# Drawpoint loading optimization strategies in block caving: A case study of Palabora Mining Company

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### Synopsis

**Palabora Mining Company is one of the largest low-grade copper mines globally. The mine uses block caving for the extraction of the orebody. This paper enumerates the drawpoint loading strategies for the overall head grade improvements, particularly for a block that is nearing depletion. A comprehensive literature review of various considerations relating to improving productivity in block caving is presented to contextualize the draw control in caving. From this study, an optimized draw control strategy is presented, which focuses on three parameters that include grade distribution, loading compliance, and tonnage splits per sector. An empirical method based on the relational study between various parameters is used to outline the key criteria to be used in the optimization of drawpoint loading in block caving.**

### Keywords

**caving, draw control, drawpoint, tonnage split.**

## Introduction

Generally, when a mining block nears depletion, it becomes more challenging to effectively extract the mineralization from the block, particularly in the case of high-grade deposits (Duffy *et al*. 2015; Jang, Topal, and Kawamura, 2015). This leads to lower recoveries, with more fines and dilution. The study by Diering *et al*., (2018) suggest various factors that contribute to such a high content of dolerite, which leads to fines accumulating in the drawpoint much quicker. This challenge requires selective mining, which is difficult to accomplish in block caving. Causes of dilution include the integration of lower-grade material in the block, as well as the ingress of external sources that further dilute the existing high-grade blocks (Jang, Topal, and Kawamura, 2015). Although waste sorting is practical in narrow vein reefs, it poses a challenge in massive mines, except with proper application of draw control strategies. (Shekhar *et al*., 2018).

Several massive mining methods are often trialled when mining companies transition from the open pit to the underground setting (Moss, Diachenko, and Townsend, 2006). Among the underground massive mining methods, the one that has gained the most popularity is block caving (Shelswell, Labrecque, and Morrison, 2018; Khodayari and Pourrahimian 2017). The preference for this method is based on its low operating cost, and high production output (Firouz and Yashar, 2017). This method is also applicable in the extraction of low-grade orebodies (Shelswell, Labrecque, and Morrison, 2018).

Although block caving offers various benefits, all these require correct timing, sequencing, and diligence in abiding with the required leads and lags, and drilling and blasting during the undercutting phase, which must be rigorously enforced. Once all these parameters are in place, and the hydraulic radius has been reached, then the benefits of this method are realized. Apart from the challenges with waste and high capital cost, block-caving is still profitable as very high production rates can be achieved (Khodayari and Pourrahimian, 2017).Other advantages are realized with minimal blasting once the block has caved with emphasis on constant monitoring by means of draw control (Shekhar *et al*., 2018).

Draw control entails the allocation of the load haul dump (LHD) vehicles in the correct areas, and ensuring that the correct quantities of ore are extracted. This approach becomes crucial to achieving waste control and life-of-mine production targets (Nezhadshahmohammad, Khodayari, and Pourrahimian, 2017). According to Rehal *et al*. 2003 (as cited in Shelswell, Labrecque, and Morrison, 2018), drawpoint loading requires effective maintenance and operations to attain the required rates. The maintenance of the drawpoint includes drawpoint rehabilitation and secondary breaking activities.

Various studies have been conducted, particularly relating to secondary breaking to increase production rates (Ngidi and Boshoff, 2011). However, there is inadequate literature regarding strategies to employ for optimal drawpoint loading as the block nears depletion. Such strategies are pivotal for understanding the factors to consider for optimizing loading, thus improving production performance. Grade performance is one of the key factors to consider in improving production.

Grade performance is influenced by various factors, which may range from the underground block size, plant recoveries, loading strategies and market conditions dictating the drawing rates, as well as the size and distribution of the drawpoints, and waste or dolerite content (Diering *et al*., 2018). In this research study we intend to highlight some of the strategies to employ to optimize drawpoint loading. In addressing the main objective of the study, we seek to answer the following questions:

- What is the influence of loading compliance on copper grade performance?
- Does an increase in tonnage split correlate with an improvement in grade performance?
- What strategies should the mine employ when prioritizing drawpoints in the cave?

## Background of the study area

The study was conducted at Palabora Mining Company (PMC), which is a subsidiary of the HBIS group, situated in the Limpopo Province, South Africa, (Figure 1). The mine commenced operations in 1956, and produces copper, vermiculite, and magnetite and other by products from the Palabora Igneous Complex (van der Spuy 1982; Killick *et al.,* 2016). The chief mineral produced is copper, which is found in the copper-bearing rocks such as carbonatite and foskorite (Southwood and Cairncross, 2017). Copper- and magnetite-bearing rocks are all enclosed in the Palabora Igneous Complex, which is complex in formation with dimensions extending 6.5 km by 2.5 km (Southwood and Cairncross 2017; Letts *et al*., 2011).

