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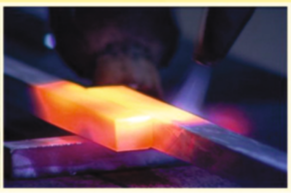


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Open Pit Optimization And Production Scheduling Of Okobo Coal Mine, Central Nigeria

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A B S T R A C T

The Okobo coal in Enjema District of Ankpa Local Government Area of Kogi State, Nigeria is a near surface deposit that is mined through the open pit method. In this investigation, models and plans of the Okobo coal mine produced, using Minex® Gemcom Software, were aligned with depth, strip ratio and optimum pit limits with the aim of defining the most profitable extraction sequence of the coal that will produce maximum possible discounted profit under certain physical and operational constraints. Sandstones, shale and clays constitute the overburden. The topsoil thickness ranged from 0.1 to 0.5 m. Coal recovery was estimated from drill data to be 95%, with losses occurring primarily at the base of the coal seam. Eight (8) expansion pits from the most valuable to the least valuable material were identified using the optimizer. Parametric analysis of mining and processing costs generated an optimized pushback of 1.7 million tonnes of 20.79 Air Dried (AD) MJ/kg coal at 12.35 stripping ratio in the $65 incremental pit. Areas with higher stripping ratio might be more suitable for underground mining. Implementation of these application would reduce cost, improved the Net Present Value (NPV) of the operation and selection of the most economical areas for mining. It is recommended that the mine pits be developed from north to south for optimum productivity.

Keywords:
Open pit mining, Geologic model, Mine planning, Production scheduling, Okobo coal

1. Introduction

Okobo coal occurs in Enjema District of Ankpa Local Government Area of Kogi State, Nigeria. It is a near surface deposit that is mined through the open pit method. Hochbaum and Chen (2000) viewed the open pit mining problem as a problem to determine the contours of a mine, based on economic data and engineering feasibility requirements in order to yield maximum possible net income. The solution to the problem requires large data sets and multiple scenarios that take into consideration geological data and ore value estimations. Picard and Smith (2004) described the open pit design problem as the problem of choosing an ultimate contour whose total profit of the blocks is maximal among all possible contours. Planning an open pit mine begins with a geologic block model and determination of whether a given block in the model should be mined or not. Zhang (2006) approached the problem of scheduling large number of blocks in a mine by combining a genetic algorithm and topological sorting to find the extraction schedule of a mine. The approach simultaneously determines an ultimate pit of a mine and an optimal block extraction schedule that maximizes the Net Present Value (NPV) subject to a number of constraints including wall slope, mining and processing capabilities. The block model, define the yearly progression of the pit surface and the annual cash flows from the mining operations during the mine life. A mining model, which is a pit design tool that facilitates identification of the best overall theoretical cash flow from the mining sequence in the deposit, could be applied. The mine design tool is based on an algorithm developed by Learchs and Grossmann (1965). The optimizer accepts inputs related to pit wall slope, mineral recovery, minimum recoverable coal seam thickness, mining and processing cost, waste costs, and product quality adjusted sales price. Variable haul costs, as defined by source area and haul cost to a dump site, can also serve as input to the optimizer.

The objective of the planning process for an open pit mine is usually to find optimum annual schedules that will give the highest Net Present Value (NPV) while meeting various production, blending, sequencing and pit slope constraints

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(Bernabe, 2001). The optimizer divides the mining model into blocks of a specific width, length, and height, in effect sugar cubing the mining model. A value is then calculated and assigned to each block. This is done by calculating the revenue obtained from each block based on adjusted quality and recovery. Coal below a specified thickness is treated as waste. Mining and processing costs for coal are assigned to the blocks containing coal and variable haulages costs can be applied. The net value of each coal block is then calculated. Similarly, waste block costs are calculated. Coal blocks have a positive value and waste blocks a negative value. The optimizer then operates on the block model to find every block or combination of blocks that will add to the value of the pit. Theoretically, every point along the wall of the pit defined has the same economic value and the average value of all ore within the designed pit will have a value greater than on the boundary. There may be diverse solutions to the scheduling problem depending on how the decision is made for each of the blocks. Decision as to which blocks should be mined in a given year, and how they should be processed defines the cash flows for that year and also impacts on future annual schedules. Large initial investments and operational budgets are required. The market prize of the ore may fluctuate. Also, the exact percentage of ore constrained in each block of a deposit is uncertain until the block is completely mined. These uncertainties are known as price and geological uncertainty respectively. Significant costs are involved in assay determination (Newman *et al.,* 2010). One of the standard procedures to reduce uncertainties and risks is to perform the evaluation process for different scenarios of the project key variables (Abdel Sabour *et al.,* 2008). Whatever is decided has long-term implications on the future and the overall economics of the mining project (Cai and Banfield, 1993; Camus and Jarpa, 1996; Hoerger, 1999).

