

# Mining Options Optimization: Open Pit to Underground

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## Abstract

*Near-surface deposits that extend to considerable depths are often amenable to both open pit mining and/or underground mining. This paper investigates the strategy of mining options for an orebody using a Mixed Integer Linear Programming (MILP) optimization framework. The MILP formulation maximizes the net present value (NPV) of the reserve when extracted with i) open pit mining, ii) underground mining, and iii) concurrent open pit and underground mining. The NPV generated at a 5% discount rate when the orebody is extracted with i) open pit mining is \$2103 M, ii) underground mining is \$822 M and iii) concurrent open pit and underground mining is \$2154 M. Comparatively, implementing open pit mining generates a higher NPV than underground mining. However considering the investment required for these mining options, underground mining generates a better return on investment than open pit mining. The results also show that in the concurrent open pit and underground mining scenario, the optimizer prefers extracting blocks using open pit mining. This is due to the fact that although the underground mine could access ore sooner, the mining cost differential for open pit mining is more than compensated for by the discounting benefits associated with earlier underground mining.*

## 1. Introduction

Mining is the process of extracting a beneficial naturally occurring resource from the earth (Newman et al., 2010) and historical assessment of mineral resource evaluations has demonstrated the sensitivity of project profitability to decisions based on mine planning. A major aspect of mine planning is the optimization of long-term production scheduling. The aim of long-term production scheduling is to determine the time and sequence of extraction and displacement of ore and waste in order to maximize the overall discounted net revenue from a mine within the existing economic, technical and environmental constraints. Long-term production schedules defines the mining and processing plant capacity, and expansion potential as well as management investment strategy. In mining projects, deviations from optimal mine plans may result in significant financial losses, future financial liabilities, delayed reclamation and resource sterilization.

The problem of optimizing reserve exploitation depends largely on the mining option used in the extraction. Some mineral deposits have orebodies that extend from near the surface to several meters in depth. Such deposits can be amenable to both open pit mining and/or underground mining. Significant value can be generated by rigorously investigating these mining options using optimization tools to arrive at the appropriate strategic plan that maximizes the overall net present value of the deposit (Roberts et al., 2009). Open pit mining usually features a relatively lower mining cost, higher stripping ratio and longer time to access ore. Underground mining on the other hand features a higher mining cost, higher grade and earlier access to ore (Anthony, 2012). There are currently limited tools or methods to directly optimize this interface. It is our objective to develop a Mixed Integer Linear Programming (MILP) framework and methodology to evaluate the financial impact of applying different mining options separately or concurrently to extract a given orebody.

The next section of this paper presents the mining options problem definition and section 3 outlines a MILP model framework for strategic mining options optimization. Section 4 covers the modeling and material flow network of the mining options problem. Details of a numerical experiment to be conducted are outlined in section 5 and the application of the MILP formulation to a case study is discussed in section 6. The paper concludes in section 7.

## 2. The mining options problem

A strategic plan is to be developed for a moderate dipping gold-silver-copper orebody that is amenable to both open pit and underground mining. It is required that in addition to these mining options, a combined case of concurrent open pit and underground mining is investigated as well. From preliminary underground mining studies, a selective underground mining method known as long hole open stopping was identified as a potentially viable underground mining method. The production schedule for such a combined case requires that both mining options compete for the same reserve during optimization. The problem presented here involves scheduling of  $N$  different ore and waste blocks: i) within the final pit limit over  $T$  different periods of extraction – OP mining, ii) within the economic stope outlines over  $T$  different periods of extraction – OS mining, and iii) within the combined final pit limit and economic stope outlines over  $T$  different periods of extraction – COPOS mining. The schedule should maximize the NPV of the operation subject to a variety of physical, technical and economic constraints. Fig. 1 shows a schematic diagram of the problem definition. A MILP formulation was developed for this strategic mining options optimization study.

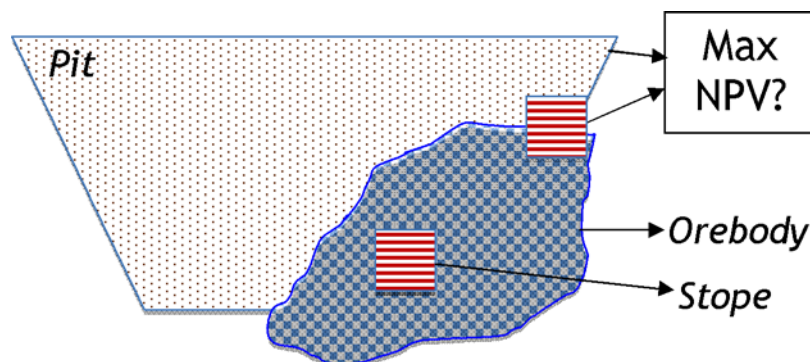


Fig. 1. Schematic representation of the problem definition showing the mining options (Ben-Awuah et al., 2015)

### 3. Integrated MILP model for OP, OS and COPOS mining

The basic problem of concern can be simplified as finding the time and sequence of extraction of ore and waste blocks to be removed from the predefined open pit and/or open stopes outlines and their respective destinations over the mine life so that the NPV of the operation is maximized. The production schedule is subject to a variety of technical, physical and economic constraints which enforce the mining extraction sequence, mining and processing capacities, and blending requirements. The notations used in the formulation have been classified as sets, indices, subscripts, superscripts, parameters and decision variables.

