

Predicting the Techno-Economic Parameters for Planning and Evaluation of Itakpe Open-Pit Mine

*Nwosu, J.I., Ononuju, F.N., and Ukaegbu, V.U.

Department of Geology, Faculty of Science, University of Port Harcourt, Nigeria.

*Corresponding Author: E-mail: joseph.nwosu@uniport.edu.ng

Abstract:

Techno-economic parameters like unit cost of mining, price per ton of concentrate used for mineral deposit evaluation etc, are critical in proper and reliable evaluation of a mineral deposit and mine planning. Every evaluation of a mineral deposit and mine planning is as reliable or unreliable as the parameters used in achieving them. Price of iron ore concentrates vary every year and even several times in a year. An overly optimistic estimate that relies on the highest price of iron ore concentrate in the world market may cause a loss of investment capital. On the other hand, an overly pessimistic approach will cause an otherwise valuable deposit to be left undeveloped. In this paper we have provided a risk-free method of price prediction for mineral deposit evaluation. We have also developed a series of models for estimating and predicting the unit cost of mining for mineral deposit evaluation and mine planning. The result of analysis shows that the unit cost of mining at Itakpe is presently 2.5USD and can vary from this 2.5USD to 3.31USD after 7 years into the future. It also shows that risk free price of iron ore concentrate for mineral deposit evaluation can vary from 90USD to 110USD in the next 7years of operation. This variable cost and price can guarantee risk free evaluation of Itakpe deposit, Kogi State, Nigeria.

INTRODUCTION

Cost of production per ton of ore and price per ton of concentrate significantly affect the value of a mineral deposit. Since a mineral deposit usually has a long life span, the cost of production per ton of ore and price per ton of concentrate cannot be assumed constant throughout the life of the mine. This therefore requires that both parameters be predicted specifically into the future to ensure that the value estimated will be realistic. In order to predict the cost of production into the future, the cost of production in the present year must first be estimated and then a prediction model can be developed to predict cost into the future. Price per ton of concentrate is affected by several factors such as demand and supply, which on its own is affected by rate of industrialization and rate of development of new iron ore deposit, inflation, politics, war etc. However, it is assumed that what happened in the past will continue to happen in future to push up the price of iron ore concentrate at the same rate as in the past. Hence, the future price of iron ore concentrate can be predicted based on the prices of product in the previous years using a scatter diagram.

METHODOLOGY

Therefore in this paper we apply the concept of risk free price. By this concept,

$$\text{Risk free price, } R_f = Q - S_t \quad (5)$$

Where, R_f = Risk free price of iron ore concentrate

Q = mean price of concentrate over t years

S_t = standard deviation of mean price from individual yearly prices over a period of t years.

To estimate the risk free price of iron ore concentration to be used in the evaluation, use is made of prices of iron ore concentrate over a number of years (for instance 30 years). Then the years are divided into segments of 5 years each. For each segment a risk free price is estimated. Then a graph of risk free price in each segment versus years is plotted. This produces a scatter diagram in which a best-fit line is drawn. This best-

fit line is now produced for a period of 7 years into the future life of the mine. Using the best-fit line, the price of concentrate for each year into the future is estimated. The price of concentrate at the 10th year is used to evaluate the mine for other years beyond the 7th year. The graph is not produced for more years beyond the 7th year because of uncertainties. Within 7 years of operation the capital cost on building, equipment and other infrastructure is usually recovered.

The standard deviation of the risk free price is estimated using the standard formular

$$S_t = \sqrt{\frac{(Q_t - Q)^2}{n}} \quad (\text{Murray et'al 2008}) \quad (6)$$

Where;

$$\begin{aligned} Q_t &= \text{price of concentrate for each year of the selected years of analysis} \\ Q &= \text{mean price of concentrate over n years being analyzed} \end{aligned}$$

