Deswik®

Block Model Knowledge for Mining Engineers – An Introduction

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1. Introduction

As a software provider for the mining industry, Deswik is regularly training mining engineers in the use of our software in mine design, planning and scheduling.

We are often called upon to train junior engineers entering their first ever planning-related role and note that many of these engineers need and want more knowledge on the planning processes beyond just how to use the software being provided. One of these requirements is knowledge on block models that need to be used for the mine planning process.

The rapid turn-over of personnel during the last minerals boom, and then the loss of experienced technically-focused personnel during the following bust means that many of the junior engineers have no on-site mentor sufficiently technically skilled to provide suitable knowledgeable help to the junior mining engineers.

With these factors in mind, this document has been written to introduce new mining engineers to mineral resource block models: their structure, the brands they may come across, the types they may come across, and issues that they will need to understand to avoid mistakes in their use.

It is not the intention to turn mining engineers into resource geologists, but it is important that a mining engineer should also be sufficiently conversant with the resource estimation procedures to understand how the resource block model was generated. A resource block model will only ever be as good as the geological foundations upon which it is built.

And as the resource block model is the foundation upon which the industry's mine plans are built, our plans will only ever be as good as the geological block model that has been given to us to use.

This document is merely a first-step introduction to the knowledge needed. We acknowledge that although this is intended to be an introduction to the topic, there is still a lot that has been covered, so we invite the reader to "dip in" where required and skip over the parts not yet relevant to their work. We also encourage the new mining engineer to read more on resource estimation beyond this document to enhance their knowledge base.

While the focus of this document is to introduce mining engineers to block models so that they have some understanding of what they are dealing with and to make sure they do not make mistakes from a lack of knowledge, it needs to always be kept in mind that the block model they have been given may not be appropriate for the task at hand. As Clive Johnson (B2Gold President and CEO), said in 2013 at a Scotiabank Mining Conference panel discussion on the topic of the failings of NI 43-101 reports:

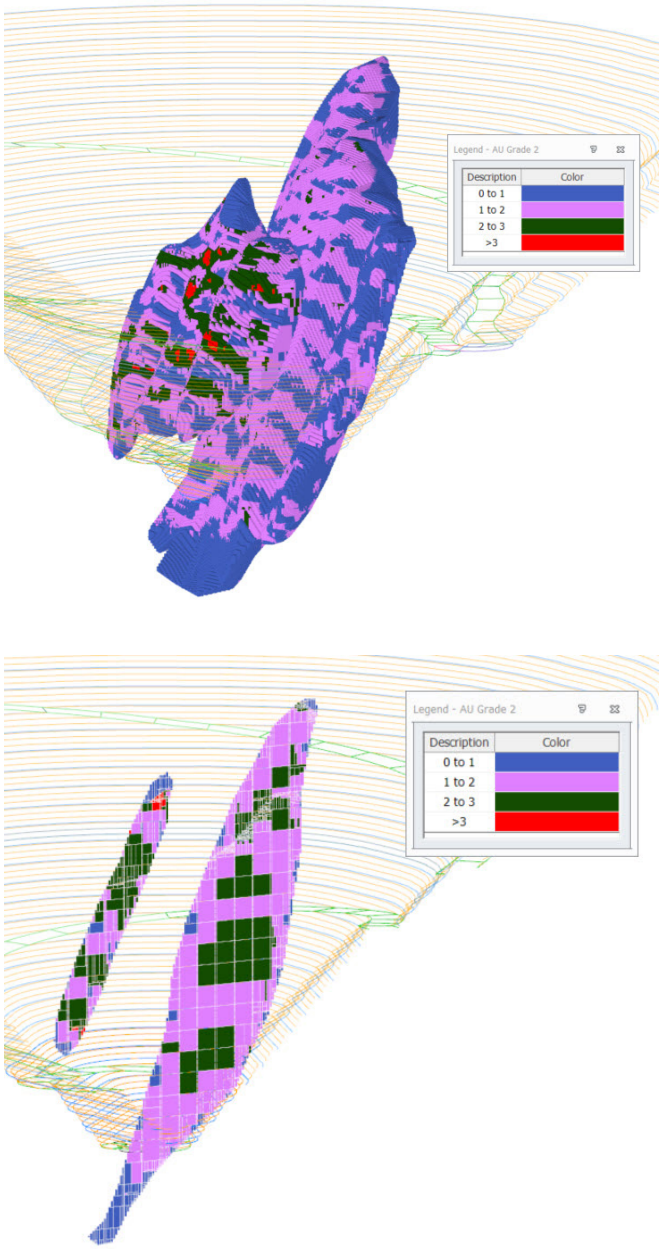
"What we typically see where it falls apart [project value] is the block model. We just say, give us your data... it usually fails right there. The extrapolation that they're using for their reserves and resources is probably completely out of whack relative to the geostatistical information or data that is there".

So be wary, but boldly go forth fortified by knowledge.

2. The Basics

A block model is a simplified representation of an ore body and its surroundings that can be thought of as a stack of computer-generated “bricks” that represent small volumes of rock in a deposit (ore and waste). Each “brick”, or cell, contains estimates of data, such as element grade, density and other geological or engineering entity values.

Figure 1: A block model of an ore body coloured by grade (shell and slice)



The cells of a block model are arranged in an XYZ grid system, and the cells may be of uniform or of irregular size.

Deswik software does not do grade estimations for the generation of block models, but allows for the interrogation and manipulation of a block model prepared by other software packages, such as Leapfrog/Edge, Datamine, Vulcan, Surpac, MineSight and Micromine. In these packages, the blocks are assigned a grade by one of a number of different estimation methods: Inverse Distance Squared, Ordinary Kriging, Multiple Indicator Kriging, and so forth.

The following sections explain these concepts further.

2.1. MODEL FRAMEWORK

The term “model framework” defines the rectangular region of space within which the model cells are located. It requires an origin, distance for each axis, and rotation angle.

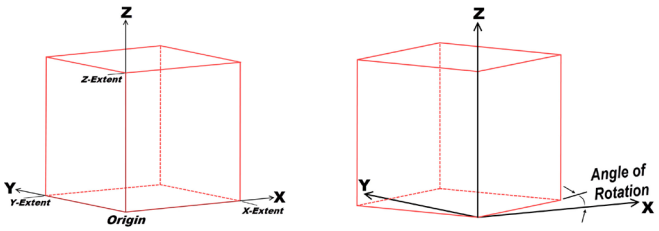
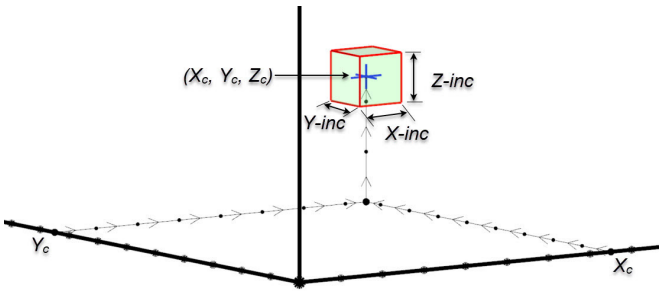


Figure 2: Standard block model framework

Within this framework are individual blocks, all with a designated length (X-increment), width (Y-increment), and height (Z-increment). The block position may be defined by

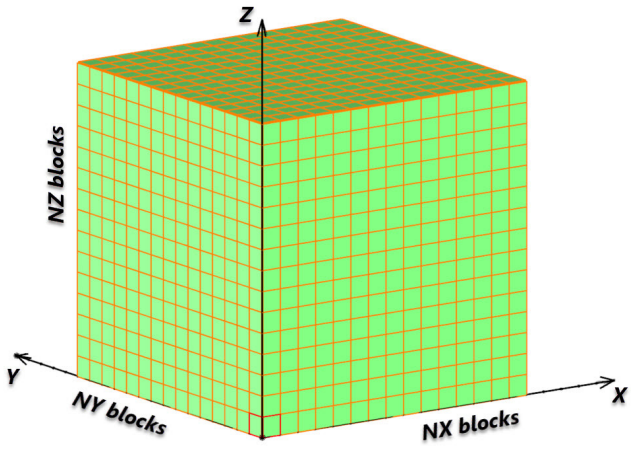


a centroid (Xc, Yc, Zc), or a block origin (Xmin, Ymin, Zmin).

Figure 3: Block model block definition

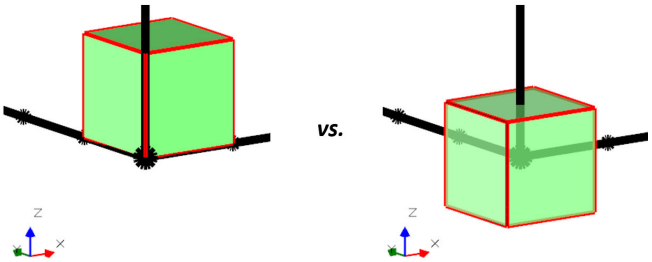
The number of blocks in each coordinate axis direction is usually specified to define the full potential model framework. Note that some modeling schemes do not necessarily need a fully “filled” block model – blocks can be missing or absent within the framework.

Figure 4: Filled block model



One final and important aspect of block model frameworks is to note how blocks are positioned at the origin. There are two options as shown in Figure 5. The block format with the "origin block" sitting along the axes (left image in Figure 5) is the most common, but the "origin block" having its centroid located on the origin (right image in Figure 5) has to be checked for, as it will sometimes occur (Note that this is the default option in Micromine models).

Figure 5: Potential block centroid to origin relationship

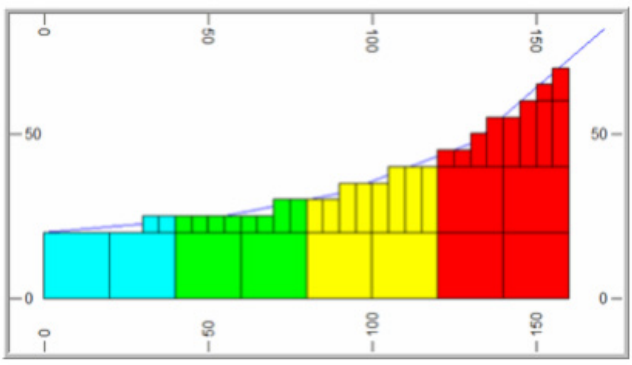


2.2. MODEL SUB-DIVISION

The first models developed partitioned the total model space into a regular three-dimensional lattice of cuboids as shown in Figure 4.

In order to better model boundaries within the model space, the blocks can be sub-divided into smaller cuboid sizes (or rectangular prisms), known as sub-blocks or sub-cells, while keeping the storage and computational efficiency of the standard block model. The sub-cells are usually stored separately from the parent blocks.

Figure 6: Sub-celling of a block model along a boundary



The sub-division process can be done in one of two ways: octree or flexible sub-division.

Octree sub-division splits the parent block into a hierarchy of cubes with automatic sub-division at the boundaries being used, so that all blocks are continually halved, resulting in blocks with sides of size "x", "x/2", "x/4", "x/8", … "$x/2^n$", where "x" is the original maximum block size (parent block), and "n" indicates the maximum amount of sub-division to be allowed. This is the method Surpac uses.

The flexible method allows sub-division to vary depending upon the angle of intersection of a particular block with boundary surface controlling the sub-division. The sub-division is infinitely variable, allowing a better volumetric interpretation of the boundary surface, producing fewer blocks for the same level of accuracy compared with the octree method. This is the method Datamine uses.

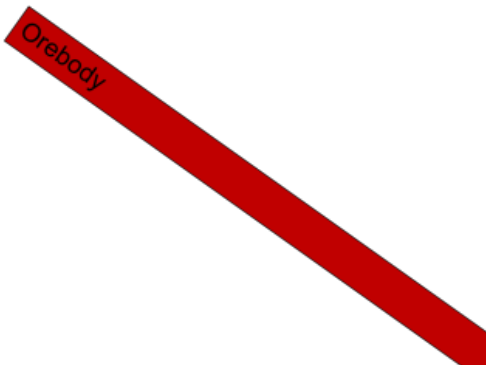
Surpac uses octree sub-division, whereas Datamine uses the flexible method; this is a major cause of incompatibility issues between the two types of models. (Note that Surpac has a "free block model" format to allow for the import and interrogation of a Datamine model.)

2.3. ROTATED MODELS

Some block modeling systems support rotated block models. A rotated model is one whose axes, and therefore cells, are rotated with respect to the coordinate system. It is particularly useful in the situation where a stratified ore body is dipping or plunging. The model cells provide a much better fit to the ore body when the model is rotated, as can be seen from the following figures.

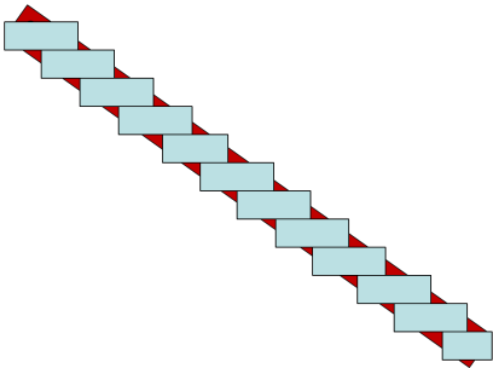
If this is your ore body shown in Figure 7:

Figure 7: Cross-section of an ore body plunging obliquely



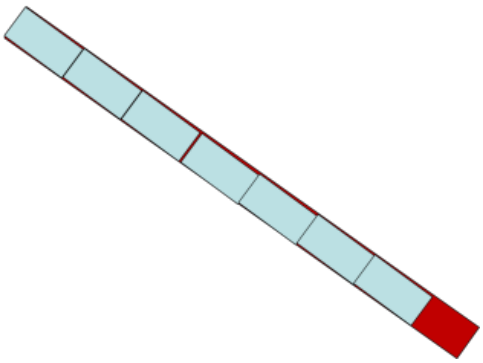
Then, a normal orthogonal unrotated block model would end up with the ore blocks looking like those shown in Figure 8.

Figure 8: Cross-section of an ore body plunging obliquely with unrotated blocks



But if the block model is rotated, a much better representation of the ore body is possible with ore blocks looking like those shown in Figure 9.

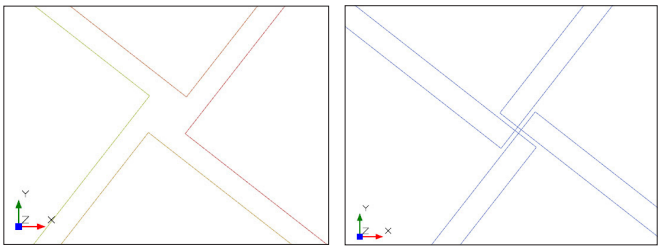
Figure 9: Cross-section of an ore body plunging obliquely with blocks rotated to Z-axis



Note that in Datamine block models, the model is stored in an unrotated format and only rotated on display or interrogation.

It is also important to note that in a rotated block model the rotated centroid positions are not systematic simple centroid values anymore. To maintain any sort of accuracy in relative block spatial positions when importing rotated block models, the centroid coordinates need to be supplied in eight- or nine-digit accuracy. Figure 10 shows two views of the block intersection points of a rotated block model that was imported with only two decimal accuracy. The result is a block model where blocks overlap or have gaps (voids) between them.

