**ABSTRACT**

The generation of a mine sequence for a block caving mine is challenging given it represents the direction for opening draw points. It is controlled by several factors such as caveability, orebody geometry, induced stress, primary fragmentation, grade distribution, production requirements, etc. and, in most cases, the main objective is to combine all of these factors to maximize the economic value of the project – and this proves to be more challenging.

Several complex theories and mathematical optimizations have been presented in the last decade, however most of them are too complex to provide a solution for real-life block caving mines when the dimension exceeds the capacity of these models, or super computers are used and processing time is an issue.

This paper presents a new option for optimizing mine sequences using the concept of ‘best and worst case’ adopted from open pit mines. The value of the sequence can quickly be evaluated using a reasonable number of iterations to provide an optimal and realistic solution. Examples of this optimization are presented in this paper to demonstrate the concept and its implementation in practical cases.
Introduction
The choice of initiation point for the sequence and the preferred direction can be influenced by several factors including shape of the orebody, access infrastructure, grade distribution, in situ stress directions and magnitudes, for example, however one of the main objectives is to optimize the value of a project by creating a production schedule that maximizes the Net Present Value (NPV).

There have been many studies and theories developed attempting to solve this problem, utilizing very complex mathematical approaches where the number of variables, constraints and formulations result in a solution that is difficult to implement and not flexible enough to add new constraints, such as mixed integer linear programming (Y. Pourrahimian, H. Askari-Nasab, D. Tannant, 2012) or integer programming (T. Elkington, L. Bates, O. Richter, 2012).

This paper will discuss an option to generate an optimal mine sequence using the approach of ‘best and worst case’ intensively used in open pit optimization (Smith, 2001) applied in Footprint Finder.

Footprint Finder
Footprint Finder, a module of GEOVIA PCBC™, was developed primarily to support a quick study of a block model to find the best elevation and orientation for locating an extraction level for block cave mining. Now it supports the creation of a simple production schedule using the sequence as input and offers opportunity to perform several runs in a short period of time to evaluate different options for direction and shape of the cave front for an optimal mine sequence.

Some of the characteristic of Footprint Finder include:
- Compare economic values for different footprints within different areas.
- Enable quick changing and evaluation of an economic model.
- Enable a comparison using different amounts of vertical mixing applied to each column using an algorithm based on Laubscher’s mixing method (Laubscher, 1994).
- Enable the construction of block models representing cumulative dollars, cumulative tons and best HOD from different starting blocks and elevations.
- Enable an initial footprint to be established for flat or inclined extraction levels.
- Assess multilevel scenarios using maximum height of draw and replacing the material by default values for the upper level.
- Evaluate simple production schedules using vertical mining rate, opening rate, mine sequence and production target per year. This option allows the use of a specific opening mine sequence for the entire footprint on each elevation, or the generation of different sequences for separate sectors of each block model level to be analyzed.

- Input data to the Footprint Finder utility from a geological block model together with mining costs, revenue factors, etc.

The graph at the left in Figure 2 shows the typical results for an evaluation of the entire block model. From it you see the value for each elevation and the tonnage reported. The best elevation is located at the level of 1200. The economic value per column is displayed at the right in Figure 2, where higher values are represented in warmer colors. The irregular shape of the economic value per elevation (red line) suggests the possibility that there may be more than one lift as the optimal solution.

Figure 1: Typical Footprint Finder’s evaluation steps.

Figure 2: Results from Footprint Finder.
The creation of a production schedule requires a defined sequence based on the shape of the cave front. This is created simply using an X-Y curve and applied with a certain direction (azimuth). An example of a production schedule using a sequence moving east in a V-shape is shown in Figure 3.

**Figure 3: Production Schedule in Footprint Finder.**

The option to create a mine sequence defining a shape and direction provides the opportunity to run many schedules to evaluate different scenarios. The option to start in a specific point and move in a circle to emulate a diamond shape is also available enabling all of the sequence options to be rapidly tested using Footprint Finder.