#### 3.1. Economic block value modeling

The objective function of the MILP model is to maximize the net present value of the mining operation. This requires that economic block values are defined based on ore parcels which could be mined selectively. The profit generated from mining a block depends on the value of that block and the costs incurred in mining and processing the block. The cost of mining a block is a function of its spatial location. When a mined block is sent to the stockpile prior to processing, then an extra cost of re-handling is applied.

The discounted economic block value for block  $k$  is equal to the discounted revenue generated by selling the final product contained in block  $k$  minus all the discounted costs involved in extracting block  $k$  and processing it. The discounted economic block value is computed separately for when the block is extracted by open pit mining and when it is extracted by open stope mining. This can be summarized by Eqs. (1) to (6).

Discounted economic block value = discounted revenue - discounted costs

$$d_k^{op,t} = v_k^t - q_k^{op,t} - l_k^{op,t} \quad (1)$$

$$d_k^{os,t} = v_k^t - q_k^{os,t} \quad (2)$$

The variables in Eqs. (1) and (2) can be decomposed into Eqs. (3) to (6).

$$v_k^t = \sum_{e=1}^E o_k \times g_k^e \times r^{e,t} \times (p^{e,t} - cs^{e,t}) - \sum_{e=1}^E o_k \times cp^{e,t} \quad (3)$$

$$q_k^{op,t} = (o_k + w_k) \times cm^{op,t} \quad (4)$$

$$l_k^{op,t} = o_k \times rh^{op,t} \quad (5)$$

$$q_k^{os,t} = (o_k + w_k) \times cm^{os,t} \quad (6)$$

Where

$t \in \{1, \dots, T\}$  index for scheduling periods

$k \in \{1, \dots, K\}$  index for blocks

$e \in \{1, \dots, E\}$  index for element of interest in each block

$j \in \{1, \dots, J\}$  index for phases (pushback)

$d_k^{op,t}$  the open pit discounted economic block value generated by extracting block  $k$  in period  $t$

$d_k^{os,t}$	the open stope discounted economic block value generated by extracting block $k$ in period $t$
$v_k^t$	the discounted revenue generated by selling the final product within block $k$ in period $t$ minus the extra discounted cost of mining all the material in block $k$ as ore and processing it
$q_k^{op,t}$	the open pit discounted cost of mining all the material in block $k$ in period $t$ as waste
$l_k^{op,t}$	the open pit discounted cost of re-handling for all material in block $k$ in period $t$ processed from the stockpile
$q_k^{os,t}$	the open stope discounted cost of mining all the material in block $k$ in period $t$ as waste
$o_k$	the ore tonnage in block $k$
$w_k$	the waste tonnage in block $k$
$g_k^e$	the average grade of element $e$ in ore portion of block $k$
$r^{e,t}$	the processing recovery factor for element $e$
$p^{e,t}$	the price of element $e$ in present value terms per unit of product
$cs^{e,t}$	the selling cost of element $e$ in present value terms per unit of product
$cp^{e,t}$	the extra cost in present value terms per tonne of ore for mining and processing
$cm^{op,t}$	the open pit cost in present value terms of mining a tonne of waste in period $t$
$rh^{op,t}$	the open pit cost in present value terms of re-handling a tonne of ore in period $t$
$cm^{os,t}$	the open stope cost in present value terms of mining a tonne of waste in period $t$

### 3.2. Integrated MILP model objective function

In the proposed integrated MILP model, the formulation is cast to ensure that material can be extracted only once by either of the mining options. The MILP model objective function can be formulated as: 1) maximizing the NPV of the open pit mining operation and 2) maximizing the NPV of the open stope mining operation. This is represented by Eq. (7). We used the concepts presented in Askari-Nasab et al. (2012) as the starting point of our development. The amount of ore processed is controlled by the continuous decision variables  $x_k^{op,t}$  and  $x_k^{os,t}$  for open pit and open stope mining respectively. The amount of material mined is controlled by the continuous decision variables  $y_k^{op,t}$  and  $y_k^{os,t}$  for open pit and open stope mining respectively. The amount of material re-handled through the open pit stockpile is controlled by the decision variable  $h_k^{op,t}$ . The continuous variables enable fractional extraction of blocks in different periods.

$$Max \left[ \sum_{t=1}^T \left( \sum_{j=1}^J \sum_{k \in B_j} (v_k^t \times x_k^{op,t} - q_k^{op,t} \times y_k^{op,t} - l_k^{op,t} \times h_k^{op,t}) + \sum_{p=1}^P \sum_{k \in B_p} (v_k^t \times x_k^{os,t} - q_k^{os,t} \times y_k^{os,t}) \right) \right] \quad (7)$$

Where

$x_k^{op,t}$ ,  $x_k^{os,t} \in \{0,1\}$  are continuous decision variables representing the portion of block  $k$  extracted as ore and processed in period  $t$  for open pit and open stope mining respectively.

