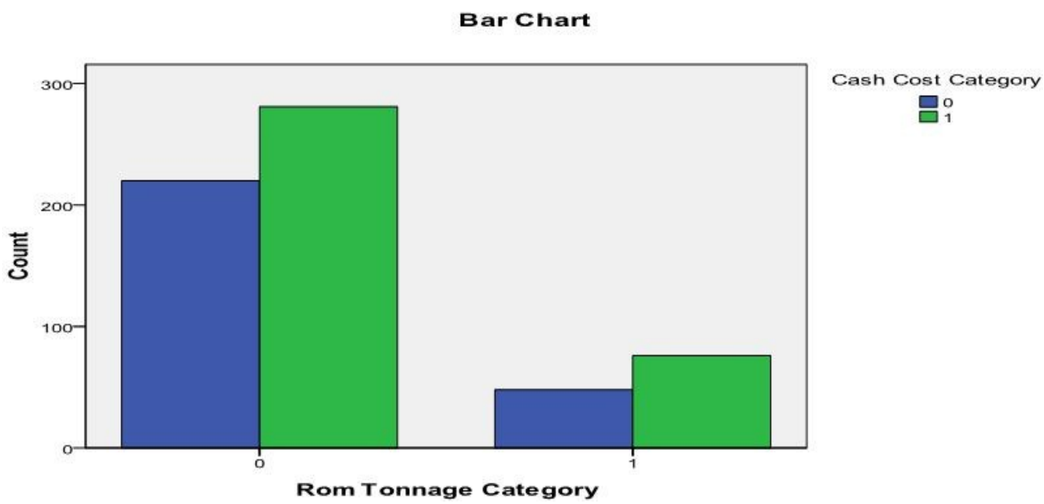

Fig. 5. Cost and rom-tonnage categories

The χ^2 test was conducted for the cash-cost category and rom-tonnage category. The results indicated that the p -value (p = .295) was greater than the chosen significant level (α = .05) the conclusion was that there was not enough evidence to suggest an association between cash-cost and rom-tonnage. χ^2 (1), = 1.098, p = .295. For this reason, the rom-tonnage category was used as a continuous independent variable in the logistic regression analysis and not as categorical variable.

B. Logistic Regression Models

Formulation

The general logistic regression models normally take the forms given in (1) to (5).

$$ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_q x_q \ldots\ldots(1)$$

In this study, p is the predicted probability of low cost and $1-p$ is the predicted probability of high cost. x_q are rom-tonnage, rom-grade and types of mines, β are the coefficients to be determined in the logistic regression analysis.

$$\frac{p}{1-p} = \text{ odds} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

or

$$p = \frac{\text{odds}}{1+\text{odds}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Odds of an event low cost is the ratio of the probability that low cost will occur to the probability that it will not occur. Take exponential in (1) and substitute in (2) and (3)

$$Odds = e^{\beta_0+\beta_1 x_1+\beta_2 x_2+\cdots+\beta_q x_q} \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Therefore;

$$p = \frac{e^{\beta_0+\beta_1 x_1+\beta_2 x_2+\cdots+\beta_q x_q}}{1+e^{\beta_0+\beta_1 x_1+\beta_2 x_2+\cdots+\beta_q x_q}} \ldots\ldots\ldots\ldots(5)$$

Thus;

$$p = \frac{1}{1+e^{-(\beta_0+\beta_1 x_1+\beta_2 x_2+\cdots+\beta_q x_q)}} \ldots\ldots(6)$$

Where $z = (\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_q x_q) .. (7)$

Thus $p = \frac{1}{1+e^{-z)}} \ldots\ldots\ldots\ldots(8)$

Logistic Model Generated

Coefficient values B and exp (B) of the individual determinant parameters and their significance as obtained from SPSS were summarized in Table1.

Table 1. Summary of the main results of logistic regression models.

