Open Pit Optimisation and Design: A Stepwise Approach*

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Abstract

The erstwhile Nkroful Mining Limited (NML) had a concession with an approximate area of 47.84 km^2 located at Nkroful in the Nzema East District of the Western Region of Ghana. The exploration data, assembled from 1997 to 2003, revealed a potential gold resource and indicated that the deposit could be mined by using open pit mining method. This paper demonstrates a stepwise approach to design an optimal open pit to exploit the deposit by using Surpac and Whittle software. Using the exploration data as the primary input, Surpac is used to create a block model of the deposit. The block model is imported into Whittle for the open pit optimisation, based on geotechnical and economic parameters derived from calculations or assembled from mines operating in Ghana. The optimal pit is then imported back to Surpac for detailed pit design incorporating a ramp and berms. The designed pit contains 5.03 Mt of ore at an average grade of 1.7063 g/t. However, it has 19.58 % more tonnes of waste, 16.05 % less tonnes of ore and 0.34 % lower average grade of ore than the respective figures in the Whittle optimal pit. The differences in the figures are due to the widening of the pit bottom and the creation of a ramp and berms in the designed pit, which resulted in the addition of some waste, ore loss and dilution.

Keywords: Optimisation, Mining, Stripping Ratio, Block Model, Pit Design

1 Introduction

The erstwhile Nkroful Mining Limited (NML), which was a joint venture company formed by Minconsult Limited (ML), Union Mining Limited (UML) and Samax Resources Limited (Samax), had a concession with an approximate area of 47.84 km^2 located at Nkroful in the Nzema East District of the Western Region of Ghana. The exploration data, assembled from 1997 to 2003 (Mireku-Gyimah, 2005), revealed a potential gold resource and indicated that the deposit could be mined using open pit mining method taking into consideration geological, geotechnical and economic parameters. This paper demonstrates how to design an optimal open pit to exploit the deposit using Surpac and Whittle software which are well accepted in the mining industry.

2 Materials and Methods Used

The pit optimisation and design in this work are carried by out using Surpac and Whittle software. The work is based on data gathered from the exploration drilling programme executed by NML as at 2003. For matters of confidentiality, all drill hole identification names and numbers have been changed. A total of 2 626 sample data from 59 drill holes were used for the analysis. The drill holes fell within 31 100 and 31 900 Northings, and 129 100 and 129 900 Eastings of local coordinates system.

The work is divided into three essential steps:

(i) Block modelling of the orebody, using Surpac software;

(ii) Exportation of the block model to Whittle software for pit optimisation; and

(iii) Exportation of the optimal pit from Whittle back to Surpac software for detailed pit design.

2.1 Block Modelling of the Orebody

2.1.1 Drill Hole Data Management

Drill hole data processing was carried out in order to present the data in a form suitable for easy retrieval and analysis, using Surpac software. The drill hole data was organised into four text files, namely: collar, survey, assay and geology text files formats required by Surpac software. Tables 1 – 4 show the arrangement of the fields and records (*i.e.* columns and rows) in each text file.

Table 1 Part of the Collar Text File (Collar.txt)

Hole Id	Y (m)	X (m)	Z (m)	Maximum Depth (m)
A01	31797.38	129893.50	78.0	23.1
A02	31752.82	129860.41	78.0	23.1
A03	31698.17	129808.78	77.0	23.1
A04	31645.00	129752.00	78.0	23.1
A05	31564.00	129693.00	78.0	23.1

Table 2 Part of the Survey Text File (Survey.txt)

Hole Id	Depth (m)	Dip (º)	Azimuth (º)
A01	23.1	-70	90
A02	23.1	-70	90
A03	23.1	-70	90
A04	23.1	-70	90
A05	23.1	-70	90

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Table 3 Part of the Assay Text File (Assay.txt)

Hole Id	Sample Id	Depth From(m)	Depth To (m)	Assay Values (g)
A01	A0116	13.4	14.4	0.12
A02	A0211	8.6	9.6	1.32
A02	A0212	9.6	10.5	1.39
A02	A0213	10.5	11.6	2.08
A03	A0317	15.4	16.5	1.05

Table 4 Part of the Geology Text File (Geology.txt)

Hole Id	Sample Id	Depth From (m)	Depth To (m)	Rock Type
A01	A0114	11.8	12.6	PH
A01	A0115	12.6	13.4	PH
A01	A0116	13.4	14.4	GQTZ
A01	A0117	14.4	15.5	GQTZ
A01	A0118	15.5	16.3	GQTZ

2.1.2 Loading and Creation of Database

This is a prerequisite for database processing and also constitutes a data validation procedure whereby any data input whose description or structure is inconsistent with the definitions made at the database creation stage is rejected. When the database is loaded, it is then ready for data processing, extraction, plotting and reporting. There is also room for data update.

