Reserve Estimation for Block Cave Mines Using GEOVIA PCBC™

Tony Diering, Ph.D. Vice President Caving Business Unit
Dassault Systèmes GEOVIA Inc.
Suite 1100, 1066 W Hastings St,
Vancouver, BC V6E 3X1
Canada

Tony.Diering@3ds.com

September 2013
Abstract

An overview of the factors affecting the calculation of a mineable ore reserve computation for a block cave mine is presented. Key factors include dilution sources, flow mechanisms, mine economics, excavation geometry, mining sequence, multi-lift or residual material situations and other computational considerations. This is based on over 25 years of experience using the GEOVIA PCBC software. The intent is to provide a detailed check list of the factors that should be considered when tackling a new project.

Introduction

This monograph provides a summary of the various factors affecting the calculation of a mineable block caving reserve using GEOVIA PCBC software. The software has been in use for over 25 years and during that time a wide variety of different block cave scenarios have been evaluated. Nothing is new or revolutionary in this monograph. Instead, the various sections should provide a check list for the reserve evaluation of a new block cave project.

The basis of the paper is centred on the simple definition of an ore reserve (compared to resource) as follows: A Mineral Resource is a concentration of metal or other commodity in the ground, which has economic potential, while an Ore Reserve is that part of the Mineral Resource, which can be economically mined. If “ore” is material that forms part of the ore reserve, then perhaps dilution can be defined as mined material that is not ore? Thus, dilution is that material which you don’t want to mine, but need to due to the shape of the ore body and choice of mining method.

The focus is specifically around block cave projects and mines as well as the specific “peculiarities” of block cave mining, which can make the ore reserve evaluation process more complicated. The broad areas covered are the effects of ore body geometry, mining geometry, material fragmentation and flow, economics and mining history/sequencing.

The experience gained during the past 25 years has been with the use of the PCBC software package developed by Gemcom Software International Inc., now owned by Dassault Systèmes GEOVIA Inc.

The intent is not to say what is right or wrong about any process or work flow, but rather to provide information about the factors to consider and how they might affect the ore reserve estimation process for a block caving project.

Some of the specifics covered in later sections are as follows:

- Dilution sources (internal vs external and geometric vs flow)
- Flow mechanisms
- Economics
- Excavation geometry
- Mining sequence and history
- Residual material in multi-lift situations
- Computational considerations
- Metal balance considerations and auditability
- How the software handles the above

It is tempting to try to provide typical values and guidance for working through the above. However, there are generally a variety of values and simple rule of thumb values, which should only be used with caution or in early stage evaluations. Another problem in the industry is the reluctance for mining companies to openly share the information. This may be due to intellectual property considerations or simply due to the difficulties of presenting this information at various conference venues. Thus, although PCBC has been widely used within the caving industry, the direct references to specific mines are limited.
**Terminology**

For purposes of this monograph, the following terminology is used:

- **Metal** is the commodity that is being extracted. This is grade * tonnes. Diamond mines are different, but for convenience, we will refer to them as “metal”.
- A **draw point** is typically one half of a draw bell.
- A **draw column** consists of the material located above a draw point.
- **Height of Draw (HOD)** refers to the extraction of material up to a given height above a draw point.
- **Haircut** refers to the process whereby an irregular HOD profile is trimmed and smoothed.
- **Peeling the potato** refers to the process of smoothing the overall outline of block caving footprint to improve its cavability characteristics.