Cost Prediction

The cost of production per ton of iron ore is not constant every year. It changes due to salary increase, cost of equipment and material increase and technology. There is the concept by some authors that cost of production will rather decrease due to advances in technology (Hahrikov V.S). However, reports show that rather than decreasing, there is a resultant increase in the unit cost of mining due to overwhelming material and salary increase, and increase in the cost of equipment purchase. Twenty years ago mining cost per ton of ore was averagely 1.5USD today cost of mining per ton of ore in some mines are over 3.0USD. Therefore prediction of future cost of production per ton of ore will lend itself to exponential growth i.e.

$$C_t = C_i e^{\lambda t} \quad (\text{Gutep et'al 1970 and Donohue 1983}) \quad (7)$$

Where;

$$\begin{aligned} C_t &= \text{Cost of mining per ton of ore at t year} \\ C_i &= \text{Initial cost of mining (at beginning of operation)} \\ C_i &= D + U_b + L_c + H_c \quad (8) \\ D &= \text{unit cost of drilling} \\ U_b &= \text{unit cost of blasting} \\ L_c &= \text{unit cost of loading} \\ H_c &= \text{unit cost of haulage} \end{aligned}$$

$$\lambda = \text{rate of increase of cost of mining per year.}$$

$$t = \text{the future time that cost of mining per ton ore is being predicted}$$

There are two critical parameters that are required to be estimated if the cost of mining into the future is to be predicted using the above model: the rate of increase of unit cost of mining and the initial cost of mining per ton ore.

Statistics in the National Iron Ore Mining shows that cost of mining per ton of ore increases by 3-5% every year due to increase in salary, cost of materials (past explosive, diesel etc) and cost of borrowing. Averagely this can be taken to be 4% (0.04).

The initial cost of mining per ton of ore can be determined on the basis of cost of unit operations i.e drilling and blasting cost per ton ore, loading cost per ton ore, and haulage cost per ton of ore. Administrative cost is not taken into consideration here since this is part of capital cost.

ESTIMATION OF COST OF MINING PER UNIT OPERATION

The main unit operations in open-pit mine include: drilling, blasting, loading and haulage.

Unit Cost of Drilling

$$D = \frac{D_d + M_d + C_d + S_d}{P_d} \quad \text{Nwosu (2017)} \quad (9)$$

Where :

D_d	=	annual depreciation allowance on drilling equipment
M_d	=	annual maintenance cost on drilling equipment
C_d	=	annual expenditure on fuelling
S_d	=	annual salary of the operators
P_d	=	annual productivity of drilling equipment.

Depreciation Allowance = Annuity on landing cost of equipment

$$\text{Annuity} = Q \left[\frac{1}{PVFA} \right] \quad (\text{Pandey 2006}) \quad (10)$$

Where;

Q	=	Landing cost of the equipment
$PVFA$	=	Present value factor of annuity

$$PVFA = \frac{1}{i} - \frac{1}{i(1+i)^t} \quad (11)$$

r = Interest rate in percentage charged on equipment landing cost

$$i = \frac{r}{100} = \frac{r}{100} = 0.1$$

t = Lifespan of the loader

Annual Maintenance cost = 40% of depreciation allowance

Consumables = hours worked $\times$ fuel consumption per litre $\times$ cost per litre of diesel.

Annual Productivity of Drilling Rig

Annual productivity of drilling rig = Annual Meterage drilled $\times$ burden $\times$ spacing $\times$ specific gravity

$$\text{Annual Meterage drilled} = NSFR \quad (12)$$

Where;

N	=	number of working days in a year
S	=	shift duration
F	=	fraction of shift time used in pure drilling
R	=	drilling rate, m/hr

Unit Cost of Blasting

Unit cost of blasting can be estimated from the formular

$$U_b = \frac{C_e + C_a}{bsHG} \quad (13)$$

Where,

$$C_e = \text{cost of explosives in one blasthole} \quad (14)$$

Where,

q	=	quantity of explosive per hole
P_e	=	price per kg of explosive

$$q = P(h + h_s - h_{st}) \quad (15)$$

Where, P = charge concentration

h	=	bench height
h_s	=	sub drilling
h_{st}	=	stemming

$$C_a = \text{cost of accessories per blasthole} = 30\% \text{ of cost of explosives}$$

$$H = \text{bench height}$$

$$G = \text{specific gravity of the material}$$

Cost of Loading

The unit cost of loading can be estimated as follows

$$\text{Unit cost of Loading} = \frac{D_l + M_l + C_l + S_l}{P_l} \quad (16)$$

Where;

- D_l = annual depreciation allowance of loading equipment
- M_l = annual maintenance cost of loading equipment
- C_l = annual expenditure on fuelling
- S_l = annual salary of the operators
- P_l = annual productivity of the loader.