After loading the database, drill hole layout and sections of the deposit were extracted from the database for plotting and display. The drill hole layout serves two significant functions:

(i) It assists mining engineers and geologists to know the pattern of the drill holes and decide as to which planes to take the sections through; and
(ii) It assists mining engineers and geologists to check drill hole collar coordinates against manually prepared maps as a way of verifying the data.

In all, twelve sections (Fig. 1) were taken; each section had an influence of 50 m on either side of the section line. The sections served as an aid for the demarcation and digitising of the ore zones or orebody outlines using 1g/t as cut-off grade.

2.1.3 Creation of Solid 3-D model

The demarcated ore zones in the sections were digitised on-screen in clockwise direction to form closed segments that were stitched together to form a wireframe model. This wireframe model was then validated to form a solid model (Fig. 2). The output files formed at the end of digitising became ore zone string files which were saved and given a location name and ID range.

2.1.4 Creating the Block Model

The following steps were taken to create the block model:

(i) Create an empty block model;
(ii) Add constraints; and
(iii) Fill the created model with attribute values.

2.1.4.1 Empty Block Moduling

An empty block model was created with the following information: block model identification name, origin, extent, and block size Fig. 3. A user block size of 10 m × 10 m × 5 m was used to conform with mining bench width and height.

2.1.4.3 Adding Constraints

The addition of constraints was primarily to control the selection of blocks from which interpolations were made or from which information was obtained. Blocks falling within the solid model were ore and waste while blocks falling outside the topography were air blocks. Blocks within the model that had a grade value below 1g/t were considered as waste and those with values of 1g/t and above were considered as ore.

2.1.4.4 Filling the Model with Attribute Values

At this stage, the empty block model (Fig. 3) was filled with attribute values. The attributes are the properties to be employed during the optimisation process in Whittle software. These were grade, specific gravity (rock density), Mining Cost Adjustment Factor (MCAF), Processing Cost Adjustment Factor (PCAF), air, waste and rock type. Some values were assigned directly and others like the grade by interpolation. The assigned attributes are in Table 5.

Table 5 Assigned Attributes

Attribute Name	Value
MCAF	1.00
PCAF	1.00
Rock Code	Air, ore and waste
Rock Density (g/cm^3)	2.73