In the initial stages, the mine was an open pit operation, and traditional to underground operations using block caving (Moss, Diachenko, and Townsend, 2006). Access to underground mining was planned to mine the crown pillar using block caving mining method, which commenced in 2001 (Sainsbury *et al*., 2016).

Block caving encompasses various stages, which include the horizontal development, undercutting, and production mining, with the ore being drawn through drawbells. PMC comprises two lifts or mining blocks, which are named Lift 1 and two blocks. Lift 1 commenced in 2001, with a capacity to produce more than 30 000 t/d from 20 crosscuts, with 332 drawpoints. Each crosscut forms part of a sector. There are four sectors each with five cross-cuts.

Undercutting commenced centrally and extended outward towards the eastern and western regions. This strategy resulted in the quicker maturity of the cave, particularly in sector 2 (Nyarela, 2019). The categorization of each sector is for ease of ore tipping as well as the minimization of traffic in the cave. Figure 2 presents the PMC block cave outline.

Various equipment is used for the block cave operation at PMC, including LHD machines, medium reach rigs (MRRs), mobile rock breaker (MRBs), lube trucks, conveyors, and winders. The structure of the block cave requires the LHD to load material from the drawpoints until there is hang-up or blockage in the drawpoint. Such blockages require the function of a secondary breaking facility that aids in creating free-flowing material, facilitating loading, conveying, and transport out to surface by means of winders (Figure 3).

## Problem statement

Various research studies have been conducted to resolve challenges related to block cave mining (Dirkx, Kazakidis, and Dimitrakopoulos 2018; Ngidi and Boshoff, 2007; Castro, Trueman, and Halim, 2007). The present investigation seeks to outline strategies to improve drawpoint loading when a mining block nears depletion, thus improving the overall production performance.


**Figure 1—Palabora Mining Company locality plan (Southwood and Cairncross, 2017)**

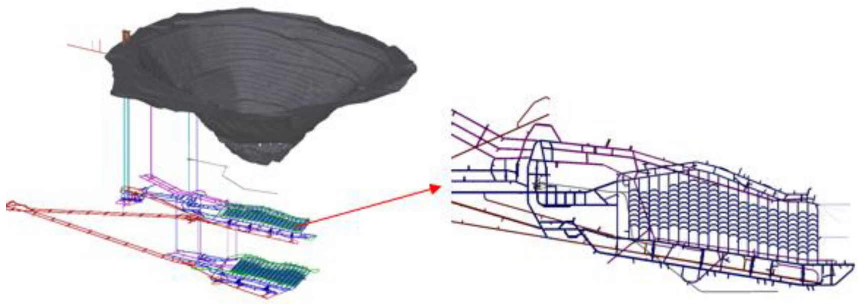

**Figure 2—Schematic representation of the Palabora block cave**

## Literature review

Block caving is an underground mining method that is gaining popularity due to its safety, cost, and higher production outputs compared to other methods (Rashidi-Nejad, Suorineni, and Asi, 2014). This is an underground massive mining method where the rock mass caves naturally under the influence of gravity (Vergugo and Ubilla, 2004). Several benefits are realized, such as the ability to effectively extract lower-grade orebodies and reduced employee risk compared to conventional mining methods. Cave initiation is by means of creating a horizontal slice by drilling and blasting the level above the production level, known as an undercutting level, to fragment the rock mass and allow gravity to further reduce the ore into smaller particles that will be drawn from the drawpoints (Vergugo and Ubilla 2004; Khodayari and Pourrahimian 2017). This process relates to cave propagation, which influences the rock mass by causing mobilization and fragmentation of the ore (Sainsbury, *et al.*, 2016). Drilling and blasting creates a zone of weak overburden to allow collapse of the rock and movement of material (Oosthuizen and Esterhuizen 1997; Rashidi-Nejad, Suorineni, and Asi, 2014). Figure 4 illustrates a schematic of a block cave mine.

