ORE BODY MODELLING AND COMPARISON OF DIFFERENT RESERVE ESTIMATION TECHNIQUES

A THESIS IS SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF TECHNOLOGY

IN

MINING ENGINEERING

By

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National Institute of Technology

Rourkela – 769008, India

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Under the guidance of

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ROURKELA

CERTIFICATE

This is to certify that the thesis entitled **"Ore Body Modelling and Comparison of Different Reserve Estimation Techniques"** submitted by **Mr. Manasa Chandra Moharaj** and **Miss. Yeshi Wangmo** in partial fulfillment of the requirements for the award of Bachelors of Technology Degree in Mining Engineering at National Institute of Technology, Rourkela is an authentic work carried out by them under my supervision and guidance.

To my best knowledge, the matter embodied in the thesis has not been submitted to any other university/ Institute for award of any degree.

Date:

Prof. H. K. Naik

Head of the Department

Department of Mining Engineering

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At the last, sincere thanks to all our friends who have patiently extended all sorts of helps for accomplishing this project.

Date: **Manasa Chandra Moharaj**

Yeshi Wangmo

CONTENTS

ABSTRACT

Generally, size of the database is too bulky to manage studies with hand effort. Thus, numerical algorithm and mathematical approaches necessitate computer applications to overcome huge computational time and processes. Currently, many computer aided systems and software serve for geological modeling. The accuracy and speed of computers enable evaluation of various scenarios within reasonably short times. Computer systems have proved very essential for mining and geological studies.

In this project, SURPAC software has been used for ore reserve estimation. The estimation has been done using three different methods i.e. inverse distance method (power2 and power 3); nearest neighbor method and ordinary krigging method.

Keeping all other parameters same, the computational time for all the above techniques were found to be nearly same. Thus, the efficiency of reserve estimation using nearest neighbor and inverse distance methods were compared with the ordinary krigging method as it is known as the best linear unbiased estimation.

LIST OF FIGURES

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Chapter 1 :

INTRODUCTION

1.1 Background Information:

Ore reserves can be classified as the following: Massive deposits; deep and very large laterally such that dumping of the waste within the pit is not possible. Stratified vein-type deposits with an inclination steeper than the natural angle of repose of the material so that waste cannot be tipped inside the pit; and Relatively horizontal stratified reserves with a thin/thick covering of overburden.

Open cast mine planning is done by developing the block models and then dividing the deposit into smaller pits which contain both ore and waste blocks which are to be mined in order to reach the pit limit and these operations are done keeping in the mind the overall optimization of the pit and reaching ultimate pit limit design.

Geological block models are used to generate economical block models by using unit costs and income. With known volume of a block, thickness and grade of ore at each particular block, it becomes possible to convert this information to economical aspect. (Volume *tonnage factor * grade = block reserve.) Economical block models have visual and numerical results; 3D appearances of them give an idea if and where an ore body is rich and how quality changes.

1.2 Project Significance:

Basically, the project is carried out to determine the best method for reserve estimation using SURPAC software. Here, how the advancement in technologies has helped mankind with accuracy and speed is also shown. Bulky database can be managed very easily using computers and the software helps it with accurate estimation.

1.3 Use of Computer Software for ore body modeling:

Generally, size of the database is too bulky to manage studies with hand effort. Thus, numerical algorithms and mathematical approaches necessitate computer applications to overcome huge computational time and processes. Currently, many computer aided systems and software serve for geological modeling. The accuracy and speed of computers enable evaluation of various scenarios within reasonably short times.

Computer programs are ready for ore body modeling after building a healthy database structure. Visual appearance of geological body is supported by numerical data such as ore reserve amount and quality composition, which are vital parameters for mine design and scheduling. Thus, computer systems are very important for mining and geological studies.

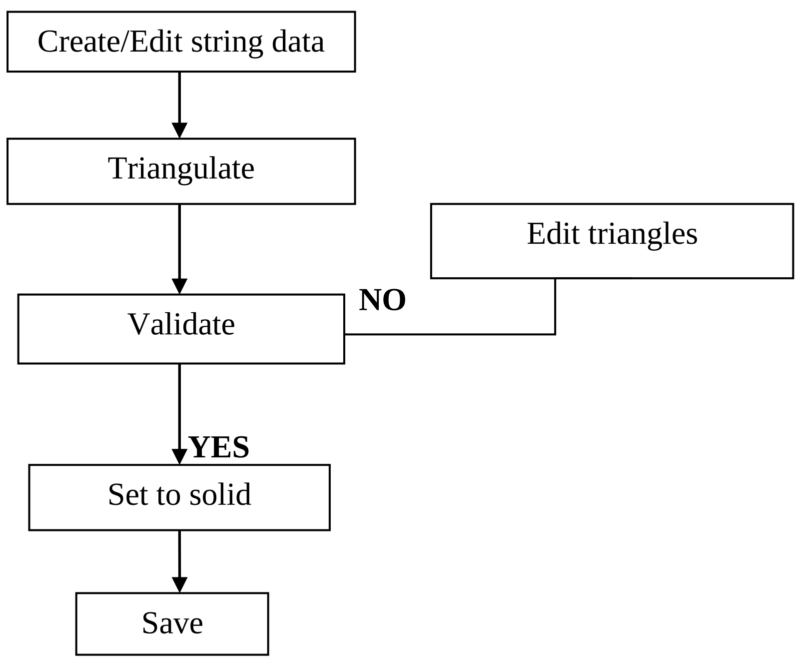
1.4 Objective:

Mine planning and designing manually is a tedious work to the planning team, i.e. to define ore boundaries, define mine configurations in sections based on available economic and technical information. This method was found to be labor intensive, prone to excess errors and time taking. Mostly, it was found that it cannot be applied to large mines with many (millions) blocks. So proper planning of mine reserve using mathematical analysis of available data is the need in today's world.