Open pit designs and production scheduling are sensitive to changes in economic variables and operating parameters. Mineable reserves shrink and expand considerably as parameters change slightly. Mining model, an open pit design tool based on algorithm developed to improve the economics of open pit mining projects, could be applied to mineral deposits to facilitate theoretical cash flow. In the past, such algorithms could not be implemented due to paucity of requisite computer hardware and application software. Nowadays, modern computers are providing the much needed tools to solve these complex optimization problems on site. In this paper, Western Goldfield Group Nigeria used the Gemcom Minex® software, a mine planning application package to optimize and schedule production operations of the Okobo Coal Reserve in Enjema District of Kogi State, Nigeria with the aim of reducing cost, improve the Net Present Value (NPV) of the operation and to select the most economical areas for mining on the basis of coal quality and overburden stripping ratio.

2. Methodology

2.1. Cross sections and exploration drill-hole data

The location map of the Okobo coal seam (Figure 1), showing the cross sections A-A to F-F. Sandstones, shale and consolidated red and brown clays constitute the major overburden. The topsoil constructed from test pits showed a thickness of about 0.5 m in areas of low gradients down to 0 m in steeper areas with slope greater than 20º. The topsoil thickness estimated from the depth of material washed out of drill holes ranged from 0.10 to 0.25 m at a break from 6º to a steeper sloping topography. Sections, A-A through F-F (Figs. 1a to 1f) showed the internal consistency of the structural geologic model of the coal deposit.

2.2. Modelling of Okobo Coal Deposit

Block model representation of the coal deposit is the starting point for the planning and production scheduling of the open pit mines. The mineralized body and the surrounded rock was divided into a three-dimensional array of regular size blocks. A set of attributes, including, grade, tonnage and density are then assigned to each one of these blocks estimated using spatial interpolation techniques: kriging and inverse distance weighting method and the exploratory drill hole sample data according to the methods of Tolwinski (1998) and (Whittle, 1999). The blocks are then divided into ore and waste blocks. The blocks whose prospective profit exceeds their processing cost are categorized as an ore block (Lane, 1988) to be sent for processing once mined while the rest are the waste blocks. An economic value was assigned to each block by taking into account its group, as ore or waste, the commodity price, mining, processing, and marketing costs.

The Okobo coal modelling provides the basis for the estimation of coal reserves in a manner consistent with established standards. The block (geological) model for this evaluation was created using Gemcom Minex® Software. This is a three-dimensional representation of the individual block component of the coal deposit, usually defined by the Northings, Eastings and elevation grid points as defined by Akisa and Mireku-Gyimah (2015), with information regarding coal quality revenues, costs and other relevant data obtained from exploration report in line with the method adopted in Akaike and Dagdelen (1999). The structure of the coal seam was converted to a structural model for use in mine surface design. The coal quality model grids were also developed and made compatible with the geologic model to produce a merged model, hereafter referred to as the mining model, which was subsequently used for mine layout, production scheduling and optimization.

A number of constraints were applied to the design of the pits, which are built into mining model. They include, Digital Terrain Model (DTM) of the topography, provision of space for roads, power lines, drainage channels, set back from the lease boundaries and adequate operating space of about 50 m wide for mining operation.