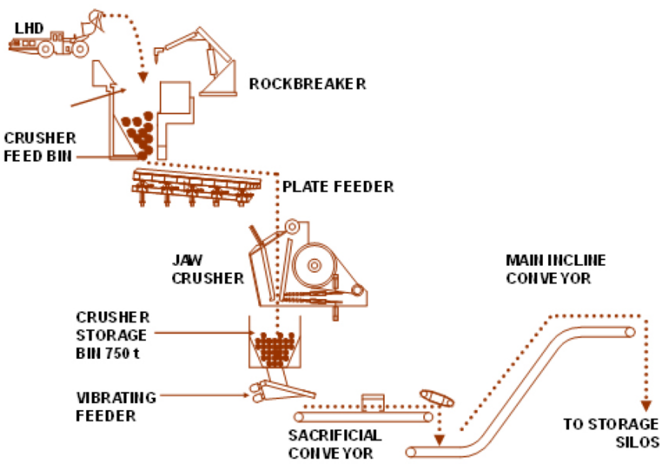


Figure 3—Palabora Mining Company ore-flow schematic

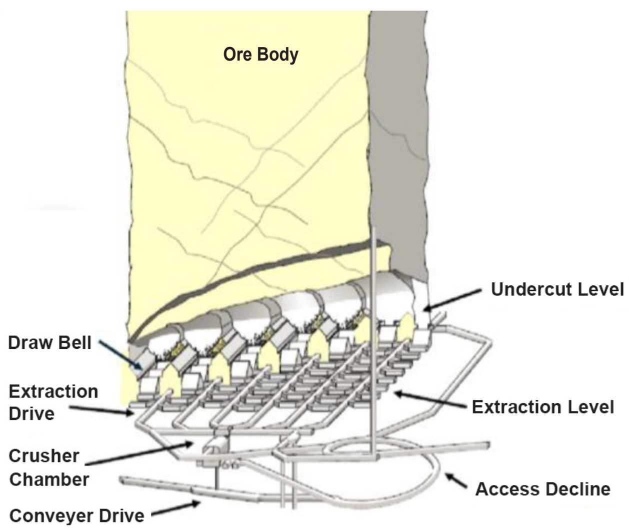


Figure 4—Block cave mine schematic (Duffy *et al.*, 2015)

The point at which caving occurs is determined by using a chart, which predicts the hydraulic radius (HR) as a function of the mining rock mass rating (MRMR) in order to determine the stable, transitional, and caving zones, as indicated in the Figure 5 (Laubscher 1990; Butcher 1999). The stability diagram enables a mine to determine at which point the cave will propagate as well as understand different rock types and zones which are classified based on the diagram.

Once caved, the material is drawn from the production level through drawbells, which connect in the form of drawpoints. Each drawpoint is loaded and maintained to ensure the maximum tonnage is are extracted from each and to ensure sustainability of the cave. Ensuring the sustainability of the cave requires the loading of ore to be controlled by means of effective draw control, which reduces the likelihood of running short of material as well as minimizing environmental challenges related to block caving. Such challenges include the risk of airblasts, early dilution, and drawpoints from which no ore is extracted for long periods (Nyarela, 2019).

Ensuring cave sustainability through draw control also entails measures to monitor and control the overall grade in the cave (Booth *et al.* 2004) (as cited in Shekhar *et al.*, 2018). Unlike in conventional mines, rock separation is a challenge, thus the optimal loading and scheduling of a block is critical in achieving the desired grade performance. This involves measures to control and reduce loading waste and low-grade drawpoints, correct assigning of LHDs, and the combination of strict adherence to optimal production schedules factoring inputs from various supporting departments such as geology and rock mechanics (Nezhadshahmohammad, Khodayari, and Pourrahimian, 2017).

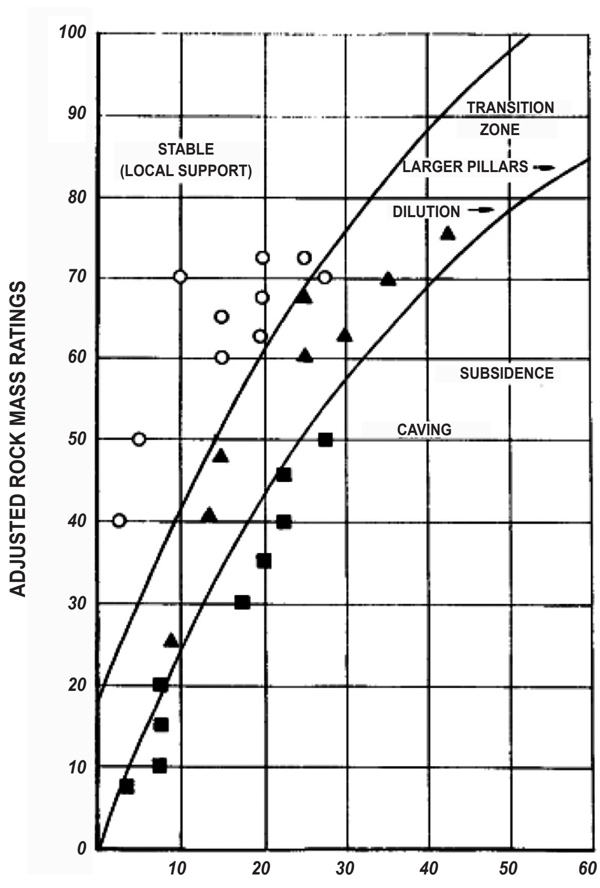


Figure 5—Stability diagram (Laubscher, 1990)