Figure 10: Close-up view of block corners of a rotated block model imported with insufficient decimal accuracy



If given data for a rotated block model with limited decimal accuracy, it may be possible (if the model is a regular model and not an irregular sub-celled block model) to mathematically unrotate the model, correct the approximate unrotated centroids to what should be the true centroids (for example an unrotated centroid of xx2.498673 was probably meant to be xx2.500), and then re-rotate the corrected centroids into a file ready for import into the software.

3. Block model "brands"

The most common block model types encountered in the mining industry are Datamine, Vulcan, Surpac, Micromine and MineSight.

Datamine format models are currently the best format for use in Deswik as they are supported by extensive commands for interrogation and manipulations[1]. Given this, we have discussed this file format more extensively than the other formats.

The Datamine format was the chosen format for Deswik when Deswik first started as we did not want to invent yet another proprietary block model format, and the general structure and format of Datamine models was publicly available and therefore well known. Many of the geological modeling packages therefore support exporting their models as Datamine models. Other model formats have had to be determined by judicious trial and error interpretation of what we think is how they store their data.

Deswik supports the direct import and conversion of Vulcan and Surpac models to Datamine format models. In addition, some basic functionality, such as solids interrogation into Deswik.Sched is supported for Surpac and Vulcan models in their native format. But any model requiring further calculations and manipulations will need to be in the Datamine format as the full suite of Deswik commands is only supported for Datamine models (and of course, for the new 2019 block model format being developed).

1. A new block model format is being developed by Deswik to overcome many of the size, speed and storage limitations of Datamine and should be available in early 2019. This file format will be compliant with the Open Mining Format (*.omf) format recommended by the Global Mining Guidelines Group (GMG).

For MineSight, Micromine and other unsupported model types, the best solution to importing into Deswik is to directly export the block models from the originating software package as Datamine format models. Alternatively, they can then be exported as CSV files, which can then be converted to a Datamine format model in Deswik.

(Advice: If you are importing a rotated block model from a CSV file, make sure you have X-Y-Z data in nine decimal accuracy as a lack of decimal accuracy will cause problems).

3.1. DATAMINE

Datamine block models will be recognized by their suffix: ***.dm.**

There are two major limitations of Datamine files that need to be understood:

(a) Datamine files only support eight characters as field names.

(b) Datamine files are limited to a total of 256 fields (if in default extended precision format).

The Datamine format is rooted in a long history. Datamine was founded in 1981 and uses the G-EXEC relational database management system developed by the British Geological Survey during the 1970s.

Datamine files are random access files stored as flat tables without any implied hierarchic or network relationships. The model structure is defined in a "model prototype" file and the spatial context of each block is stored as part of the record for each block using implicit positioning, which saves both storage space and processing time. This is done using the IJK indexing code (see Figure 11 and Figure 12), allowing rapid access by the computer program to any part of the model.

Some mathematics relating to the IJK code are:

$$IJK = NZ \times NY \times I + NZ \times J + K$$

The IJK can also be determined from the model coordinates system:

$$I = ROUND[(Xc-XParentINC/2)/XParentINC]*XParentINC – XmORIG)/XParentINC$$

$$J = ROUND[(Yc-YParentINC/2)/YParentINC]*YParentINC – YmORIG)/YParentINC$$

$$K = ROUND[(Zc-ZParentINC/2)/ZParentINC]*ZParentINC – ZmORIG)/ZParentINC$$

Where XParentINC, YParentINC and ZParentINC are the X, Y and Z sizes of the Parent Blocks (to any subcells).

The model prototype structure uses the fields shown in Table 1.

Table 1: Datamine block model prototype structure fields

FIELDS	DESCRIPTION
XMORIG, YMORIG, ZMORIG	XYZ origin of the model. Datamine sets the origin with respect to the corner of the first parent cell and NOT its centroid.
XINC, YINC, ZINC	XYZ cell dimensions (increments).
NX, NY, NZ	Number of model parent cells in XYZ. Datamine allows a value of one for modeling seams. The number of cells, in combination with the cell parent size, defines the extent of the model dimensions.
XC, YC, ZC	XYZ cell centre coordinates.
IJK	Code generated and used by Datamine to uniquely identify each parent cell position within the model. Subcells that lie within the same parent cell will have the same IJK value.
I	Block (cell) position along the x-axis (zero "0" for the first position, and increasing by integer values).
J	Block (cell) position along the y-axis (zero "0" for the first position, and increasing by integer values).
K	Block (cell) position along the z-axis (zero "0" for the first position, and increasing by integer values).

Figure 11: Datamine IJK schema

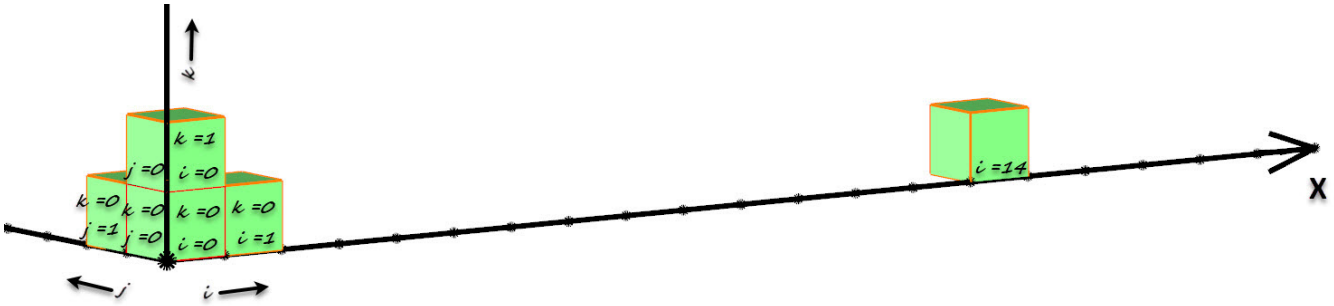
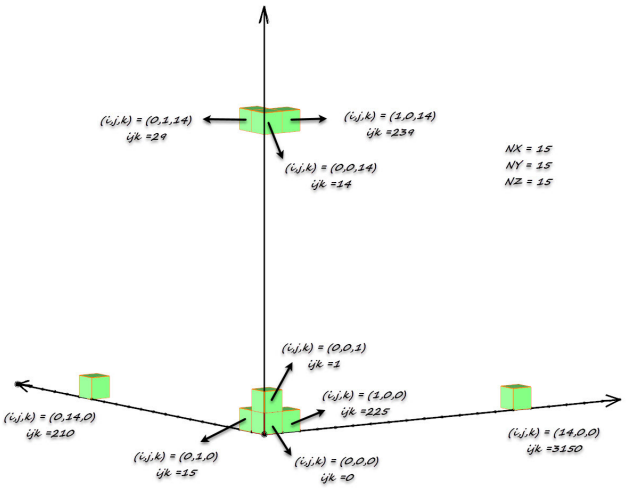


Figure 12: Datamine IJK schema



There are two versions of the DM format – single precision (SP) and extended precision (EP).

The original single-precision DM format was based on 2048-byte “pages”. (These are the Fortran records of 512 × 4-byte words). The first page contained the data definition while subsequent pages contained the data records.

There are two data types - text or alpha ("A") and floating point numeric ("N").

Integer items in the Data definition page are stored as Fortran REAL*4 or REAL*8 values in the single and extended precision formats respectively.

There are a few special numeric codes which are used within the data.

- -1.0 E30 = "bottom"; used as the missing data code for numeric fields also known as the “null value”. (For text fields, missing data is simply all blanks.)
- +1.0 E30 = "top"; and is used if a representation of "infinity" is needed.
- +1.0 E-30 = "TR" or "DL"; used if it is required to represent an assay value of "trace" or "below detection limit".

All text data is held in REAL variables, not the Fortran CHARACTER type, though the stored format is identical. This allows the use of a simple REAL array to hold a whole page buffer, and another REAL array to hold the whole of each logical record for writing or reading. This concept originated in the British Geological Survey G-EXEC system in 1972 and was the key to Datamine’s generality - rather than needing to pre-define specific data formats for every different combination of text and numeric fields.

The "extended precision" (EP) Datamine file format has pages twice the size of the "single precision" file format - 4096 bytes in length - and the page structure is simply mapped into 8-byte words instead of 4-byte words.

The "single precision" Datamine file format is effectively a legacy format, and hopefully will not now be often encountered. These files can only have 64 fields whereas the "double precision" files can have 256 fields. If a "single precision" file is encountered, Deswik does have a method of converting it to a "double precision" file. (Search the Help files in such a situation.)

The EP Datamine file format allows the full Fortran REAL*8 (or DOUBLE PRECISION), but for text data only the first four bytes of each double-precision word are used. The EP file structure is therefore inefficient in data storage terms for files which have significant amounts of text data.

Datamine block models have two “levels” of blocks: parent blocks and child blocks (sub-blocks or sub-cells). When a Datamine model is created, the user specifies the parent block size, which will be consistent for the life of the model.

During the process of creating a Datamine block model, sub-blocks are created along boundaries so that a parent block can have any number of child blocks, and they can be of any size. Each parent block can conceivably have a different number of child blocks.

3.2. DATAMINE - UNICODE

Datamine Unicode block models will be recognized by their suffix: ***.dmu**.

A major limitation with the Datamine file format is that it

stores all text in ASCII format, which falls apart when you are trying to work in a symbolic language like Russian, Polish, Japanese, Chinese, and so forth.

In order to service the required non-English language markets that Deswik has entered, it was necessary to enable the Datamine format to support "Unicode" (which did not even exist when the Datamine format was invented). Unicode is a standard like ASCII, but one that is much, much larger and provides a unique number for every character, no matter what the language.

Note that this Unicode format of Datamine is not supported by any other package other than Deswik, but it closely follows the Datamine format. By following the Datamine format for this modification, it could be implemented without making changes to any of the routines or functions that Deswik already had for Datamine model manipulation.

Note that a ***.dmu** block model has the following features:

(a) There is no limit on the size of the field name (used to be eight characters, now it can be anything).

(b) There is support for any language, directly encoded to the file.

(c) There is still a hard limit of 256 fields, but now your text field only counts for one of those fields. Previously, if your text column had a width of 20, it would count as five fields, so you can effectively squeeze more fields in now if you are using text.

(d) Variable text lengths are available. If you had a column with AAAA in it and AAAAAAAA, you would need to define beforehand that the column has eight characters. Now, it does not care about the number of characters (maximum or minimum) there are in a column.

The author's recommendation is that you should probably not use ***.dmu** files unless you actually have to. There are many more users using ***.dm** files, so any software bugs relating to block models are more likely to be found and fixed for ***.dm** files than for ***.dmu** files.

3.3. SURPAC

Standard Surpac models are identifiable by their suffix: ***.mdl**.

A secondary Surpac block model format is the 'free block model', identified by the suffix ***.fbm**.

Surpac uses the octree sub-division method, in other words. a regular method of sub-blocking, so that parent blocks must be divided into fractions of $1/2^n$, i.e. $1/2$, $1/4$, $1/8$, etc. The sub-blocking is defined when you create the model. However, the actual division of blocks is not performed until it is needed. This means that the number of blocks is always the minimum possible.

Surpac also has the concept of a "super-block" where identical blocks are agglomerated until no further agglomeration can be done; this means that the stored model size of a Surpac block model can be much smaller than a Datamine block model.

The different sub-cell sizing regimes mean that many Datamine models cannot be converted to a native (mdl) Surpac block model if irregular sub-celling is present. Surpac provides the "free block model" format for importing and manipulating Datamine block models in Surpac. (But even in Surpac this is restrictive in what can be done with such a model).

If given a "***.fbm**" block model, it is best to go back to the source and see if the original Datamine "***.dm**" block model can be obtained, or if you have access to Surpac, it can be exported as a "***.dm**" file. Otherwise, arrange an export of the data in "***.csv**" format and convert in Deswik to a Datamine model.

As of March 2018, Deswik will support an "***.fbm**" free block model. However what can be done with such models is limited.

Note that Surpac fields can also be of type "**Calculate**". This type of field is only calculated when the field is used - using an equation that populates the description column of the field. Again, as of August 2018, Deswik will support Surpac models that use calculated fields (in release build **2018.3.433** upwards).

While Deswik will support the direct use of a Surpac model in tools such as interrogation, slice display (not shell display), querying of a cell and reading for the pit design tool, the command set available for use and manipulation is very limited. It is therefore recommended that Surpac models are converted to Datamine format as this will allow greater flexibility and usability in Deswik.CAD, by allowing the ability to add fields used in the checking of the block model processes.

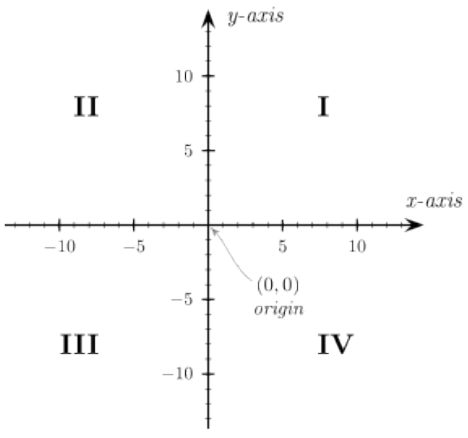
In converting a Surpac model, note that Surpac allows models to be built in any of the four cartesian quadrants (I, II, III and IV) as shown in Figure 13, without needing to use negative coordinates. To import such a model into a Datamine format, Deswik software provides, during the import process, options to:

(a) Flip the X-Y axes.

(b) Multiply X by "-1".

Limitations of this method include:

Figure 13: Cartesian quadrants



Note that Deswik does not support v1.0 Surpac block models; routines have been built based on interpretation of v4.0 Surpac models. Such models will need to be imported using the "*.**csv**" import process.

3.4. VULCAN

Vulcan block models can be identified by the file extension suffix *.**bmf**. There may also be an associated *.**bdf** file, which is a block definition file (used in the creation of the block model, but not needed once the block model has been created).

There are several versions of the Vulcan block model.

The original Vulcan block model format (Classic) stored all data for all blocks. This meant that if you had a million blocks with the default value, your block model file had written the default value one million times. This resulted in a very large model file.

The 'Extended' format writes all default information to the header and then references the header for any blocks with default values. This means that the block model file will write this value to the header once (not a million times) if you have a million blocks with the default value in the "Extended" format. This method saves a significant amount of file space.

Deswik supports the **bmf** v6.0 version of Vulcan block models.

As for Surpac models, there is limited functionality for Vulcan models in Deswik; they can be directly interrogated, displayed (slicing only) and used in the pit design tool.

The block model files cannot however be altered or manipulated, and there are no plans to support the alteration of the Vulcan block models.

The data types for Vulcan block models are:

- *Name*: This is for string-type data (i.e. geologic domains). The data is stored in the block model as integer data and then converted back to the name values using a translation table.
- *Byte*: This is an integer value between 0 and 255. The byte variable type takes up one byte of memory.
- *Short*: This is an integer value between -32,768 and +32,767 requiring two bytes of memory.
- *Integer*: This data type records integer values between positive and negative two billion. It uses four bytes of memory.
- *Float*: This is a real number using four bytes of memory. It can store up to seven significant figures.
- *Double*: This is a real number using eight bytes of memory. It can store up to fourteen significant figures.

3.5. MINESIGHT

A MineSight block model will generally have a *.**dat** suffix (Micromine block model files also use the *.dat suffix). Note that MineSight uses the *.**dat** suffix for other types of files as well, such as raw drill hole data and project control files.