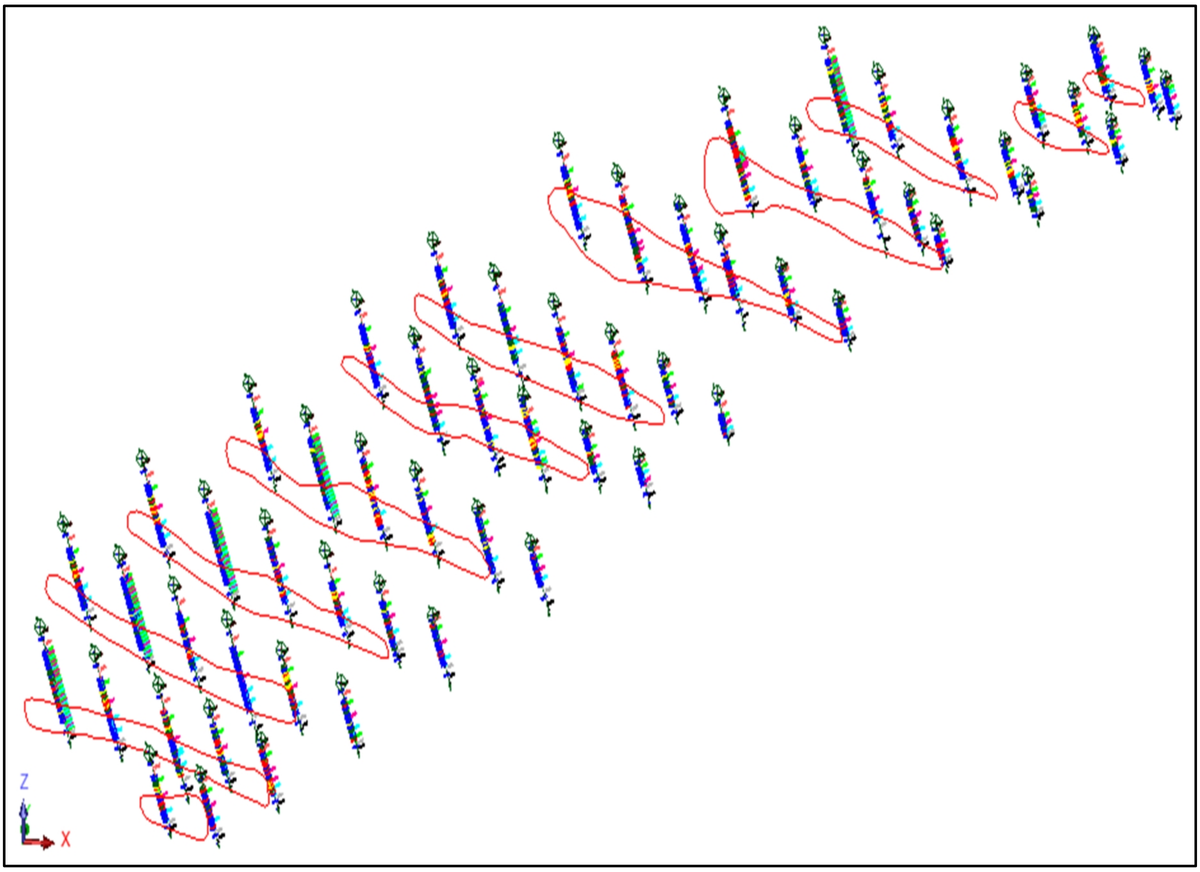

Fig. 1 Digitised Ore Zone Sections

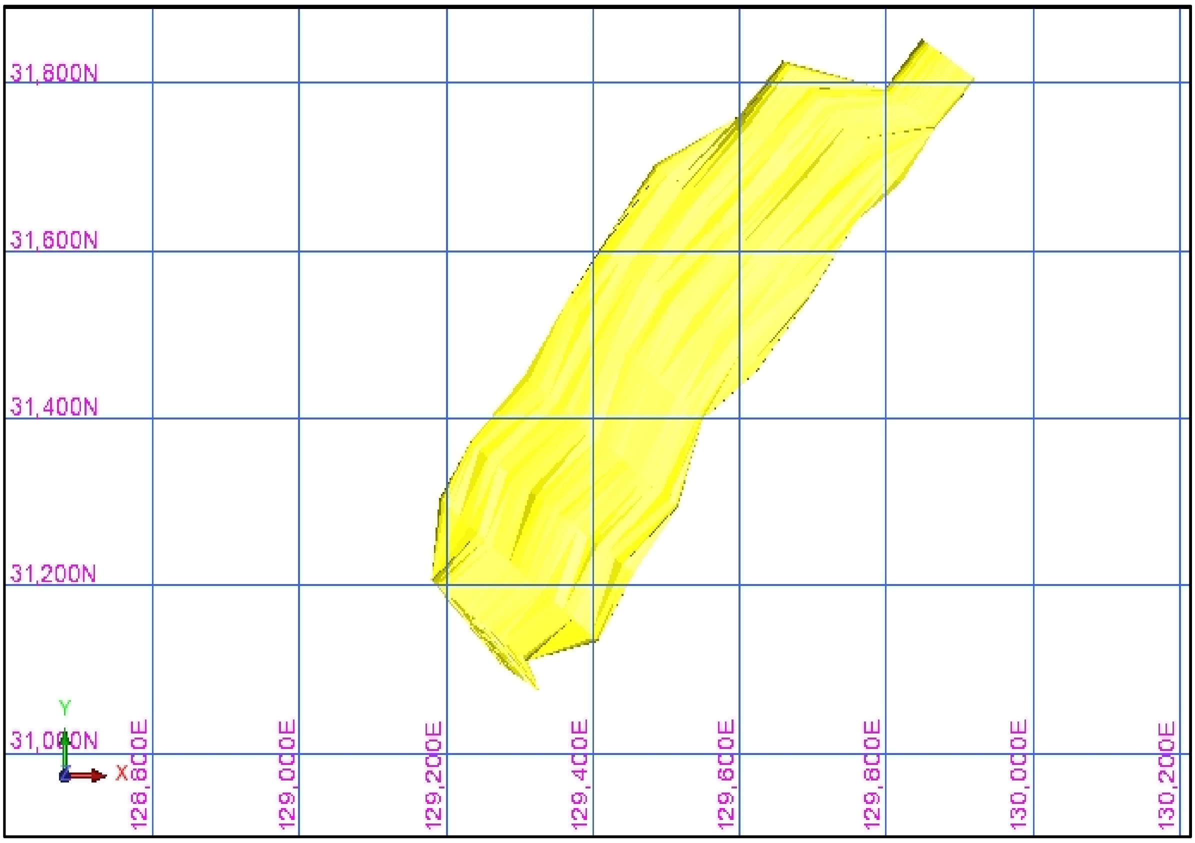

Fig. 2 Solid Model of the Orebody

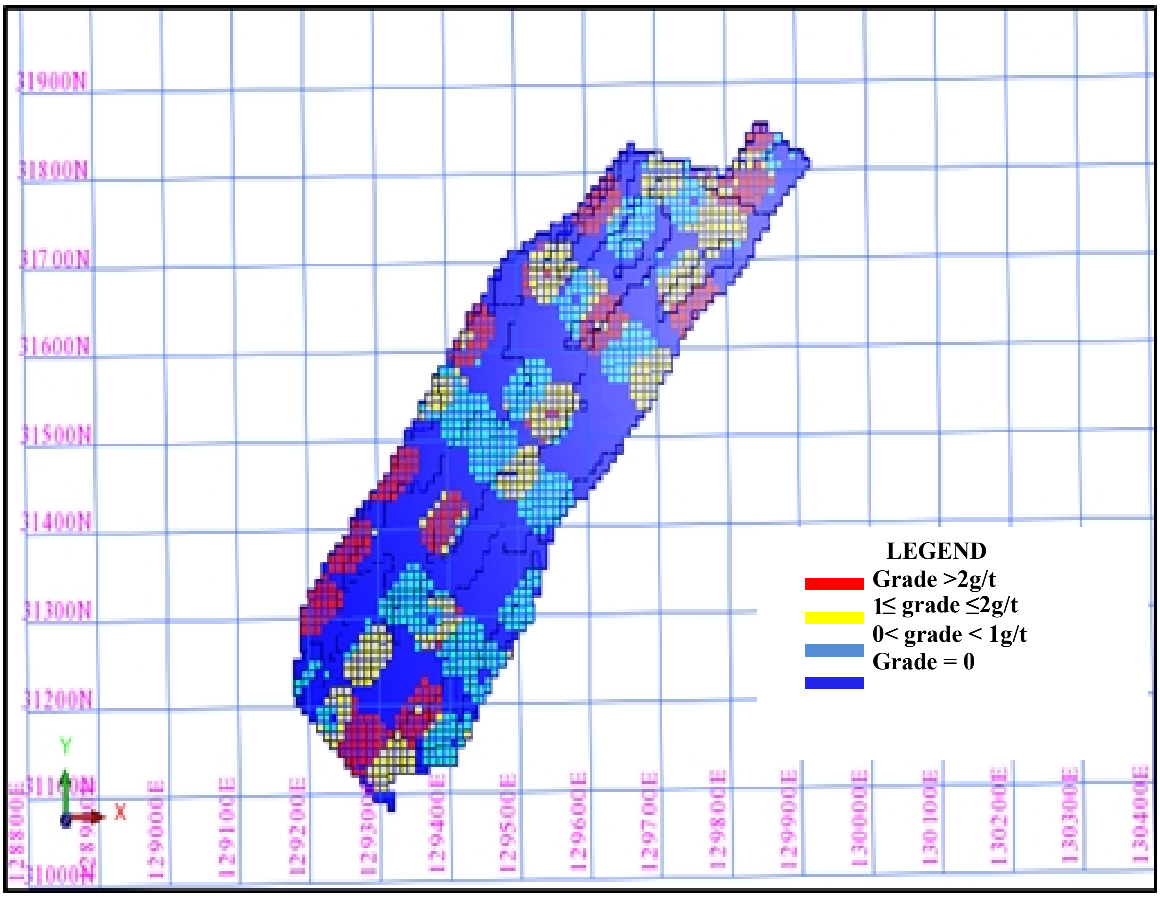

Fig. 3 Block Model

2.1.4.4 Block Grade Estimation

The grade of each block in the block model was estimated using Inverse Distance Weighting (IDW) method, expressed in Equation 1, which is available as a module in Surpac.

$$Z_B = \frac{\sum Z_i \frac{1}{d_i^n}}{\sum \frac{1}{d_i^n}} \qquad (1)$$

where: Z_B is the estimated grade of a block;

Z_i is the grade of sample i;

d_i is the distance from the centre of the block of sample i located within a specified search distance, D_s, around the block; and n is a positive integer power index (Al-Hassan, 2012).

In this study, a power index of +2 was considered acceptable based on a comparative cross-validation exercise carried out during the pre-feasibility study of the mine (Mireku-Gyimah, 2005). In order to determine an appropriate search distance, D_s, directional semi variographs were drawn and analysed.