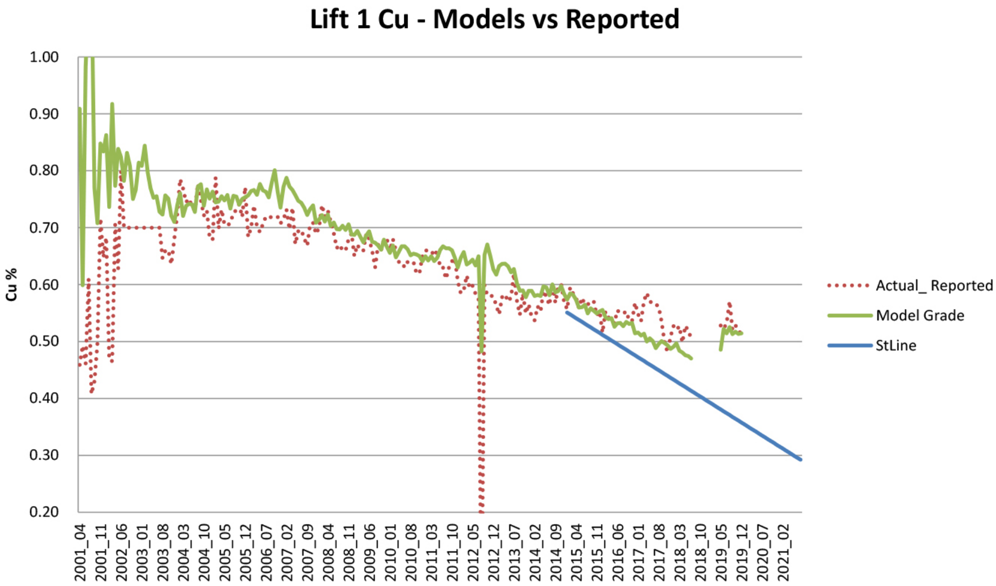


**Figure 6—Lift 1 grade performance**

## Research methodology

We conducted an empirical study based on the actual data extracted from the mine's daily records. This study investigates 261 drawpoints, which encompass 19 crosscuts, categorized into four sectors. Each sector is categorized into crosscuts of five, with the exception of sector 2. The data covers the period between January 2017 and June 2018. The justification for this period is based on the need to acquire consistent data for a period longer than twelve months continuously, whereby the monthly tonnages, compliance, and grade distribution are available.

Correlational analysis is adopted to determine the relationship between different variables in order to determine the impact that one variable has on the other (Kumar and Chong 2018; Miot 2018). The key focus is on improving the overall head grade, which plays a significant role in the recovery of the metal from underground. For this reason, this study intends to determine factors that influence the improvements in the head grade, by focusing on the loading compliance, tonnage splits, and grade distribution. The reliability of the data-set is determined using both the SigmaXL® tool and Microsoft Excel®.

## Results and discussion

### *Research question 1*

In addressing the research question: 'what is the influence of loading compliance on copper grade performance?', the key interest is due to the observed decline of the head grade, with emphasis on in seeking to understand the underlying factors that influence the decline. Figure 6 presents historical data of the mine's grade performance. Since the inception of block caving at PMC, the grade has fallen from above 0.7% to around 0.5% as the reserves were depleted. The projected straight-line average grade demonstrates that there is still a decline anticipated to below 0.4% copper grade.

The results in Figure 6 also present a positive grade trend between 2017 and 2019, as denoted by the red-dotted line (actual head grade). The Gems PCBC® model indicates that in the same period there would be a decline to below the 0.5% mark; however, the actual grade recorded between 2017-2019 is still above the model value. Various factors led to the positive grade performance, and it is the intent of this study to outline some of those factors in order use them as strategies for the remaining years of mining.

The first objective is based on the need to analyse the influence of the loading compliance on the head grade. This includes ensuring the incorporation of an effective draw control by focusing mainly on high-grade drawpoints. In this analysis, the intent is to determine whether the improved compliance is proportional to an improved grade. The results, presented in Figure 7, indicate a correlational analysis of the two variables - grade and compliance.

According to Miot (2018), a correlational analysis evaluates '*two quantitative variables*' using the Pearson's or the Spearman's correlation coefficient, which makes use of scatter plots to graphically analyse the interrelatedness between the variables. The Pearson's correlation coefficient, denoted, $r_p$, is categorized as positive weak or positive strong and negative weak or negative strong. Values between zero and 0.5, and zero and -0.5, are considered weak, whereas the values between 0.5 and 1 and -0.5 and -1 are considered moderate to strong, which could be used to justify the relevance of the variables to one another (Kumar and Chong 2018; Miot 2018). The degree of variability between the two factors is represented by the coefficient of determination ($R^2$) value, which measures how far the values are from the fitness line. The values for the $R^2$ value range between zero and 1.