**Dilution Sources**

There seem to be many different definitions of dilution and this monograph will not attempt to rigorously define what is or is not dilution. For our purposes, dilution is material, which you don’t really want to mine, but end up mining due to ore body shape and mining method. In block caving, three dilution sources can be listed as follows:

- **Internal dilution** within the ore body. This would include low grade inclusions within the main ore zone such as dykes or sills.
- **External dilution** around the fringes of the ore zone. In a block cave, these are conveniently separated into the bottom, sides and top of the cave zone.
  - Dilution around the sides depends upon the draw point layout and how the cave propagates whether this is vertical, less than vertical or expands beyond vertical limits.
  - Dilution around the bottom usually originates from the requirement for the draw points to be in a single plane (or almost planar) whereas the base of the ore body can have any shape.
  - Dilution from the top of the cave is the primary source for flow dilution to enter into the ore zone.
- **Flow dilution**. This is a term that is useful in the context of block caving. One may define a geometric outline and say that this is what is intended to be mined. The geometric outline may include dilution from the base, sides and interior as described above or the dilution may flow into the ore material during the extraction process. Flow dilution would (based on this definition) be essentially unique to cave mining methods. Flow dilution is, therefore, very dependent on the various flow mechanisms, some of which are described later.

People will often refer, in a general manner, to the amount of dilution expected for a block cave. Figures of 10% to 20% are common. It is useful to try to categorize this via the above sources of dilution.

**Ore Body Shape and Aspect Ratio**

An ideal ore body for block caving is large, uniform and would have sides close to vertical. The more the shape deviates from this ideal shape, the more likely it is that dilution sources would be problematic. The deviation from ideal in the horizontal plane would affect cave shape and hydraulic radius. The vertical to horizontal ratio will have a large effect on side dilution. For a narrow high ore body, the risk of the cave NOT propagating to conveniently follow the sides of the ore zone is high.

If the length to width ratio or height to width ratio exceeds 3:1 or 4:1, then side dilution is likely to be problematic. For example, if an ore body is 200m X 120m, and one hopes to extract a vertical column of 500m, then the height to width ratio would exceed 4:1 and the risk of poor recovery of the top of the ore zone is high.

The side contact of the ore body is also significant. There are three cases:
• A gradual reduction of grade/value as one moves away from the ore zone. This is moderately favorable. If the cave or mining extracts material outside the target ore zone, then the dilution material still may contribute metal.
• Sharp reduction in grade/value, but without a sharp geological contact. This is unfavorable.
• Sharp reduction in grade/value, but with a matching sharp clean geological contact (e.g.: a weak kimberlite pipe within stronger host rock). From an ore recovery perspective, this is convenient, since the contact will help with the separation of ore and dilution.

Flow Mechanisms

Detailed description of flow mechanisms is beyond the scope of this paper. However, a list (Diering 2007) is as follows:

• Vertical mixing
• Horizontal mixing (similar to diffusion)
• Toppling
• Rilling
• Erosion
• Compaction
• Major surface movements (eg Pit Failures)
• Inclined flow along a contact

The various flow mechanisms are shown in Figure 1 (from Diering 2010).

![Flow Mechanisms Diagram](image)

The understanding and impact of these mechanisms dominates a large part of the dilution and ore reserve calculations in a block cave mine. The three primary ones are likely to be vertical mixing, rilling and erosion mechanisms.

From an ore reserve perspective, and also within the PCBC program, we start by constructing a column of material above each draw point for which properties are derived from the block model. This is referred to as a slice file (as separate and distinct from a block model). As the different mechanisms take place, material may either remain within a draw column or else be transferred to other draw points. This is important from the perspective of ore reserve definition, since confidence in extracting material is strongly related to how much it moves around within a cave. It is reasonable to suppose that material which moves extensively in an uncertain manner would have a lower confidence limit than material, which moves downwards directly into the underlying draw point. There are three cases to consider:

• Material moves, but remains within the same single draw column. (Vertical mixing and erosion and compaction. Inclined cones can still fall into this category).
• Material moves from one draw column to another. (Rilling and horizontal mixing)
• Material moves from outside the defined draw columns into or on top of the draw columns. (Toppling and pit failure).

This is summarized in Table 1.