**Best and Worst Case Concept**

The concept of “best and worst case” has been popular for open pit optimization for more than 15 years (Smith, 2001) using GEOVIA Whittle™. Whittle is able to generate a series of nested pits based on the economic values (grades, revenue factor and costs) defining limits on where to mine and when, however they do not identify a production schedule in terms of the optimal period in which a block should be mined. The best case scenario defines a schedule associated with mining a pushback completely before proceeding to the first bench in the subsequent pit. In this manner the highest value ore is mined as early as possible maximizing NPV. The worst case scenario defines a schedule where the entire bench across all pushbacks is mined prior to proceeding to the second bench. This results in pre-stripping the entire deposit, defers ore production and minimizes cash flow by placing stripping costs up front while delaying revenue opportunities.

The ‘best and worst case’ concept provides two non-operational schedules, but defines a range of best and worst case scenarios to evaluate other operational options located in between and will provide the ability to assess them based on their delta from the best defined solution.

The same concept was adapted and implemented in a block caving mining environment to identify the best and worst sequence, based on the results obtained from Footprint Finder where each block column can be treated individually as a drawpoint to calculate its economic value based on the metal price, cost and grade and dilution profile, etc.

The sequence definition opens each block column using a certain shape and direction and thereby is suitable for block caving purposes where geotechnical, design and operational constraints need to be satisfied.

The best and worst case concept can be easily implemented in block cave mines to understand the maximum and minimum NPV, where the cash flow is calculated using a discount rate per year. The order of extraction of each column is very important and has a big impact over the NVP calculated. In this case, the best sequence will be the extraction of the column sorted from the highest to the lowest economic value and the worst sequence will be the opposite. Both cases are non-operational but provide a valid reference for planning purposes defining the maximum and minimum value of any operational sequence. Figure 4 describes an example of the application of this concept showing a plan view of the block model in Microsoft Excel™, where it is possible to see the best and worst sequence, based on the economic value of each block.

**Figure 4: Application of Best and Worst sequence.**
Figure 5 demonstrates an example of the best and worst sequence concept and how other sequence options are located within this range. The opportunity to identify the value of the best option is an excellent reference for a mine planner when they are comparing different alternatives for a sequence.

If a sequence value is close to the best case, then there is little opportunity to improve the sequence. If the difference between best and worst cases is small, then the overall project itself is not sensitive to sequencing. A simple plot such as the one in Figure 5 is very useful when assessing the effectiveness of various sequences.

**Application of This Concept in Real Footprint**

The Regal deposit (Bui, 2014) is a fictitious ore body but it is modeled as a massive porphyry copper deposit similar to many of the large block cave mines currently in operation. The overall view of the copper distribution in 3D and the plan view at the level of 1200 is shown in Figure 6.

An example of the application of mine sequence optimization using the concept of best and worst case was done in the Regal deposit using Footprint Finder shown in Table 1.

**Table 1: Inputs for Footprint Finder (Regal deposit).**

<table>
<thead>
<tr>
<th>Footprint Finder parameters</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXIT_DIL</td>
<td>60%</td>
<td>first dilution entry (inbound)</td>
</tr>
<tr>
<td>TON_C counterfeit</td>
<td>1,000</td>
<td>Development cost per m² area</td>
</tr>
<tr>
<td>DISCOUNT</td>
<td>25%</td>
<td>Discount rate (5 or 10%)</td>
</tr>
<tr>
<td>MAX</td>
<td>100</td>
<td>Maximum allowable HOD</td>
</tr>
<tr>
<td>TONS_MAX</td>
<td>3,000,000</td>
<td>Max tons/year in schedule</td>
</tr>
<tr>
<td>YEARS_BUILD</td>
<td>3</td>
<td>Years to build operation</td>
</tr>
<tr>
<td>NEW_DEF</td>
<td>1%</td>
<td>New block per period</td>
</tr>
<tr>
<td>H.MAX</td>
<td>50</td>
<td>Max vertical mining face [m/yr]</td>
</tr>
</tbody>
</table>

**Mine Sequence Applied for the Entire Footprint**

For this example, only one level will be evaluated at 1200 where the optimum elevation was found based on a run of the entire block model. Figure 7 shows the result of the Footprint Finder evaluation for each block, where the height of draw is displayed at the left and the economic value at the right. A black line was digitized to limit the footprint to form a more realistic shape for a block cave footprint. Note the size of the footprint (1,500m long and 400m width in average) and the distribution of the economic value outlines three potential areas of high grade where the sequence could start.
The best and worst sequence was created for the footprint defined by the black line and the graphic results are shown in Figure 8, with the start of the sequence shown in warmer colors. Three points are highlighted as high economic values and offer potential initial points for the sequence.