The anisotropic ratios were almost equal to 1; this was an indication that the mineralisation is almost isotropic. Omni directional semi variograms were therefore drawn from which the search distance, D_s= 40 m was deduced. The results of the analysis are shown in Table 6.

Table 6 Variogram Report

Variogram Parameters	Values
Major / Semi-Major Ratio	0.98
Major / Minor Ratio	1.05
Max Search Distance of Major Axis (m)	40
Sill (g)	0.94
Nugget (g)	0.86

2.2 Pit Optimisation

Pit optimisation was carried out, using Whittle software. The resource block model and the economic and technical parameters were used to produce a set of nested pits. Fig. 4 depicts a summarised flow chart for the pit optimisation process.

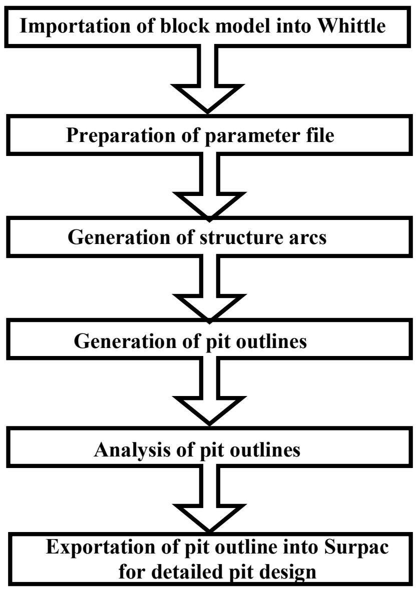

Fig. 4 Flow Chart for Optimisation in Whittle

2.2.1 Importation of Block Model into Whittle

The parameter file and the contents of the block model were exported from Surpac to Whittle using the "block model to Whittle" interface in the Surpac software for pitoptimisation.