Model	B	df	sig	Exp (B)	χ^2	-2 log likelihood	Cox & Snell Square	Nagelkerke R Square	Wald	H-L test	Percentage correct
Model with constant only											
						831.561					57.9
Constant	0.320	1	0.000	1.377					15.268		
Model with determinant parameters											
		4			32.084	799.477	0.051	0.069		0.120	62.4
Rom tonnage	0.13	1	0.038	1.013					4.310		
Rom grade	-1.105	1	0.000	0.331					20.693		
Open pit		2	0.001						13.244		
Underground	0.671	1	0.004	1.957					8.518		
Both OP&UG	- 0.118	1	0.669	0.889					0.183		
Constant	0.695	1	0.012	2.003					6.336		

Coefficient values B: Based on the sig. and Wald statistic values, the variables rom-grade, rom-tonnage, open pit and underground mine and a constant were found to be significant. The highest value of Wald statistic was 20.693, $p < .01$ for rom-grade and the lowest was 4.314 $p < .05$ for rom-tonnage. The only insignificant variable was both open pit and underground mine category with Wald statistic value of 0.183, and $p = 0.669$ ($p > .05$).

Substitute the coefficient values B obtained in Table 1 into (6), the logistic equation can be written as:

$$\text{Probability of low cost } p = \frac{1}{1+e^{-(0.695+0.012\, rom\ tonnage-1.105\, rom\ grade+0.671\, UG)}} \quad (7)$$

Discussion on the Logistic Model

The main outputs from the Logistic Regression Analysis as obtained from SPSS were summarized in Table 1 and explained as follows:

- *The exp (B) Values*:

These values provide the odds ratio for all the variables in the equation. For example, when rom tonnage is increasing by a 1 unit that is one million tonne per year, the odds ratio becomes 1.013 times large and therefore the mine is 1.013 more times likely to belong to high cost. The odds ratio for rom-grade was less than 1 meaning that the effect of rom-grade was in the opposite direction compared to that of rom-tonnage. When rom-grade increases by a 1 unit that is 1.0 g/tonne, the odds ratio is 0.331 more times likely to belong to low cost. When the category of mine changes from open pit to underground mine, the odds ratio 1.957 more likely to belong to high cost.

- *Percentage Correct:*

The percentage correct for a model with constant only was 57.9% and 62.4% for a model that include rom-grade, rom-tonnage and type of mine. This implies that the usage of rom-grade and rom-tonnage category without any mathematical model has ability to predict cost at a percentage correct 57.9%. The percentage correct increased to 62.4% (an increase of 4.5%) when rom-grade and rom-tonnage are included in the model. The model with rom-grade and rom-tonnage established in this study appears better than the model with only constant (guess).

- *χ^2 test:*

The model χ^2 value obtained was $\chi^2(4)$, = 32.084, $p < .001$ indicating that the model that contains only the constant has poor fit. The rom-grade and rom-tonnage do have a significant effect and created essentially a different model.

- *The Cox and Snell R Square:*

The obtained value of 5.1% indicated that the variation in cost is explained by the logistic model.

- *Nagelkerke R Square*:

The obtained value of 6.9% indicated a very weak significant relationship between cost vs. rom-grade and rom-tonnage as well as type of mine. This implies that rom-grade and rom-tonnage are not the only determinants of cost. There are other parameters such as those of rock-mass, mine-design and country variations which affect cost.

- *Hosmer and Lemeshow Test (H-L) Statistics:*

The obtained value 0.120 is greater than 0.05 indicated a non-significant between the model prediction and the observed values. This shows that the model is quite a good fit.

Logistic Model Validation

Tanzania's gold mines were selected for model validation. Rom-grade and rom-tonnage for each mine were tabulated enabling categorization based on the rom-grade. It can be seen in Table 2 that Buzwagi, North Mara, Golden Pride, New Luika and Geita gold mines were categorized as low grade mines while Tulawaka and Bulyanhulu gold mines were categorized as high grade mines based on the cut-off value 5.385 g/t. The corresponding probabilities calculated using (7) indicated that probability for Tulawaka and Bulyanhulu were less than 0.5 (low cost mine) while for Buzwagi, North Mara, Golden Pride, New Luika and Geita gold mines were greater than 0.5 indicating (high cost) mine. The predicted values agree well with the actual values.