$y_k^{op,t}, y_k^{os,t} \in \{0,1\}$	are continuous decision variables representing the portion of block $k$ mined in period $t$ for open pit and open stope mining respectively. Fractions of $y$ characterize both ore and waste material in the block.
$h_k^{op,t} \in \{0,1\}$	is a continuous decision variable representing the portion of block $k$ re-handled in period $t$ from the open pit mining stockpile
$B_j$	represents the set of blocks within the mining phase $j$
$B_p$	represents the set of blocks within the mining stope $p$

### 3.3. Integrated MILP model mining and processing constraints

The MILP model constraints are used in controlling the mining, processing, stockpiling and plant head grade targets in the mining options. They are defined in the form of upper and lower bounds which limit the amount of resource allocated to the associated activity. These constraints are represented by Eqs. (8) to (17).

$$T_{m,lb}^{op,t} \leq \sum_{j=1}^J \left( \sum_{k \in B_j} (o_k + w_k) \times y_k^{op,t} \right) \leq T_{m,ub}^{op,t} \quad (8)$$

$$T_{m,lb}^{os,t} \leq \sum_{p=1}^P \left( \sum_{k \in B_p} (o_k + w_k) \times y_k^{os,t} \right) \leq T_{m,ub}^{os,t} \quad (9)$$

$$\left( (o_k + w_k) \times y_k^{op,t} \right) + \left( (o_k + w_k) \times y_k^{os,t} \right) = o_k + w_k \quad (10)$$

$$T_{pr,lb}^{op,t} \leq \sum_{k=1}^K (o_k \times x_k^{op,t}) \leq T_{pr,ub}^{op,t} \quad (11)$$

$$T_{pr,lb}^{os,t} \leq \sum_{k=1}^K (o_k \times x_k^{os,t}) \leq T_{pr,ub}^{os,t} \quad (12)$$

$$\sum_{t=1}^T \sum_{k=1}^K \left( (o_k \times m_k^{op,t}) - (o_k \times h_k^{op,t}) \right) = 0 \quad (13)$$

$$\sum_{k=1}^K (g_k^e \times o_k \times x_k^{op,t}) - \bar{g}^{-op,t,e} \sum_{k=1}^K (o_k \times x_k^{op,t}) \leq 0 \quad (14)$$

$$\sum_{k=1}^K (g_k^e \times o_k \times x_k^{op,t}) - \underline{g}^{op,t,e} \sum_{k=1}^K (o_k \times x_k^{op,t}) \geq 0 \quad (15)$$

$$\sum_{k=1}^K (g_k^e \times o_k \times x_k^{os,t}) - \bar{g}^{-os,t,e} \sum_{k=1}^K (o_k \times x_k^{os,t}) \leq 0 \quad (16)$$

$$\sum_{k=1}^K (g_k^e \times o_k \times x_k^{os,t}) - \underline{g}^{os,t,e} \sum_{k=1}^K (o_k \times x_k^{os,t}) \geq 0 \quad (17)$$

Where

$m_k^{op,t} \in \{0,1\}$	is a continuous decision variable representing the portion of block $k$ mined in period $t$ and sent to the open pit stockpile
$T_{m,ub}^{op,t}, T_{m,lb}^{op,t}$	are the upper and lower bounds on the available open pit mining capacity in period $t$
$T_{m,ub}^{os,t}, T_{m,lb}^{os,t}$	are the upper and lower bounds on the available open stope mining capacity in period $t$
$T_{pr,ub}^{op,t}, T_{pr,lb}^{op,t}$	are the upper and lower bounds on processing capacity of ore from open pit mining in period $t$
$T_{pr,ub}^{os,t}, T_{pr,lb}^{os,t}$	are the upper and lower bounds on processing capacity of ore from open stope mining in period $t$
$\bar{g}^{op,t,e}, \underline{g}^{op,t,e}$	are the upper and lower bounds on required average head grade of element $e$ in period $t$ in open pit mining
$\bar{g}^{os,t,e}, \underline{g}^{os,t,e}$	are the upper and lower bounds on required average head grade of element $e$ in period $t$ in open stope mining

Eqs. (8) and (9) are the mining capacity constraints for open pit and open stope mining respectively. These constraints are controlled by the continuous decision variables  $y_k^{op,t}$  and  $y_k^{os,t}$ . These inequalities ensure that the total tonnage of material mined (ore and waste) in each period is within the range of the total available equipment capacity in that period. Eqs. (8) and (9) are used in manipulating the stripping ratio over the mine life. The set mining capacity is a function of the ore reserve, targeted mine-life, designed processing capacity, overall stripping ratio and the available capital for mining fleet acquisition.

Eq. (10) represents the concurrent mining constraint that controls the mining options. This constraint is controlled by the continuous decision variables  $y_k^{op,t}$  and  $y_k^{os,t}$ . This inequality manages the relationship of block extraction in the open pit mining and in the open stope mining. It ensures that all blocks are extracted once either through the open pit and/or through the open stope mine. This constraint can be extended to represent mining bins which are made up of accumulation of blocks.

Eqs. (11) and (12) represent the processing capacity functions which control the mill feed quantities for open pit and open stope mining respectively. These constraints are controlled by the continuous decision variables  $x_k^{op,t}$  and  $x_k^{os,t}$ . These inequalities help the mine planner to provide a uniform feed throughout the mine life resulting in an effectively integrated mine-to-mill operation. Depending on the ore grade distribution of the orebody, the processing target may not be achieved in some periods. In such cases, pre-stripping and stockpiling could be explored to provide a uniform mill feed. This amounts to forcing the optimizer to mine waste in the early periods, or mining more ore than needed when available and feeding the mill with the stockpiled ore when required.