2.3. Pit optimisation and parametric analysis

Exploration data, including those of Table 1, obtained from Okobo coal mine was used as input for mining modelling. The data in Excel format was loaded into a geological database created. The text files were classified under tonnage, thickness, net calorific values, ash content, sulphur and volatile matter. Plans and sections were extracted from the database to produce geologic sections. The sections were used in the delineation and digitisation of the coal seams. Attribute records of the coal seams from each block and constraints were added to the mining model. Values were assigned to attributes, mining and processing costs. A series of pit expansion from the most valuable to the least valuable material per tonne mined were outlined (optimisation).

Parametric analysis controls the pit definition and other inputs used (Akisa and Mireku-Gyimah, 2015). The parameter used for parametric analysis include the cost figures, pit slope angle, capital cost, mining cost, processing cost, mining recovery, mining dilution and the percentage of the revenue received from the sale of the product at some defined point. In reporting the result of the analysis, the percent parameter was transformed into monetary units. The sales price is multiplied by the parameter (in percentage) to give the amount of money, after all mining costs reserved for undiscounted expenses, taxes, interest, loan repayment, and profit has been deducted.

The unit value of the coal between each progressive block reduced as the allowable cost of mining and processing increased. This defines the theoretical sequence that will maximize the cash flow in the mine. It should be noted that the pits defined by this parametric analysis are not practical units. They only form a guide on how to develop the deposit. The actual planned mining sequence should be as close as practicable to this progression so as to maximize the net present value (NPV) or discount cash flow-rate of return (DCF-ROR) on the project. The selection of the optimal pit was based on the NPV at a Minimum Rate of Return (MRR), which was determined by a combination of parameters.

Table1. Drill-hole data on Okobo coal seam and the lower and upper carbonaceous shale

Seam	Coal (k tonnes)	Average Thickness (meters)	Minimum Thickness (meter)	Maximum Thickness (meter)	Net CV (MJ/kg)	Ash (%)	Sulfur (%)	Volatile Matter (%)
Upper Carbonaceous Coal		0.73[2]						
Okobo Seam	11,324	1.73	0.04	3.33	19.62	8.61	0.57	32.48
Lower Carbonaceous Shale	7	0.08	0.01	0.57	17.78	18.94	0.41	30.73
Total/Average	**11,332**				**19.62**	**8.62**	**0.57**	**32.48**

[1]Statistics reported for seams bounded by the subcrop line and lease boundary
[2]Only hole BH-35 had top of coal carbonaceous shale; Coal quality reported on an as-received basis AR

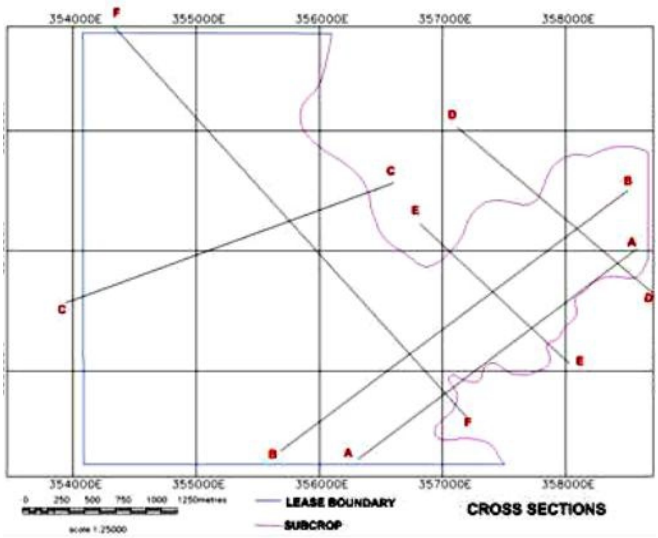


Figure 1. Location map showing sections A-A, B-B, C-C, D-D, E-E and F-F of Okobo mine.

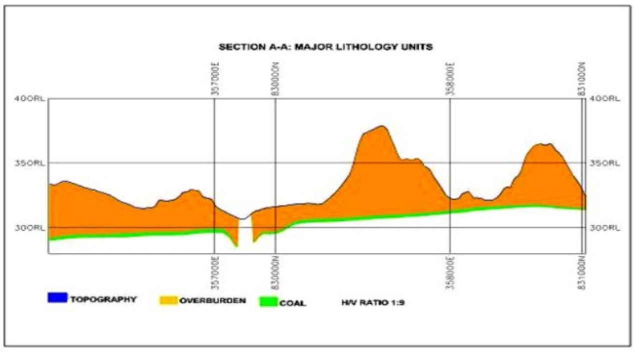


Figure 1a. Section A-A of Okobo coal mine.