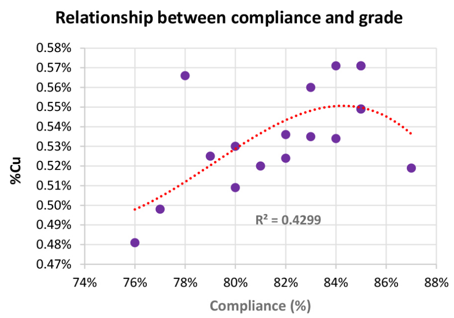


**Figure 7—Relationship between loading compliance and grade**

The results presented in Figure 7 indicate a correlation coefficient of 0.583 and coefficient of determination ($R^2$) value of 0.4299. In this instance, the variability can be explained by the R-squared value of 43%. Although the correlation coefficient ($r_p$) is moderate, it is not significant enough to indicate that an improvement in loading compliance is a sole determinant influence on the head grade proportionally. Loading compliance is a factor of the overdrawn and underdrawn drawpoints and does not necessarily influence the improvements in head grade. It factors whether the LHD loaded where it was assigned to load. The schedule should be designed in such a manner that it factors other variables, and does not focus on only one aspect (compliance).

### *Research question 2*

In addressing the research question, '*Does an increase in tonnage split correlate with the improvement in grade performance*?', the data relating to the tonnage split is collected and analysed. According to Butcher (1999), block caving is a preferred option due to its ability to meet a high production target. However, loading should be conducted as per a set schedule, which forms part of draw control (Shekhar, *et al*., 2018; Duffy, *et al*, 2015). Figure 8 presents the mean tonnage distribution across the cave that covers the study period. The figure shows that sectors 1 and 2 have been allocated higher tonnage splits for the period of study. Considering the tonnage split in isolation provides a distorted view; as such, the data is further interrogated to determine whether improvements in head grade are a result of an increase in the daily loaded tons.

A further analysis is presented in Figure 9 and indicates the relationship between loaded tons and grade performance. The relationship is negative. This means that an increase in tonnage does not improve grade performance. The results also indicate that when intending to optimize loading in block caving, the approach should not be to increase the number of loading splits in various sectors, as this does not necessarily influence the overall head grade. The degree of variability between the two variables can be explained by the R-squared value of 19%, which is negligible and cannot be used to justify increasing tonnage split to increase head grade.

### *Research question 3*

In addressing the research question, '*What strategies should the mine employ when prioritising drawpoints in the cave*?', this section presents various strategies to employ in order to improve the overall head grade. The results in both Figures 7 and 8 indicated that improvements in loading compliance and increased tonnage have a minimal effect on the head grade if carried out as sole determinants. This section highlights elements to consider to, improve the head grade.

### *Strategy 1: Drawpoint loading strategies in block caving*

The first strategy entails incorporating the prioritization of medium- to high-grade drawpoints in the drawpoint loading scheduling. This strategy does not negate other considerations, but rather ensures that there are minimal blockages and stoppages on the priority drawpoints. Figure 10 highlights the grade distribution across the cave. The Figure depicts assay grades - not based on the geological model but sampled from the drawpoints.

The red blocks represent high-grade drawpoints, those above 0.61% copper grade, and the orange blocks indicate the medium-grade drawpoints, whereas the green blocks indicate the low-grade drawpoints. To be optimal, the schedule should not only allocate loading of all the high-grade drawpoints, but should incorporate various considerations that include the geology, rock mass behaviour, production requirements, and drawpoint history. This strategy does not ignore geotechnical consideration such as stress distribution and minimization of stress buildup by constant loading and reducing of idling drawpoints.