Eq. (13) represents the stockpile management constraint which controls the level of the stockpile during the mine life of the open pit mining operation. The constraint is controlled by the continuous decision variables  $m_k^{op,t}$  and  $h_k^{op,t}$ . This equation ensures that all the material stockpiled in the open pit operation is re-handled back to the processing plant by the end of mine life. Thus, limits the

stockpile material to only the ore that has potential positive cash flow in the future prior to the end of the mine life. Stockpiling is not recommended for open stope mining due to the relatively high cost of production.

The grade blending constraints are represented by Eqs. (14) to (17). These constraints monitor the mill feed quality and are controlled by the continuous decision variables  $x_k^{op,t}$  and  $x_k^{os,t}$ . Eqs. (14) and (15) specify the limiting grade requirements for material from the open pit operation for processing whilst Eqs. (16) and (17) specify the limiting grade requirements for material from the open stope operation for processing. The objective of blending in production scheduling is to mine in a way that the run-of-mine materials meet the quality and quantity specification of the processing plant. The mill head grade is a function of the ore grade distribution, processing plant design and mine cash flow requirements.

### 3.4. Integrated MILP model general constraints

The general constraints that apply to the MILP model discussed relate to the mining precedence and the logics of the variables during optimization. These have been documented in Ben-Awuah et al. (2012) and Ben-Awuah and Askari-Nasab (2013). These constraints include:

- a) Open pit vertical mining precedence: all the immediate predecessor mining blocks above the current mining block should be extracted prior to extracting the current mining block.
- b) Open stope vertical mining precedence: all the immediate predecessor mining development decline above the current development level should be extracted prior to extracting the current development decline.
- c) Open pit horizontal mining precedence: all the immediate predecessor mining phases preceding the current mining phase in the horizontal mining direction are extracted before or together with the current mining phase. These are referred to as absolute and concurrent precedences respectively.
- d) Open stope horizontal mining precedence: all the immediate predecessor mining stope and development drive preceding the current mining stope and development drive in the horizontal mining direction are extracted before or together with the current mining stope and development drive. These are referred to as absolute and concurrent precedences respectively.
- e) Variables logic control: the logic of the mining, processing and stockpiling variables with regards to their limits and definitions are within acceptable ranges.

## 4. Modeling the mining options problem

The mining options problem is modeled as a multiple mine and destination optimization problem in Evaluator (Snowden Mining Industry Consultants, 2013); an optimization modelling platform. The modelled problem is solved with a commercial optimization solver Gurobi (Gurobi Optimization, 2013). Fig. 2 shows a schematic material flow network diagram of the scheduling project. The COPOS problem is set up to ensure that during concurrent mining all material is mined once by either of the mining options. This is enforced using Eq. (10). The COPOS problem was modeled with two mining nodes namely OP and OS. The OP node holds all the mining blocks data relating to open pit mining and the OS node holds all the access development and mining stopes data relating to open stope mining.

Material from the open pit operation can be sent to the open pit processing plant, open pit stockpile or open pit waste dump based on the material type and mine economics. Material sent to the open pit processing plant results in a product that generates revenue for the open pit mining project. Material sent to the open pit stockpile is later re-handled back to the processing plant. The open pit stockpile management constraint (Eq. (13)) ensures that by the end of mine life no material is left on the stockpile. This equation indirectly constrains the stockpile material to only those that can

still generate positive cash flow in the future. Material that does not qualify for processing or stockpiling is sent to the open pit waste dump. The constraints set up to control the open pit mining operation are mainly the mining capacity, processing limits, stockpiling control and ore quality requirements throughout the mine life. The vertical and horizontal mining sequences for the open pit mining blocks and mining phases which include both absolute and concurrent precedences are defined as well.

Material from the open stope operation can be sent to the open stope processing plant or access development waste dump based on the material type and mine economics. The access development includes both decline and drive developments. Material sent to the processing plant results in a product that generates revenue for the open stope mining operation. The decline and drive development material mined prior to stope developments are sent to the access development waste dump. No other waste or stockpile materials are extracted due to the high cost of production associated with underground mining. The constraints set up to control the stope mining are mainly mining capacity, processing limits and the ore quality requirements throughout the mine life. The vertical and horizontal mining sequences for the mining stopes, development declines and development drives which include both absolute and concurrent precedences are applied as well.

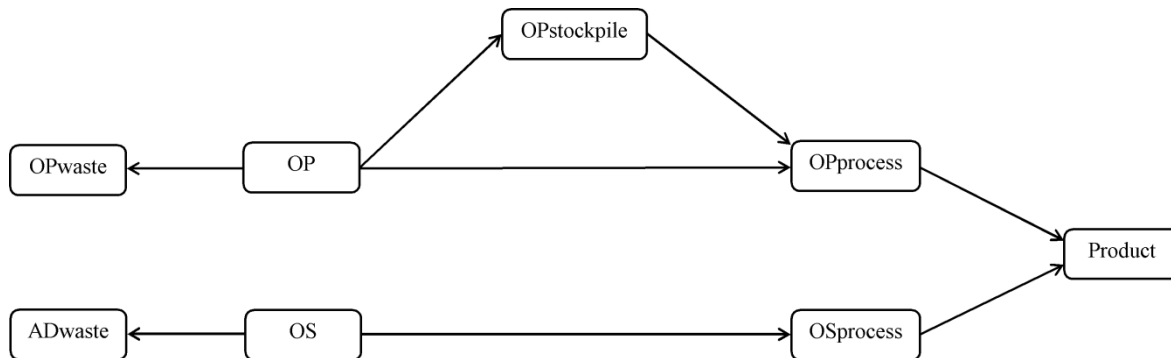


Fig. 2. Schematic material flow network diagram (Ben-Awuah et al., 2015)