Annual depreciation is equal to the annuity charged on the landing cost of the equipment over its lifespan. i.e

$$D = A \left[\frac{1}{PVFA} \right]$$

Where;

- A = Landing cost of the equipment
- $PVFA$ = Present value factor of annuity

$$PVFA = \frac{1}{i} - \frac{1}{i(1+i)^t}$$

Annual Maintenance cost = 40% depreciation allowance

Annual cost of consumables = hours worked $\times$ fuel consumption per litre $\times$ cost per litre of diesel.

Salary = annual salary of the personnel in charge of loading operations.

Annual productivity of payload = No of cycles per annum $\times$ bucket payload

$$\text{No of cycles per annum} = \frac{d \ h \ f}{j} \quad (17)$$

Where

- d = number of working days per annum
- h = number of working hours per shift (only one shift in operation)
- f = factor for utilization of working hours
- j = loader cycle time (secs)

$$\text{Bucket payload} = m \ F \ S_g \quad (18)$$

Where;

- m = bucket capacity in m^3
- F = bucket capacity utilization factor.
- S_g = specific gravity of iron ore.

Cost of Haulage

The methodology of estimating unit cost of haulage follows the same pattern as unit cost of loading.

$$\text{Unit cost of Haulage} = \frac{D_h + M_h + C_h + S_h}{P_h} \quad (19)$$

Where;

- D_h = annual depreciation allowance of haulage equipment
- M_h = annual maintenance cost of haulage equipment (40% depreciation allowance)
- C_h = annual consumable cost of haulage equipment
- S_h = annual salary of the operators of haulage equipment
- P_h = annual productivity of haulage equipment

Depreciation is done using the same formula 10 & 11 as appropriate.

Annual truck productivity = No of cycles per annum $\times$ dumper payload

No of cycles per annum is estimated using formula (17). However the cycle time for haulage equipment is estimated as follows.

$$\text{Cycle time} = \frac{L}{V_L} + \frac{L}{V_e} + t_m + t_d + t_e \quad (20)$$

Where;

- L = distance from the mine to ore stockpile (3km)
- V_L = Speed limit for loaded truck (30km/h)
- V_e = Speed limit for empty truck (60km/h)
- t_m = maneuvering time at loading point
- t_d = dumping time
- t_e = waiting time at loading point

RESULTS AND DISCUSSION

In order to utilize the above method for the evaluation of Itakpe deposit, the techno-economic data relating to Itakpe deposit are utilized (table 1) while the prices of concentrates over the past 30years(table 2) are used to estimate the risk free price.

Table 2: Prices of iron ore concentrate over the past 25yrs.

Year	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Price (\$)	31	27.59	28.79	30.03	29.31	31.95	37.90	65.00	69.33	122.99

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Price (\$)	155.99	79.98	145.86	167.75	128.50	135.36	96.95	55.85	58.42	71.76

Year	2018	2019	2020	2021	2022
Price (\$)	69.75	93.85	108.92	161.71	99.86

(Macrotrends.net)

The above years are now divided into five segments i.e.

- 1998 – 2002 = 1st segment
- 2003 – 2007 = 2nd segment
- 2008 – 2012 = 3rd segment
- 2013 – 2017 = 4th segment
- 2018 – 2022 = 5th segment

For each segment, a risk free price is calculated using formular i.e for segment 1.

$$\text{Mean price per ton of concentrate} = \frac{31 + 27.59 + 28.79 + 30.03 + 29.31}{5} = 29.34\text{USD}$$

$$S_t = \frac{(31-29.34)^2 + (27.59-29.34)^2 + (28.79-29.34)^2 + (30.03-29.34)^2 + (29.31-29.34)^2}{5} = 1.15$$

Risk free price

$$P_f = 29.34 - 1.15$$

= 28.19USD

The risk free price for other segment have been calculated and tabulated below (table 3).