Other file types from MineSight include:

- *.**srg** (polyline files)
- *.**msr** (MineSight Resource format files), used to hold geometry object data (strings, surfaces, solids).

Traditionally, MineSight block models have used a whole block modeling system (fixed block sizes with no sub-celling) with model items identifying the percentages of the block within geological domain contacts. Most MineSight models encountered will still be of this type. This approach allowed very large mines to be modelled within computing memory and storage limitations of the past, and hence was popular with large mines (and for many years the only way large mines could have a single block model cover their whole site).

Since 2013, MineSight has offered sub-blocking (sub-celling) which generates an additional file associated with the 3D block model that is only applied to sub-blocked areas and items.

3.6. GEMS

Geovia GEMS block model files will have the suffix *.**txt.**

GEMS uses a partial percent model approach with no sub-celling.

Unfortunately, Deswik knows very little about GEMS files.

3.7. MICROMINE

A Micromine block model will have the suffix *.**dat** (the same as MineSight files).

It can be converted directly in Deswik to a Datamine format. From version 2018.4 the extended (rotated) format will also be supported. (As of November 2018, this is in process of being bug fixed).

No facilities are supplied to use a Micromine block model file directly in Deswik; they must be converted to Datamine format.

4. Block Model Types

Most of the block model types differ by:

a. How assayed samples are used to populate the blocks (in other words, how sample grades are interpolated/ extrapolated into a block).

b. How the estimates within a block are presented.

c. How blocks are physically constructed or represented.

With respect to how samples are used to populate blocks, all block models use surrounding sample data to inform an estimate of each block, as shown diagrammatically in Figure 14. How to weight (λ in Figure 15) and average these surrounding samples is the basis of differences between the models discussed in the following section.

Figure 14: Diagrammatic of the estimation of samples into a block

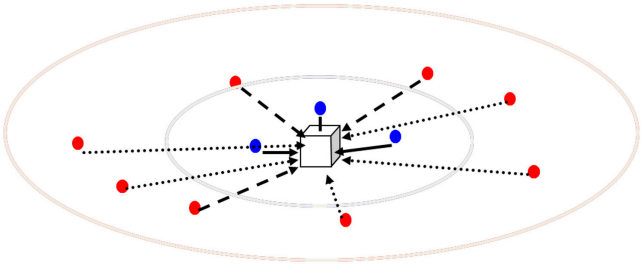
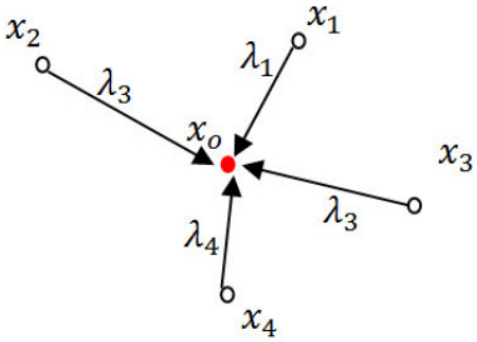


Figure 15: Sample weights for four sampled points located around the point xo where estimation occurs



4.1. INVERSE DISTANCE MODELS

Inverse distance weighted (IDW) models are one of the earliest and simplest models around. Some geologists will still use them – commonly when there is a high nugget effect and variograms are difficult to determine. They also use it to compare it to one of the other "higher order" methods to ensure nothing has gone astray with those methods, as the results globally should still be similar: ±5% or so.

The rationale behind the IDW model is that closer samples are more like the block grade than samples further away. So closer samples get more weighting and are weighted by an inverse of the distance – usually, but not always, raised to a power of two (Inverse Distance Squared) or three (Inverse Distance Cubed).

The inverse of the separation distances is rescaled, so they sum to one – ensuring that the estimated grade is unbiased when compared with the sample grades.

4.2. ORDINARY KRIGED MODELS

Ordinary Kriging (OK) was developed by Danie Krige (a South African mining engineer) and Georges Matheron (a French engineer).

A key feature of the OK method is that it uses any spatial correlation that may exist between sample points to inform the weighting of the effects of sample points on a prediction point. The weights are generated by the "variogram" for the geological domain for the block being estimated. In essence this is a spatial-based regression approach to obtaining the "best" weighting to apply to the samples informing the block estimate.

The variogram is the statistical function that describes the spatial variability of some measure (for example grades) and is calculated using a measure of variability between pairs of points at various distances apart from each other.

When we analyse pairs of samples separated by a specific distance, we will usually find that at smaller distances, the differences between those pairs of samples are less than when the samples are further apart. The grades of the sample pairs are related to each other, and the strength of that relationship varies with distance between the samples.

The resulting variogram describes the variability between points as a function of distance.

It is usual to find that the nature of the variability will differ with direction.

Because this process of calculating and using the variogram is statistics in a geospatial framework, it is referred to as "geostatistics".

The OK method was also developed to address the volume-variance effect. The volume-variance effect describes the increase in grade dilution as we select larger volumes; estimated high-grade blocks have lower grade than predicted and estimated low-grade blocks have higher grade than predicted. Also, the larger the volume the lower the variability in grades (differences between the highest and lowest grades distributed through the deposit).

The implications of the volume-variance effect are that estimates need to be adjusted to reflect the volumes that will be mined when reporting from a resource model with an applied selectivity criterion (e.g. a cut-off grade).

In summary, the OK method addressed two conditions:

- Least overall difference between predicted grade and actual grade,
- Unbiased estimate (sum of sampling weights equals one).

Given an appropriate variogram model, OK will outperform IDW because the estimate will be smoothed in a manner conditioned by the spatial variability of the data (known from the variogram).

4.3. LINEAR VS NON-LINEAR METHODS

Ordinary Kriging and Inverse Distance Weighting are "linear" estimation methods. A linear interpolation method is a method where the weights assigned to each of the N sample locations inside the estimation neighbourhood are independent of the specific data values at these locations.

Non-linear geostatistical estimators contrast with linear estimators in that they allocate weights to samples that are functions of the grades themselves; in other words, they are not solely dependent on the location of data. A non-linear method will attempt to estimate the proportion of small blocks or "selective mining units" (SMUs) that exceed a given cut-off value within a larger block (or "panel").

In the situation when only wide-spaced drilling is available, properly implemented linear estimation techniques can generally be expected to produce grade-tonnage relationships that are over-smoothed compared to final production estimates (and production itself) (De-Vitry, Vann & Arvidson, 2007). This yields locally inaccurate predictions of the recoverable tonnes and grade above a cut-off grade. The smoothing is partly a function of the drilling density, but also depends on block size, search distance and variogram type and parameters.

Over-smoothing in an OK model is normally controlled by reducing the maximum number of composites (i.e. aggregated samples on a drillhole) used in the estimation of a block, to the point where OK is no longer a good local estimator and becomes increasingly more "conditionally biased". The resulting models are usually a compromise between a desired global SMU distribution and using enough composites to ensure good local estimation.

In addition, when dealing with a strongly skewed sample distribution, for example many gold, tin and uranium deposits, estimating the mean by a linear estimator (for example by OK) is risky. In effect, as the weights do not depend on the sample grades, the presence of extreme values can make any linear estimate very unstable.

According to the block modeling literature (for example Caers, 2000; Journal, Kyriakidis and Mao, 2000) it is mathematically impossible to obtain a single estimation map (linear estimate) that is both locally and globally accurate. When smoothing of the estimate is unacceptably high, it is generally considered that a non-linear method might give a better estimate.

When using non-linear estimation for recoverable resources estimation in a mine, the panels (parent block) should generally have dimensions approximately equal to the drill spacing, and only in rare circumstances (in other words strong continuity) can significantly smaller panels be specified.

There is a number of non-linear methods currently being used in the mining industry. They include:

a. Disjunctive Kriging (DK) (Matheron, 1976; Armstrong and Matheron, 1986a, 1986b);
b. Indicator Kriging (IK) (Journel, 1982, 1988) and variants (Multiple Indicator Kriging (MIK), Median Indicator Kriging, and so forth);
c. Probability Kriging (PK) (Verly and Sullivan, 1985);
d. Lognormal Kriging (LK) (Dowd, 1982) and its generalisation to non-lognormal distributions; Multigaussian Kriging (MK) (Verly, 1983);
e. Uniform Conditioning (UC) (Rivoirard, 1994);
f. Residual Indicator Kriging (RIK) (Rivoirard, 1989).

In commercial industry practice, the MIK method is the most common of the non-linear estimation methods, although occasionally a UC model may be encountered.

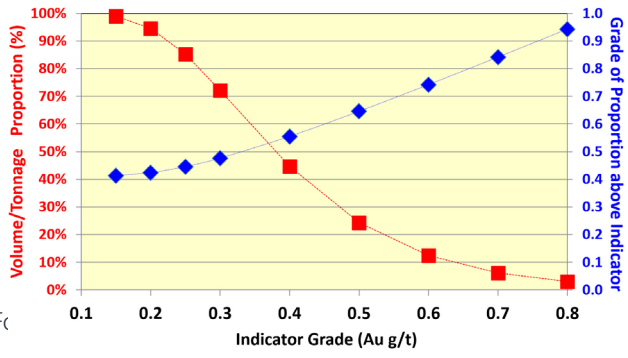
It should be noted that a number of practitioners hold that non-linear methods cannot result in estimates that can be considered as Measured in the JORC Code (2012), because of the uncertainty of the location of the SMU-sized ore blocks within an estimate panel. Although the decision to use a non-linear estimate is often a result of a lack of knowledge of geological boundaries within a panel, this may or may not be material to the overall ore tonnage estimate when considering the panel size with the mine production scale. This is a matter for the Competent Person to assess, but should be a conscious additional consideration in the assessment process.

4.4. MULTIPLE INDICATOR KRIGED (MIK) MODELS

MIK is the most common of the non-linear resource modeling techniques used. It will be discussed in detail here because it is a more difficult model to use appropriately than an Ordinary Kriged model which is straightforward in use and interpretation, and with which more of your colleagues are likely to be familiar with.

MIK estimation results in a resource model where each block in the estimate has a probabilistic estimate of tonnage and grade, which is presented as an expected tonnage proportion and an expected grade above a number of cut-off (or "indicator") values for each block. Effectively it is like having a tonnage-grade curve available for every block in the model, as shown in Figure 16.

Figure 16: Example of MIK model tonnage-grade distribution for a single block



Fc

Table 2 (a three-value subset from a full set of usually 10 to 15 values).

Table 2: Example subset of indicator values, proportions and grades

INDICATOR CUT-OFF GRADE	PROPORTION ABOVE	GRADE ABOVE
⋮	⋮	⋮
0.2	0.61	0.53
0.3	0.45	0.68
0.4	0.31	0.95
⋮	⋮	⋮

The indicator distribution is usually supplied as it was determined - in the form of a cumulative grade-tonnage curve, which you may see referred to as the CCDF – or conditional cumulative distribution function.

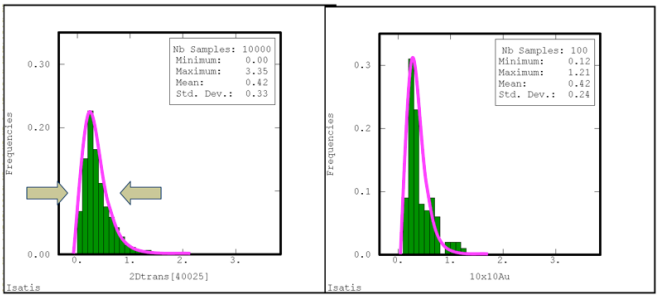
The indicator values (cut-offs for the distribution in each block) are often at regular grade intervals but get closer together in the upper grade portions. Some practitioners state that the indicators should be chosen to give approximately the same amount of metal in each of the indicator class intervals, while others chose indicators that correspond to various cut-off grades of interest.

The model is produced by imposing on the estimate for each block an uncertainty distribution around the estimate, based on an approximation of the distribution of sample grades in the neighbourhood of each block.

The model variance is then adjusted according to a volume variance correction (also known as a "change of support" correction). This produces an approximation of the distribution of grades at the scale of the chosen SMU, where the SMU is taken to approximate the minimum practical mining unit.

Since the variance of the grades of SMU size blocks is much less than the variance of the grades of the small drilling samples that the initial estimate is derived from, the support correction compresses the distribution, as shown in Figure 17. In practice, we see that the histogram of samples usually has a much longer "tail" than the histogram of the mining blocks.

Figure 17: Example of compression of distribution of grades for raw samples to SMU samples



Following the support correction, the portion of the distribution above a selected cut-off grade changes; specifically the tonnage above the cut-off grade (which is usually well above or to the right of the modal value) will get much smaller for the SMU distribution compared to the original assay samples distribution. Thus, the grade-tonnage curve is very much a function of support chosen by the geologist who built the model. (Note that this may be done prior to any decisions by the mining engineer with respect to likely scale of mining and size of equipment).

In the literature on MIK modeling, this alteration in the tonnage and grade above a cut-off grade is often considered to reflect the impact of ore loss, dilution and expected mining recovery, so that these are built into the estimates of the resource for blocks of the selected SMU size. However, it should be noted that this is not the case for all sources of dilution and loss (only those related to geological distribution within the modeled SMU) (Bertinshaw & Lipton, 2007).

MIK is useful when a deposit has spatially integrated populations (for example, cross-cutting structures with multiple phases of mineralization). It is a method that tends to be used when further domaining is not practical or possible, or the drill density is insufficient to describe the geological features in detail. However, Coombes (2008) maintains that MIK "should NEVER be used in place of good geology and domaining."

4.4.1. SOME MIK TERMINOLOGY YOU NEED TO KNOW

Panels:

The basic unit of an MIK block model is a panel that normally has the dimensions of the average drill-hole spacing in the horizontal plane.

The panel should be large enough to contain a reasonable number of blocks or SMUs (about 15).

SMU (Selective Mining Units)

The SMU is the smallest volume of rock that can be mined separately as ore or waste and is usually defined by a minimum mining width.

As a user of the block model, know what SMU the geologist has used. For example, the author has seen models using Z-values less than the bench height, when the mine always mines by full bench height. This guarantees incorrect results if the model is used without further post-processing of the model by the mining engineer.

The SMU is usually significantly smaller than the sampling grid dimensions, in particular at exploration/feasibility stages.

Support

Support is a term used in geostatistics to denote the volume upon which average values may be computed or measured. When there is a large nugget effect, or (equivalently) an important short-range structure, then the impact of change of support will be pronounced.

E-Type

The E-Type grade is the average grade of the panel (including waste) and is derived from the combination of all bin grades and proportions: the sum of the proportions multiplied by the average sample grade. (Note that the E-Type grade is not necessarily equal to the "zero" indicator average grade as the E-Type grade is calculated prior to change of support modifications.)

4.4.2. WHEN YOU MIGHT SEE MIK USED

MIK models are reasonably common for gold mines run by Australian companies. They were also adopted by Newmont in its in-house software platform, beginning in 1988 for their North American mines (gold).

Indicator methods are known to deal with the problem of estimating extreme grades more successfully than traditional linear methods, such as OK. So, you will see these models used at deposits where sample grades show the property of extreme variation and consequently where estimates of grade show extreme sensitivity to a small number of very high grades. Hence, they are used in a lot of gold operations.