2.2.2 Preparation of Parameter File

The parameter file containing essential economic and technical parameters as well as the appropriate range of revenue factors needed for optimisation was set up using FXED in Whittle software. The factors considered include milling and mining recovery factors, cost figures, overall pit slopes, mining dilution factors and categories of ore to be processed. Table 7 is a summary of all the cost figures and parameters used in the optimisation.

Table 7 Cost Figures and Parameters used for Optimisation

Mining cost per tonne	$4.68
Processing cost per tonne	$19.44
Price of gold	$40.6/g ($1134.00/oz)
Selling cost	$0.90/g ($25.70/oz)
Capital cost	$64 000 000
Discount rate	10 %
Mining recovery	95 %
Mining dilution	5 %
Revenue factor range	0.3 to 2 at 0.02 steps
Overall pit slope angle	45º

2.2.3 Generation of Structure Arcs

The structure arcs necessary for the optimisation were generated using the FXST programme in Whittle software. The purpose of the arcs are to ensure that the slope angle requirements are converted into a form suitable for pit optimisation. The output then becomes the input for the pit optimisation. In all, a total of 655 786 arcs were generated as an output.

2.2.4 Generation of Pit Outlines

The optimisation carried out produced a set of nested pit outlines. This was based on the range of revenue factor values defined in the parameter file. A total of 54 nested optimal pits were generated covering the range of revenue factor values from 0.3 to 2. This was achieved through the 3-D Lerchs-Grossman algorithm employed by the Whittle Optimiser. The results were kept in a results file containing all blocks that must be mined to obtain the maximum value for a particular pit. The results file then became the input for analysis.

2.2.5 Analysis of Pit Outlines

A number of analyses were carried out by the optimiser. Microsoft excel was used to prepare a graph from the output data to enhance easy interpretation. The optimal pit was selected based on worst case and best case scenarios as shown in Fig. 5. It is a graph of NPV at a minimum rate of 10% against the pits. The best case scenario involves mining out the first pit (the smallest pit) and then mining out each subsequent pit shell from the top down, before starting the next pit shell. However, the worst case scenario consists of mining each bench completely before starting on the next bench. The advantage of the best case scenario lies in setting an upper limit to the achievable Net Present Value although its schedule is seldom feasible because the push-backs are usually too narrow(Anon, 1998).

2.2.6 Selection of Optimal Pit

Net Present Value (NPV) was used as the criterion for the selection of the optimal pit in this work. From the result (Table 8), Pit 36 was selected as the optimal pit with a best case NPV value of $105 113 678. Table 8 presents the incremental pit value analysis that shows that the NPV increases gradually to Pit 36 and then starts reducing at Pit 37 up to Pit 52.

Table 8 Incremental Pit Values

Pit No.	NPV($)	Increase in NPV
31	105 105 377	0
32	105 108 039	2662
33	105 112 230	4191
34	105 112 597	367
35	105 113 528	931
36	105 113 678	150
37	105 112 847	-831
38	105 111 820	-1027