Table 3: Risk free prices of iron ore concentrate for 25 years

Segment	Years	Risk free price (USD)
1	1998 – 2002	28.19
2	2003 – 2007	34.95
3	2008 – 2012	105
4	2013 – 2017	54
5	2018 – 2022	80

With the above data, a scatter diagram is plotted and line of best-fit is established. The line of best-fit is extended to 7 years into the future.

The prices of individual years into the future are established using the best-fit line and the results are tabulated (table 4).

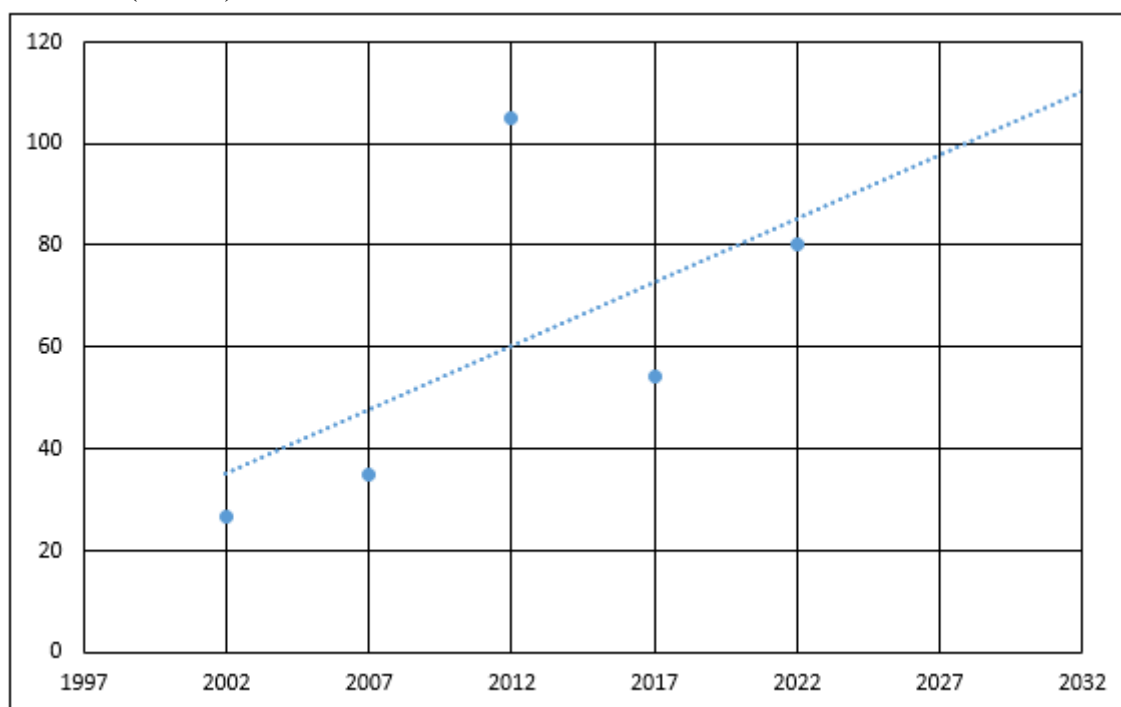


Fig: Best-fit diagram for risk free price prediction.

Table 4: Projected price of iron ore over the next 7yrs.