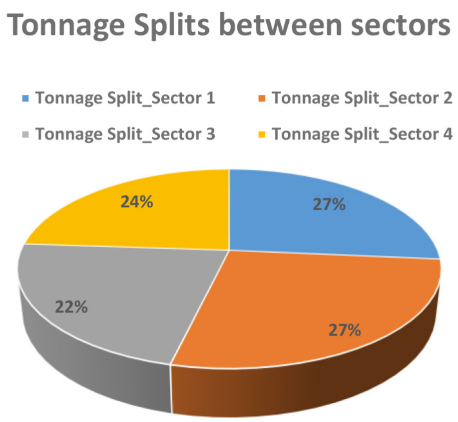


**Figure 8—Tonnage split between sectors**

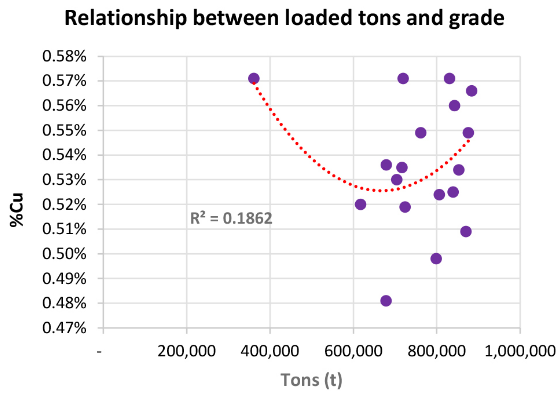


**Figure 9—Relationship between loaded tons and grade**

This strategy focuses on ensuring that priority is given to the medium to high-grade drawpoints to optimize metal recovery. As with any strategy, the intent is to make the mine productive. By prioritization, the focus should not be on one specific sector. Although sectors 1 and 4 have a high concentration of high-grade drawpoints, these should not be treated in isolation while neglecting loading from other sectors. If prioritization is given to a specific sector due to the increased number of high-grade drawpoints, the objective to optimize will not be realized, as presented in Figure 11.

Figure 11 analyses the relationship between sector allocation and the grade. The analysis presents a weak positive relationship, with a correlation coefficient ($r_p$) of 0.452 and coefficient of determination ($R^2$) value of 0.1733. According to Brown (2003), the $R^2$ determines the '*degree to which the two sets of numbers vary together*'. In this regard, the data presented demonstrates a low degree of variance, thus indicating a poor justification that an increase in loading allocation in Sector 4, which has high-grade drawpoints (Figure 10), would improve grade performance. The results indicate that there is no positive relationship between the increment in the sector allocation and overall head grade.

A drawpoint is not productive if only one factor is highly prioritized, such as loading of high-grade drawpoints, but it should be a combination of other factors, which include improved

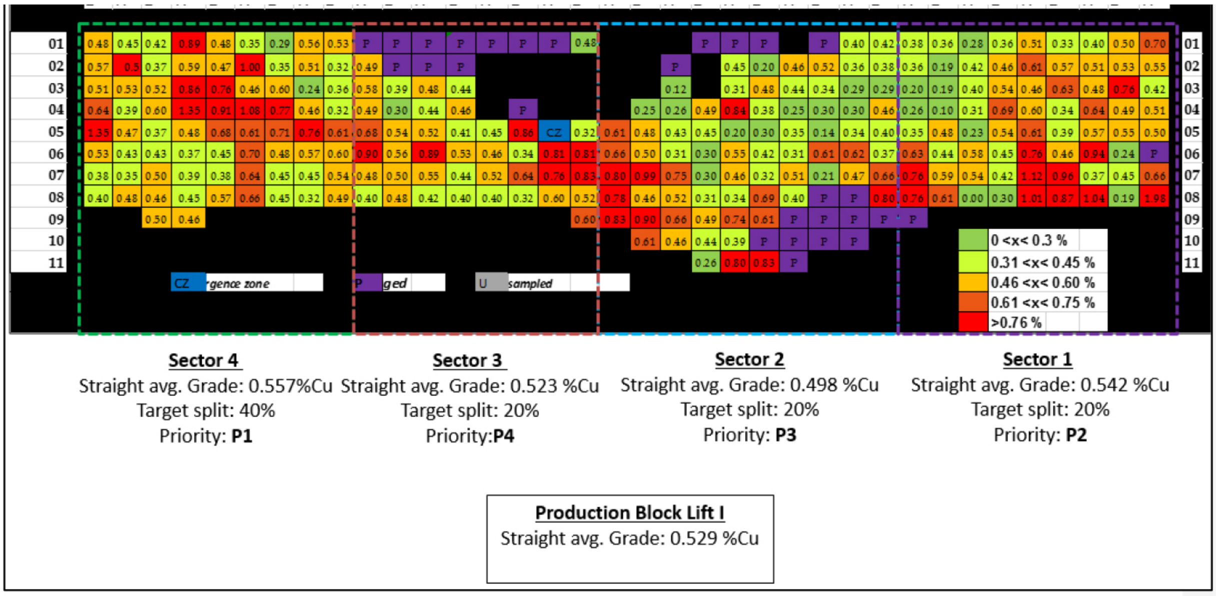


**Figure 10—Lift 1 grade distribution**

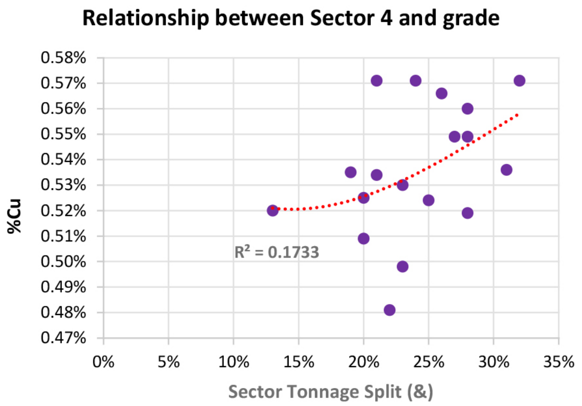


**Figure 11—Relationship between sector 4 and grade**

tonnages, loading compliance, and correct sector allocation. This strategy enables the organization to holistically consider the underground factors that influence the head grade. Other factors, such as the concentrator recoveries, play a pivotal role; however, those that the mining operations can influence include the factors indicated in Table I.