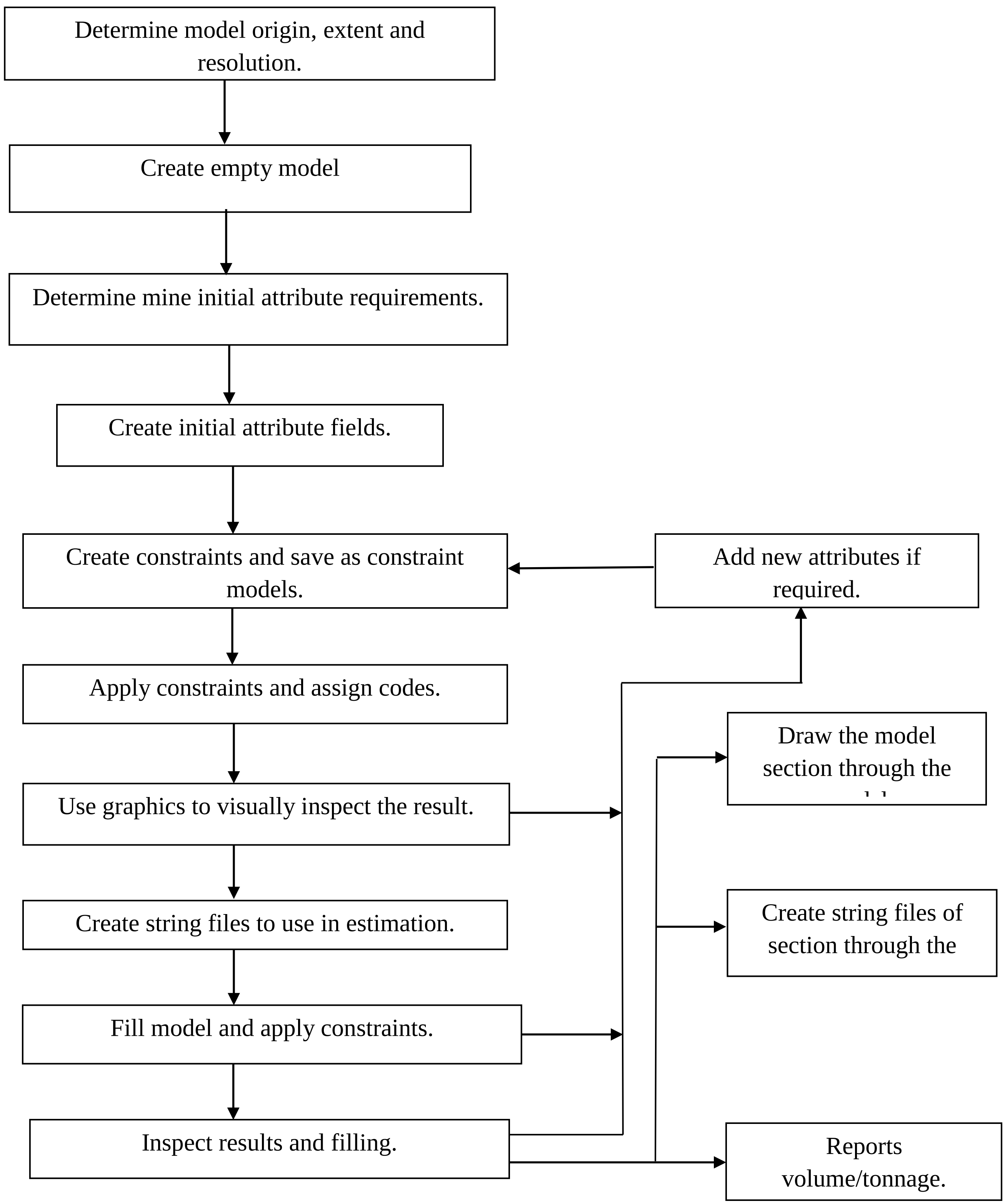
Thus, with improvement in technologies and evolvement of computer software and algorithms, the mining industry is blessed in terms of analysis of data using these software to plan the mine, optimizing and more accuracy.

The main objective of this work is to find out the most appropriate method for reserve estimation by block modeling using SURPAC. It aims at estimating the ores using different methods i.e. ordinary krigging; inverse distance (power2 and 3); and nearest distance method. The comparison between the above methods is carried out (if any method underestimates or overestimates) then the best method is decided accordingly.