<table>
<thead>
<tr>
<th>Movement</th>
<th>Predictability</th>
<th>Risk level</th>
<th>Reserve classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical within a draw column</td>
<td>Overall behaviour is well understood even if difficult to model</td>
<td>Low</td>
<td>This would form part of the highest confidence level of reserve (E.g. Measured)</td>
</tr>
<tr>
<td>Horizontal between draw columns</td>
<td>Rilling is well understood, but more difficult to model. Depends strongly on cave propagation and mining sequence</td>
<td>Moderate</td>
<td>Material which rills may still be recovered, but often, dilution material can rill into a gap delaying the arrival of higher ore.</td>
</tr>
<tr>
<td>External material flowing into draw columns</td>
<td>Highly unpredictable</td>
<td>High</td>
<td>Great caution should be exercised before including this material in an ore reserve</td>
</tr>
</tbody>
</table>

Table 1 Reserve classification suggestions for different flow types

The above may seem obvious when put into a table, but there are examples where material to the sides of a block cave layout have been included as part of the stated ore reserve but, have not been recovered leading after the fact to ore reserve write downs. This situation is, potentially, quite common since it can occur any time a block cave is initiated beneath an exhausted open pit.

The above mechanisms are modelled within the PCBC software. In a typical study, the mechanisms may be turned on or off and the effects on ore / metal recovery studied as part of the overall risk assessment process.

**Fragmentation**

Though fragmentation is fundamentally important in any block cave evaluation, the direct assessment of fragmentation is a geotechnical responsibility beyond the scope of this paper. However, it must be emphasized that the cavability of the rock mass and the subsequent fragmentation during the extraction process will directly influence all the flow characteristics mentioned above. Fragmentation will strongly influence draw point spacing, dilution entry (flow dilution) and overall ore recovery. There are many ways the fragmentation characteristics will influence the other inputs into PCBC such as layout, fines migration and vertical mixing inputs and, in production schedules, the production rate from each draw point.

**Economics**

Given that an ore reserve is what can be economically mined (in today’s terms), a discussion of the economics of the block cave is justified. The common workflow within PCBC to assess the mining reserve (based on metal prices, recoveries and operating costs) is as follows:

• Set an undiscounted dollar value to each tonne of rock in the input model.
• Calculate the draw column above each draw point.
• Make an allowance for vertical mixing and erosion in each draw column.
• Evaluate the economic limit for each draw point. (independently of others)
• Adjust this to lower and upper limits if too low or too high.
• Adjust the values vertically to take some account of the time required to mine a tall column of rock
• Make adjustments to irregular heights or to trim isolated high column heights. (Haircut)
• Refine the above to take account of non-vertical or non-linear flow mechanisms. This is done by dynamic Best HOD calculations within the production scheduler.
• Refine the above to take account of variable shut-off grade with time.

Within PCBC, the initial approach would be to build the draw point layout and draw columns, do pre-vertical mixing and run the Best HOD tool, which gives a report of the tonnes and value contained within the draw column above each draw point. This is convenient for initial assessments and for set up of the detailed draw point layout. Later, within the production scheduler, the more complex adjustments due to mixing and time dependencies would be included.

The following topics are discussed in more detail here:

• Maximum HOD
• Minimum HOD
• Haircut
• Time or vertical discounting

**Maximum HOD**

It is economically compelling to try to mine high columns from a single layout. There is a high capital cost to set up a layout, but the cost per tonne can be reduced if a higher column can be mined. The key factors to be considered here are:

• Geotechnical risk associated with the way in which the cave will propagate. If the cave does not go where you want it to go, you will not recover all the material
• Geotechnical risk associated with the draw point stability. If the draw point fails before you are finished mining, you will not recover all the material.
• Flow risk. The higher you mine, the more difficult it will be to predict how the draw columns will interact and how material will flow into the draw points.
• Economic risk. It takes longer to mine a taller column, so the higher it goes, the higher the risk of economic impact (e.g. metal prices or time discounting etc.)
• Aspect ratio risk. If the height to width ratio is high, then using a higher maximum HOD is high risk.
• Cave management risk. If the block cave is poorly managed during operation, then there will be increased risk of loss of draw point infrastructure. This is an extension of the draw point pillar stability mentioned above.
• Limited by past mining and residual material. In a multi-lift situation, the maximum HOD is usually limited to the base of the previous mining horizon even if there is ore grade material left from the previous mining. This is due to reluctance or inability to classify the residual material as ore.