Year	2025	2026	2027	2028	2029	2030	2031	2032
Price (\$)	92.5	95	97.5	100	102.5	105	107.5	110

COST PREDICTION**Table 5: Input Data:**

Bench height	Sub drilling	Stemming	Specific gravity	Landing cost of drilling rig	Cost per kg of dynamite
10m	2m	3m	3.6	70,000 USD	3USD

Powder Factor	Drilling rate	Interest rate	Life of drilling rig	Shift duration	Shift utilization in pure drilling	Supply cost per liter of diesel
0.9kg/m ³	15m/hr	10% per annum	10 years	8hrs	0.4 (40%)	2USD

NIOMC Project Report; 1980

4.1 Unit cost of Drilling

From formular (9) Annual cost of drilling, $D = \frac{D_d + M_d + C_d + S_d}{P_d}$

Depreciation Allowance = Annuity on landing cost of equipment

$$\text{Annuity} = Q \left[\frac{1}{PVFA} \right]$$

$$PVFA = \frac{1}{0.1} - \frac{1}{0.1(1+0.1)^{10}} = 6.1$$

$$= 70,000 \left[\frac{1}{6.1} \right] = 11,400 \text{USD}$$

$$\begin{aligned} \text{Annual Maintenance cost} &= 40\% \text{ of depreciation allowance} \\ &= 0.4 \times 11,400 \\ &= 4,560 \text{USD} \end{aligned}$$

$$\begin{aligned} \text{Consumables} &= \text{hours worked} \times \text{fuel consumption per litre} \times \text{cost per litre of diesel.} \\ &= 250 \times 8 \times 0.4 \times 25 \times 2 \\ &= 40,000 \text{USD} \end{aligned}$$

Annual Salary of 3 operators on drilling rig

$$= 3 \times 600 \text{USD} \times 12 = 21,600 \text{USD}$$

3 = No of operators
600USD = Salary per operator
12 = No of months per annum

Annual Cost of Drilling

$$= 11,400 + 4,560 + 40,000 + 21,600 = 77,560 \text{USD}$$

Annual Productivity of Drilling Rig

$$\begin{aligned} \text{Annual productivity of drilling rig} &= \text{Annual Meterage drilled} \times \text{burden} \times \text{spacing} \times \text{specific gravity} \\ &= 250 \times 8 \times 0.4 \times 15 = 12,000 \text{tons} \end{aligned}$$

Where;

$$15 = \text{drilling rate, m/hr}$$

$$\text{Burden, } B = 0.85 \sqrt{\frac{p}{q}}$$

Charge concentration, $P = 7.4d^4\Delta$

$$P = 7.4 \times (1.03)^4 \times 0.92 = 8.17 = 8\text{kg/m}^3$$

$$= 0.85 \sqrt{\frac{8}{0.9}} = 2.78\text{m}$$

Spacing, S = 1.25B

$$S = 1.25 \times 2.78 = 3.48\text{m}$$

Then annual tonnage

$$= 12,000 \times 2.8 \times 3.5 \times 3.6 = 423,360$$

Therefore cost of drilling per ton of material

$$= \frac{220,920}{423,360} = 52\text{cents or } 0.52\text{USD}$$

4.2 Unit Cost of Blasting

$$\text{Cost of blasting per ton of ore} = \frac{C_e + C_a}{b \times s \times H \times G}$$

$$q = 8(10 + 2 - 3) = 72\text{kg}$$

$$\text{Therefore, } C_e = 72 \times 3\text{USD} = 216\text{USD}$$

$$\begin{aligned} \text{Cost of Accessories per hole, } C_a &= 30\% \text{ of cost of explosive} = 0.3 \times 216 \\ &= 64.8\text{USD} \end{aligned}$$

$$\text{Cost of blasting per hole} = 216 + 64.8 = 280.8\text{USD}$$

Tonnage generated from blasting per hole = burden x spacing x (Bench height + subdrilling) x Specific gravity

$$= 2.78 \times 3.48 \times 12 \times 3.6$$

$$= 418\text{tons.}$$

$$\text{Cost of blasting per ton of ore} = \frac{280.8}{418} = 0.67\text{USD}$$

$$\text{Cost of drilling and blasting per ton of ore} = 0.52\text{USD} + 0.67\text{USD} = \underline{\underline{1.19\text{USD}}}$$