Once the best and worst sequence is complete, the evaluation for other possible sequences is possible and the options are then evaluated:

- Start in the border of the footprint and advance with a flat shape or V-shape for cave front. Both options are common since there are geotechnical constraints to be considered (e.g. lead/lag, abutment stress, etc.)
- Start in the center of the footprint and move in a diamond shape. This option is very attractive from the NPV perspective, since the sequence can start where the high grade is located, but it also generates many challenges from the operational perspective, since it concentrates a lot of the activity in the same area, meaning one production drift may support production, construction and development all at the same time.

For each run a production schedule was created and the discounted cash flow was calculated to create a comparison between them all. A sample schedule is shown in Figure 9.

The summary results are shown in Figure 10 where it is possible to see the location of the best and worst sequence, two lines of runs for sequences created using a flat and arrow (45 deg.) cave front shape and one additional line starting at the centre of the footprint from 18 different initial points located in the highest economic value.

The values of the operational sequences are in a range of 75% to 85% from the best option. In general, central options are optimal when compared with flat and V-shaped options.
Four sequence results are shown in Figure 11, with the start of the sequence shown in warmer colors. Due to the size of the footprint all of these options create very long faces (more than 500m) and are very difficult to maintain in practice. In addition, when comparing values for each option, the differences between them suggest initiation in the center of the footprint generates a more complex scenario for operation, construction and development. As a result of these studies, a new analysis was completed dividing the footprint into two zones (East and West) where each zone was evaluated independently to identify new options and a possible better overall sequence.

Mine Sequence Applied in Two Zones (East and West)
Because of the orebody shape and grade distribution, the footprint was divided into two zones as shown in Figure 12.

Sequence Evaluation for West Zone
Using the same procedure described before, a new set of sequences were modeled for the West zone. Due to the size of this zone only one center sequence was created starting at the highest economic value. The result of 38 sequences evaluated for this portion of the footprint is shown in Figure 13.
Figure 14 outlines three of the best alternative sequences for this zone, with the start of the sequence shown in warmer colors. In this zone, it is clear that the best alternative is to start in the center or using a V-shape with 280 deg. of azimuth. The economic value of both options is very similar determining the best alternative should be the V-shape to avoid operational complexities.

Sequence Evaluation for East Zone
The same process was repeated for the East zone, but in this case more sequences were completed starting at the center of the footprint due to its size and the different locations of high grade. The result of 45 sequences evaluated for this zone of the footprint is shown in Figure 15.

Figure 16 shows four of the best alternative sequences for this zone, with the start of the sequence shown in warmer colors. In this zone, the results using a flat or V-shape are very similar. Surprisingly the option to start in the center was not
better than the others. This is an indication that any of the best shape options could be used. Taking into consideration the complexity of the operation the best sequence is using a V-shape with an azimuth of 80 deg.

Final Results for Sequence Selection
Comparing all the options evaluated for the Regal deposit, the best option divided the footprint into two zones. The sequence starts in the middle of both zones moving with a V-shape first East then West. It is clear that the benefits are not only economical, since the operation of two zones is much easier and offers more flexibility. The comparison between sequences for two zones versus the entire footprint is shown in Figure 17.

More work needs to be completed to detail the final sequence model given this was just a quick analysis of a number of different options, however this tool provides strong evidence for alternatives that could be modeled for an optimal result. The next step is to take these results and create a model in GEOVIA PCBCTM, where the footprint can be modelled explicitly by drawpoint adding more resolution and detail to the analysis including opening sequence details by month and by zone, and a more sophisticated dilution/mixing model added as a 3D Cellular Automation.

Conclusion
The results presented in this paper demonstrate that the mine sequence optimization for block caving using the concept of ‘best and worst case’ is a very useful tool for a mine planner to get a maximum and minimum value limit for a sequence, creating a valid reference to compare any sequence created using all of the typical constraints for a block cave mine. Also it is helpful to have the opportunity to generate and evaluate several runs at once and to be able to see the impact of the cave front shape, orientation, starting point, etc. on the production schedule and final NPV.

This is not a complex mathematical optimization solution for this problem since it is a simple iterative process, however it provides the advantage of a very easy and straightforward method to evaluate many different scenarios that provide enough information to make the right decision in short period of time.

References