1.5 Work flow (Solid model):



1.6 Work flow (block model):



Chapter 2 :

LITERATURE REVIEW

2.1 Geostatistical Ore Reserve Estimation (By: MICHEL DAVID and ROGER A. BLAIST):

Matheron's geostatistical method (the estimation of ore reserves) has been developed to the point at which real-life problems may be handled effectively. The steps involved in the method are as follows:

i. Obtaining the variogram,

ii. Fitting a model, and

iii. Producing block estimates.

All three steps are a bit difficult, and any user may need a deep understanding of the theory to avoid any failure. Geological considerations must guide the entire ore appraisal. In the four cases discussed in this paper, the ore structures vary enormously. In the porphyry coppers studied (deposits A and B) the structural controls are extraordinarily complicated with billions of mineralized fractures, whereas in the flat iron formation (deposit C) the structure is very simple, and in the folded and metamorphosed iron formation (deposit D) it is more complex. Yet, the slime basic mathematical approach is applicable to all four deposits.

The properties of the ore are relatively constant along strike or along dip with some particular geological direction. When ore boundary problems are dealt with and automatic kriging is used then the geologist's advice is very essential. In a kriging program, unless a digitizer is available, it is very difficult to define appropriately the limits of ore. Once grade contours are defined, it is a simple matter to compute the grade-tonnage curve by drawing the cumulative distribution of the estimated block grades. Thus, as knowledge of a deposit improves, so does the grade-tonnage curve.

2.2 Three-Dimensional Model of Cangshang Gold Mine Based on Surpac (Ping Huang, Peng Yang, Yizhou Chen and Chengjun Liu): The three-dimensional geological model of Cangshang Gold Mine, including the geological database, ore body model and block model, was established by mining software Surpac, which simplified the complicated hand-drawing and reserve calculation. The three-Dimensional development system visualization was also studied on the basis of conducting the vectorization of the whole development system design including excavation and construction project. The establishment of mine three-dimensional geological model simplified the complicated hand-drawing and reserve calculation. The calculation results are accurate, which can be used in the resource estimation, reserve calculation and mine design of the mine production stage.

The three-dimensional model of ore body was established by using of Surpac software.

2.3 A retro-review, Merks, J W, 2005

(**Geostatistical Ore Reserve Estimation, David, M, 1977, Elsevier Scientific Publishing Company): The author in this book describes everything in chapters (mainly 1, 3, 9, 10, 12, 13 chapters are focused).**

In chapter **1**, the author alludes to spatial dependence between ordered data but ignores the difference between independently measured and functional dependence.

In chapter **3**, the author shows why geostatistics cannot possibly provide unbiased confidence limits for metal contents and grades of ore reserves as a measure for risk.

In chapter **10**, the author makes it perfectly clear that the distance-weighted average at a selected position is a functionally dependent value of a set of independently measured values at different positions in a sample space.

On the same page the author pontificates, "Writing all the necessary co-variances for that system of equations is a good test to find out whether one really understands geostatistics!"

In chapter **12**, the author confirms, "There is an infinite set of simulated values", and ponders how to, "make that infinite set smaller and get the model closer to reality".

In chapter **13**, the author recalls Gy's lifetime preoccupation with "the variance of sampling errors" but in Bias Generation, he proffers the bizarre claim that high variances generate bias.

David's textbook proves beyond reasonable doubt that geostatistics is an invalid variant of mathematical statistics because it violates the fundamental requirement of functional independence and ignores the concept of degrees of freedom.

2.4 Erarslan, 2001: Geological Block Models: used to generate economical block models by using unit costs and income. As volume of a block, thickness and grade of ore at each particular block is known, then it becomes possible to convert this information to economical aspect. Multiplication of volume, tonnage factor and grade give block reserve. Economical block models have visual and numerical results. 3D appearances of them give an idea where ore body is rich and how quality changes.

2.5 Comparison of Polygonal and Block Model Reserving Techniques in Gemcom

A case study on a Thin Reef Deposit (pieter-Jan Grabe1 and Warren P. Johnstone2):

From the results of this work, the following conclusions are drawn:

1. There is no appreciable difference between the results of the two methods.

2. The block model method applied to the thin reef deposit in this case, proved to be valid and accurate.

3. Polygonal reserving can be an effective way to validate primary reserving through block modeling.

4. Spatial trends relevant at the scale of mining can be distinguished from the block model plots.

To summarize, the tonnage and grade estimates are remarkably similar suggesting that the methodology applied in both techniques is appropriate. Howsoever, a proper examination of the assumptions reveals that the block model technique is more comprehensive. This finding is complimented by the speed, ease-of-use and downstream applicability of the block model module in Gemcom.

2.6 Ore body Modeling : An Integrated Geological-Geostatistical Approach

(by Indranil Roy and B. C. Sarkar)

(Department of Applied Geology, Indian School of Mines, Dhanbad - 826004):

They concluded that ore body modeling is a reflection of geological and geometrical reality of an ore deposit. Geologists and mining engineers can benefit from such an integrated modeling approach by honoring the deposit geology, understanding the statistical distribution and emphasizing the spatial continuity studies. The model can act as principal guides for development of mineral inventory model and grade-tonnage curves which ultimately can lead to a value model in terms of economic extraction of the ore body.