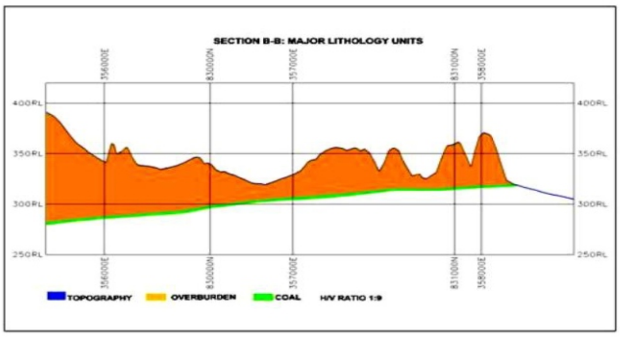


Figure 1b. Section B-B of Okobo coal mine.

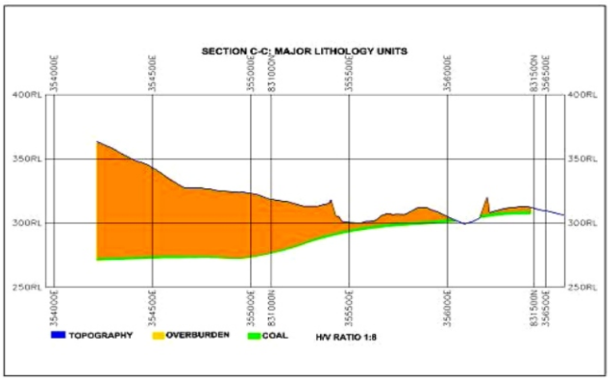


Figure 1c. Section C-C of Okobo coal mine.

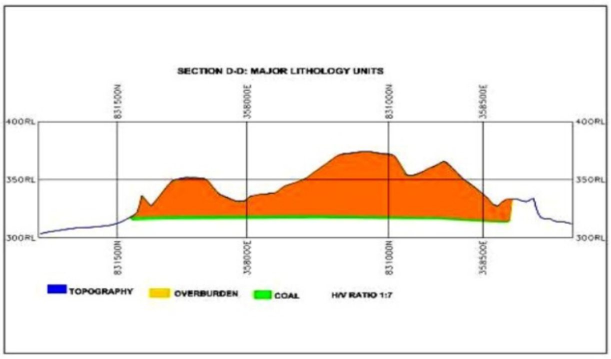


Figure 1d. Section D-D of Okobo coal mine.

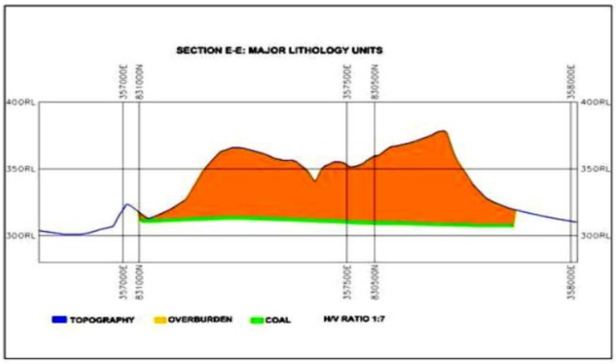


Figure 1e. Section E-E of Okobo coal mine.

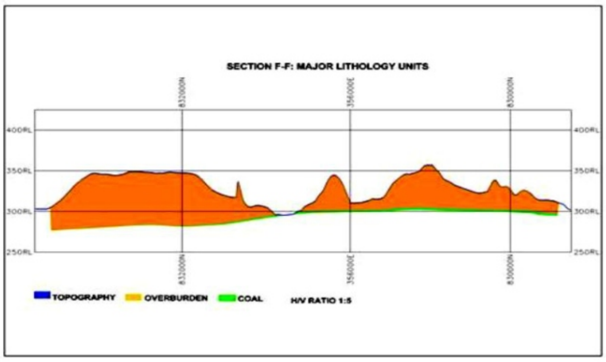


Figure 1f. Section F-F of Okobo coal mine.