Data for grade, tons, compliance, and tonnage split shows that there is a significant differences between the variables when considered as improvement factors if treated in isolation as the, p-value was less than 0.05, when using ANOVA statistical analysis method as reflected in Table II. This difference is very large as the p-value came to the figure of 0.0000. Increasing the confidence level of 95% will probably not assist in this case. The null hypothesis ($H_o$), which states that there is no difference, must be rejected for this data-set comparison.

### *Strategy 2: Drawpoint loading management — defining the optimal point*

An effective way to manage drawpoint loading is by ensuring an effective draw control (Bull and Page 2000, (cited in Shekhar *et al*., 2018). This involves finding the optimized balance between compliance, grade distribution, and tonnage split, as presented in Figure 12. This optimized loading point enables the scheduling of the blocks to be carried out by taking into cognizance various factors, which on their own may not have a positive influence on the grade, but combined, may improve the overall head grade and the production performance of the cave. Optimized loading involves finding an overlapping point between tonnage splits, grade distribution and loading compliance, as presented in Figure 12. Note that the larger influences are those of loading compliance and grade distribution. Understanding the grade distribution in the cave enables proper planning and scheduling, which also influences loading compliance, as critical drawpoints are prioritized.

The significance of the strategy is further analysed by the following proposed splits, based on the sector grade distribution, as presented in Figure 13. The proposal is to allocate a minimum daily target of 20% loading splits for sectors 1, 2, and 3 and 40% for sector 4, which equates to 5 000 t for sectors 1 through 3 and 10 000 t for sector 4.

The application of this strategy demonstrates the positive influence that the tonnage split can have on the overall head grade, provided the loading compliance is maintained at 75% minimum across the cave. In comparing the proposed splits and grade, the degree of variability is 0.872, also expressed at 87.2%, which is sufficiently significant to justify the strength of the relationship between two variables (Figure 14). The significance in the correlation is based on considering other factors, and not treated in isolation.

## Conclusion

This study sought to outline strategies to optimize a block cave mine that is nearing depletion, particularly as relates to grade performance. The first approach was determining whether loading compliance influences grade performance. The results indicate that loading compliance is an insignificant factor if treated in isolation, thus it cannot be used to justify any significant improvement to grade performance. The second factor was on determining whether an increase in tonnage split correlates with an improvement in grade performance. The condition is minimal, and thus does not justify that increasing loading in high-grade drawpoints

*Table I*

**Loading optimization factors in block caving**

| Overall drawpoint grade optimization factors | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Grade** | **Tons** | **Compliance** | **Tonnage split Sector 1** | **Tonnage split Sector 2** | **Tonnage split Sector 3** | **Tonnage split Sector 4** |
| Jan-17 | 0.549% | 761 825 | 85% | 30% | 19% | 24% | 27% |
| Feb-17 | 0.536% | 679 011 | 82% | 32% | 19% | 18% | 31% |
| Mar-17 | 0.571% | 830 667 | 85% | 30% | 24% | 22% | 24% |
| Apr-17 | 0.571% | 719 476 | 84% | 9% | 31% | 28% | 32% |
| May-17 | 0.571% | 361 256 | 85% | 29% | 28% | 22% | 21% |
| Jun-17 | 0.566% | 884 012 | 78% | 27% | 29% | 18% | 26% |
| Jul-17 | 0.549% | 875 652 | 85% | 27% | 31% | 14% | 28% |
| Aug-17 | 0.560% | 842 658 | 83% | 25% | 28% | 19% | 28% |
| Sep-17 | 0.535% | 716 774 | 83% | 24% | 33% | 24% | 19% |
| Oct-17 | 0.498% | 798 853 | 77% | 24% | 28% | 25% | 23% |
| Nov-17 | 0.481% | 678 617 | 76% | 29% | 27% | 22% | 22% |
| Dec-17 | 0.509% | 870 305 | 80% | 25% | 30% | 25% | 20% |
| Jan-18 | 0.525% | 839 379 | 79% | 27% | 33% | 20% | 20% |
| Feb-18 | 0.520% | 617 299 | 81% | 29% | 35% | 23% | 13% |
| Mar-18 | 0.534% | 852 763 | 84% | 27% | 31% | 21% | 21% |
| Apr-18 | 0.530% | 703 939 | 80% | 15% | 35% | 27% | 23% |
| May-18 | 0.524% | 806 305 | 82% | 32% | 23% | 20% | 25% |
| Jun-18 | 0.519% | 723 921 | 87% | 35% | 7% | 30% | 28% |
| Mean | 0.536% | 753 484 | 82% | 26% | 27% | 22% | 24% |