## 5. Computational experiment

The MILP model for the mining options problem was implemented on a gold-silver-copper orebody which has a potential for both open pit mining and underground mining. The objective was to use the MILP model to investigate a potential mining strategy that maximizes the overall profit for this deposit. The performance of the proposed model was assessed based on net present value and smoothness of the generated schedules. The MILP model was setup for OP mining and OS mining to compete for the same material during optimization subject to each method's respective mining and economic parameters.

An initial analysis of the orebody for OP mining resulted in a final pit shell being generated. Based on the incremental revenue factors, four pit stages were identified and designed as the main stages suitable for the open pit mining operation. Similarly, initial analysis of the orebody for selective underground mining option resulted in the decision to use long hole open stope mining with blocks above a cut-off grade of \$80/t net smelter return (NSR). This had the potential for an economically viable underground mining operation. Table 1 summarizes the mineable inventory for OP and OS mining. It should be noted that the total ore tonnes for OP mining is 143 Mt; for OS mining is 147 Mt; and for COPOS mining is 147 Mt (Table 1). Since this study includes a combined option of simultaneous open pit and open stope mining, the block model had to be re-blocked to a common size that would serve both OP and OS requirements. Each block in the economic block model therefore carries an economic block value,  $d_k^{op,t}$  when it is extracted by OP mining and  $d_k^{os,t}$  when it is extracted by OS mining. In this case, the decision to mine a block during optimization is based



mainly on the mining economics. All scenarios were solved to within 1% optimality gap. In the COPOS mining option, no geotechnical assessment of the interaction of the mining systems was done.

Table 1. Total mineable inventory

<b>Mining phases</b>	<b>Ore tonnes (Mt)</b>	<b>Au (g/t)</b>	<b>NSR (\$/t)</b>
OP_1, OP_2, OP_3, OP_4	143	1.13	50.45
OS	4	2.50	115.95

## 6. Results and discussions

The optimization study was based on three scenarios namely: i) open pit mining only (OP); ii) open stope mining only (OS); and iii) concurrent open pit and open stope mining (COPOS). All scenarios were based on a high pre-production capital with corresponding lower operating costs. The mineable inventory for OP and OS combined is 147 Mt of ore with recoverable metal of 4.34 Moz Au. A production schedule was generated with the MILP model using the mining and processing constraints summarized in Table 2.

Table 2. Summary of mining and processing constraints

<b>Scheduling constraints</b>	<b>Mining option scenario</b>		
	<b>OP</b>	<b>OS</b>	<b>COPOS</b>
Mining limit, OP (Mtpa)	80	-	80
Mining limit, OS (Mtpa)	-	3	3
Processing limit, OP (Mtpa)	11	-	11
Processing limit, OS (Mtpa)	-	3	3
Vertical mining rate limit, OP (m/yr)	96	-	96
Vertical mining rate limit, OS (m/yr)	-	50	50

After investigating the scenarios at a 5% annual discount rate, the results of the production schedule optimization have been summarized in Table 3. The results show that for OP mining option, the total ore processed was 83 Mt generating an NPV of \$2103 M over nine years mine life. For the OS mining option, the total ore processed was 18 Mt generating an NPV of \$822 M over nine years mine life. For the COPOS mining option, the total ore processed by the open pit processing plant was 83 Mt and the total ore processed by the open stope processing plant was 3 Mt generating a total of \$2154 M over nine years mine life.

Table 3. Production scheduling optimization results

<b>Mining option scenario</b>	<b>Total ore processed OP/OS (Mt)</b>	<b>Mine life OP/OS (yrs)</b>	<b>NPV (\$M)</b>
OP mining	83/0	9/0	2103
OS mining	0/18	0/9	822
COPOS mining	83/3	9/9	2154

Fig. 3 to Fig. 10 show the production schedule profile over the mine life for each of the mining options. Fig. 3 and Fig. 4 show that during the OP mining, all the material extracted come from the OP mining phases alone. Mining starts from OP phase 1 (OP\_1) and phase 2 (OP\_2) and progresses to phases 3 and 4 maintaining a relatively uniform stripping ratio from year 2 to the end of mine life. Year 1 was mainly used for pre-stripping and ore processing starts in year 2. The

processing plant operated at its maximum capacity throughout the mine life. Material from the stockpile was used in supporting the processing plant from year 6 (Fig. 5).

Fig. 6 and Fig. 7 show that during the OS mining, material is extracted from both the open pit phases and the open stope phase. Mining starts from open pit phases 2, 3 and 4 (OP\_2, OP\_3 and OP\_4) and progresses to the open stope phase (OS) and open pit phase 1 (OP\_1). Year 1 is mainly for underground access development. Processing starts in year 2 and ramps up to full capacity in year 3. All material mined is processed since it falls above the cut-off grade.