3 Results and Discussion

3.1 Optimization and pushback generation

Exploration drill data (Table 1), of the Okobo coal seam shows that the lower carbonaceous shale could be mined with the Okobo seam without significant impact on the coal quality, except in few locations with shale thickness of over 0.5 m, which was not computed with the tonnage as shown in Table 1. Coal recovery was estimated to be 95% with losses occurring primarily at the base of the coal seam. The parameters used to define the strategic sequence for exploitation of the Okobo coal deposit are the margin controlling the optimizer pit expansions based on coal quality and the monetary values.

3.1.1 The $80 Margin Optimizer Pit

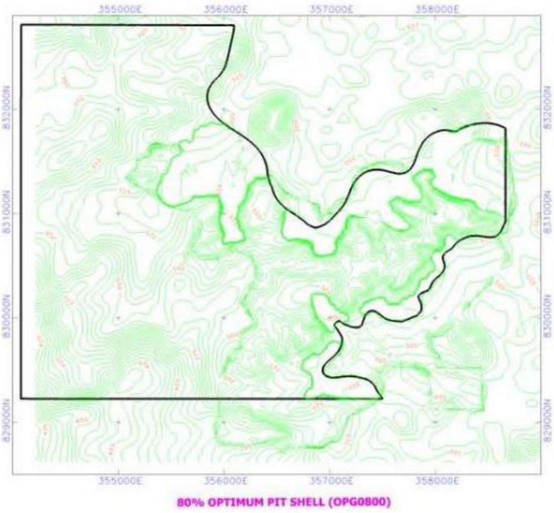
The $80 margin optimizer pit is shown in Figure 2a. There are three distinct areas of interest, two on the north side adjacent to the sub-crop line and the remaining one adjacent to the southeast sub-crop line. The southeast area is further sub-divided into three smaller areas of interest. These three areas are prototype pits that have the highest profit potential within the sub-crop area.

3.1.2 The $75 Margin Optimizer Pit

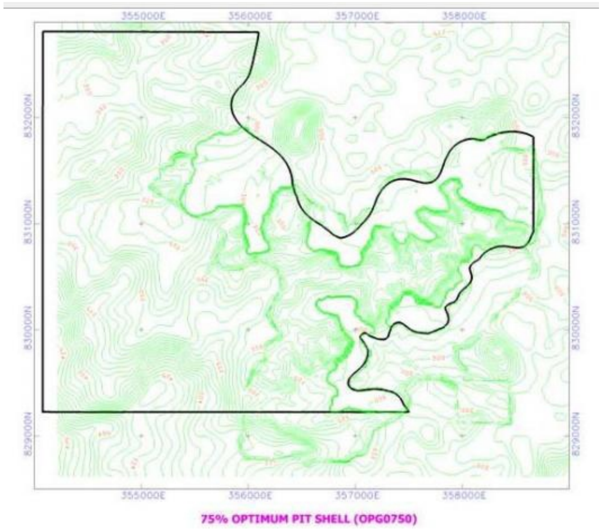
A $5.00 reduction in margin added approximately 100,000 tonnes to the northern area and another 300,000 tonnes to the southeast pit. The changes along the boundary of the north pits are barely perceptible on Figure 2b relative to Figure 2a. From a mine planning perspective, there is no opportunity to develop a separate expansion between these two optimizer pits. The two areas will either be merged into the $80 margin pit or included in the $75 margin pit or some combination of both. The three separate areas in the southeast, formed at the $80 margin level, have merged into two areas, both having the potential to be the basis for a practically mineable pit.