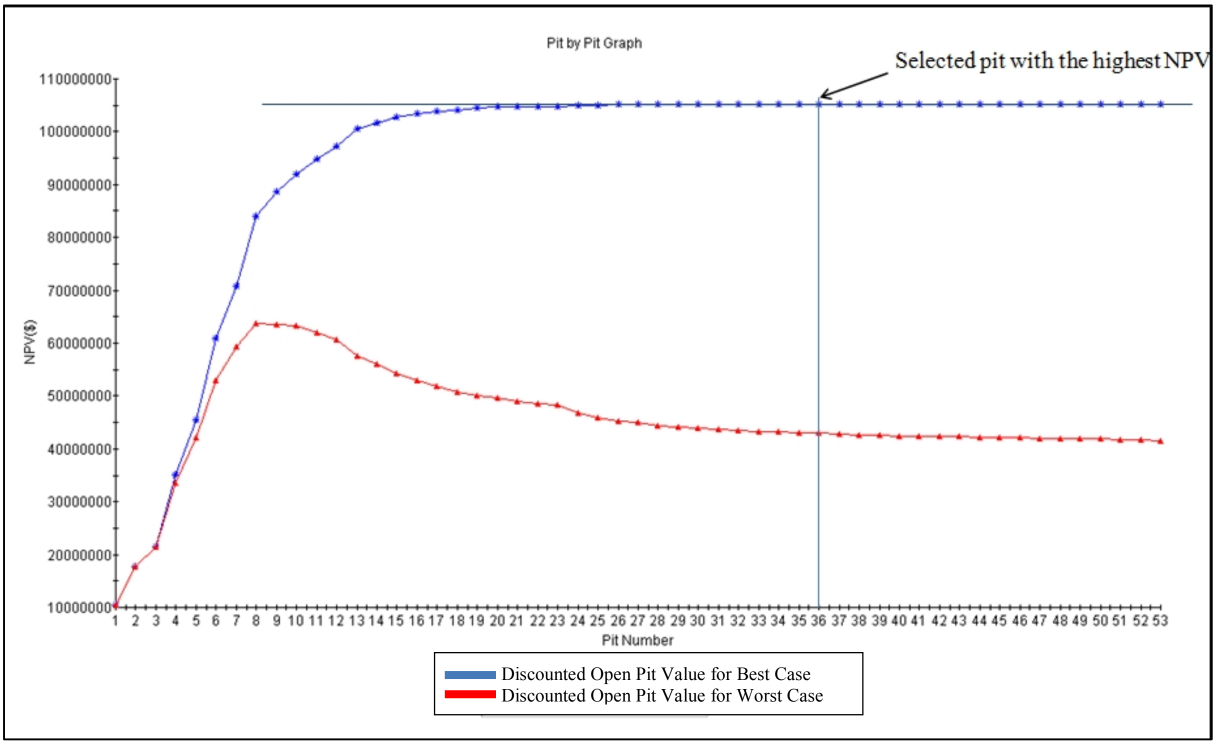

Fig. 5NPV vs Pit Number

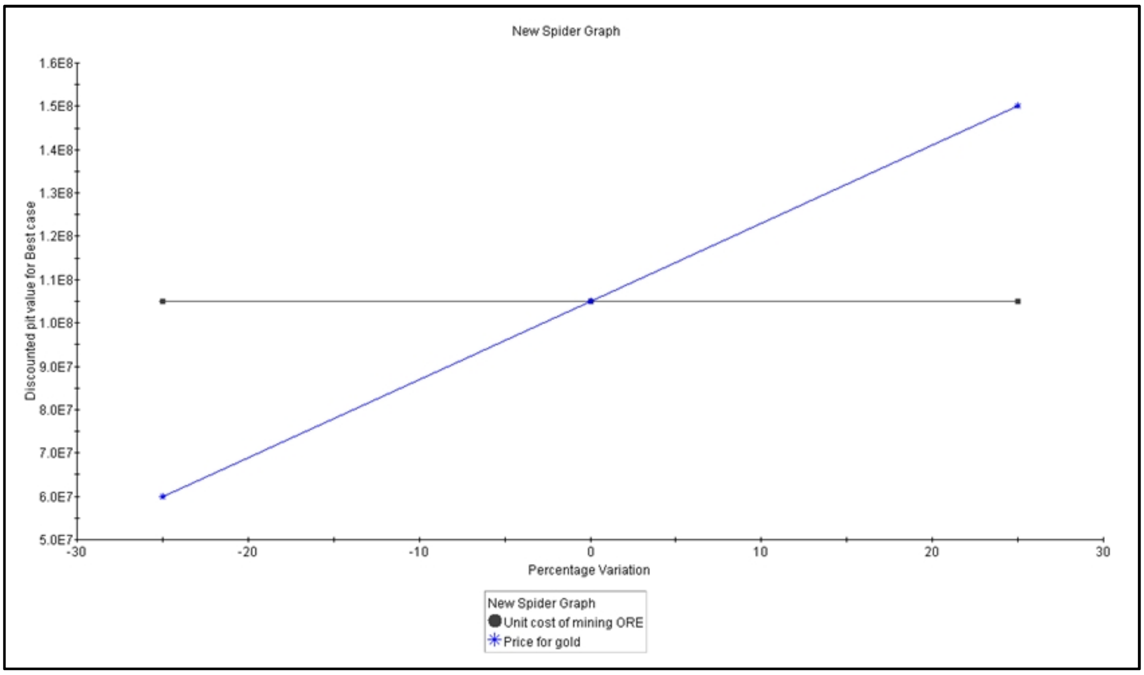

Fig. 6 Sensitivity Analysis Graph

2.2.7 Sensitivity Analysis

First, based on the selected optimal nested pit, the effect of varying the gold price while keeping all other economic parameters constant was examined; the base case figure for gold price was varied from -25% to 25% so as to check the effect of the changes in gold price on the NPV.

Second, based on the selected optimal nested pit, the effect of varying the mining cost while keeping all other economic parameters constant including the gold price was also examined; the base case figure for the mining cost was also varied from -25% to 25% so as to check the effect of the changes in mining cost on the NPV. Fig.6shows the results of these analyses. The graph indicates that the NPV is very sensitive to changes in gold price but marginally sensitive to mining cost assuming all other parameters remained constant.

2.3 Detailed Pit Design

The optimal pit outline of Pit 36 generated by Whittle (Fig. 7) was exported into Surpac for the detailed pit design. The designing process involved the addition of berms and a haul road to the pit outline generated by the Whittle optimiser. The ‘Pit Design’ menu of Surpac software was used to carry out the design. Prior to the designing of the optimal pit, a Digital Terrain Model (DTM) of the surface topography and the string files consisting of bench outlines (contours) of the Whittle optimal pit were generated. Table 9 contains the parameters used to undertake the final pit design.