An overall list of situations of when you may see an MIK model is for mineralization styles characterised by:

- Poor boundary definition
- High grade variability
- Low grade continuity
- The presence of extreme values
- The presence of multiple populations.

4.4.3. SOME IMPORTANT ISSUES AND LIMITATIONS WITH MIK

There are several recognized issues with MIK models:

1. Visualization Difficulties

   Unlike an OK model, an MIK model cannot be plotted with a single grade on a block for comparison to drilling (except for the E-type grade value).

   Geostatisticians and geologists therefore have difficulty in visually validating MIK estimates and must rely almost exclusively on statistical validations.

2. Unknown Ore Location within a Panel

   The proportions in the conditional cumulative distribution function (the tonnage-grade curve for each block) are probabilities. The proportions do not tell us where the ore will be mined within the panel. It simply tells us the proportion.

   Grade control is required to locate that proportion. So, in general, MIK models are not particularly useful for planning of selective underground operations and tend to be limited to large-scale low-grade bulk open pit operations.

   There is also an assumption of "free selection" within a panel, i.e. that all SMUs above a cut-off grade can be mined regardless of their relative locations. This is not necessarily true; there will likely be situations where isolated SMU-sized blocks will end up being sent to waste (and vice versa, isolated SMU-sized waste blocks included in the ore).

3. Less than SMU-sized proportions

   Although MIK methods are supposed to have "change of support" done to the SMU size, you will almost always find indicator proportions (especially upper ends) that imply a volume proportion above a cut-off grade that is less than the SMU size being used.

   This requires some post-processing before the model is used. It is recommended to zero these proportions out before use to prevent accumulation of small effectively unrecoverable tonnages into "recoverable" tonnages over larger volumes, such as benches or domains. These small proportions are not mineable in practice.

   For example, for a 20m × 20m × 10m (4000 m3) panel, with an SMU size of 5m × 8m × 10m (400 m3 or 10% of the panel), if the indicators are as shown in Table 3, it can be seen that there are two indicators ("1.1" and "1.2") for which the proportion above the indicator is less than a SMU size block.

Table 3: Example subset of indicator values, proportions and grades, with less than an SMU size above some of upper indicators

INDICATOR CUT-OFF GRADE (G/T)	PROPORTION ABOVE INDICATOR	GRADE ABOVE INDICATOR (G/T)	VOLUME ABOVE INDICATOR (M^3)	% OF SMU ABOVE INDICATOR
⋮	⋮	⋮	⋮	⋮
0.8	0.30	1.1	1200	300%
0.9	0.17	1.25	680	170%
1.00	0.10	1.5	400	100%
1.1	0.06	1.8	240	**60%**
1.2	0.04	2	160	**40%**

The recommended correction to remove the sub-SMU-sized proportions is shown below in Table 4. This correction has effectively resulted in "loss" if the ore cut-off grade happened to be 1.1 g/t. If the ore grade cut-off was for example 0.9 g/t, then no effective change in ore tonnage would be noticed (for this particular block).

Table 4: Example subset of indicator values, proportions and grades, adjusted so that no indicator proportion less than an SMU size

INDICATOR CUT-OFF GRADE (G/T)	PROPORTION ABOVE INDICATOR	GRADE ABOVE INDICATOR (G/T)	VOLUME ABOVE INDICATOR (M^3)	% OF SMU ABOVE INDICATOR
⋮	⋮	⋮	⋮	⋮
0.8	0.30	1.1	1200	300%
0.9	0.17	1.25	680	170%
1.00	0.10	1.5	400	100%
1.1	**0.00**	1.8	0	**0%**
1.2	**0.00**	2	0	**0%**

There can be similar problems at the lower end indicator values with "unrecoverable" waste smaller than an SMU size that will in fact be mined as dilution with the ore. If the volume of waste (below a cut-off indicator value) is less than SMU size (as for the 0.50 g/t indicator in Table 5), then add that waste into that indicator bin and make the proportion and grade the same as that of the whole panel (Table 6).

Table 5: Example subset of indicator values, proportions and grades, with less than an SMU size below an indicator

INDICATOR CUT-OFF GRADE (G/T)	PROPORTION ABOVE INDICATOR	GRADE ABOVE INDICATOR (G/T)	VOLUME ABOVE INDICATOR (M^3)	% OF SMU ABOVE INDICATOR
⋮	⋮	⋮	⋮	⋮
0.40	1.00	0.55	0	0%
0.50	0.96	0.8	160	**40%**
0.60	0.68	0.85	1280	320%
0.70	0.45	0.98	2200	550%
0.80	0.3	1.12	2800	700%

Table 6: Example subset of indicator values, proportions and grades, with less than an SMU size below an indicator – adjusted so that no indicator proportion less than an SMU size

INDICATOR CUT-OFF GRADE (G/T)	PROPORTION ABOVE INDICATOR	GRADE ABOVE INDICATOR (G/T)	VOLUME ABOVE INDICATOR (M^3)	% OF SMU ABOVE INDICATOR
⋮	⋮	⋮	⋮	⋮
0.40	1.00	0.55	0	0%
0.50	**1.00**	**0.55**	0	**0%**
0.60	0.68	0.85	1280	320%
0.70	0.45	0.98	2200	550%
0.80	0.3	1.12	2800	700%

4. Order Relation Problems

MIK models use different variograms for each indicator value, and because of this the variograms may sometimes be inconsistent from one cut-off to another. This can result in blocks in the MIK model for which more metal has been estimated above a higher indicator value than above a lower indicator value.

This of course cannot physically happen – as cut-off grades increase, the contained metal must decrease. Such a problem is referred to as an "order relation" problem.

There are three conditions of consistency that must be met by the CCDF for each block:

- The proportion should not increase with increasing indicator cut-off.

  For example, if the proportion at 0.5 g/t indicator is 0.6, the proportion at 0.6 g/t indicator cannot be 0.65.

- The contained metal should not increase with increasing indicator cut-off.

  For example, for a panel of 4000 m^3 and a density of 2.7, if the proportion and grade at 0.5 g/t indicator is 0.6 and 0.9 g/t (giving contained metal above 0.5 g/t cut-off of 5,832 grams), the proportion and grade at 0.6 g/t indicator cannot be 0.55 and 0.99 g/t, as this would give a contained metal above 0.6 g/t cut-off of 5,881 grams, which is greater than the metal above the lower value cut-off indicator.

- The grades of increments should be within indicator cut-off boundaries

  For example, if on doing the maths for the grade of the material between two indicator values, say 0.5 and 0.6, the grade of the material in that indicator bin must be between 0.5 and 0.6; it cannot, for example, be 0.61.

Order relation problems should be checked for when a model is delivered. Do not just assume that it has been done correctly by the geologist that has handed it over. (It often is not.)

Most commercial and public domain MIK programs correct order relation problems by smoothing the grade-tonnage vector of a panel if they violate order relations.

If you discover order relation issues, hand the model back to the geologist. If the issues are minor in number, the geologist can fix the problems by smoothing (using an averaging function, not an upwards or downwards adjustment process). If the order relation problems are numerous, it indicates that there is an inherent distortion of the grade-tonnage relationship being estimated by the MIK model in use – and there is a problem in the MIK method being used.

5. Change of Support Method Inappropriate

Change of support is not "built in" into any MIK software. The model builder must select a suitable method.

Historically there are several methods used for the change of support (without going into the mathematics) called:

- Affine
- Lognormal
- Indirect Lognormal
- Gaussian
- Conditional Simulation

The methods mainly differ in how they treat the skewness of the data. (The Affine corrections retain the same skewness as the raw data. The Gaussian removes all skewness to a Normal (or Gaussian) distribution; the others do something in between these two extremes.) The different methods can easily result in a different distribution, so it begs the issue as to which method should be used for a "correct" result.

All the methods have some major commonalities:

1. They leave the mean unchanged.
2. They apply a variance adjustment.
3. The resulting block distribution must be less selective (referred to as "Cartier's Relation").

It should be noted that Affine corrections are perhaps the most widely used but are no longer considered appropriate. While they reduce variance, they do not de-skew the distribution. The shape of the distribution of SMUs is identical to that of samples. In situations of high skewness (high nugget effect or pronounced short-scale structure in the variogram of grades) such support corrected models perform particularly badly (Vann, 2005).

In contrast, the appropriateness of direct or indirect lognormal corrections is very distribution dependent; conditional simulation is often perceived as too complex and costly in time, and Gaussian methods (that assume a normal distribution - totally de-skewing the raw data distribution to be symmetrical) are probably true only for very high nugget situations (Vann, 2005).

Whatever the method used, there is no guarantee that the corrections applied at a local level are consistent with the same type of correction applied at a global level.

6. Wrong SMU Size for Mine Planning

The SMU size selected by the geologist for the resource model may not resemble the SMU size decided upon by the mining engineer.

This will need some sort of modification if it is to be considered, or the model should be returned to the geologist to generate a new block model with the new selected SMU.

7. Practical Difficulties in Use

A major problem for MIK models is some practicality issues in their use. They are more complex to use as an input to open pit optimization, mine scheduling or detailed mine design because each block carries an approximation of the local grade distribution and the exact location of ore boundaries is not specified by the model.

Mining engineers will typically convert the model to a simpler model with a single grade, or at least a partials model with a predefined cut-off grade.

Additionally, the specific cut-off needed for mine planning may not align with indicator values, requiring some interpolation in order to be used.

8. Uncorrelated Multiple Elements Issues

MIK is also not ideally suited to deposits where multiple elements that are important revenue or penalty elements are to be modeled because the technique only models the distribution of a single variable. Unless all the variables are strongly correlated, it is not possible to evaluate a second or third variable against a cut-off grade specified for the primary variable (Bertinshaw & Lipton, 2007).

This can be a problem in high silver content gold mines, and in copper mines with a high gold content.

Additionally, this limitation makes MIK models poorly suited for iron ore deposits which typically require estimation of variables including Fe, SiO_2, and P, and bauxite deposits which require the estimation of Al_2O_3 and SiO_2.

9. Mean vs Median Top Indicator Value

The grade in the last indicator class (the top class) can have a substantial effect of the overall metal in the estimate. To limit the effect of extreme grade outliers on the estimate grade for the top class, it is common to use the median rather than mean grade of the estimates for the top indicator class, or alternatively use a trimmed mean (with an upper sample top-cut), or value corresponding to a hyperbolic or power fit to the upper-class data. The consequences of this choice, which is often arbitrary, can be very significant and strongly impact the estimation of the richest zones of the ore body (which may or may not reflect reality).

4.4.4. HOW TO USE MIK MODELS IN INTERROGATIONS

The most common way to deal with MIK models is to calculate the tonnage and metal within "bins" of interest: converting the MIK grade and tonnage factors from fractions above a grade to tonnes and metal between indicator grades (and from those two numbers the grade in each bin can be calculated).

This should be done first, for every grade bin and for every block, to check for order relation problems.

Additionally, do the following before using the model:

I. Make the "less than one SMU" adjustments to the CCDF for each block for both the upper ore end and the lower waste end.

II. Make any dilution/loss adjustments, although this may be applied to the post interrogated grade bins.

An example of how to calculate tonnes and grade for ore intervals is given below using a generic MIK indicator CCDF shown in Table 7.

Table 7: Generic MIK indicator table

INDICATOR CUT-OFF VALUE	PROPORTION ABOVE INDICATOR CUT-OFF VALUE	GRADE ABOVE INDICATOR CUT-OFF VALUE
i_0	p_0	g_0
i_2	p_1	g_1
i_3	p_2	g_2
i_4	p_3	g_3
i_5	p_4	g_4
i_6	p_5	g_5
i_7	p_6	g_6
i_8	p_7	g_7
i_9	p_8	g_8
i_{10}	p_9	g_9
i_{11}	p_{10}	g_{10}
i_{12}	p_{11}	g_{11}
i_{13}	p_{12}	g_{12}
i_{14}	p_{13}	g_{13}
i_{15}	p_{14}	g_{14}

If we assume the following cut-off values:

Waste / low-grade cut-off grade = i_5
Low-grade / medium-grade cut-off grade = i_8
Medium-grade / high-grade cut-off grade = i_{10}

If the panel volume = Vol and the panel in-situ bulk density = SG, then tonnage and metal for the three ore grade bins are:

Low-Grade: *tonnes low-grade* = $p_5 \times Vol \times SG - p_8 \times Vol \times SG$

metal low-grade = $p_5 \times g_5 \times Vol \times SG - p_8 \times g_8 \times Vol \times SG$

grade of low-grade = metal low-grade / tonnes low-grade

Medium-Grade: *tonnes medium-grade* = $p_8 \times Vol \times SG - p_{10} \times Vol \times SG$

metal medium-grade = $p_8 \times g_8 \times Vol \times SG - p_{10} \times g_{10} \times Vol \times SG$

grade of medium-grade = metal medium-grade / tonnes medium-grade

High-Grade: *tonnes high-grade* = $p_{10} \times Vol \times SG$

metal high-grade = $p_{10} \times g_{10} \times Vol \times SG$

grade of high-grade metal high-grade / tonnes high-grade (= g_{10})

The waste tonnage will be:

Waste: *tonnes waste* = $p_0 \times Vol \times SG - p_5 \times Vol \times SG$

If the cut-off grade being used does not coincide with a specific indicator value, then it will be necessary to insert a new "indicator" value at the appropriate point and to interpolate an appropriate set of values for the proportion and grade (and metal).

If a value cut-off is being used (for example, a net smelter return), it may be necessary to calculate tonnes, grades and metal for each and every indicator bin, calculate the revenue for each bin, calculate the costs for each bin, and determine whether their return is positive or negative for each bin. Then flag each indicator bin as ore or waste, and sum up the ore tonnes and metal for each block into a set of ore fields.

4.5. LOCALISED INDICATOR KRIGING / UNIFORM CONDITIONING

Localised Indicator Kriging (LIK) and Uniform Conditioning (UC) are uncommon types of models that are used to overcome some of the inherent problems in using MIK models. They are variants of the same objective – to remap MIK histograms into SMU-sized blocks within a larger panel block.

LIK/UC eliminates the un-mineable slivers of low or high grade when dealing with small tonnages for indicators that have small proportions (below the actual SMU size).

The LIK process involves creating an OK model using a block size that is at or near the SMU size. This model will likely be over-smoothed or conditionally biased.

The OK model is only used to locate the MIK distribution that will then be used to overprint the OK estimated grades.

The MIK histogram (the proportion of the block in each indicator bin) for each panel is then divided into evenly spaced tonnage bins where the number of bins is equal to the number of SMU blocks in the panel. The grade value for each block is then calculated by interpolation of the MIK histogram.

Once the panels are defined, the blocks in the OK model are ordered in a list by grade in increasing order from lowest to highest in each of the panels (the location of the blocks is not moved). Then the grades from the remapped histograms are placed into the blocks in the same order, replacing the OK value and transforming the distribution to that of the MIK model.

The SMU blocks within the panel have the same selective estimate basis as the parent MIK histogram but are now presented as SMU-sized OK blocks that can be more easily dealt with in the mine planning process.

4.6. CONDITIONAL SIMULATION (CONSIM) MODELS

Conditional simulation (ConSim) is in effect a spatial extension of Monte Carlo simulation. A series of potential model "realisations" are generated, representing a range of plausible possible models that are consistent with the known statistics of the grade variogram and grade histograms.