Fig. 8 and Fig. 9 show that during the COPOS mining option, material is extracted from both the open pit phases and the open stope phases. Mining starts from open pit phases 1 and 2 and open stope access developments (AD). Mining progresses to the open stope phase and open pit phases 3 and 4 maintaining a relatively uniform stripping ratio from year 2. Year 1 is used mainly for pre-stripping for the open pit mining and access development for the open stope mining. Ore processing starts in year 2 at full plant capacity and remains steady for the rest of the mine life. Material from the stockpile was used in supporting the processing plant from year 6 (Fig. 10). All material processed for the open stope mine comes from the open stope phase.

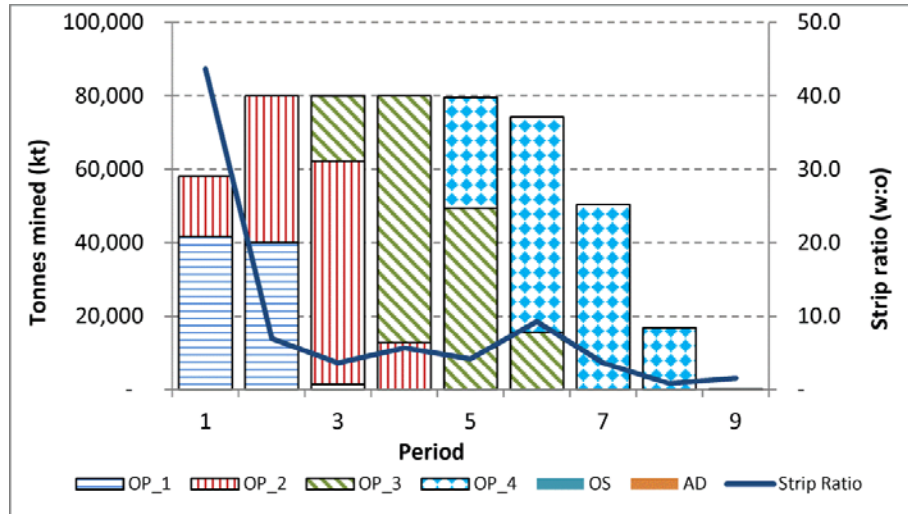


Fig. 3. OP mining – mining by phases

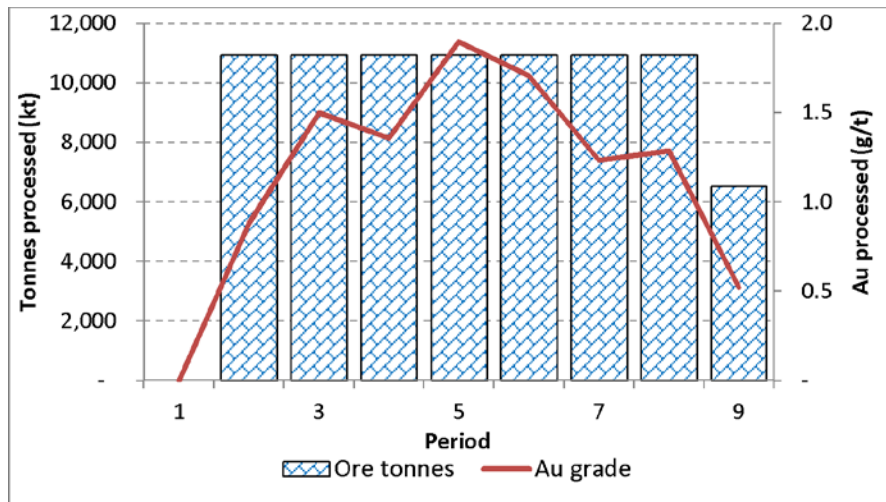


Fig. 4. OP mining – ore processed

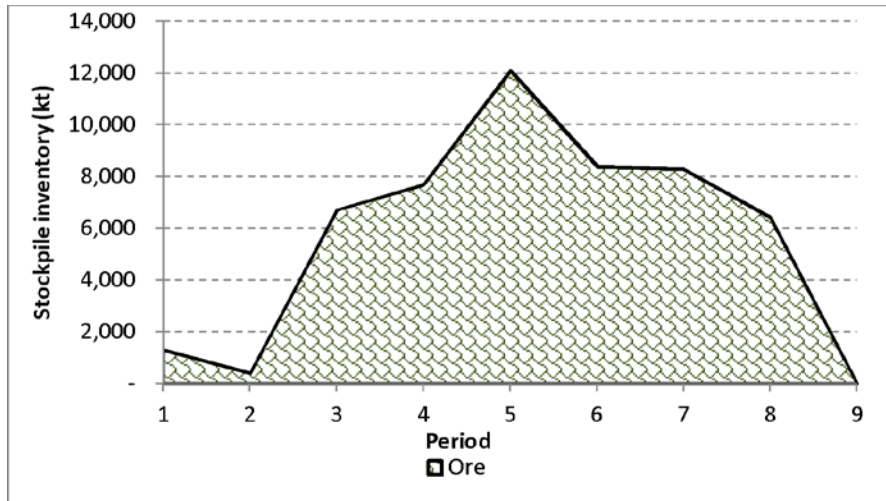


Fig. 5. OP mining – stockpile variations

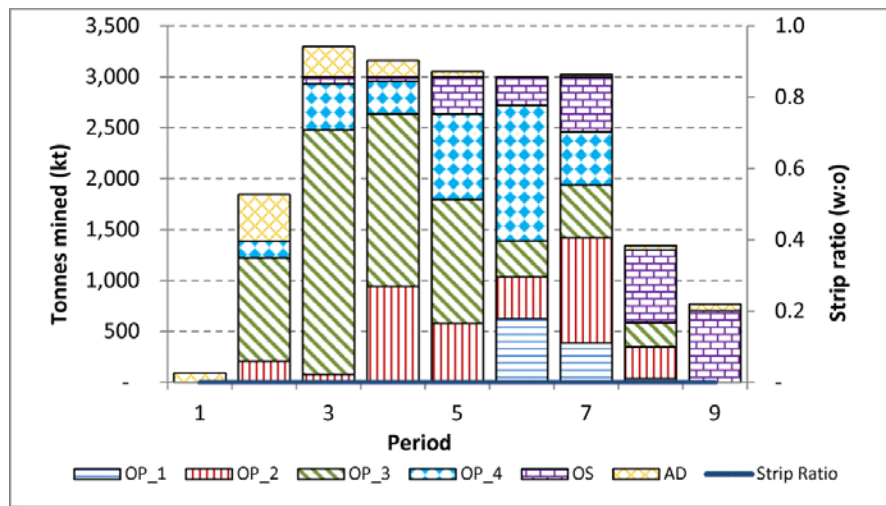


Fig. 6. OS mining – mining by phases

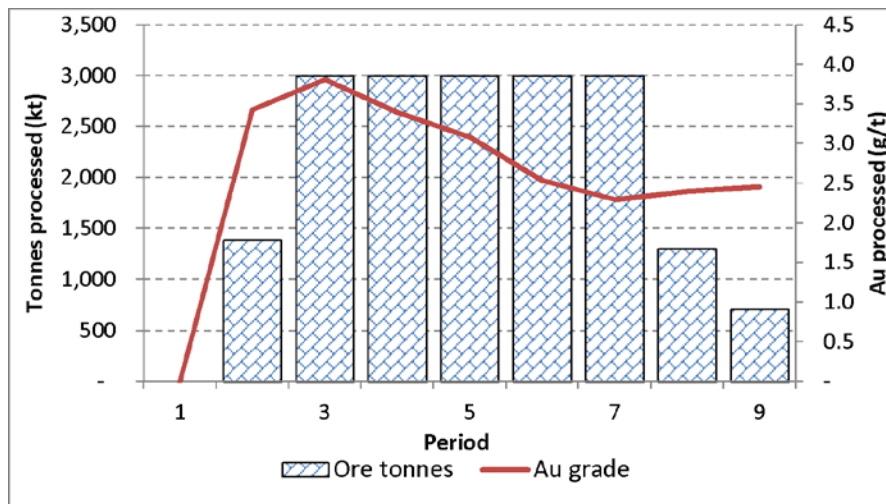


Fig. 7. OS mining – ore processed

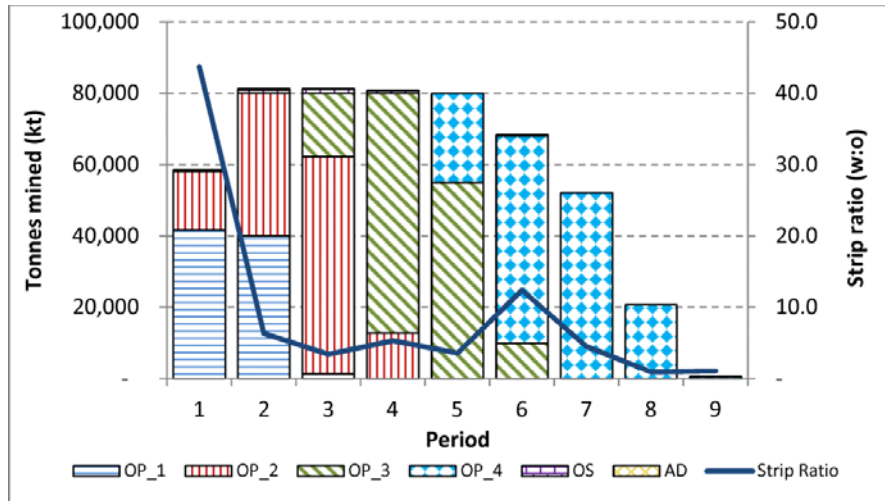


Fig. 8. COPOS mining – mining by phases

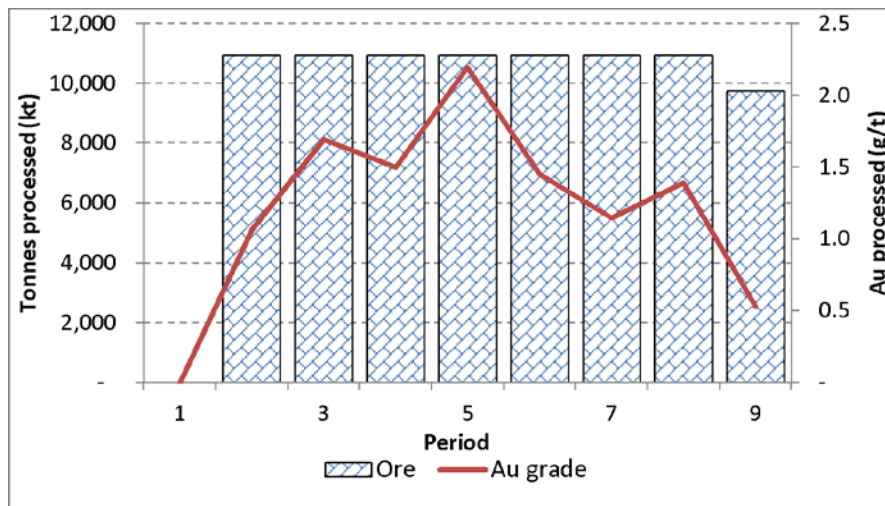


Fig. 9. COPOS mining – ore processed

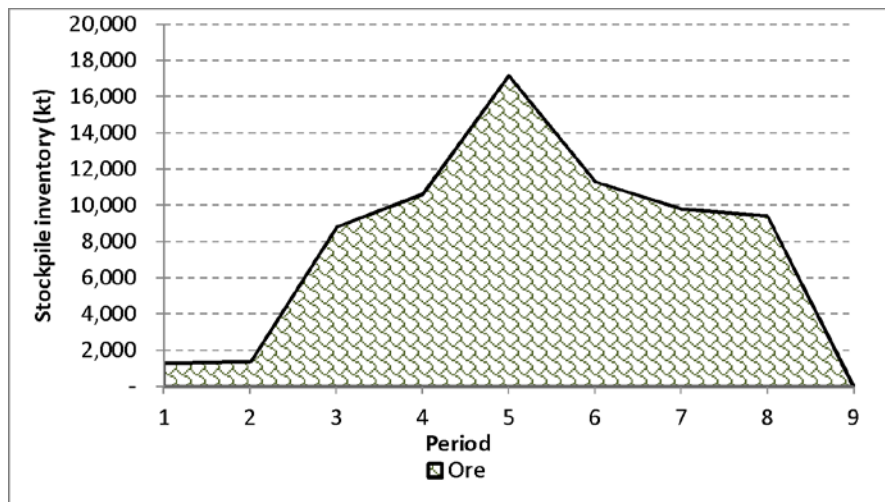


Fig. 10. COPOS mining – stockpile variations