*Table II*

**Statistical analysis results from ANOVA**

| One-Way ANOVA & Means Matrix | | | | | | | |
|---|---|---|---|---|---|---|---|
| $H_0$: Mean 1 = Mean 2 = ... = Mean k | | | | | | | |
| $H_a$: At least one pair Mean i ≠ Mean j | | | | | | | |
| Summary Information | Grade | Tons | Compliance | Tonnage split sector 1 | Tonnage split sector 2 | Tonnage split sector 3 | Tonnage split sector 4 |
| Count | 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| Mean | 0.005 | 753 484 | 0.820 | 0.264 | 0.273 | 0.223 | 0.239 |
| Standard deviation | 0.000 | 126 269 | 0.031 | 0.061 | 0.069 | 0.039 | 0.047 |
| UC (2-sided, 95%, pooled) | 22274 | 775 758 | 22275 | 22274 | 22274 | 22274 | 22274 |
| LC (2-sided, 95%, pooled) | -22274 | 731 210 | -22273 | -22274 | -22274 | -22274 | -22274 |
| ANOVA Table | | | | | | | |
| Source | SS | DF | MS | F | p-value | | |
| Between | 8.759E+12 | 6 | 1.460E+12 | 640.96 | 0.0000 | | |
| Within | 2.710E+11 | 119 | 2.278E+09 | | | | |
| Total | 9.030E+12 | 125 | | | | | |
| Pooled standard deviation = | 47725 | | R-Sq = | 97.00% | | | |
| DF = | 119 | | R-Sq adj. = | 96.85% | | | |

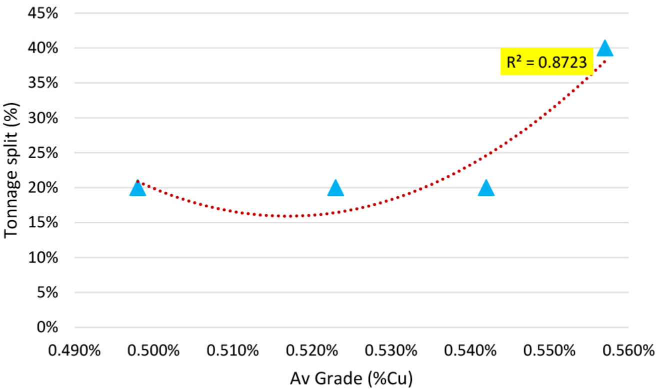


**Figure 14—Optimized drawpoint loading point**

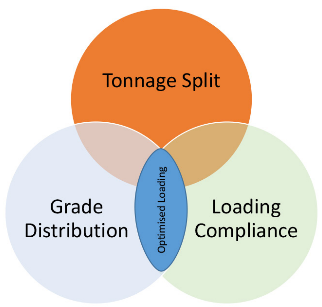


**Figure 12—Optimized drawpoint loading point**

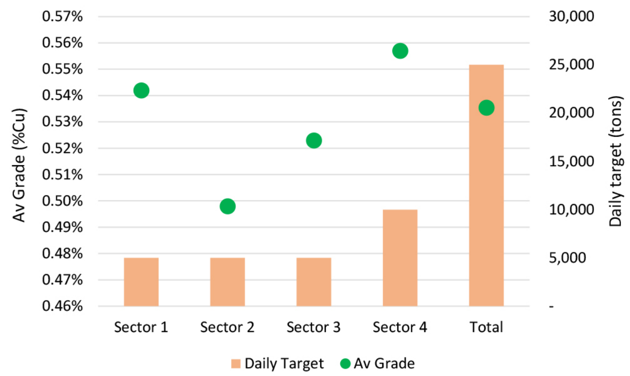


**Figure 13—Optimized drawpoint loading point**

Achieving optimized head grade for a mine that is nearing depletion could be challenging. An organization needs to find a balance between the production requirements and as ascertaining that maximum metal is extracted from the block cave. To achieve this, the study outlined three parameters, which should not be applied in isolation. The focus should not be on one aspect, but rather a collective effort to ensure maximum benefit to the overall production performance. To this effect, the study emphasizes that by maintaining the loading compliance above 75% and increasing the tonnage split for the high-grade sector could potentially improve the overall head grade. The correlational analysis demonstrates a strong positive relationship between these three variables, thus justifying the need for an optimized loading strategy.

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