Practical use of such models in mine planning is still very much the realm of academics and researchers, so if presented with one of these models to use, it is recommended that a "long" discussion be held with the client /"requester" to

understand what it is they would like to be done with the model.

The purpose of the ConSim model is to characterise and reproduce the variance of the input data.

A simulation is called "conditional" if generated realisations are faithful to the sampled points. Specifically, a conditional simulation block model is claimed to simulate both the spatial and statistical characteristics of a deposit, thus being able to:

- Reproduce the variability of the input data.
- Reproduce the continuity of the input data.
- Measure the likelihood of the desired outcome (risk).
- Recognise that many equally likely models of reality exist.

In conditional simulation:

a. Grade is simulated on a dense grid of points.
b. The simulations are averaged into SMU blocks.
c. Tonnage and grade estimates are obtained by applying a cut-off to the SMUs.

The outcome is a series of equiprobable realisations as shown in Figure 18.

Although it is believed by geologists working in this field that the method will improve the understanding of potential geological uncertainty, which a single geological estimate cannot possibly provide, there are some major drawbacks which probably currently precludes the use of ConSim models in practice:

1. The method is a magnitude more time consuming than other methods.
2. There is no easy accepted means of using the ConSim results in mine planning. It currently requires multiple designs and schedules as shown in Figure 19.
3. There has been very little work, if any, on quantifying how well a given collection of realisations represents the total range of uncertainty in mine designs. Indeed, Dimitrakopoulos et al. (2007) state that "although the simulated orebody models are equally probable, the corresponding designs are not" (p.76).
4. Heidari (2015), using a known well drilled deposit, showed that the real model (an exhaustive data set) was closer to the edge of the spaces of uncertainty of the simulated models (using a sparser data subset) rather than the centres (so the "average" of the realisations was actually a poor indicator of the "truth").

Figure 18: Example of a number of model outcomes with ConSim

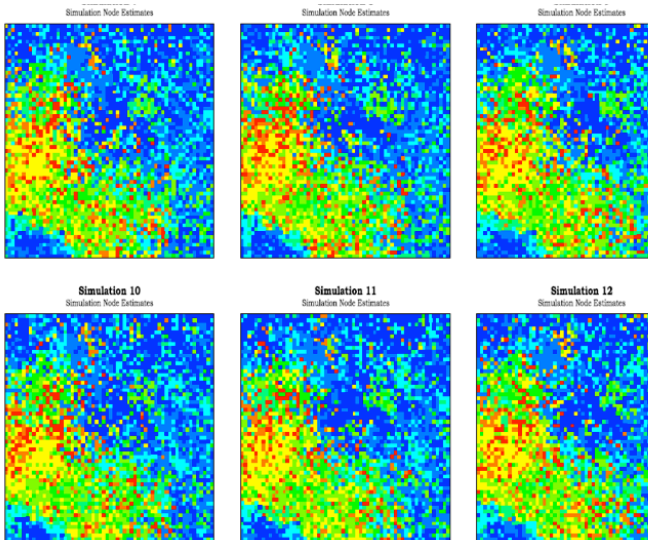
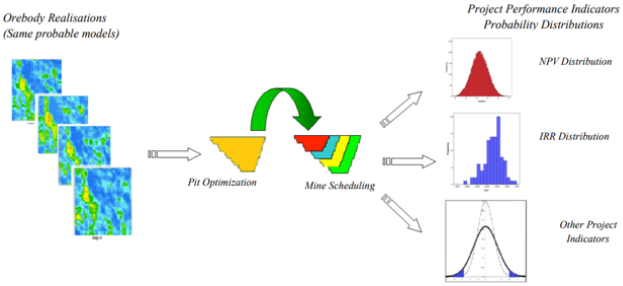


Figure 19: Risk-based method for mine planning using ConSim



(after Heidari, 2015)

4.7. GRIDDED SEAM MODELS

Gridded Seam Models (GSM) are used for stratiform deposits. Technically, they are not "block models".

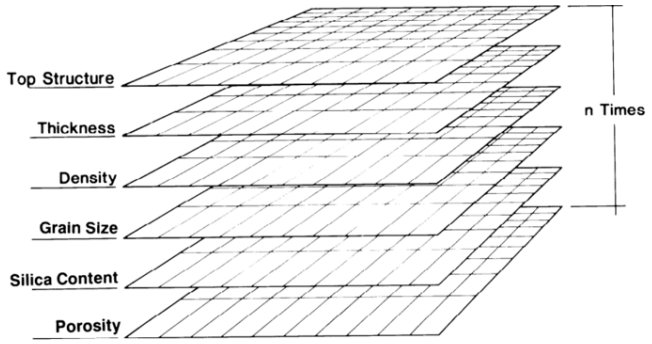
They have constant block dimensions in the X- and Y-direction (they can be rectangular) but only have one block per seam in the Z-direction and its thickness varies with the thickness of the seam.

They consist of a set of two-dimensional matrices, each grid representing a surface or value as shown graphically in Figure 20. The grid files are contained within a table type structure or as individual files with a proscribed naming convention, allowing the software to maintain an "understanding" of each surface's part in the whole.

The surfaces are the results of interpolation from a set of irregularly spaced data to a regular and fixed matrix called a "grid". The method of interpolation onto the grid can differ by software package.

There is generally a low disk space requirement as each grid point is defined by its position from a reference point. (In other words, there is no need to store all the easting and northing coordinates).

Figure 20: Structure of a gridded seam model



(after Badiozamani, 1992)

4.8. HARP MODELS

A Horizon Adaptive Rectangular Prism (HARP) model is a hybrid stratigraphic block model that tries to more closely match the shape of the interpreted boundaries than a block model.

A HARP model is specifically designed to allow stratigraphic units to be represented with virtually no loss of structural integrity by allowing the tops and bases of the individual HARP blocks to "bend" in concert with the input surfaces. They are thus able to follow and represent features such as complex normal, reverse and thrust faulting.

HARP models are a product of Maptek-Vulcan, developed and described in Odins (2011).

A HARP model has two main features that allow it to follow the stratigraphy closely:

1. An infinitely variable block height, so that the vertical extent of the block is exactly that of the horizon thickness at any given plan location.
2. The four corner points of the base and top of a block, along with a central fifth point have fully independent elevations.

Thus, each HARP model consists of ten points (five top and five bottom) which allow it to closely follow stratigraphic horizons as shown in Figure 21.

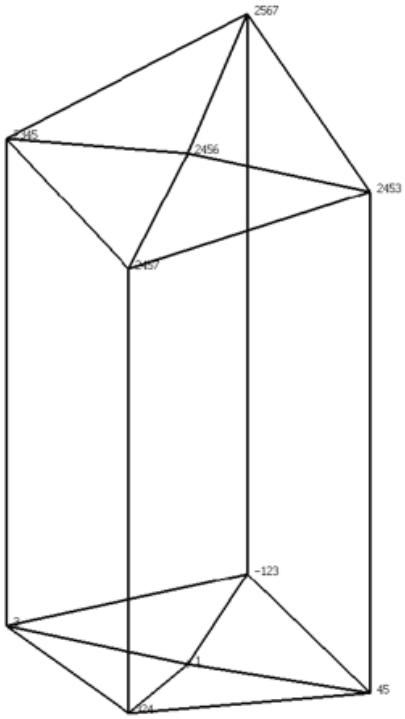
Each individual HARP block in the model "knows" its own horizon name, location, extents, volume and potentially thousands of associated parameters.

The blocks do not have to extend continuously from one horizon to the next. Sub-blocking can be used to create a block with a fixed thickness relative to the top or bottom surfaces.

HARP models retain virtually all the attributes of a standard block model. Users have at their disposal a wide range of grade estimation options, including, but not limited to, variography and unfolding, kriging, cokriging and simulation.

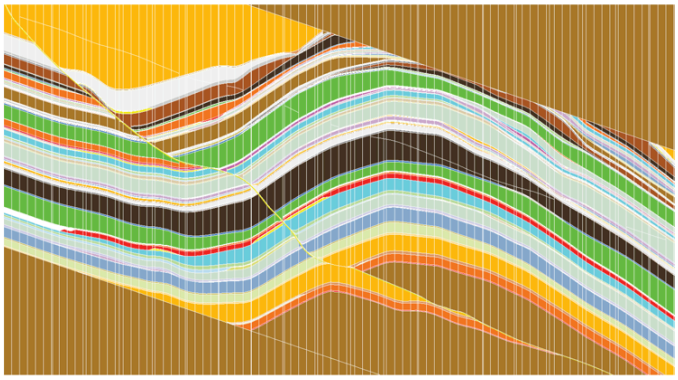
At this stage, Deswik does not support HARP models. It will be necessary to import the surfaces that were used to generate the Vulcan HARP model and then create and interrogate a Datamine model against the Vulcan HARP model using these surfaces.

Figure 21: Diagrammatic view of single HARP block, showing corner relative levels



(source: Odin, 2011)

Figure 22: HARP model representation of a reverse fault



(source: Odin, 2011)

5. Problems to be cognisant of

5.1. OVERVIEW

It is probably true that all block models you receive and use will be "wrong" in some way, but hopefully most will be accurate enough to be useful if used correctly.

Given that most models will be wrong to some degree, it is useful to understand where and how the model may be incorrect so that it can be judged as adequate or not.

A resource block model will only ever be as good as the geological foundations upon which it is built.

It is not the intention to turn the engineer reading this document into a geologist, but the author would encourage engineers to read and reflect upon the geological inputs into the models being used, and the modelling techniques used to create the models. It will enhance your work.

In the following sections, the author will touch upon some material to get the engineer started on understanding the limitations of the data they have received.

5.2. SOME SOURCES OF ERROR

Dominy, Noppe and Annels (2002) list five broad principal geological reasons for incorrect resource estimates:

1. Poor sample and assay quality data
2. A lack of detailed mine geology and fundamental understanding of the deposit
3. Poor interpretation of grade distribution characteristics
4. Poor understanding and application of computer-assisted estimation techniques
5. The failure to recognize the effect of selectivity and the change of support or volume-variance effect, namely, that mining needs to be controlled on the grades of large tonnage blocks and not small-volume samples.

In addition, there is the simple issue of a lack of sufficient data.

Dominy, Noppe and Annels (2002) also list a good set of reasons seen in practice for downgrading of resource/reserve estimates as a result of feasibility and operational due diligence studies/audits. These were found to usually relate to:

- Drill hole orientation with respect to the ore zone/dominant mineralization orientation
- Inadequate primary sample, sub-sample or pulp volumes
- Assay quality, accuracy and repeatability (precision and bias)
- Poor correlation between analyses of duplicate field splits
- Poor or variable core sample recovery
- Highly variable sample recovery
- Biased sampling techniques
- Presence of coarse gold
- Inappropriate and/or mixed drilling techniques (e.g., wet RC)
- Poor correlation between analyses from twinned holes (e.g., RC vs RC or RC vs DDH)
- Down-hole contamination/smearing
- Lack of down-hole orientation surveys in long holes
- Combination of sample data which are incompatible statistically or from the point of view of sample quantity and quality
- Problems with the compositing of raw sample data
- Poorly understood or demonstrated geological and/or grade continuity
- Inappropriate geological interpretation and geological modelling techniques
- Inappropriate resource estimation techniques
- Inadequate determination of bulk density of ore and waste
- Poor dilution and loss assessment
- Impractical mine planning assumptions (block continuity and practical mining shapes)
- Metallurgical recovery issues

AMC Consultants have a similar list of issues discovered during audits, which include:

- Clustered drilling data producing low data density at the margins of the mineralization
- Incorrect geological interpretations and assumptions
- Geological domains unrelated to grade continuity
- Too few or too many geological domains
- Insufficient data to characterise domain grade distribution
- Data clustering—declustering required to define grade statistics
- Mixed data populations resulting in ambiguous results
- Mixing of sample types, for example, old/new, RC/core, UG/surface
- Sampling or analytical errors
- Anomalous or unusual grades
- Grade cutting strategies
- Lack of analytical skills to characterise grade statistics
- Incorrect interpretation of results
- Poorly constructed wireframe estimation domains
- Inadequate data, variable data density, excessive extrapolation
- Working at an unsuitable scale
- Poor grade estimation method selection
- Inappropriate treatment of outlier values
- Inappropriate model controls/excessive smoothing
- Inappropriate block size for data density

- Bias in estimates, over smoothing
- Inappropriate incorporation of edge dilution/loss of mineral
- Inappropriate cut-off grade selection
- Estimates that do not reconcile with geology and raw data

(source: AMC, Lessons Learnt presentation)

The purpose of the above list is to illustrate that there are many reasons for a block model to be erroneous and there is little that can be done by mining engineers to identify this (except reconciliation with actual results from grade control drilling and plant performance). Just be aware that this circumstance is not rare.

It should be noted that a 10% error in grade estimation is not uncommon (for example, over a one-year period), and is generally regarded as acceptable. For an underground operation it is considered that, even for a good operation, production costs are at a level of at least 50% to 75% of the mine site revenue. It can be seen that even a 10% decrease in grade can translate to a 20% to 40% decrease in operating surplus. This is enough to make a financially stretched project non-viable.

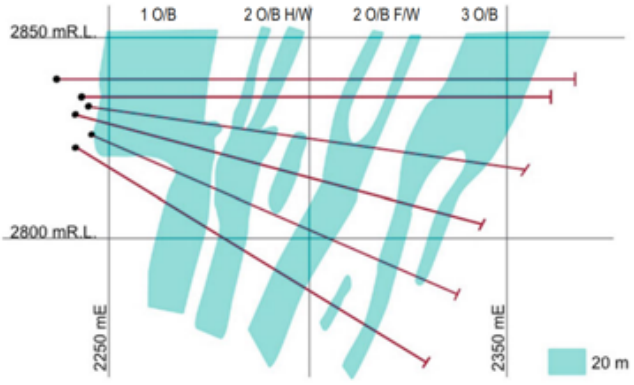
5.3. INSUFFICIENT DATA

In geological modeling there will always be an issue of "is there enough data?" The key is to be able to collect enough data (drilling spacing) to undertake reasonably accurate long-term planning, and to define better accuracy during mining using grade control drilling.

In the feasibility study stage, costs will usually prohibit a drilling density to define an entire ore body with good accuracy.

An example of an effect of "more geological data" is shown in Figure 23 from a study undertaken by Dowd and Scott (1984) for a complex group of three silver/lead/zinc ore bodies at the Hilton mine in north-western Queensland, Australia. Interpretation of the ore body boundaries at a 20m drill spacing is much smoother (less variable, more continuous) than the interpretation estimated from a 5m spacing.