3.1.3 The $70 Margin Optimizer Pit

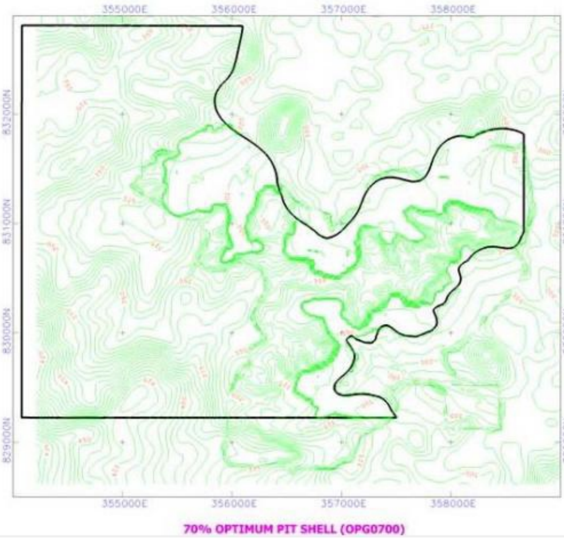
Due to the margin reduction from $75 per tonne to $70 per tonne, the north pits added 600,000 tonnes with a very small change in the boundary. The southeast pit added 200,000 tonnes with a notable change as a result of the merging of two segments ($70 per tonne) into one long pit as shown in Figure 2c. The expansion of the pits was limited by the surrounding hills and increase in stripping ratio.



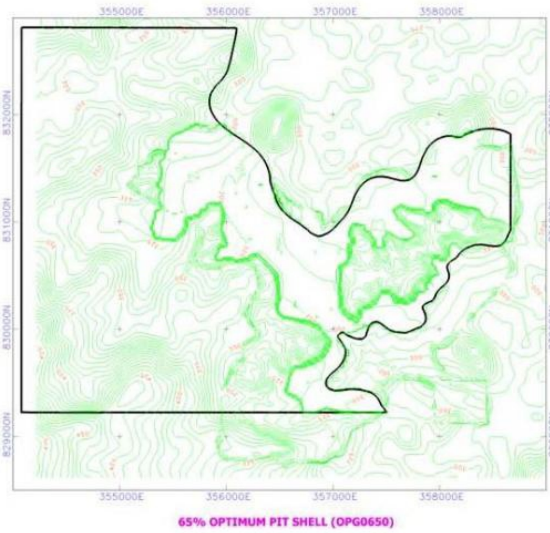
(a)



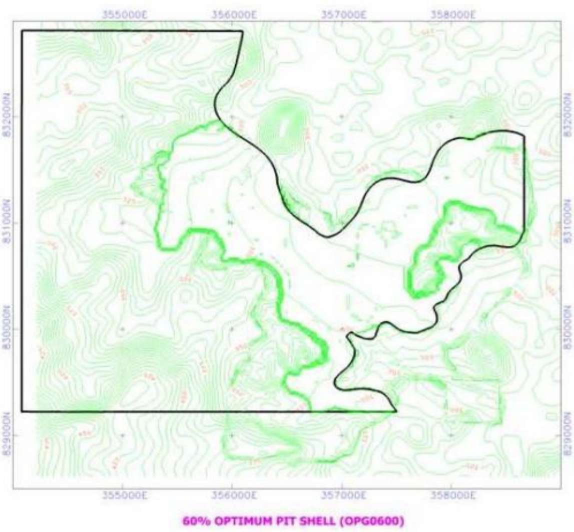
(b)



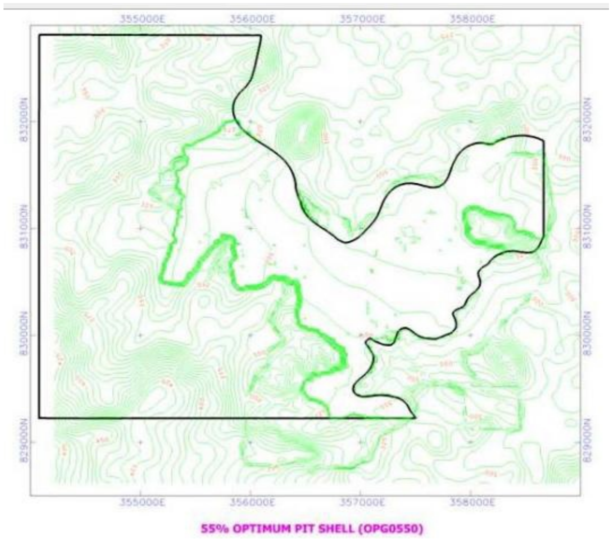
(c)



(d)



(e)



(f)

Fig. 2a-f. The (a) \$80 (b) \$75 (c) \$70 (d) \$65 (e) \$60 and (f) \$55 margin optimizer pits.