## 7. Conclusions

We have developed, implemented and verified a MILP formulation and methodology which seeks to evaluate the value of an orebody using different mining options with complex production requirements. The MILP optimization framework has proved to be robust in providing a global optimization solution when assessing different mining options. It can also be extended to determine the change-over point between an open pit mining operation and an underground mining operation. The different mining options were evaluated based on the assumption of a high pre-production capital investment with low operating cost. The NPV generated at a 5% discount rate when the orebody is extracted with i) OP mining option is \$2103 M, ii) OS mining option is \$822 M and iii) COPOS mining option is \$2154 M. A summary of the conclusions drawn after the mining options optimization study with the MILP model are:

1. In the COPOS mining scenario, the optimizer prefers extracting blocks using OP mining. This is due to the fact that although the OS mine could access ore sooner, the mining cost differential for OP mining is more than compensated for by the discounting benefits associated with earlier OS mining.
2. The COPOS mining option generates a higher relative NPV compared to the individual mining cases. However, it requires a higher capital expenditure (CAPEX) outlay. The addition of the OS material to the OP material only adds a marginal increase of 2% in NPV which cannot offset the CAPEX required to develop an OS mining operation.
3. Comparatively, the OP mining option generates a higher NPV than the OS mining option. However considering the investment required for these mining options, the OS mining option generates a better return on investment than the OP mining option.