In weaker rock, maximum HOD values would often be set around 250m to 300m. Under more favourable circumstances, maximum HOD values can go higher. Some mines plan to mine up to 1000m columns (or more). This can be done, but the above risks should be taken into account in terms of ore reserve statement. A block of highly drilled material for which the grade is well estimated, but is 700m above a layout and to the side of the deposit, is high risk material for inclusion in the ore reserve.

**Minimum HOD**

Often, due to the hydraulic radius requirements of cave initiation or to reduce stress loading of extraction tunnels, it is required to mine material from draw points, which are below shut-off grade. The question arises as to what minimum HOD should be used. Economics would push towards a low value, while geotechnical considerations would require a higher value. Typical values range from 50m to 300m. It is useful to look at the economic impact of different minimum values and also to take cognisance of where these columns are
located within the overall footprint. Pillar strength would be another consideration. Ceasing to mine low grade draw points can result in convergence issues affecting the extraction of adjacent higher grade draw points.

Haircut

An ideal block cave would have all draw points with a similar maximum HOD (e.g. 400m). However, there are circumstances where some very irregular top profiles are encountered. In these circumstances, a haircut is well justified:

- A small high grade zone high up in the ore column can yield a very irregular HOD profile. In this case, the zone should be inspected and consideration given as to whether it is realistic to expect it to be extracted. This ties in to the concept of aspect ratio. To expect a few draw points to extract material up to 500m adjacent to many draw points, which are extracting only 300m, is unrealistic. The Haircut tool in PCBC will help to assess whether to chop out the high grade bit or increase the draw in the low HOD areas to help with the extraction of the high grade section
- A follow on from the previous item arises in multi-lift situations. One will often encounter draw points on the edges of the deeper layout, which extract tall columns adjacent to the previous mining lift. This is especially likely since the lower lift will often be evaluated at higher metal prices than were present during the mining of the upper lift. However, whether or not this side material can be extracted should be closely evaluated. In stronger rock, it is likely that the cave sides will migrate into the upper footprint and reduce the chances of extraction of this side material.

Time or Vertical Discounting

Often an ore reserve would not be sensitive to vertical discounting of a draw column. However, there are considerations for taking a closer look at vertical discounting:

- Variable shut-off grade is expected for a large deposit.
- The deposit contains many variable grade “pods.” A small high grade zone lying above a large low grade zone is unattractive. Unless some vertical discounting is implemented, the value of high above low or low above high will be the same. But, the reality is that high grade material at the base of a draw column is much more valuable and hence a better candidate to include in an ore reserve.

Excavation Geometry

In any mining method, the excavation geometry plays a very important role in the conversion from a mineral resource into a mineable reserve. Block cave mining is probably the least selective mining method in use today.

The following factors are discussed in this section:

- Draw point spacing vs. ore body recovery. Hoped for vs. real draw cone. (Effect of erosion).
- Maximum panel or undercut width.
- Minimum span and Hydraulic Radius.
- Flat vs. inclined caves.
- Block cave vs. Panel cave.
- Peeling the potato! (Converting a numerical footprint into a practical footprint (analogous to Whittle pit to design pit conversion).
- Geometric resolution and detail at base of draw cone. The nitty gritty around the draw bells and undercut.
Draw Point Spacing

The draw point spacing is one of the trickiest and most contentious design considerations in block caving. Of course, draw point spacing is very closely related to the expected fragmentation so the range of options open to a planner may be limited. Effects of being too close or too far apart are discussed, below. The ideal is in the middle.

Too close

If the draw points are spaced too closely, one positive aspect could result but it is associated with many negatives. The potential will exist to recover the whole ore body above the layout since the draw cones or ellipsoids of draw from each draw point will overlap and the ingress of dilution material can be effectively managed.