2.7 Determining the Best Search Neighborhood in Reserve Estimation, using Geostatistical Method: A Case Study Anomaly No 12A Iron Deposit in Central Iran (JOURNAL GEOLOGICAL SOCIETY OF INDIA, Vol.81, April 2013, pp.581-585):

Ordinary kriging and non-linear geostatistical estimators are now well accepted methods in mining grade control and mine reserve estimation. In kriging, the search volume or ‘kriging neighborhood’ is defined by the user. The definition of the search space can have a significant impact on the outcome of the kriging estimate. In particular, too restrictive neighborhood can result in serious conditional bias. Kriging is commonly described as a ‘minimum variance estimator’ but this is only true when the neighborhood is properly selected. Arbitrary decisions about search space are highly risky. The criteria to consider when evaluating a particular kriging neighborhood are the slope of the regression of the ‘true’ and ‘estimated’ block grades, the number of kriging negative weights and the kriging variance. Search radius is one of the most important parameters of search volume which often is determined on the basis of influence of the variogram. In this paper the above-mentioned parameters are used to determine optimal search radius.

Kriging is commonly described as a ‘minimum variance estimator’ but this is only true when the neighborhood is properly defined. Read phonetica Search radius is one of the most important parameters of search volume which often is determined on the basis of influence of the variogram. Usually the variogram range is used as a criterion for determining the radius search and depending on the condition the optimized radius may be different. In this paper an attempt was made to determine optimal search radius with criteria to look at when evaluating a particular kriging neighborhood i.e. the slope of the regression of the ‘true’ and ‘estimated’ block grades, the number of kriging negative weights and the kriging variance. Therefore, these statistics for 15 ellipsoids were summarized, graphed and the optimal search radius was found by determining where increasing the size of it does not significantly improve the estimate. The obtained search radius through the cross validation was compared with search radius suggested by others which were determined on the basis of variogram search. The results show that the suggested search radius is the best.

Chapter 3 :

METHODOLOGY

3.1 Modeling of deposit using SURPAC:

For various purposes in mine, Surpac software is used. In this, we are going to discuss only on reserve estimation and valuation.

Block models are used in Surpac for reserve estimation and valuation. To generate a block model, Solid model and surface topography are required. Most importantly, cut-off grade is needed for valuation of the reserve using block model.

Further, to create a solid model, geological database is to be generated.

3.1.1 Geological Database:

The starting point of all mining projects is the drill-hole data. It continues the bases on which feasibility studies and ore reserve estimation is done. A number of tables are included in a geological database, containing different data. Each table contains a number of fields, having many records and with each record containing the data fields.

Surpac uses a relational database model and supports several different types of database, i.e. oracle, paradox and Microsoft access.

Two mandatory tables required in Surpac within a database:

1. Collar; and
2. Survey.

Collar table:

The information in this table describes the location of the drill-hole collar, the maximum depth of the hole and whether to calculate a linear or curved hole trace when retrieving the hole. For each drill-hole, an optional collar data may also be stored. For instance, data drilled, type or drill-hole or project name.

In a collar table, the mandatory fields are as given below:

1. Hole_id
2. Y
3. X
4. Z
5. Max_depth
6. Hole_path

Survey table:

It stores the drill-hole survey information, used for calculating the drill hole terrace co-ordinates. The mandatory field in a survey table includes:

1. Down-hole survey depth,
2. Dip, and
3. Azimuth of the hole.

In case of a vertical hole which has not been surveyed, the depth would be the same as the max_depth field in the collar table; the dip would be -90 and azimuth would be zero.

Optional fields may include information's taken at the survey point. For example: core orientation.

Other Optional Tables:

Apart from the mandatory tables, the optional tables include: geology and assay. These tables are added and used to store information.

Three optional tables that can be added to a database:

1. Interval
2. Point
3. Discrete.

Interval table:

This table requires the depth_from and depth_to fields respectively.

Depth_from- the depth at the start of the interval; and

Depth_to- the depth at the end of the interval.

Point table:

This table requires the depth_to field (the depth where the sample was taken). The Y, X and Z fields are used to store the calculated co-ordinates of the sample depths.

Discrete table:

This table requires the unique samp_id and its position in space, i.e. its Y, X and Z co-ordinates. This table is basically suited for storing and later processing geochemical soil.

Sequencing of the fields in the table:

Row sequence is important while creating a database in surpac. The row sequence should be same in all the tables as a little change may lead to misleading values.

Column sequence is not important because surpac is so designed that it asks for the column number of each field in the last stage of database creation.

Contents of Database files & folders:

- .ddb file (database file)
- .pdx folder
- .dcs file (format file)
- .rej file (contains the rejected information)
- .not file (text file of the report generated after the database is created)

The database definition file (.ddb) contains:

- the type and name of database.
- where the database is located (ie. a path location).
- table names, field names and formatting of each field type.

In order to use the database in other system three files are mandatory to copy given as ".ddb" file, ".dcs" file, ".pdx" folder.

Importing Data:

While importing data two things are important to pay attention to, such as

- Naming the format file
- Checking the "overlapping sample check"

The name of format file should be same as database name for simplicity as both files are required for use in other systems.