Table 9 Pit Design Parameters

Parameter	Value
Bench Slope Angle (Degrees) (°)	70
Bench Height (m)	5
Ramp and Haul Road Width (m)	20
Ramp Gradient (%)	10
Berm Width (m)	3.2
Final Slope Angle (Degrees)	45
Bench Width (m)	10

The optimal pit was designed as follows:

(i) Design process;
(ii) Pit-topography intersection; and
(iii) Addition of haul roads.

2.3.1 The Design Process

The expanding pit design approach was used in this work. Thus the design began from the bottom of the pit and expanded upwards till the surface topography was intersected.

The design slope method was chosen to define the slope angles. This ensured that each lift of the pit edge was inclined at an angle corresponding to the design slope angle. Safety berms were inserted at intervals of 10 m. This corresponded to every two-bench lifts.

2.3.2 Pit-Topography Intersection

A DTM of the designed pit was built and intersected with the DTM of the surface topography. The results were extracted to form a pit-topography string file and a DTM.

2.3.3 Addition of Haul Road

The nature of the pit required the creation of a ramp to be used for haulge of ore and waste. It was created on the high elevations (Fig. 8).

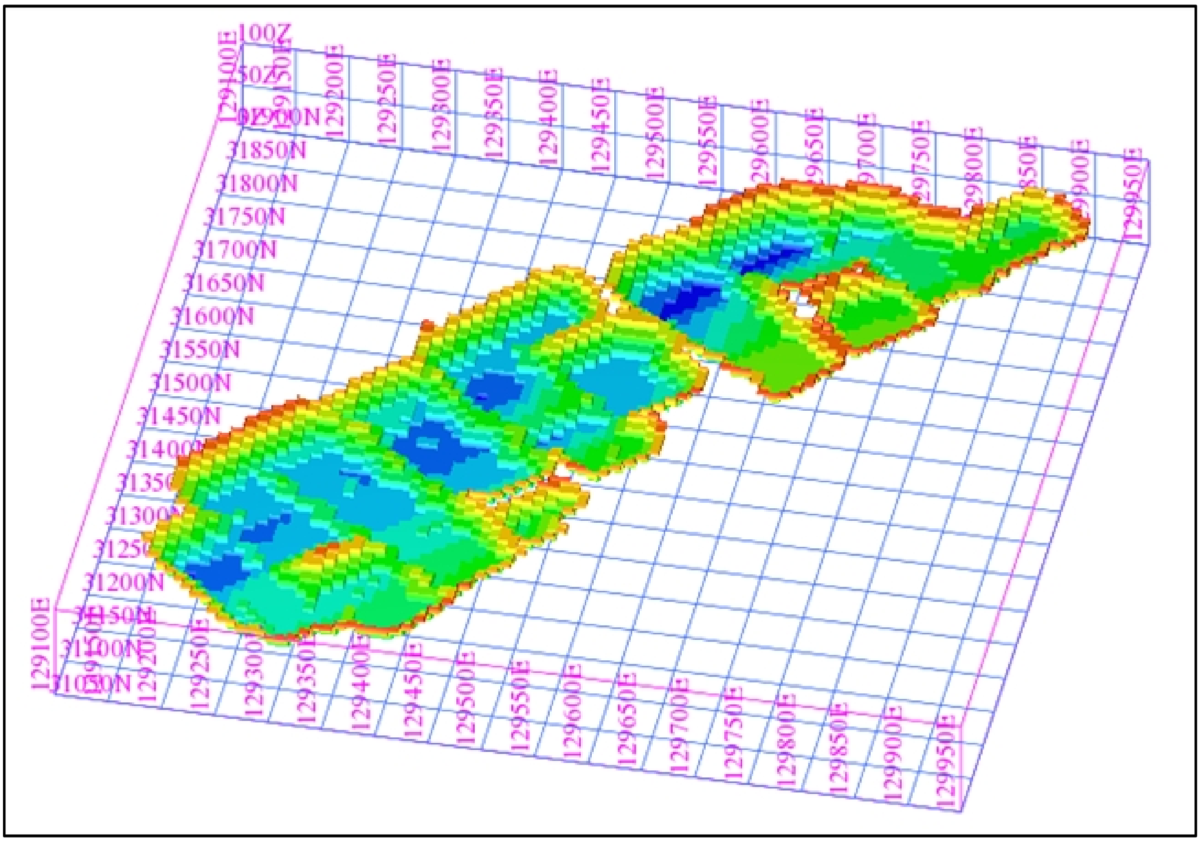

Fig. 7 Exported Whittle Optimal Pit Outline

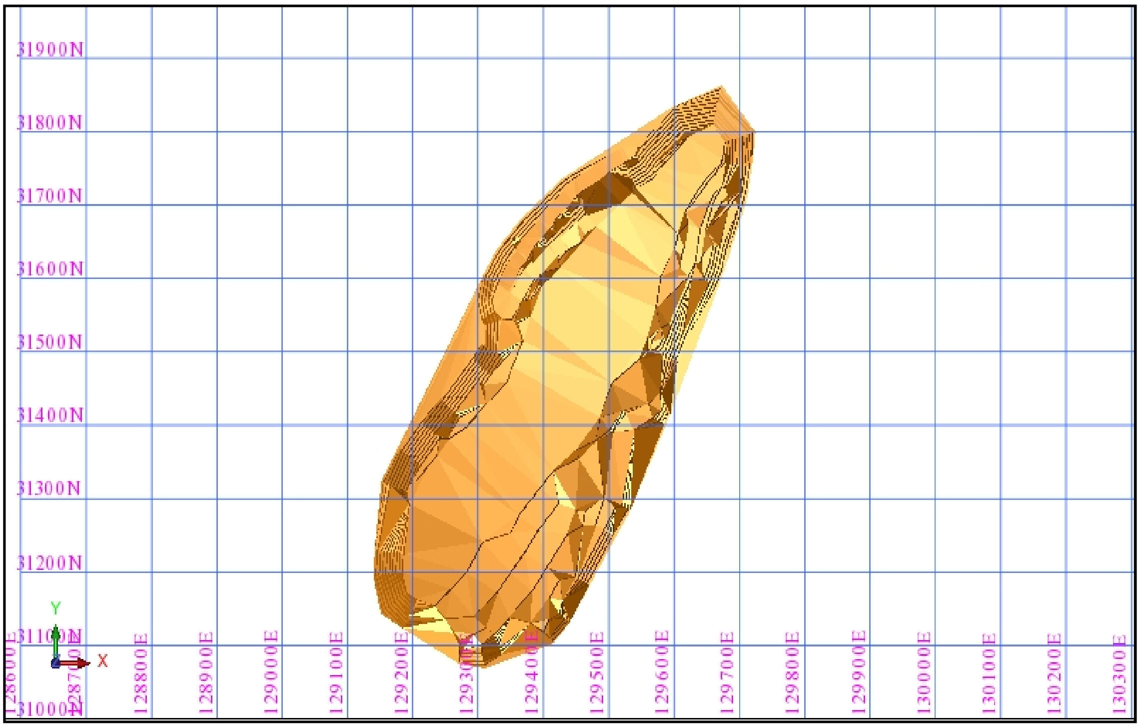

Fig. 8 Optimal Pit Design with Switchback Road

3 Results and Discussion

The volumes of ore and waste as well as the respective tonnages in the Whittle optimal pit and in the final pit designed in Surpac were calculated. The results are shown in Tables 10 and 11. The designed pit contains 5 034 120 t of ore at an average grade of 1.7063 g/t. However, it can be deduced from the two tables that the tonnage of ore in the designed pit decreased by 16.05 % as compared to the tonnage of ore in the Whittle optimal pit; while the tonnage of waste in the designed pit increased by 19.58 % when compared to the tonnage of waste in the Whittle optimal pit. Also the average grade of ore in the designed