There are many negative side effects from a draw point spacing which is too close:

- There are more draw points to be developed, which will be more expensive.
- The extra draw points will take longer to construct, which will in turn limit the maximum production potential. In a large panel cave, the maximum production potential is proportional to the number of new draw points developed per period. (Diering 2008)
- There will be significant risk of the pillars around the draw points being too weak. In that case, the pillars fail and the result is loss of recovery of the ore body and loss of production capacity as less draw points become available.

Too far apart

Positives in this case are:

- As the spacing increases, the potential for increased production (in a panel type cave) increases

If the draw point spacing is too big, there are several positives and potential negatives:

- Larger equipment can be put into larger service excavations.
- Capital cost per ton of rock mined can decrease.
- Pillar strength is increased.
- Pillars can absorb more brow wear.

Negatives are:

- Not all the ore is recovered. Cave behaviour is altered and early dilution ingress is likely with parts of the ore body remaining intact or unrecovered above the major pillars for the production tunnels.
- Irregular cave propagation can result with adverse stress conditions on the layout.
- Fragmentation may deteriorate and there may be reduced life for draw points (due to early dilution ingress) causing early draw point closure and reduced production rate.

Figure 2 shows output from a 2D Cellular Automaton tool in PCBC representing a vertical cross section for a test case. The left side of each image represents eight closely spaced draw points with regular draw, while the right side represents four points, which are more widely spaced with higher tons being extracted from each draw point. The horizontal (coloured) bands represent different...
zones or rock. These are preserved more effectively with closer spaced draw points and the incomplete extraction from the right side is clear on the bottom row of images. The upside down “V” shapes to the lower right demonstrate the potential for loss of reserves if the draw point spacing is too large.

**Maximum Panel or Undercut Width**

One may wonder why mineable reserves from a block cave would be limited by maximum panel width, but it turns out that this can be significant. In larger block caves, there is likely to be a need to split the ore zone into panels. In this case, the maximum width can be limited by cycle time or, in the case where electric loaders are being used, then the maximum length of the electric cable. A typical value would be around 300m. So, if you have an ore body, which varies from 280 to 350m in places, it may be impractical to split this into two smaller panels, but if the maximum panel width is limited to 300m, then some of the edges of the ore body would likely end up being trimmed.

Another limitation can be linked to the maximum length of the undercut, which in turn depends on the undercut sequence or direction. If the undercut face gets too long, then the rate of advance of the undercut face can become too slow and geotechnically problematic. So, the maximum panel length would be limited by the undercut face in this situation.

The end result from either of the above situations is the excavation geometry will result in lower recovery from the ore body.

**Minimum Span and Hydraulic Radius**

Minimum span is determined by the Hydraulic Radius (Laubscher). This is the minimum span, which should be used in the block cave to ensure that the material will cave after undercutting. Thus, the hydraulic radius will limit the ability to recover some smaller parts of the ore body or alternatively, additional low grade draw points would be required to be developed to ensure cavability.

Having a computer tool such as PCBC is very useful in this situation. The alternate footprints can quickly be evaluated to see which of the two alternatives would be more favourable.

A related constraint is that it will often make sense to ensure that the ore body is mined as a single footprint rather than being split into several independent footprints. The reason for this relates to the added difficulty of starting up a new cave.

**Flat vs. Inclined Caves**

Most of the above rules relate to a flat cave layout; the tunnels are almost flat, but may have a slight drainage gradient. If an ore body has a footwall inclination of around 45 degrees, then there is merit in considering an inclined cave. In either case, flat or inclined, there will be ore losses and dilution inclusions due to the planar nature of the bottom side of the cave. Unless the ore body is very large and is to be mined out in several lifts, one will usually end up with some draw points, which are initiated in low grade ore and have to mine the low grade before reaching the economic material. In these cases, the inclination of the draw points has to be matched up reasonably with the base of the ore body.