Figure 23: Cross-sectional interpretation based on 20m and then 5m drill spacing



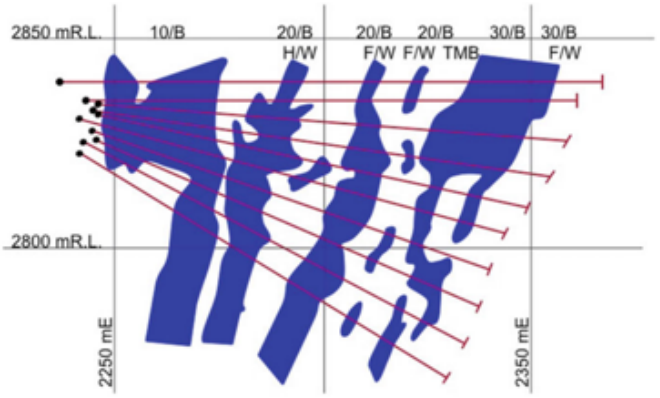
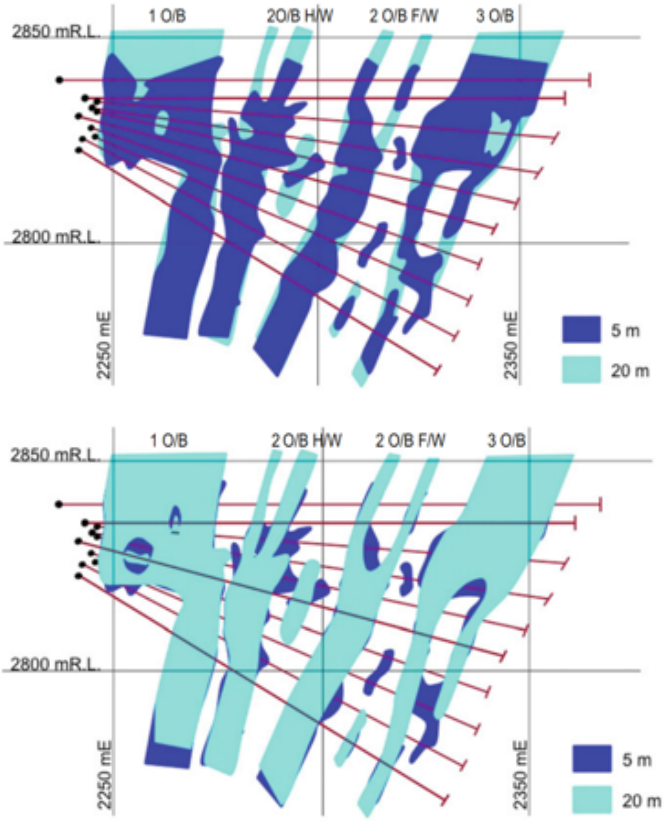


Figure 24 shows overlays of the 5m spacing interpolation on the 20m spacing interpolation and vice versa. The amount of dilution and loss that would be incurred in using the 20m spacing versus the 5m spacing interpretations can be seen.

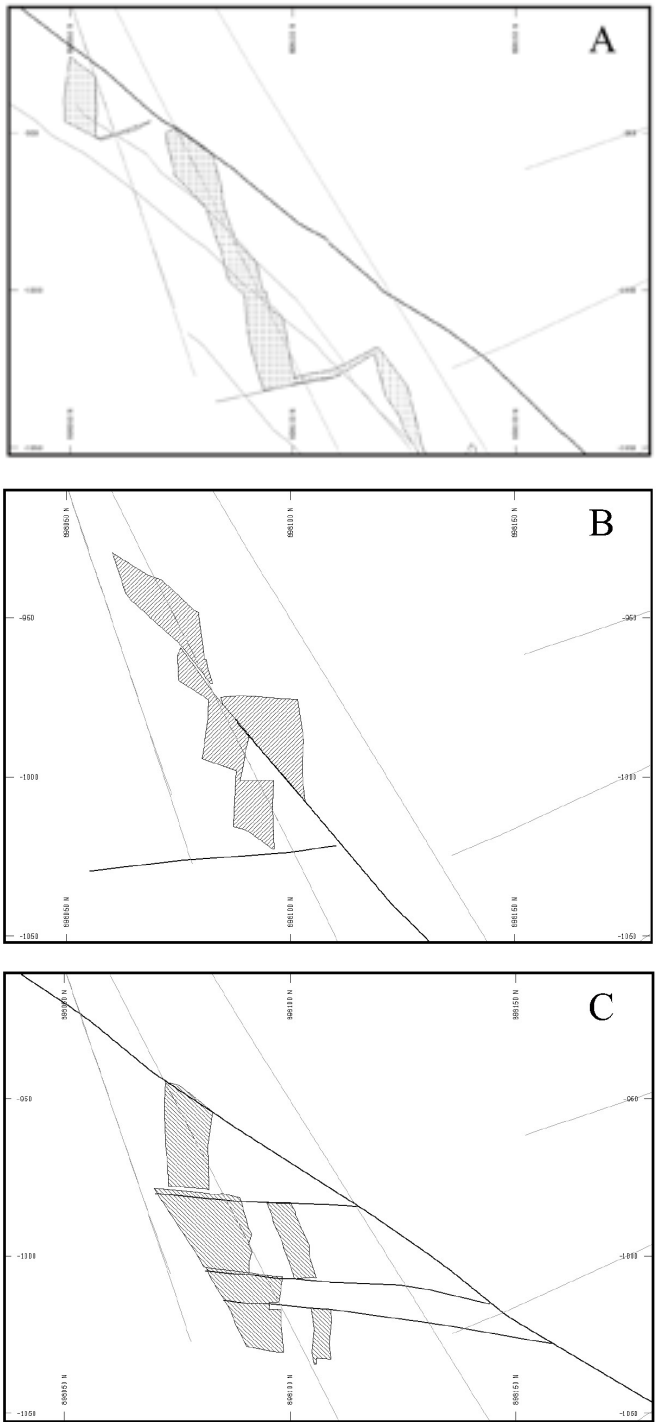
Figure 24: Overlay of 20m interpolation and 5m interpolation.

(a) If used 20m model, visible light blue represents dilution; (b) If used 20m model, visible dark blue areas represent ore loss



It should also be noted that even with the same data different geologists can give different interpretations, based on their experience and biases. An example of this is given in Figure 25 where three geologists, given the same drill hole data, have interpreted the ore lenses quite differently.

Figure 25: Cross-section of geological interpretations from three geologists with same data



(source: Jackson et al, 2003)

5.4. LACK OF FUNDAMENTAL UNDERSTANDING OF GEOLOGICAL CONTROLS

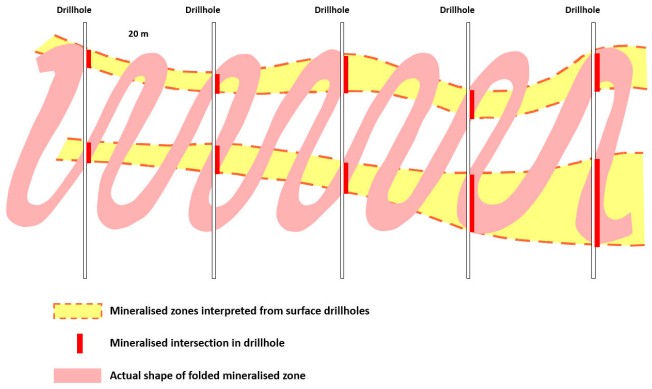
Geological models are only as good as the quality and interpretation of the data and the appropriateness of the scale on which the data are collected.

Grades are interpolated or extrapolated into blocks and the interpolation/extrapolation are typically constrained by wire frames of the deposit boundaries defined by drill hole logging, sampling and mapping of the deposit.

The Stekenjokk mine in Sweden provided one of the most striking examples of the perils of interpolating ore continuity from surface drilling data without a deeper understanding of macro and micro structure present.

Two gentle ore horizons were assumed, but the ore actually occurred in a tightly folded complex, as shown diagrammatically in Figure 26.

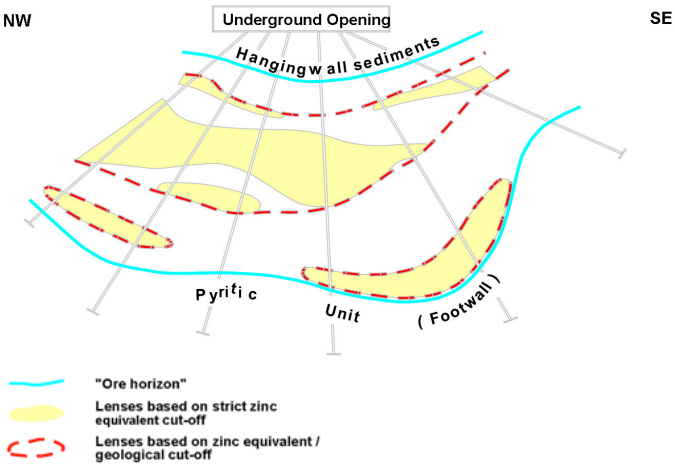
Figure 26: Interpretation versus actual ore structure at Stekenjokk mine



(Original source: Hoppe, 1978; Cleaned Diagrammatic: AMC presentation, drawing by Draftex Pty Ltd.)

Another example of "joining the dots" versus using all available geological information is shown below in Figure 27 (diagrammatic of actual data from Lady Lorretta mine).

Figure 27: Diagrammatic cross-section showing interpretation of mineralized lenses

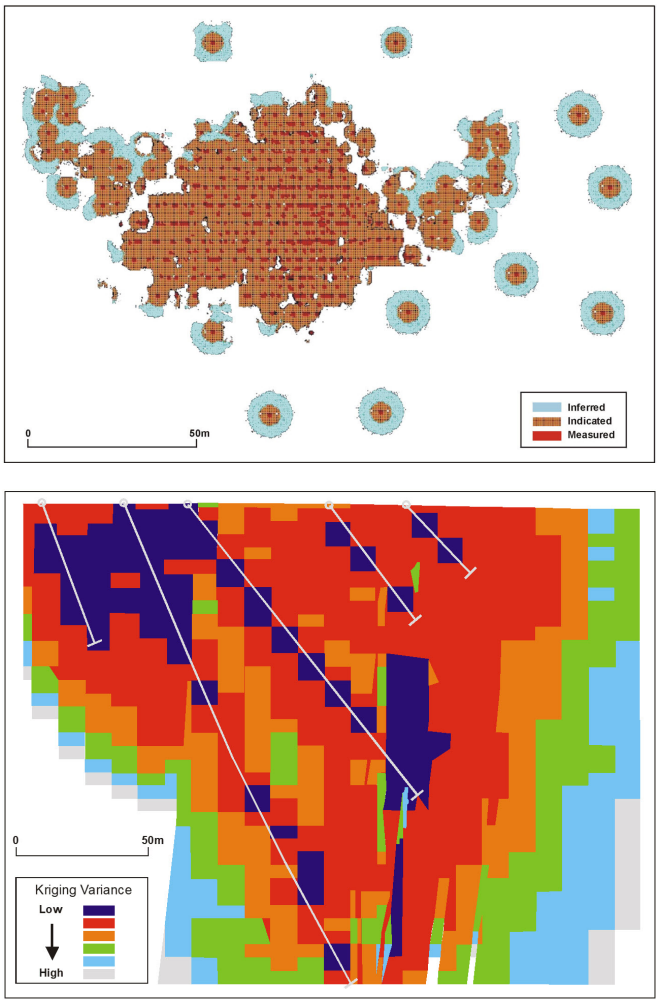


(source: Stephenson, 2009)

It will be difficult for engineers using geological models to recognise such errors, but one error that can be checked for is the issue of the "spotted dog" block model.

The "spotted dog" is a term coined by Stephenson et al (2006) to describe a model that has resulted from resource confidence classification being attributed solely to the presence of drill holes without any consideration of the geological continuity in the deposit as shown in Figure 28.

Figure 28: The "spotted dog" geological model



It should be noted that these "spotted dog" models are likely to be inconsistent with, if not actually in breach of, the requirements of reporting standards such as the JORC Code, SAMREC Code, Reporting Code NI 43-101 / CIM Standards and even Industry Guide 7 of the SEC. All these standards discuss continuity of geology and grade in terms of drillholes (plural), implying a correlation BETWEEN drillholes, not around individual drillholes.

It appears that these types of models have increased in occurrence due to the increased use of geostatistics for grade estimation, giving a greater ability to generate and make use of block-by-block parameters and attributes, and geologists spending more time with the details of a block model and less time (often no time) examining and interpreting hard-copy cross-sections and plans.

On the topic of cross-sections, it should be noted that the common practice of most geologists is to interpret a deposit by vertical cross-section. Jun Cowan notes that this is probably a bad practice for interpretation of ore bodies (https://www.linkedin.com/pulse/why-i-give-geological-cross-sections-cold-shoulder-jun-cowan/), as most mineral deposits rarely have a horizontal controlling structural feature.

Geologists routinely plot and interpret cross-sections vertically. (It is what they were taught to do). But the geological patterns that need to be conveyed cannot be understood if the cross-section is not a symmetry plane of the 3D mineralization pattern.

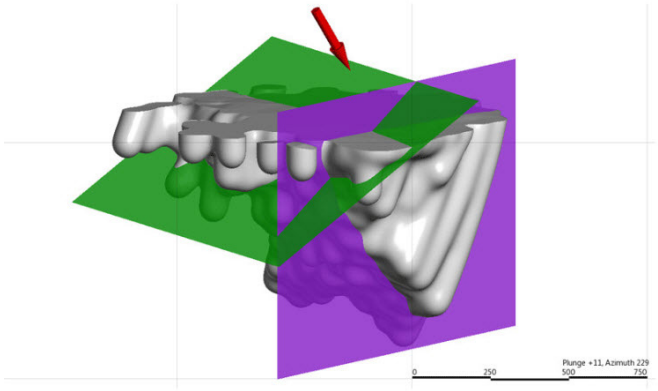
Cowan points out that we have forgotten the very basic and effective techniques of identifying symmetry patterns that exist in deformed rocks that control mineralization. Symmetry analysis - an essential skill considered a prerequisite of kinematic analysis and developed nearly 90 years ago - is no longer practiced by modern geologists.

The mining industry as a whole routinely ignores symmetry of mineral deposits, despite the fact that most mineralised trends mimic the underlying structural symmetry of host rocks. Rarely will resource geologists look at mineralization patterns to inform them of structural symmetry. It is therefore not uncommon for the symmetry of mineral deposits, and therefore the controls of mineralization, to go unnoticed for many years.

A typical example of a mineral deposit with its default cross-section orientations (purple) (in other words, parallel to drillhole fence) and the symmetry plane (green) is shown in Figure 29. The linear structural axis, coincident with the long axis of mineralization, is parallel to the red arrow.

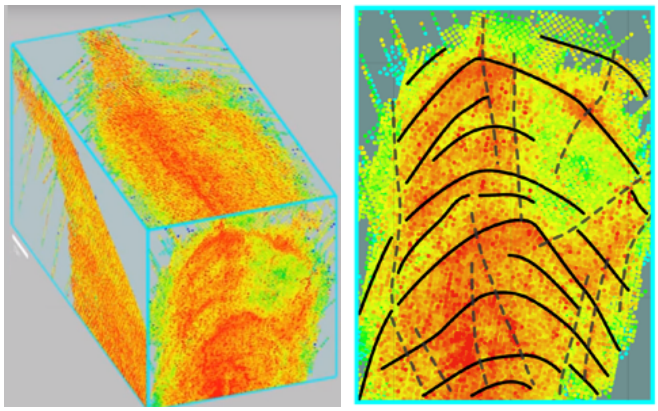
Such a deposit is not suitable for geological interpretation using traditional cross-sections parallel to the drill hole fences. This non-parallelism between cross-sectional planes and the symmetry section is typical of most mineral deposits.

Figure 29: Typical example of default cross-section versus position of symmetry plane



Figures 30 and 31 show how the use of non-standard sections (normal to ore body plunge) can be used to discover aspects of the controlling mineralization structures.