Overlapping of data may occur between the assay and lithology data as they refer to same interval of a bore hole. The process of lithology and assay sampling is elaborated in fig2. Therefore checking of the overlapping should be done.

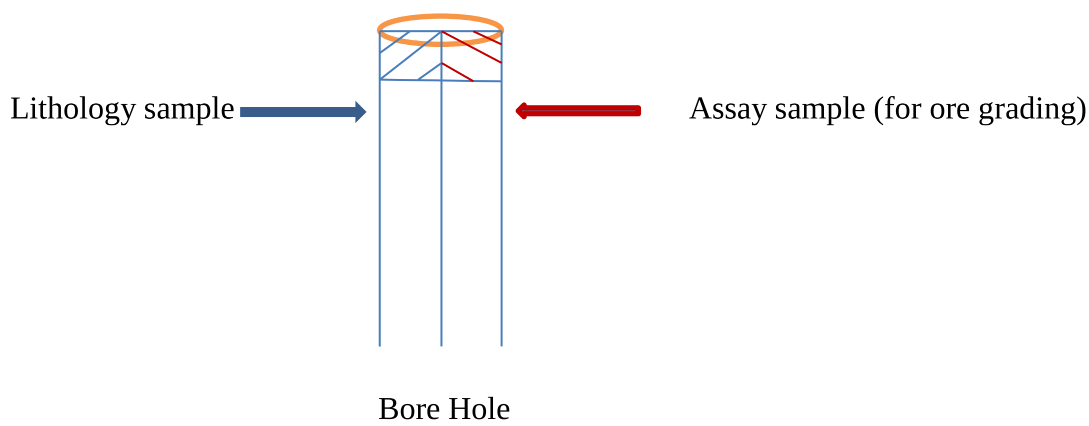


Fig2. Lithology and assay sampling

3.1.2 Solid Models: 3-dimensional triangulation of data.

For example: a solid object formed by wrapping a DTM (digital terrain models) around strings representing sections through solids.

It is based on the same principles as DTMs. It uses triangles to link polygonal shapes together and defines a solid object or a void.

The resulting shapes are used for:

- Visualization;
- Volume calculation;
- Extraction of slices in any orientation
- Intersection with data from the geological database module.

DTM: It is used to define a surface, its creation is automatic. Triangles are formed by connecting groups of 3 data points together by taking their spatial location in the X-Y plane into consideration.

It has drawbacks, i.e. it cannot model a str that may have fold backs or overhangs. For instance:

- Geological structure
- Stopes
- Underground mine workings (declines, draw points, etc).

With a set of triangles from the points contained in the string, a solid model is created. In a plane view, the triangles created my overlap but when a third dimension is considered, it does not overlap. The triangles in a solid model completely enclose a structure.

Terminologies:

Solid model: It is made up of a set of triangles (non-overlapping). The triangles form objects that may have a numerical identifier between 1 and 32000. In a solid model, objects represent discrete features.

A trisolation is a discrete part of an object and is a positive integer. Object and trisolation number gives reference to all the objects contained in a solid model. An object trisolation maybe open or closed. It is open when there is a gap in the set of triangles that makeup the trisolation. An object can be open/closed and the reasons are as follows:

For closed object-

1. It can have its volume determined directly by summing the volumes of each of the triangles to an arbitrary datum plane.
2. It always produces closed strings when sliced by a plane.
3. I could be used as a constraint in the block modeling module.

For an open object-

1. It can't provide the same capabilities; when sliced by a plane the strings it produces maybe open or closed or both.

3.1.3 Block Models:

Block models are a form of spatially referenced database that provides a means for modeling a 3D body from point and interval data like drill-hole sample data.

Model space: - 3D co-ordinates spatially define the model extents.

- Minimum Northing (Y), Easting (X), and Elevation (Z)
- Maximum Northing (Y), Easting (X), and Elevation (Z)

Blocks and Attributes:

The geometric dimensions in each axis are defined by the centroid of each block, i.e. its co-ordinates (Y, X and Z). For each of the properties to be modeled, each block contains attributes. The attributes/properties may contain character/ numeric string values. User defines the block size so it varies a lot once it is created.

Constraints:

It is a logical combination of one or more spatial objects on selected blocks. With it, all block model functions are performed. Objects used in constraints are plane surfaces, DTMs, solids, closed strings and block attribute values. It is saved to a file for rapid re-use and maybe used as components of other constraints.

3.1.4 Estimation:

After a block model is created and all attributes defined, the model is filled by the required estimation.

3.2 Estimation Methods:

3.2.1 Nearest Neighbor Method:

Nearest neighbor interpolation which is also known as proximal interpolation or point sampling is a method of multivariate interpolation in one or more dimensions.

Interpolation is the method of approximation of the value of a function for a given point in some space. The nearest neighbor method selects the value of the nearest point in the predefined space and does not consider the value of other neighboring points.