**Block Cave vs Panel Cave**

Block caves and panel caves are each variants of the block cave mining method. In general, a panel cave would apply to a larger ore body and the shapes of the panels would be closer to rectangular in shape. If using a block cave, there would be more flexibility in the shape of the footprint, but this would still be limited by minimum and maximum widths and overall curvature.
Footprint Outline

This generally needs to be created without sharp or concave corners. Ideally, it should be convex in shape. If the ore body perimeter is irregular, then the process of smoothing the footprint edges is analogous to peeling a potato. Bits sticking out need to be trimmed off and indentations cause trouble. A peeled potato reduces the original reserve due to the loss of tonnage, which was required to be removed. This seems obvious, but often the process of smoothing the footprint outline can cause considerable loss of value. This loss of value needs to be quantified and compared against the operational convenience of the simpler outline.

The process of smoothing the outline is quite similar to what is done in open pit evaluations when an optimal pit outline, such as is generated using GEOVIA Whittle™ Pit Optimization, is converted into a practical minable pit with haul roads and benches, etc.

Geometric Resolution and Detail at Base of Draw Cone

The final adjustment to the ore reserve occurs when detailed adjustments are made around the base of each draw cone to reflect the accurate volumes and tonnages of each draw point (or half draw bell). This usually requires manual calculation of what the true volume will be and then adjusting the computed volumes in PCBC at the base of each cone (Figure 3). Often, the potential reserve tonnages lost at the base of the footprint can be recovered later using pillar retreat or from a second mining lift. For larger lift projects (500m), the tonnage in the bottom 15m is relatively insignificant, but still needs to be accounted for in the overall reserve calculations.

Care should also be exercised to ensure that material from tunnels (on production and undercut levels) is not double counted between production and development tonnages.

Mining Sequence and History

Mining sequence can have a direct or indirect effect on the computed ore reserve for a block cave. There are various indirect influences to be considered. For larger projects, a variable shut-off grade may be employed. In this case, the tonnes will generally be decreased from newer draw points using the higher shut-off grade. This requires that the Best HOD process be imbedded within the production schedule, so that if the sequence changes, different draw points will be mined at different points in time and have different reserves. This process can be quite complex especially when there are other constraints active simultaneously such as maximum and minimum HOD. It should also be mentioned that the choice of mining sequence can have a very large effect on the NPV of a block cave even if the same ore reserve is mined, depending on when the higher grade portions of the deposit are mined.

Another common constraint is that sequencing should be set up with a single initiation point for a block cave mine. Once separate panels are used, the sequencing becomes more flexible.

Once a block cave has been in operation for several years and actual mining history is available, then the process of updating reserves is further complicated by this mining history. Areas will be encountered where the official reserve (in the model) has already been mined out, but the sampled grades at the draw points are sufficient to justify mining from those areas. Other areas will be encountered where the grades are too low and the draw points are required to be closed early. A tool exists within PCBC called LSQ (Least Squares) which can use the local draw point samples to update the estimate of material in the draw column for short term corrections in the forecast.
In general, the sequencing of draw points requires a careful trade-off between the geotechnical constraints from overall stresses and undercut face shape combined with the need to mine higher grade draw points earlier in the sequence. The example in Figure 4 (Richter 2008) from the Finsch mine shows the undercutting sequence. It was a good compromise between targeting higher grades and geotechnical constraints.

**Non-linear Material Flow**

Another consequence of the mining sequence manifests itself when working with more advanced flow models, which are imbedded in the PCBC production scheduler. The mineable reserve is a direct function of the mining sequence. As soon as a mixing algorithm is used when material moves between draw points or from outside the draw point domain into the cave zone, then the mined grades will depend on mining sequence or rate. Draw points, which are mined first or faster, will tend to "rob" material from other adjacent draw points or sources. The dilution model and recovered grades will then vary and the total mineable reserve will also depend on the sequence. This can be confusing to those not familiar with flow models in a caving environment.

This is perhaps the key reason why cave management and good draw control are crucial for successful block cave operation. As soon as there is poor draw control, there will also be a loss of ability to generate reliable forecasts. The other consequence of poor draw control is an increase in dilution or lower recovery of ore or both.