3.1.4 The $65 Margin Optimizer Pit

The $65 margin pit shows a significant break from the $80 margin pit through the $70 margin pit. The hills dividing the southeast prototype pits from the two north prototype pits have been removed connecting the three pits and opening the coal between the three areas (Fig. 2d).

This identifies an incremental 1.7 million tonnes of 20.79 AD MJ/kg coal at 12.35 strip ratio in the 65 incremental pits compared with the combined $70 incremental pits that exposed 600,000 tonnes of 20.77 AD MJ/kg coal at 10.51 strip ratio. This will likely present a detailed scheduling challenge that will need to be addressed when fitting the mining method to the topography and the practical pit that will need to be developed.

3.1.5. The $60 Margin Optimizer Pit

The $60 margin optimizer pit (Fig. 2e), expands both east and west from the opening made by the $65 margin optimizer pit. The westward expansion is too small to form a practical mining unit. The expansion to the east appears to make a reasonable mining unit.

3.1.6. The $55 Margin Optimizer Pit

In Figure 2f, the $55 margin optimum pit extended both east and west. On the east side, a residual hill barely accessible is left isolated, which suggested it either be left alone or merged with the $60 margin pit. On the west, the pit extended the boundary of the prototype pit into the remaining higher terrains. Both east and west pushbacks are marginal mineable units.

3.2. Production scheduling

Eight strategic mine areas were identified as presented in Figure 3. The strategic mining sequence should start with the 1.1 million tonnes in Mine Area 1. Mine Area 1 was established with closely spaced drilling as documented in the exploration report. A coal haul road was proposed around the southwest end of Mine Area 1 (Fig. 3), which must be to the west of any site selected for the crusher. The southwest pit will be mined first. An exposed high wall will be left behind until the mine progresses from the north to the south. Backfill will be placed against the wall to avoid long-term coal exposures, spontaneous combustion, coal weathering and to prevent water accumulations and potential safety issues. Before the coal in Mine Area 1 pit is exhausted, development work will start on the northern edge of the deposit in the Mine Area 2, followed by Mine Area 3. A coal haul road is proposed between Mine Area 2 and the crusher in Mine Area 1(Fig. 3). This road passes from north to south along the western edge of the mining area. As coal in Mine Area 3 is developed, the coal haul road will be extended into the new areas.

Mine Area 4 occupy the area between Mine Areas 1, 2, and 3, as shown in Figure 3. It has a significant increase in strip ratio and will require significantly more lead time to develop than Mine Areas 2 and 3. Production scheduling will require simultaneous development of Mine Areas 3 and 4. Mine Area 5 is located to the south of Mine Area 3 and north of Mine Area 1. Mine Area 5 butts up against the high hills to the east and to Mine Area 4 to the west. Integrating Mine Area 5 into the earlier mine areas and Mine area 6 will improve the production scheduling. Access to the high topography, production sequencing, and equipment utilization would be difficult with an ordered sequence. A development on a broad front through Mine Areas 4, 5, and 6 appears to offer an opportunity to approximate the strategic sequence while allowing for a well-organized utilization of equipment, access, and open operating reserve. Mine Area 7 is a relatively high strip ratio resource on the west side of the mine area. It has similar strip ratio and economics as that of Mine Area 6 (Fig. 3).

A broad front advance running for about 1,500 meters from pit 2 on the northwest end to Mine Area 4 on the southeast end is amenable to strategic development. Mining the Mine Areas 4, 5, and 6 together would facilitate higher rates of coal production. The development options suggested that a chevron shaped advancement of the pit from north to south would provide opportunity to develop and advance the mining face steadily and help to manage the strip ratio open the reserve potential and minimize haulage distances. Mine Area 8 is a significant resource; however, the high stripping ratio might indicate that it is more suitable for underground mining. Cash flow analysis of Mine Area 8 would determine whether it is economic to include this resource in the surface mining reserves. The production schedules of the Okobo mine as planned on base case production is presented in Figure 4.