3.2.2 Inverse Distance Method

The inverse-distance weighted procedure is versatile, easy to program and understand, and is fairly accurate under a wide range of conditions (Lam, 1983). Using this method, the property at each unknown location for which a solution is sought is given by:

$$P_i = \frac{\sum_{j=1}^{G} Pj/Dij^n}{\sum_{j=1}^{G} 1/Dij^n}$$

Where Pi is the property at location i; Pj is the property at sampled location j; Dij is the distance from i to j; G is the number of sampled locations; and n is the inverse-distance weighting power. The value of n, in effect, controls the region of influence of each of the sampled locations. As n increases, the region of influence decreases until, in the limit, it becomes the area which is closer to point I than to any other. When n is set equal to zero, the method is identical to simply averaging the sampled values. As n gets larger, the method approximates the Voronoi tessellation procedure (Watson and Philip, 1985). Usually, the value of n is set arbitrarily.

Watson and Philip (1985) listed some of the limitations of the inverse-distance weighted procedure. The major limitation is that estimates are bounded by the extrema in the sampled values. Additionally, the radial symmetry which this procedure imparts to the data obscures the effect of linear features such as ridges or valleys. For n £ 1, the derivative of the interpolated surface is discontinuous at the sampled locations, while for n >1, the surface is flat at these sampled locations.

3.2.3 Ordinary Krigging Method

The main venture in ordinary kriging is to build a variogram from the dissipate point set to be interpolated. A variogram comprises of two parts: an experimental variogram and a model variogram. Assume that the worth to be interpolated is alluded to as f. The experimental variogram is found by figuring the variance (g) of each one point in the set as for each of other points and plotting the variances versus separation (h) between the points. A few equations might be utilized to figure the variance, yet it is ordinarily calculated as half the difference in f squared.

Once the experimental variogram is figured, the following step is followed o characterize a model variogram. A model variogram is a straightforward function that models the pattern in the experimental variogram.

At small partition distances, the variance in f is small. As it were, points that are near one another have comparable f values. After a certain level of partition, the variance in the f qualities gets to be arbitrary to some degree and the model variogram levels out to a value corresponding to the average variance.

When the model variogram is built, it is used to compute the weights used as a part of kriging. The basic equation used in ordinary kriging is:

$$F(x,y) = \sum_{i=1}^{n} w_i f_i$$

where n is the amount of scatter points in the set, fi are the qualities of the scatter points, and wi are weights alloted to each one disperse point. This comparison is basically the same as the mathematical statement utilized for inverse distance weighted interpolation aside from that instead of utilizing weights based on an arbitary function of distance, the weights utilized as a part of kriging are focused around the model variogram. The weights are found through the result of the following equations:

$$w_1S(d_{11}) + w_2S(d_{12}) + w_3S(d_{13}) = S(d_{1p})$$

$$w_1S(d_{12}) + w_2S(d_{22}) + w_3S(d_{23}) = S(d_{2p})$$

$$w_1S(d_{13}) + w_2S(d_{23}) + w_3S(d_{33}) = S(d_{3p})$$

where S(dij) is the model variogram assessed at a separation equivalent to the separation between points i and j. For example, S(d1p) is the model variogram assessed at a separation equivalent to the separation of points P1 and P. Since it is essential that the weights add up to result unity, a fourth mathematical statement is added:

$$w_1 + w_2 + w_3 = 1.0$$

Since there are currently four mathematical statements and three unknowns, a slack variable, l, is added to the equation set. The last set of equations is as takes after:

$$w_1S(d_{12}) + w_2S(d_{22}) + w_3S(d_{23}) + \lambda = S(d_{2p})$$

$$w_1S(d_{12}) + w_2S(d_{22}) + w_3S(d_{23}) + \lambda = S(d_{2p})$$

$$w_1S(d_{13}) + w_2S(d_{23}) + w_3S(d_{33}) + \lambda = S(d_{3p})$$

$$w_1 + w_2 + w_3 + 0 = 1.0$$

The mathematical statements are then solved for the weights w1, w2, and w3. The f quality of the interpolation point is then computed as:

$$f_p = w_1 f_1 + w_2 f_2 + w_3 f_3$$

By utilizing the variogram as a part of this style to figure the weights, the normal estimation error is minimized in a least squares sense. Hence, kriging is once in a while said to generate the best linear unbiased estimate. Nonetheless, minimizing the normal error in a least squared sense is not generally the most imperative criteria and in a few cases, other introduction plans give more fitting outcomes (Philip & Watson, 1986).

A vital characteristic of kriging is that the variogram might be utilized to ascertain the normal error of estimation at every interpolation point since the estimation error is a function of the separation to neighboring scatter points. The estimation variance might be ascertained as:

$$s_z^2 = w_1 S\left(d_{1p}\right) + w_2 S\left(d_{2p}\right) + w_3 S\left(d_{3p}\right) + \lambda$$

While interpolating to an object using the kriging method, an estimation variance data set is always produced along with the interpolated data set. So that, an iso-surface plot of estimation variance can be generated on the target mesh.