**Residual Material in Multi-lift Situations**

As more block caves are developed, there are increasing number of instances in which a second or multi-lift situation is encountered where the deeper lift is wholly or partly beneath a previously mined block. Within PCBC, there are three basic approaches to modelling this situation:

- Assume a simple low grade background value for the various grade elements in the mined out areas.
- Use zones of constant grade in the mined out areas with grade values decreasing upwards. This would generally be linked to the shut-off grade that was used during the earlier mining. If a draw point was shut off at 1% Cu, then it is not unreasonable to assume that the grade of the material left behind in the draw point would be close to but less than 1%.
- Simulate the historical mining as accurately as possible and then use the residual slice file to estimate the remaining material. There are custom tools within PCBC to facilitate this process and the approach is gaining in popularity. The challenge is to try to provide a material classification for this residual material. It is possible to drill into old mining areas to firm up on the confidence of the estimate.

When mining beneath a previous mining area, there are several factors to be taken into account:

- What was the shut-off grade in effect for the previous lift? With generally increasing metal prices, it is likely that the previous shut-off grade would have been high enough to leave economic material behind.
- What was the overall tonnage recovery from the previous lift? For example, if the reserve had been stated at 100Mt, but only 75Mt was recovered, then it seems reasonable to assume that the other
25Mt is still in the ground and can potentially be mined. Although this seems obvious, it often turns out that the residual material is substantially discounted or written off altogether from reserve statements.

- Are there areas where pre-mature collapse of the draw points took place with incomplete recovery, which would leave higher grade material for subsequent extraction?
- Was there incomplete recovery of the ore due to early dilution entry and non-interacting draw cones? In this case, the average grade of the residual material could locally be higher than the previous shut-off grade.

It is the opinion of the author that the quantification and categorization of residual material will play a more important role in the future. However, if the material cannot be given a resource or reserve classification (e.g. Measured, Indicated or Inferred), then the metal from that source should not be included in the calculations. Effectively working through this situation can be complex.

An example of a deposit where multiple lifts have been mined (or planned) is shown in Figure 5 (Diering 2010) for the Cullinan Diamond Mine in South Africa.

Other Considerations

Computational Considerations

When working on a project it is often necessary to work with many different grade elements. Consider an example where there are eight metallurgical domains with different metal recovery characteristics, five metals to be tracked (e.g. Cu, Au, Ag, As, Mo) and it is also required to track Measured, Indicated, Inferred and Other material in the reporting. Within PCBC, due to the material mixing process, individual particles are not tracked. Instead, fractions of blocks are merged to form the slice file and the mixing algorithms work with fractions of slices. Thus, we cannot track and report rock types as easily as for other mining methods. In the above example, up to 240 grade attributes could be required for fully comprehensive reporting. The previous limit in PCBC was 20 grade attributes. This has recently been increased to 40 and will be further increased to 100 in the near future. However, even if the program can track and report all the attributes, the actual process of collating and managing this larger number of attributes can be formidable. Care must be exercised to select an appropriate list of elements with which to work.

A second consideration arises with the treatment of the Inferred material. For planning purposes, it may be decided to include this material. However, for official reporting purposes to the stock exchange, it may be required to “zero out” the grades for Inferred material. While this can quite easily be done, it does add to overall complexity and work flow and is also prone to errors for the unwary.

A third consideration arises out of the treatment of mined out areas. Usually and currently, a geologist may prepare the in-situ resource block model. However, if previous mining has occurred, then the onus would likely fall on the planning engineer to make adjustments to the block model for the mined out areas. This can lead to complications in terms of accountability and sign-off responsibilities.

Metal Balance

It is recommended to perform metal balance calculations as part of any PCBC reserve evaluation process. This is a very useful check and there are three principal areas where this is particularly useful.
• Assessment of what percentage of the geological resource has been converted into a mineable reserve.
• Comparative studies of different alternatives. In the early stages of a project, many different scenarios will be evaluated in varying levels of detail. However, tracking the metal totals for the different scenarios is very useful for relative evaluation and weeding out less attractive alternatives.
• Metal balance is particularly useful in multi-lift scenarios. The basic approach is to start with an in-situ resource A. If the mined metal is B, then metal remaining in the ground should be C where C = A - B.