4. Sensitivity analysis for the COPOS mining option shows that as the discount rate or mine life significantly increases some OP material become attractive for OS extraction in the early years of mine life.

## 8. References

- [1] Anthony, F. (2012). Open pit to underground. *International Mining*, 8 (1), 88-90.
- [2] Ben-Awuah, E. and Askari-Nasab, H. (2013). Incorporating waste management into oil sands long term production planning. *Transactions of the Institution of Mining and Metallurgy, Section A*, 122 (1), 33-45.
- [3] Ben-Awuah, E., Askari-Nasab, H., and Awuah-Offei, K. (2012). Production scheduling and waste disposal planning for oil sands mining using goal programming. *Journal of Environmental Informatics*, 20 (1), 20-33.
- [4] Ben-Awuah, E., Richter, O., and Elkington, T. (2015). *Mining options optimization: concurrent open pit and underground mining production scheduling*. in Proceedings of 37th International Symposium on the Application of Computers and Operations Research in the Mineral Industry, Fairbanks, Alaska, pp. 1061-1071.
- [5] Gurobi Optimization. (2013). Gurobi, Ver. 5.5. Houston.
- [6] Newman, A. M., Rubio, E., Caro, R., Weintraub, A., and Eurek, K. (2010). A review of operations research in mine planning. *Interfaces*, 40 (3), 222-245.
- [7] Roberts, B., Elkington, T., van Olden, K., and Maulen, M. (2009). Optimizing combined open pit and underground strategic plan. *Mining Technology*, 122 (2), 94-100.
- [8] Snowden Mining Industry Consultants. (2013). Evaluator, Ver. 18. Perth.