Chapter 4 :

RESERVE ESTIMATION

4.1 Data used in the project

- From an iron ore mine in India
- Mandatory tables (survey, collar)
- Optional tables (assay, lithology)
- Tables are in .csv format (created using excel sheet)

Survey	Collar	Assay	Lithology
Hole id	Hole id	Hole id	Hole id
Y	Y	Depth from	Depth from
X	X	Depth to	Depth to
Z	Z	Iron	lithology
Depth	Depth		
Hole path	Dip		
	Azimuth		

Table 4.1 Attributes of diff. tables used

Optional fields

After creating the database the borehole data were imported. Total 39 boreholes had been used in this project for reserve estimation. Cut-off grade is assumed to be 50 (because on reality there is hardly any iron mine whose cut-off grade is below 50). The figure below shows the display of some of the boreholes. The red portion represents ore (iron percentage > 50) and the blue portion represents waste.

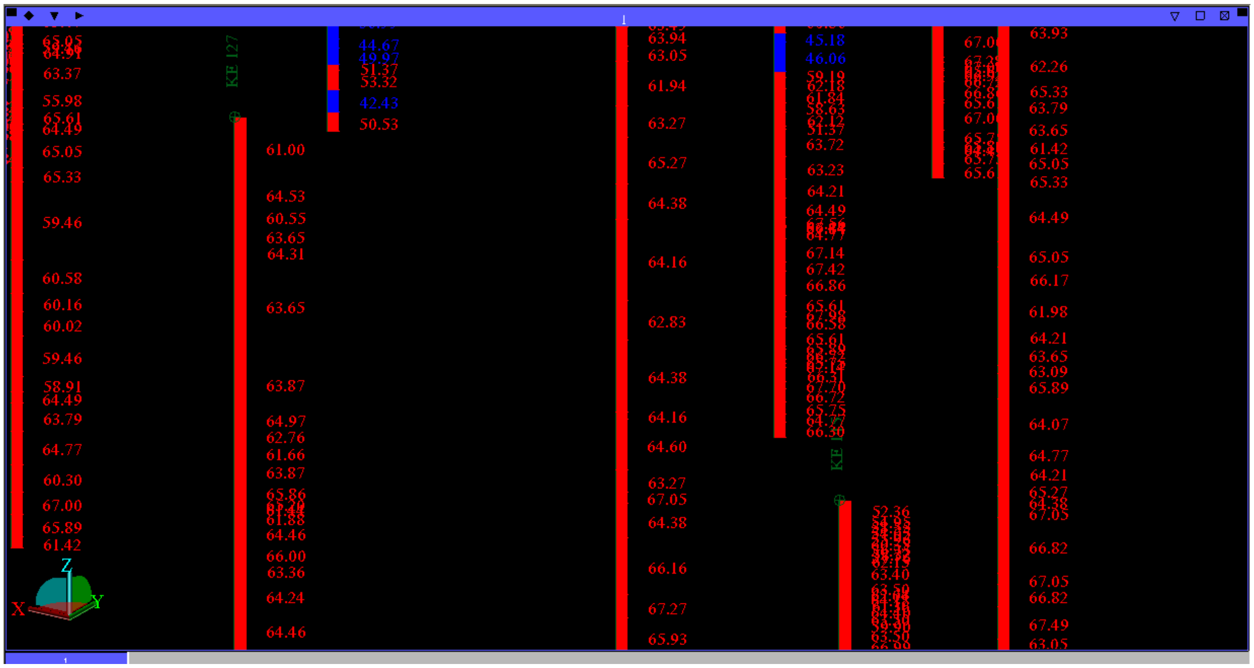


Figure 4.1 Borehole display according to assay value

4.2 Generated Solid Model

Creating a solid model in SURPAC involves different steps. First of all we define the geology pattern of the drill holes according to the ore percentage. Then we have to do sectioning of the bore holes. Sectioning means to divide the entire span of drill holes to different parallel planes equally spaced and along any particular direction (which can be set by the user). Each section contains some drill holes (there might be a section which doesn't contain any drill hole).

Then digitising was done, one by one, in all the sections. In this process we take the ore which has the ore percentage of our interest. Thus segments are created in all the sections. Then we combined all the segments to one string file. After that the string file was checked for any spikes or duplicate points or the rotation of each segment. All the spikes, duplicate points were removed and rotation was set to anticlockwise.