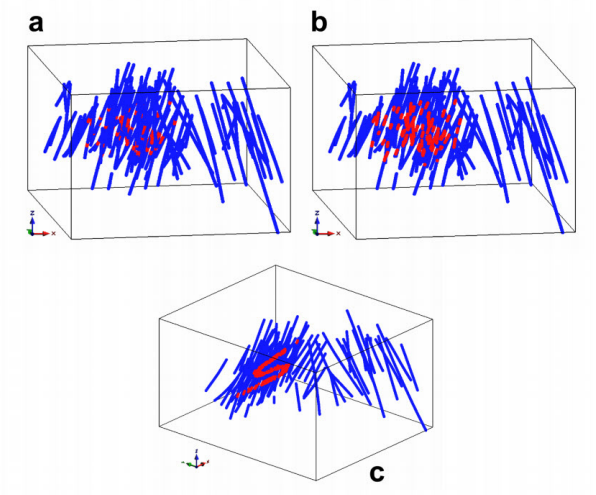
Figure 30: Example of how structure can be interpreted with grade samples plotted on projection to symmetry plane



(Cowan, 2014)

Figure 31: A synthetic grade dataset with 'ore' in red and 'waste' in blue to illustrate the power of correct symmetry plane selection

a) Low grades surround the high grade, so the geometry of the ore cannot be deciphered easily. b) Maximum Intensity Projection on an arbitrary viewing direction yields nothing that is geologically sensible. c) Only the down-plunge orientation reveals a fold profile. (Cowan, 2014)



5.5. SELECTIVITY – SMU – DILUTION – LOSS

In general, estimating blocks that are considerably smaller than the average drilling grid (say, appreciably less than half the size) is potentially very risky. In very high nugget situations (epithermal and shear hosted gold, for example), even blocks with dimensions approximating the drill spacing may still be highly risky.

The commonplace practice of estimating blocks that are far too small is symptomatic of the misunderstanding of basic geostatistics.

The concept of a SMU is discussed further in a following section as this is one area that an engineer can have an influence on after a geological model has already been delivered.

In association with the SMU are the parallel issues of dilution and loss. Again, this is discussed further in a following section as it is very much in the hands of the engineer to ensure that dilution and loss have been appropriately considered.

6. The concept of an SMU

6.1. OVERVIEW

The conventional definition of the SMU is the smallest volume of material on which ore/waste classification is determined.

The SMU is a concept that comes out of geostatistical estimation and relates to the smallest unit that can be mined selectively. This will vary with the style of the mineralization, the mining method and equipment size. Typically, it can be quite small in selective operations (in other words, a couple of truck loads – a few hundred tonnes in a typical open pit gold mine) but in practice having a large number of small blocks interpolated will leave most neighboring blocks having the same or very similar grades. Thus, in practice many geostatistical workers will avoid estimating a block smaller than a quarter to one fifth of the drill spacing, which is fine for global resource models. This is normally over and above any partial block volumes related to geological boundaries.

However, when doing pit optimization or life of mine scheduling, it is desirable to represent the actual degrees of selectivity possible in practice. This is where estimates of the likely proportion of the mineralized block that could be selectively mined becomes important. The key to these estimates is predicting the tonnages of material of the SMU or greater sized units that could be selectively mined. This could be only a portion of the block that has been estimated, or an aggregation of blocks that have been estimated.

Resource geologists will use techniques that involve the interrogation of a deposit's grade tonnage curve and estimation error to compute these proportions.

So, the concept of the SMU is to select the smallest regular cell size that can be practically mined by appropriately sized mining equipment. The size of equipment is selected to match the scale of the operation. This approach is based on the premise that large equipment cannot generally mine small SMU sizes. Also, there is an assumption generally made that the mining fleet numbers should be minimized, by choosing the largest possible equipment.

Typically, consideration for SMU choice includes:

- Resource model parent block size
- The average width or depth of the deposit
- Production bench height, or flitch height
- Final batter height
- Effect on project economics of dilution and contaminants
- Production capacity and thus a preconceived notion of excavation and haulage equipment size

In reality, SMU selection appears to be a complex and "murky" field. From extensive reading there is no industry-wide agreed method of selecting the SMU, and it is often a "thumb-suck" by the resource geologist. This is especially so for a new project resource model, where the work has not even been done to decide what the mine might look like and what equipment size might be.

It should also be noted that it is impractical and impossible to freely select a single SMU of ore amid waste, just as it is impossible to freely reject a single SMU of waste amid ore. (So there will be loss and dilution effects above and beyond just SMU size selection.) Nevertheless, even large bulk mining equipment may have the ability to mine within a couple of meters of a boundary if the conditions are favorable.

Leuangthong et al (2004) discusses a method of selecting the SMU based on a definition of the SMU as "the block model size that would correctly predict the tonnes of ore, tonnes of waste, and diluted head grade that the mill will receive with anticipated grade control practice". This is highly sensible, as it is the ideal situation that a mine planning and scheduling engineer wants: an SMU size that gives a reasonable match to the actual production (if possible).

Leuangthong et al (2004) believe that this size must somehow not only be related to the ability of the equipment to select material, but must also be based on the data available for classification (blast-holes or dedicated grade control drilling), the procedures used to translate that data to mineable dig limits, and the efficiency with which the mining equipment excavates those dig limits.

Numerous sources of dilution must also be accounted for including internal dilution due to grade variability within the SMU, external dilution resulting from geological/geometric contacts, and operational dilution that accounts for production errors, pressures and schedule demands.

While the concept of using the SMU to get a match between the resource and the actual production is an extremely worthy goal, there are other issues with this approach: effects such as minimum practical size dig blocks (bigger than the SMU), mining imperfection effects (such as blast movement) and the "data effect" (lack of enough geology sample data). All these lead to reconciliation problems - the most common being that the resource model ends up over-predicting the metal in the resource model when compared to the tighter drilled (and therefore greater informing data quantity) grade control model. The author has noted that for the circa ten or so mines that he has seen detailed reconciliation information for, around 70% had resource models that over-predicted the contained metal by over 10% (and up to 35% difference).

It is commonly noted by resource/reserve practitioners working in operating mine environments that mines tend to mine more tonnes at lower grade than the resource model says (probably 90+% of the time). Whether this leads to over- or under-prediction of the contained metal will depend upon the shape of the grade tonnage curve and the cut-off grade being used. But in all these cases, the higher tonnage will lead to higher costs than predicted per unit of metal. The author has always suspected that the SMU selection has been a large part of this problem (not the only one of course).

In searching for advice on SMU selection, it was noted that in one study at Buzwagi (Rocca et al, 2007) the following conditions were used:

- The bucket width is less than 75% of the narrowest SMU block dimension.
- A minimum of two truckloads required per block, so approximately 10 excavator buckets per SMU.

So, these conditions might be a reasonable starting point for assessing an SMU to be used.

To apply an SMU to an OK model, the model will need to be regularized to the SMU size. In Deswik, this means creating a new model framework (and blank-filled blocks) at the new block model size and using the regularization command to populate that new block model with the data from the unregularized block model (Thought has to be given as to how different materials being "smeared" into one SMU will need to be considered as by definition, an SMU can only be of one material type).

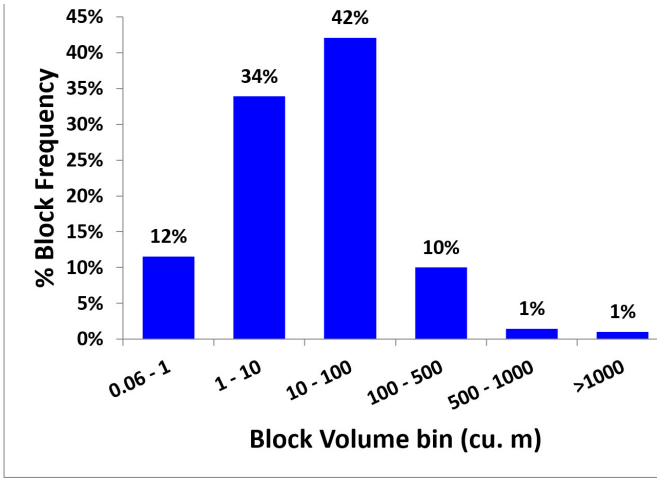
To apply an SMU to an MIK model, several approaches are used. If, as a user of the model, you are happy with the SMU size selected by the geologist when the change of support correction was applied, then it is only necessary to ensure that ore proportions and waste proportions in each and every block are greater than the SMU size being used. If the fundamental SMU size used by the resource geologist in building the MIK model is too small, then it is best to go back to the resource geologist and ask for a new model at the agreed SMU size. (Change of support corrections need specialist software and knowledge).

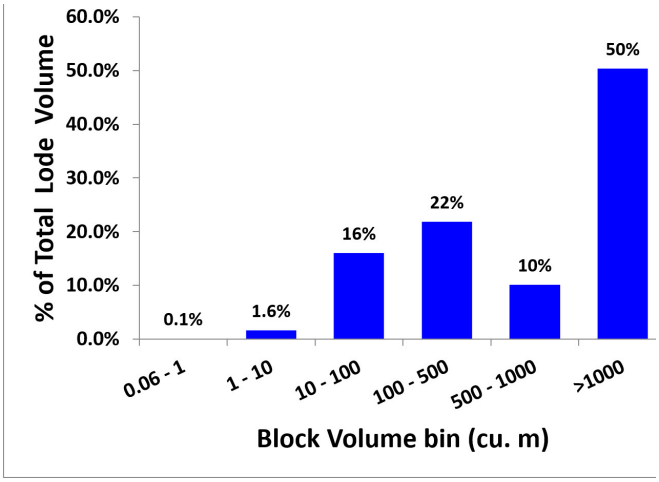
6.2. EFFECT OF SMU ON A PIT OPTIMIZATION

In order to understand the effect of the use of an appropriate SMU versus not using an SMU, the author undertook an analysis of an SMU regularized model pit optimization versus the original irregular block model (using the standard Deswik training block model). This small study highlighted the size of the potential volume error in resulting RF=1 shell with an over-selective block model.

The irregular block model sub-celled to the ore lode boundary has blocks down to the size of 0.06 m^3. The distribution of the size of the blocks (including all the sub-celled blocks) is shown by frequency and by volume in Figure 32.

Figure 32: Distribution of size of ore lode blocks by number frequency and volume in the unregularized sub-celled model



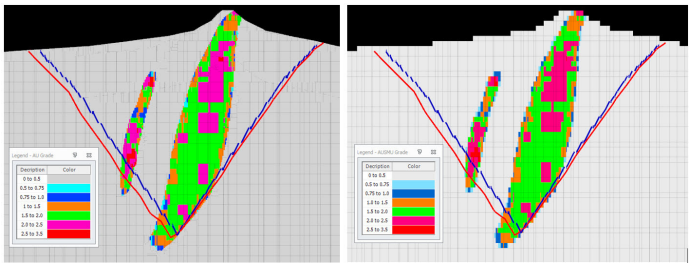


The SMU size selected for the analysis was 250 m^3. The process of regularization is such that every block (100%) in the block model now has a size of 250 m^3.

The two potential RF=1 shells are shown in Figure 33 against the irregular over-selective block model on the left and the SMU regularized block model on the right.

For the irregular over-selective block model, the resulting RF=1 shell (red section shell in Figure 33) was 15% larger (in volume) than the SMU regularized block model RF=1 shell (blue section shell in Figure 33), and more importantly, with a calculated 122% greater value per total moved tonnes in the shell (a value that will not be achieved in practice).

Figure 33: Cross-section of pseudoflow RF=1 shells for irregular raw block model versus SMU regularized block model



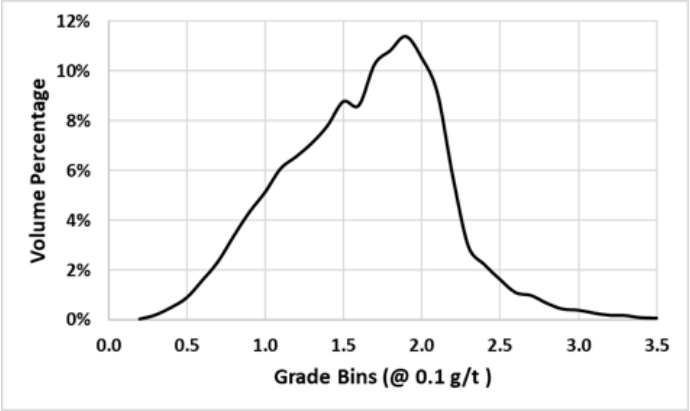
Note that for this study:

(a) Mill recovery was a function of grade, and hence value per block varied by a greater percentage than just the grade change.

(b) The average grade of the ore lodes only changed by about 2% with SMU regularization (1.59 g/t vs. 1.63 g/t), but the result of the optimization changed by much more – indicating the sensitivity of the project to dilution.

(c) The volume of ore lode material passing a specific grade changed with the SMU regularization as shown in Figure 34. (The SMU model had a higher volume below each cut-off grade, and therefore a lower volume above each cut-off grade compared to the raw sub-celled block model.) The effect of the SMU regularization will therefore change differently based on the cut-off grade required.

Figure 34: Change in volume below a specific cut-off grade for SMU regularized model versus raw block model.



6.3. ADVANTAGES AND DISADVANTAGES OF USING SMU FOR DILUTION LOSS ASSESSMENT

Reconciliation of the resource along the mining process chain up to the processing (and sales) results will determine if the use of an SMU is appropriate for the estimation of dilution and loss effects for practical mining.

There are situations where the use of a regular SMU may not be appropriate.

Advantages of using an SMU include:

- It has relatively fast calculation times, enabling a variety of SMU sizes to be tested.
- It can be used in combination with other mining recovery and dilution allowances.
- It includes diluent mineralization grades from boundary cells. This is particularly important with deposits with gradation grade boundaries.
- It includes modeling of the loss of ore at deposit boundaries.
- It enables the economic evaluation of diluted cell grades through optimization software. This is an important consideration for marginal grade ore blocks at depth.

(Bannister, 2016)

Disadvantages of using an SMU include:

- Mining equipment can mine shapes other than rectangular cuboids.
- Mining dilution and recovery estimates are based on accurately mining the SMU cuboid not the interpreted deposit geometry.
- Deposits with strong physical and visual geological boundaries are not recognized in the dilution estimate.
- Proposed grade control systems, such as further drilling, mapping and ore spotting are not allowed for.
- Geological model and survey mark-up accuracies are not considered.
- Displacement of ore resulting from blasting heave and throw are not considered.
- Ore loss due to edge effects in blasted ore are not considered (unexcavated toe of ore blocks next to waste blocks).
- Ore dilution due to edge effects in blasted ore (crest of waste block falls into ore block during excavation).
- Ore dispatch misdirection is not included.
- SMU orientation to the deposit boundaries and cell centroids have a significant influence on mining recovery and dilution.
- SMU cell orientation changes are time consuming and generally not undertaken.

(Bannister, 2016)

7. Dilution and loss

7.1. OVERVIEW

In converting the information contained in a mineral resource "block model" to a mining recoverable set of tonnages and grades (the ore reserves), a number of modifying factors, including dilution and loss, need to be considered and allowed for.

Invariably some form of dilution or loss will occur in the physical mining process. Unless a resource reconciliation suggests otherwise (for example, a positive reconciliation result giving more tonnes, grade or metal than that modeled), it will invariably be due to an underestimate in the underlying resource model that is masking the dilution and loss effects.