Table 2. Categorization of Tanzania's gold mines

Mine	Rom-grade	Rom-tonnage	Type of mine	Category
Buzwagi Gold Mine	1.25		OP	Low grade
North Mara Gold Mine	3.363	2.384	OP	Low grade
Golden Pride Gold Mine	1.934		OP	Low grade
New Luika Gold Mine	3.21		OP	Low grade
Geita Gold Mines	1.9	5.218	OP	Low grade
Tulawaka Gold Mine	12.56	0.382	OP	High grade
Bulyanhulu Gold Mine	11.57	0.930	UG	High grade

V. Conclusions

Logistic Regression Analysis was conducted aimed at establishing logistic model of cost effect of rom-grade and rom-tonnage in the justification of categorization of gold mines, worldwide. The following can be concluded:

- Evidence shows that gold mines can be categorized based on rom-grade at a cut-off value of 5.385 g/t and association between cost and rom-grade was strong $\chi^2(1)$, 7.441, $p = .006$. However, there was not enough evidence to categorize gold mines based on rom-tonnage at the cut-off value of 7.37 Mt/y since no association between cost and tonnage were found $\chi^2(1)$, 1.098, $p = .295$.
- The percentage correct for a model with constant only was 57.9% whereas the percentage correct for a model that include rom-grade, rom-tonnage and type of mine and was 62.4%. This indicates that the model with rom-grade and rom-tonnage established in this study appears better than the model with only constant (guess).
- The relationship between cost vs. rom-grade and rom-tonnage was weak with *Nagelkerke R Square value* of 6.9%. This implies that rom-grade and rom-tonnage were not the only determinants of cost and therefore should be used with precaution.
- The results of validation of the model indicated that the prediction results of the model using Tanzania's gold mines agreed well with the actual results.

The established cut-off value of a rom-grade of 5.355 g/t may be used to categorize gold mines worldwide and the developed model of cost vs. rom-grade and rom-tonnage can be used in prediction of cost in the justification of the proposed category.

Appendix

Appendix 1. Rom Grade Category * Cash Cost Category Cross-tabulation

			Cash Cost Category		
			0	1	Total
Rom Grade Category	0	Count	214	244	458
		% within Rom Grade Category	46.7%	53.3%	100.0%
		% within Cash Cost Category	68.8%	58.9%	63.2%
		% of Total	29.5%	33.7%	63.2%
	1	Count	97	170	267
		% within Rom Grade Category	36.3%	63.7%	100.0%
		% within Cash Cost Category	31.2%	41.1%	36.8%
		% of Total	13.4%	23.4%	36.8%
Total		Count	311	414	725
		% within Rom Grade Category	42.9%	57.1%	100.0%
		% within Cash Cost Category	100.0%	100.0%	100.0%
		% of Total	42.9%	57.1%	100.0%

Appendix 2. Rom Tonnage Category * Cash Cost Category Cross-tabulation

			Cash Cost Category		Total
			0	1	
Rom Tonnage Category	0	Count	220	281	501
		% within Rom Tonnage Category	43.9%	56.1%	100.0%
		% within Cash Cost Category	82.1%	78.7%	80.2%
		% of Total	35.2%	45.0%	80.2%
	1	Count	48	76	124
		% within Rom Tonnage Category	38.7%	61.3%	100.0%
		% within Cash Cost Category	17.9%	21.3%	19.8%
		% of Total	7.7%	12.2%	19.8%
Total		Count	268	357	625
		% within Rom Tonnage Category	42.9%	57.1%	100.0%
		% within Cash Cost Category	100.0%	100.0%	100.0%
		% of Total	42.9%	57.1%	100.0%

ACKNOWLEDGMENT

The data used in this paper were provided by Raw Materials Group.

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AUTHOR'S PROFILE

Karim Rajabu Baruti was born in Kigoma, Tanzania in 1964. He received his B.Sc. and M.Sc. degrees in Mining Engineering and Environmental Management and Development from the University of Zambia in 1992 and Australian National University in 2001, respectively. He received his Ph.D degree from the Department of Chemical and Mining Engineering, College of Enginee--ring and Technology, University of Dar es Salaam, Tanzania in 2012. He is the author of a book titled "Modeling the impact of mine and country variations on the cost and country-benefit of gold mining"