4.3 ESTIMATION OF UNIT COST OF LOADING

Unit cost of haulage can be estimated using the following formular

$$\text{Unit cost of haulage, } H = \frac{\text{Depreciation} + \text{Maintenance} + \text{consumables} + \text{salary}}{\text{Annual Productivity}}$$

Depreciation: is estimated using annuity method on landing cost of equipment rather than mere straight line method. This is to take care of possible inflation on the cost of equipment after it had exhausted its lifespan.

$$\text{Thus depreciation} = 300,000 \left[\frac{1}{PVFA} \right]$$

$$i = \frac{10}{100}$$

$$\text{From formular (11) } PVFA = \frac{1}{0.1} - \frac{1}{0.1(1+0.1)^{10}} = 10 - 3.86 = 6.14$$

Thus depreciation allowance on loading equipment

$$= 300,000 \left(\frac{1}{6.14} \right) = 48,900\text{USD}$$

Maintenance = 40% of Depreciation

$$= 0.4 \times 48,900$$

$$= 19,560\text{USD}$$

Consumables (fuel consumption)

Fuel consumption per annum = $250 \times 8 \times 0.8 \times 75\text{ltrs} = 120,000 \text{ liters}$

Annual cost of fueling = litres consumed x price per litre

$$= 120,000 \times 2\text{USD} = 240,000\text{USD}$$

Salary

Operators = 1000USD

Foreman = 600USD

Annual salary for foreman and operator = $1600 \times 12 = 19,200\text{USD}$

Total annual expenditure

= Depreciation + Maintenance + consumables + salary

$$= 48,900 + 19,560 + 240,000 + 19,200 = 327,660\text{USD}$$

Annual Productivity of Loading equipment = No of cycles per annum x productivity per cycle

$$\text{No of loader cycles per annum} = \frac{250 \times 8 \times 0.8 \times 60 \times 60}{65} = 66,462 \text{ cycles}$$

$$\text{Annual productivity of loader} = 66,462 \times 6\text{m}^3 \times 0.7 \times 3.6 = 1,004,905$$

Where;

0.7 = bucket capacity utilization factor

3.6 = specific gravity of Itakpe Iron Ore

6m^3 = bucket capacity of 992C payloader

Cost per ton of loaded materials

$$= \frac{327,660}{1,004,905} = 0.33\text{USD or 33cents}$$

4.4 ESTIMATION OF UNIT COST OF HAULAGE

The calculation of unit cost of haulage follows the same pattern of unit cost of loading with its own specifics.

$$\text{Unit cost of haulage} = \frac{\text{Depreciation} + \text{Maintenance} + \text{Consumables} + \text{Salary}}{\text{Annual productivity of haulage equipment}}$$

$$\text{Depreciation of haulage equipment} = 200,000 \left[\frac{1}{\text{PVFA}} \right]$$

$$\text{PVFA} = \frac{1}{0.1} = \frac{1}{0.1(1+0.1)^6} = 10 - 5.65 = 4.35$$

$$\text{Thus depreciation} = 200,000 \left(\frac{1}{4.35} \right) = 46,000\text{USD}$$

$$\begin{aligned} \text{Maintenance} &= 40\% \text{ of Depreciation} \\ &= 0.4 \times 46,000 \\ &= 18,391\text{USD} \end{aligned}$$

Consumables

No of litres consumed per annum = $250 \times 8 \times 0.8 \times 50\text{litres}$

$$= 80,000\text{litres}$$

Where:

250 = number of working days per annum

8 = no of working hours per shift

0.8 = factor for effective utilization of working hours per shift

50 = diesel consumption of dumper per hour

Therefore, annual operating expenses on consumable for the dumper

$$= 80,000 \times 2\text{USD}$$

$$= \underline{160,000\text{USD}}$$

Salary

Dumper operator = 800USD per month

Foreman = 500USD per month

Monthly salary of operator and foreman = 1,300USD

Annual Salary = $1,300 \times 12$ = 15,600USD

Annual productivity of dumper = No of cycles per annum $\times$ dumper payload

Dumper payload = 73×0.75 = 55tons

$$\text{From formula (19), Cycle time} = \frac{3}{30} + \frac{3}{60} + 2 + 2 + 3 = 16$$

$$\text{No of cycles per annum} = \frac{250 \times 8 \times 0.8 \times 60}{16}$$

Where:

60 = no of minutes in one hour

16 = duration or cycle time of the dumper in minutes

$$= \frac{250 \times 8 \times 0.8 \times 60}{16}$$

$$= 6,000 \text{ cycles}$$

Annual productivity of dumper = $6,000 \times 55\text{tons}$ = 330,000tons

$$\text{Therefore, unit cost of haulage} = \frac{46,000 + 18,391 + 160,000 + 15,600}{330,000}$$

$$= \underline{0.73\text{USD or 73cents}}$$

Therefore, unit cost of loading and haulage = 33cents + 73cents = 1.06USD.

Therefore, $C_i = D + U_b + L_c + H_c$

$$0.52 + 0.67 + 0.33 + 0.73 = 2.25\text{USD}$$

Uncalculated cost = 10% of C_i = 0.225

Therefore, for Itakpe deposit $C_i = 2.25 + 0.225 = 2.475 \cong 2.5\text{USD}$

Therefore cost projection for Itakpe mine for 7yrs (formula 7)

$$C_1 = 2.5 e^{0.04} = 2.60$$

$$C_2 = 2.5 e^{0.04 \times 2} = 2.71$$

$$C_3 = 2.5 e^{0.04 \times 3} = 2.82$$

$$C_4 = 2.5 e^{0.04 \times 4} = 2.93$$

$$C_5 = 2.5 e^{0.04 \times 5} = 3.05$$

$$C_6 = 2.5 e^{0.04 \times 6} = 3.18$$

$$C_7 = 2.5 e^{0.04 \times 7} = 3.31$$

$$C_8 = 2.5 e^{0.04 \times 8} = 3.44$$

$$C_9 = 2.5 e^{0.04 \times 9} = 3.58$$

$$C_{10} = 2.5 e^{0.04 \times 10} = 3.73$$

The table below shows the projected techno-economic data for the lifespan of the west-pit cash flow developments

Table 6: Projected techno-economic data of Itakpe deposit for 10years

Years of Prod.	Unit cost of mining (USD)	Unit cost of waste removal (USD)	Concentrate yield per ton of ore	Projected price per ton of concentrate	Cost of processing per ton of ore
1	2.6	2.08	0.35	87.5	3.6USD
2	2.71	2.17		90	2.86
3	2.82	2.25		92.5	2.981
4	2.93	2.35		95	3.102
5	3.05	2.44		97.5	3.223
6	3.18	2.54		100	3.355
7	3.31	2.65		102.5	3.498
8	3.44	2.75		105	3.641
9	3.58	2.87		107.5	3.784
10	3.73	2.98		110	3.938

DISCUSSION

The estimation of unit operating cost of mining was done according to the unit operations, namely; drilling, blasting, loading and haulage.

The estimate was done based on annual cost of operating an equipment divided by the annual productivity of the equipment. The only exception is the unit cost of blasting which was based on the cost of blasting a hole divided by the tonnage generated by the blasthole within its area of influence. We then predict the future unit cost of mining for each year of operation using exponential model. A rate of increase of 4% was assumed considering the increase in salary and cost of consumables.

The unit cost of mining and price per ton of concentrate used in the evaluation and planning of open pit mine should be variable on yearly basis into the future. However, this prediction should be limited to 10 years into the future. The prediction of future prices based on the prices in the previous years is on the assumption that those factors (political, economic etc) that occurred in the past will likely occur in the same fashion in future, hence the line of the best-fit is straight line.

CONCLUSION

The conclusion that can be drawn from the above is that the risk free price that can be used for economic evaluation of Itakpe mine is between 90USD to 110USD for the time period between 2025 to 2032. However each year has its own risk free price as shown by the scatter diagram and table 6. The unit cost of mining, waste removal and processing are also specified in table 6. This means that different costs and prices are used for each year of evaluation.

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