Audit Trail

Many block cave projects evolve over a period of 10 years or more from concept through to construction. Then the mine may operate for an additional 30 years. It is really important to have thorough documentation of the various models and reserves statements generated during this extended time frame. Many tools exist within PCBC to facilitate this process, but instances still occur where a previously calculated reserve report cannot be replicated. This is usually due to factors such as changing block models, changing inputs such as metal prices and recoveries, user error and different versions of the software. A good audit trail should document full work flow of all key inputs with graphical evidence of the steps taken to generate final reserve reports.

Summary

A concise summary of the above factors has been put into Table 2 to provide a check list of factors to consider during a block cave evaluation.

<table>
<thead>
<tr>
<th>Dilution</th>
<th>Flow</th>
<th>Economics</th>
<th>Excavation</th>
<th>Geometry</th>
<th>Sequence and history</th>
<th>Residual and multi-lift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Side</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Base</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Flow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Flow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ore body</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Shape</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Aspect</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Contacts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical</td>
<td>Max HOD</td>
<td>Draw point</td>
<td>Start point</td>
<td>Single vs. multi-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>Min HOD</td>
<td>spacing</td>
<td>- Interior</td>
<td>lift</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rilling</td>
<td>Haircut</td>
<td>Tunnel spacing</td>
<td>- Exterior</td>
<td>Simple background</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Erosion</td>
<td></td>
<td>Hydraulic radius</td>
<td>Single vs. multi</td>
<td>Computed background</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Topping</td>
<td></td>
<td>Flat vs. inclined</td>
<td>panel</td>
<td>Confidence level</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compaction</td>
<td></td>
<td>Block vs. Panel</td>
<td>Number of cave</td>
<td>Historical records</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inclined</td>
<td></td>
<td>Perimeter</td>
<td>initiation points</td>
<td>Metal balance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pit Failure</td>
<td></td>
<td>- Smooth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Foot Failure</td>
<td></td>
<td>Base of cones</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fragmentation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Abbreviated reserve evaluation check list
The PCBC Software

Considerable time and effort has been spent over the years to provide consistent reporting. A balance is required between the need to develop and improve the flow algorithms against the need to provide consistent and repeatable reporting.

Another consideration is that there are no analytic solutions against which to validate results. Instead, results are validated against observations of historical mining. But, this validation process usually points to new ways to improve the algorithms providing improved calibration.

Attempts are also made to validate reserve statements with other general purpose software packages, which do not have mixing algorithms. These comparisons are useful, but not capable of providing a full validation. A consequence of the above is that a good balance of caution and user experience is required for more complex analyses.

Conclusions

The GEOVIA PCBC software has evolved over more than 25 years to work with the above situations. Every block cave has its own unique challenges, but most of these will fall into the above categories. When starting a new project, it is not known beforehand which of the above factors will be key drivers and which can be largely ignored. Thus, it is hoped that the check list provided in this paper will aid with the evaluation of future block cave mining projects.

REFERENCES


For more information, visit www.3ds.com/GEOVIA/PCBC.

Dassault Systèmes, the 3DEXPERIENCE Company, provides business and people with virtual universes to imagine sustainable innovations. Its world-leading solutions transform the way products are designed, produced, and supported. Dassault Systèmes’ collaborative solutions foster social innovation, expanding possibilities for the virtual world to improve the real world. The group brings value to over 170,000 customers of all sizes, in all industries, in more than 140 countries.

CATIA, Solid Works, SIMULIA, DELMIA, ENOVIA, GEOVIA, EXALEAD, NETVIBES, 3DSWYM and 3DVIA are registered trademarks of Dassault Systèmes or its subsidiaries in the US and/or other countries.