pit decreased from 1.7121 g/t in the Whittle optimal pit to 1.7063 g/t (representing 0.34% decrease). The differences in the tonnages of ore and waste and the average grade of ore in the designed pit and optimal pit are due to the fact that during the pit design, the pit bottom was widened to give adequate room for equipment maneuverability, a ramp was introduced to facilitate haulage of ore and waste and berms were added for safety purposes, all of which led to the addition of some waste, some ore loss and dilution.

Table 10 Results From Whittle Optimal Pit

	Volume (m^3)	Tonnage (t)	Gold (g/t)
Ore	2196500	5996445	1.7121
Waste	3295000	8995350	0.06
Total	5491500	14991795	
Stripping Ratio: 1.5:1			

Table 11 Results From Final Pit Design In Surpac

	Volume (m^3)	Tonnage (t)	Gold (g/t)
Ore	1844000	5034120	1.7063
Waste	4097000	11184810	0.08
Total	5941000	16218930	
Stripping Ratio: 2.22:1			
Expected Revenue: $331 305 460.10			

4 Conclusions

The following conclusions were drawn at the end of the study:

(i) Given any exploration data such as that of NML, Surpac and Whittle software can be used to design an optimal open pit;

(ii) In this study, the optimal pit outline generated by Whittle software contained 5 996 445 tonnes of ore at an average grade of 1.7121 g/t of gold; the NPV of this pit is sensitive to changes in metal price but marginally sensitive to cost of mining; and

(iii) The final pit designed using the Surpac software contains5 034 120 tonnes of ore at an average grade of 1.7063 g/t and a total volume of material (waste and ore) of 5 941 000 m^3. However, the designed pit contains 19.58% more tonnes of waste, 16.05% less tonnes of ore and 0.34% lower average grade of ore than the respective figures in the Whittle optimal pit. The differences in the figures are due to the widening of the pit bottom and the creation of a ramp and berms in the designed pit which resulted in the addition of some waste, ore loss and dilution.

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