The pits developed using the Gemcom Minex® Optimizer program are theoretically perfect but often not practicable, because the pits are not combined or divided into practically mineable units. The necessary smoothing of the pits outline to mining areas that can be executed effectively were not incorporated into the program. Also, adjustments to the pit limits for specific slope stability requirements, and problems were not undertaken. Adequate provisions were not made for placement of access to the mine and roads for truck haulage of coal to crusher or stockpiles, and haulage of waste to dumpsites either within or outside the pit. Buffer zones along property boundaries, water drainage and stream diversions were not integrated into the plan. The mine areas should have been integrated into the mining method applied in an executable sequence for the program to run effectively. Adjustments to the pits as stated above in the optimizer parametric analysis resulted in reduction of the net unit value of the Okobo coal to be mined in the practical pits.

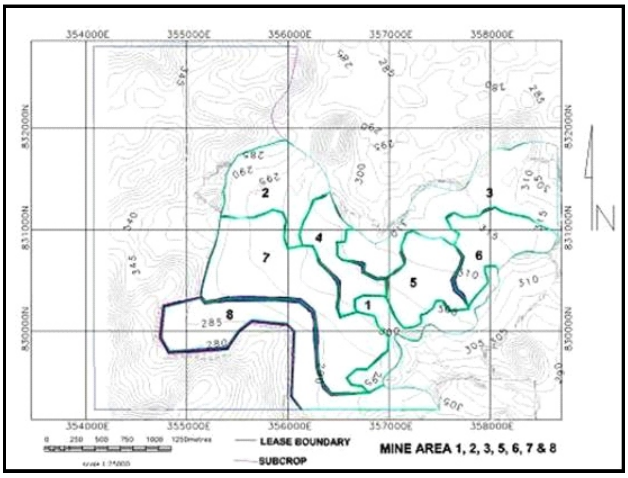


Fig. 3. The Practical Pits (1 to 8) of Okobo coal mine.

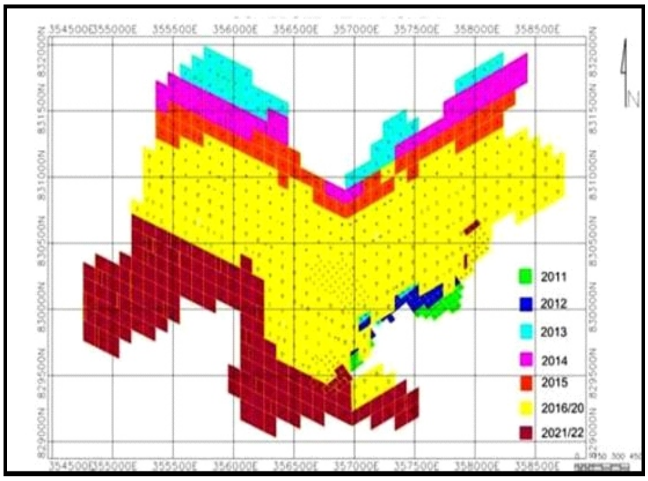


Fig. 4. The Base Case Production Schedules of Okobo coal mine.

4. Conclusions

Models and plans of Okobo coal mine were produced using Minex® Gemcom Software, a mine planning application package for coal and other stratified deposits which was designed to allow surveyors, geologists and engineers to work together effectively throughout the life of a mine. These designs were integrally linked to a geologic model so that mine designs can align with economic or geological considerations such as depth, strip ratio or optimum pit limits. It defined the most profitable extraction sequence of the coal, which produced maximum possible discounted profit while satisfying a set of physical and operational constraints. The open pit operation improved the economics of the coal operations using the Net Present Value as a criterion (Hoerger, 1999). The software package used overcome the shortcomings of traditional mine planning techniques in providing Net Present Value maximized mine plans and schedules. The most economical mine areas were selected through optimization processes based on quality and low stripping ratio as priority area for the first ten years of mining from 2011 to 2021. The use of these optimization tools and strategies provided opportunities for increased returns on the capital invested in Okobo coal project.

It is recommended that the pit bottom should be at least 50 m wide to ensure adequate operating room for the mining operation. Recovering seams of less than 0.5 m were considered uneconomic and should be added to the waste. Hence, this was not included in the calculation of tonnage. It is recommended that the mine pits be developed from north to south for optimum productivity.

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