Approaches that have been used for estimating dilution and loss include:

- Percent factor estimates (based on historical mine call factors or industry allowance "guesstimates")
- Surface area expansions / dilution skins
- The use of an SMU – regularized on the block model grid or irregular along a contact boundary

Whichever method is used, reconciliation to treatment plant feed tonnes, grade and actual mineral product produced that allow tuning of the method to give acceptable results is recommended.

The modifying factors that need to be considered include the following:

a. Reserve model/grade control model reconciliation factors

   This refers to the differences between the short-term grade control model (close spaced drilling) and the long-term Mineral Resource model (less dense resource drilling). The factors are generally determined by reconciliation between the two types of models.

   Dilution and loss modeled by this process is due to the uncertain knowledge of the ore body, which is improved with increasing drilling density.

b. Internal Dilution

   This is the inclusion of waste with an ore block. An MIK model is claimed to include this effect, but review the MIK model write up section of this document for some of the further modifications that may be required.

c. External dilution and loss

   This refers to the addition of materials along the edges of the economic SMUs within a block and along the edges of blocks with other blocks.

   Dig block mark-out smoothing also leads to dilution and loss. It has been observed that some operations will estimate this effect manually by digitizing a series of dig block polygons over the resource model for a series of planned benches.

d. Imperfect mining factors (dilution and loss)

   This refers to the effects of things not being perfect in mining.

   - Ore – especially blasted ore – will move from its grade control drilled locations.
   - Sheeting and grading of roads and benches will move ore and waste around resulting in dilution and loss.
   - Due to geometry, the operation of excavation equipment cannot be physically matched with the shape and size of the ore body, and therefore excavators will mine bits from adjacent blocks, lateral and vertical. The grade control model blocks are vertical, but the excavator digs a face at the rill angle.

Mining operator errors can occur, including waste sent to the mill and vice versa, and under/over-digging of marked out ore blocks.

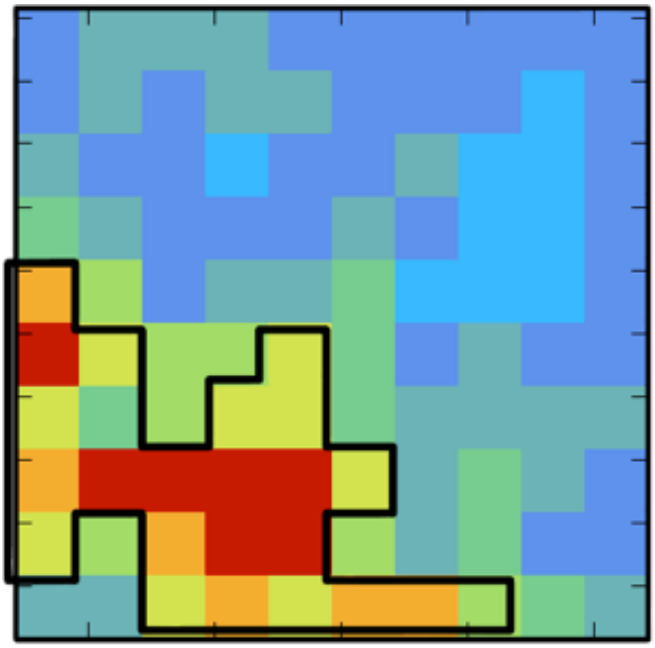
All these need to be considered and accounted for in the conversion from a mineral resource to an ore reserve.

The net results of these imperfect operational sources of dilution and loss are difficult to estimate and require the use of actual mining operation reconciliations to properly quantify.

7.2. MARK-OUT SMOOTHING DILUTION/LOSS

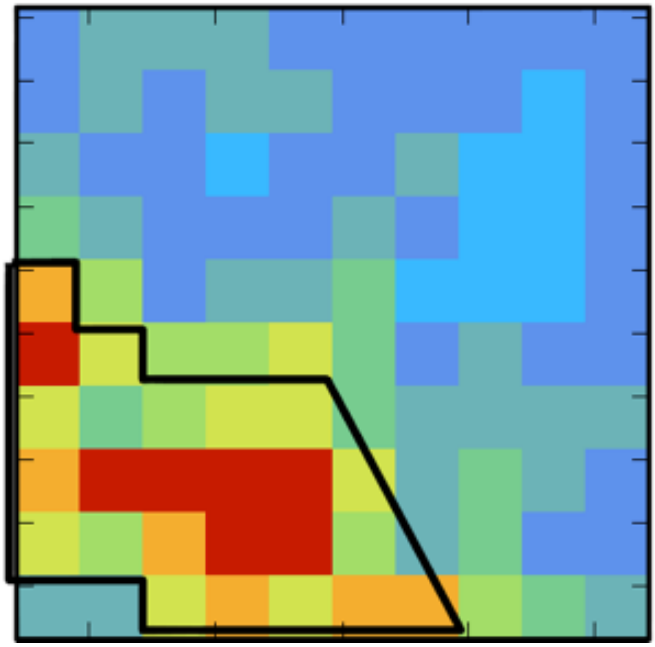
An example of mark-out smoothing causes of dilution and loss is shown in Figure 35 and Figure 36. In this example, the grade control blocks within a parent resource block that have been determined as ore are shown in Figure 35. However, the grade control geologists will mark this out as a more practical dig shape, for example, as shown in Figure 36.

Figure 35: Example of grade control drilled blocks within a resource parent block that may be considered as ore



(from Vann, 2005)[2]

Figure 36: Example of grade control geologists likely mark-out of the ore drilled blocks within a resource parent block



2. "One Day Linear MIK Modelling Short Course Notes", John Vann, Quantitative Geoscience (QG), July 2005.

7.3. DILUTION SKIN APPROACH

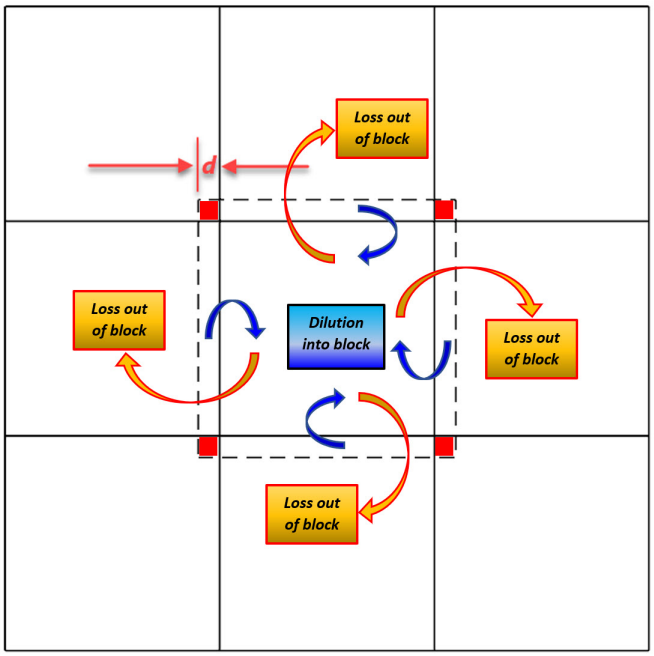
In the dilution skin approach to dilution and loss, blocks can be expanded by a "skin" of material or ore zones can be expanded.

Block Expansions – OK Models

In this approach, the process is shown schematically in Figure 37.

An area of overlap with each of the neighboring blocks is evaluated and the tonnage and grade of that overlap are added to the central block. The new tonnage and grade of the block are a tonnes weighted average of the original block tonnes and grades and the tonnes and grade added from each of the neighboring blocks. The tonnage needs to then be rebalanced so that an equivalent volume loss occurs so that no extra volume has arisen in the block. Conservation of mass and conservation of metal must be honoured.

Figure 37: Schematic of expansion of a block model cell by a dilution skin



In addition to the four blocks to north, south, east and west, the blocks above and below may need to be considered.

The algorithm can be made to have different "skin" sizes in different directions.

Block Expansions – MIK Models

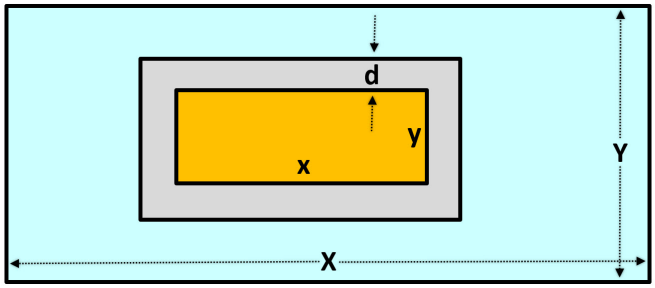
Below is one method of applying a dilution skin within a MIK model framework.

Assume that any proportional volume of material above a selected cut-off grade (indicator) in a block is of the same X-Y ratio as the parent block. Add a dilution skin of size "d" around the ore proportion as per Figure 38. The dilution skin will be of the grade of the increment below the selected indicator value. If there is insufficient tonnage in the increment below, then the next increment down is added until the tonnage is achieved.

If the resulting tonnage factor is greater than "1", then it is set at a value of "1". (In other words, block tonnage will be conserved).

This adjustment is done for each indicator value in turn, resulting in a modified ("diluted") set of indicator proportions and grade.

Figure 38: Diagram of the dilution skin application algorithm for an MIK block



Wireframe Expansions

In this method, the wireframes used to generate the resource model ore domains are expanded outwards from the ore domain.

Waste blocks inside the new expanded wireframe are flagged as ore blocks to be included in mining as ore; it may require sub-celling to isolate these blocks.

These "dilution blocks" can then be incorporated into a schedule as ore when bench block tasks are created. They can also be tagged as ore parcels when models are regularized for use in Pseudoflow pit optimization model preparation.

Figure 39: Diagram of the wireframe expansion dilution skin application

Limitations of this method include:

- Overlapping wireframes and folded reef wireframes confuse the wireframe expansion process.
- The original construction of wireframes needs to consider this later use.
- It does not suit folded ore bodies.
- There is a need to check each final wireframe.

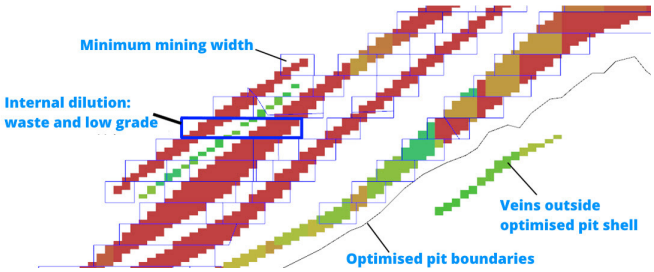
7.4. OUTSIDE OF BLOCK MODEL DILUTION TECHNIQUES

It should be noted that the objective of modeling dilution and loss is to ensure that our forecasts using the resource/reserve block model are as close as possible to what we believe will actually happen in operating practice. This is best done by trying to replicate as close as possible the mechanisms and extents of the dilution and loss as they occur in practice and reconciling the modelling results with history where available.

To achieve this objective, it will sometimes be better to model dilution and loss outside of the block model and on specific mining shapes or specific ore body shapes that may be used for scheduling.

One approach that has been used to model dilution successfully has been the use of the underground "Stope Optimizer" (https://www.deswik.com/product-detail/deswik-stopeoptimizer/) to evaluate minable ore shapes on open pit benches with the bench height being the stope height.

Figure 40: Section of an open pit showing use of Stope Optimizer to determine minable shapes for export into a schedule



8. Before you start using the block model

8.1. UNDERSTAND YOUR BLOCK MODEL

It is extremely important to understand your block model well before starting to work with it. Expect this to take a couple of days if you are given a model you have never seen before. Ask for a field summary table from the geologists as a minimum, preferably get a full resource model report.

Make sure you know what all the fields mean. Are they integer, double, string or character fields? Are there any "calculated" fields, such as Surpac fields that are calculated "on the fly"? Are they all necessary for your work? What default values are used? We would recommend you look at the statistics of each of the fields in the model.

What is the model framework? Is the framework in the right place? Are blocks regular or irregular? Is it rotated? What is smallest size to largest size?

Is the block model complete within the framework or is it just some of the blocks within the framework, with much of the framework being empty?

Do not assume that the geologist has handed you a block model completely ready for you to start work. For example, it may have default values of "-99" for density or grade, and there may be blocks still in the model with these default values. It does not take many "-99" density blocks included in a block model for an interrogation to give wildly incorrect tonnages!

Also, be aware that geological block models can be flawed. The two most common problems are insufficient geological support (for example, uncertain lithology boundaries and insufficient sample density) and deficient data integrity (poor QA/QC, missing components in the sampling such as fine friable contaminants in a hard rock core). See Section 5, *Problems to be Cognisant of*, earlier in this document.

8.2. BLOCK MODEL CHECKS BEFORE USE

We would like to think that models are fully validated and ready for use when they are handed over, but experience suggests otherwise. It is therefore prudent to undertake the following checks of a block model before using it:

- Check that you have latest block model. Record the supplied file name and confirm that this is the correct model to use.
- Get a summary of the model fields from the resource geologist. Make sure the model you have been given has these fields (or at least the ones you need).
- Save the model as a different named model from the resource geologist's model (a planning-related name with date) and delete fields not needed (for example, "number of samples" used in grade estimate, and other resource model creation related fields). This will make the model smaller and more manageable.
- Check that the minimum required fields are present: Density, Resource class (Measured, Indicated, Inferred), Grades, and Rock/Material Type Classifications.
- Understand the model framework: origin, model limits, and parent block size. These should be noted.
- Determine the type of grade interpolation estimation method used in the construction of the block model: OK, MIK, CS.
- Check the minimum and maximum of all numeric fields.

  It is common to find "-99" "default flag" values still in blocks (especially air blocks). If such values occur, and it is for an obvious reason (such as an air block) correct it yourself (in other words, set it to "zero"). Otherwise, send it back to the geologist to correct.

  Make sure the range of numbers makes sense, especially grades and densities. The author has seen models with grades of over 100% in blocks. They weren't meant to be PPM values. They were percentages arising from geochemistry equations manipulating PIMA hand-held assays, and just not checked for sense.) Check for negative values.
- Check for sub-blocking.
- Run some basic visual checks:
  - Visually check that grade=0 in undefined areas.
  - Visually check that the ore resource classes seem appropriate.
  - Visually check for field consistencies. For example, ensure if Density=0 that the grade also equals 0.
- Determine if the model values are "whole block" or "partial block". ("Partial block" means that there may be multiple material types within a single block and it has fields that specify the proportion of each material in that block.)
- Check the resource report (or with the person who generated the model) for any dilution applied to the resource.
- Check global model tonnes and grade by running reports in CAD for the total resource at three or more different cut-off grades and by resource class. Compare with the stated totals in the resource geologist's resource report. (This may be for whole model or for a particular subset, such as inside a mineral resource shell.)
- Find out what SMU size was used by the geologist (if applicable) in model creation.
- Determine how density was estimated. (This will give you an understanding on accuracy levels. Were they kriged? Are they a simple bulk average assignment for rock type? Are they based on a calculation from mineralogy?)
- For MIK models, check for order relation errors and correct them (or get them corrected). These can sometimes cause havoc in your later work.
- Check wireframes for oxidation boundaries against block models material types.
- Check wireframes for geological domaining coded in the model.

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