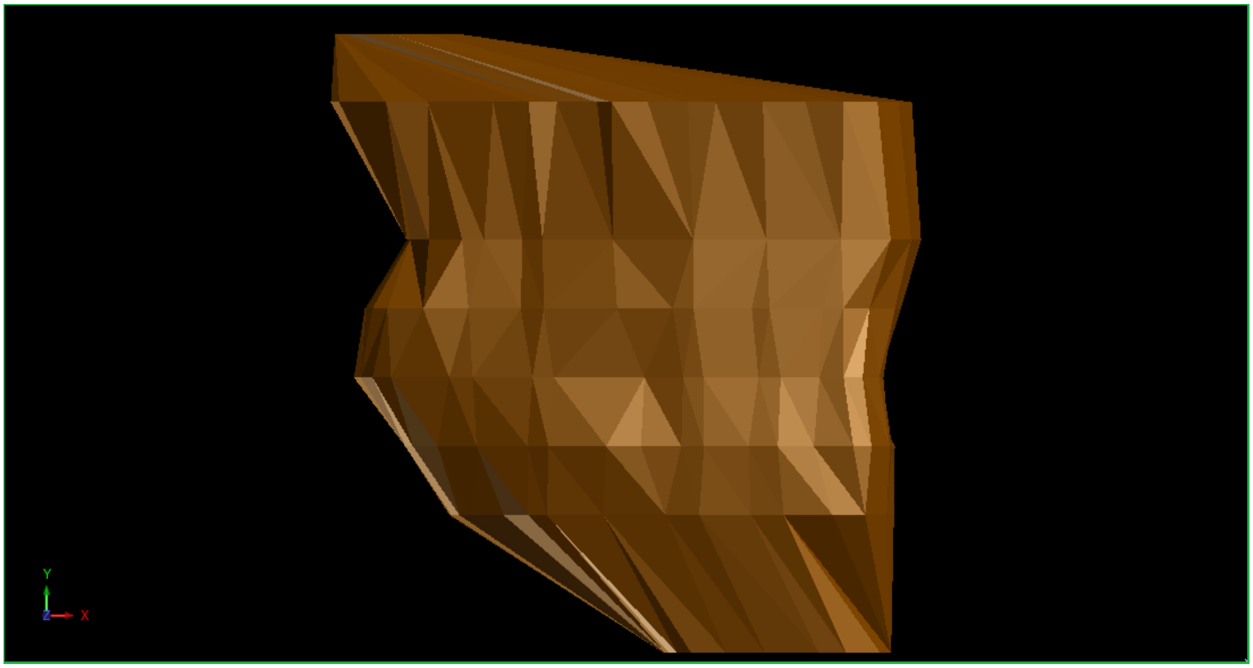


Figure 4.2 Plan view of solid model

The generated solid model report contains the trisolation extents, surface area and volume of the solid. In this project the above properties are found to be:

Trisolation Extents

X Minimum: 1120.170	X Maximum: 1594.023
Y Minimum: -500.000	Y Maximum: -50.000
Z Minimum: 697.818	Z Maximum: 873.191

Surface area **:** 477214

Volume **:** 13290520

4.3 Block model geometry:

3D coordinates spatially define the model extents. Block size used for interpolation and reporting. The minimum and maximum co-ordinates taken are:

X Minimum: 1100 X Maximum: 1600

Y Minimum: -550 Y Maximum: 0

Z Minimum: 690 Z Maximum: 880

Step distance in x, y, z directions are taken as 50, 50, 10 respectively and the block model is created.

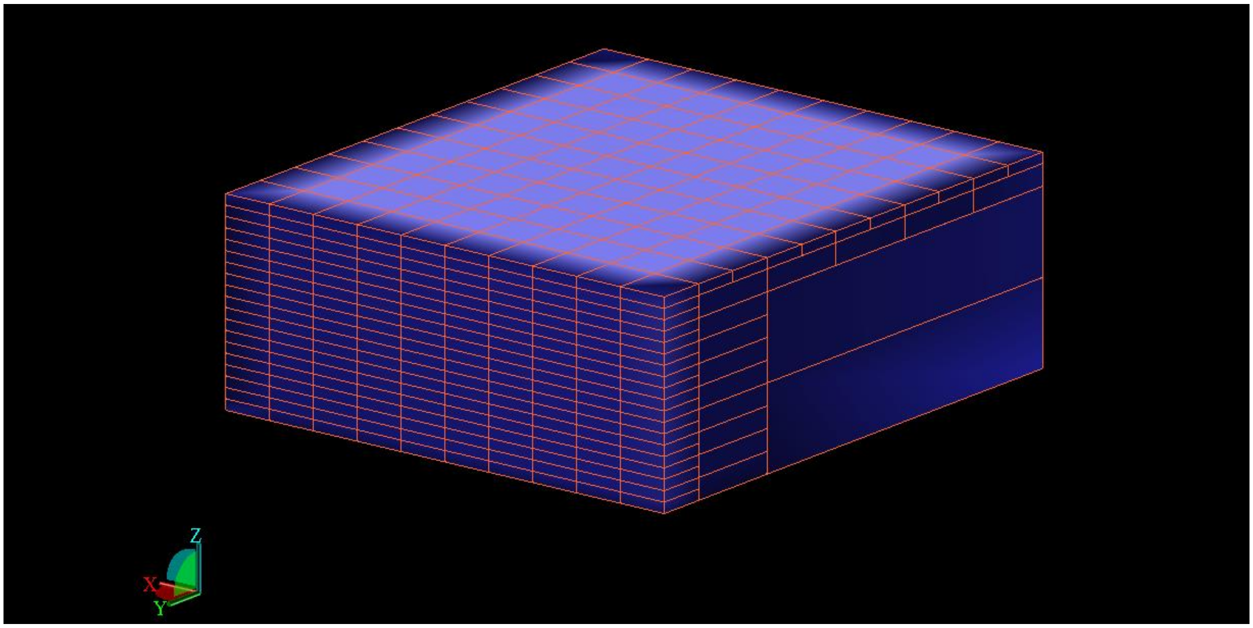


Figure 4.3 Display of generated block model

Now we can have the view of constrained block model by adding different graphical constraints. After adding the created solid model as a constraint to the block model it took a new look which is shown below.

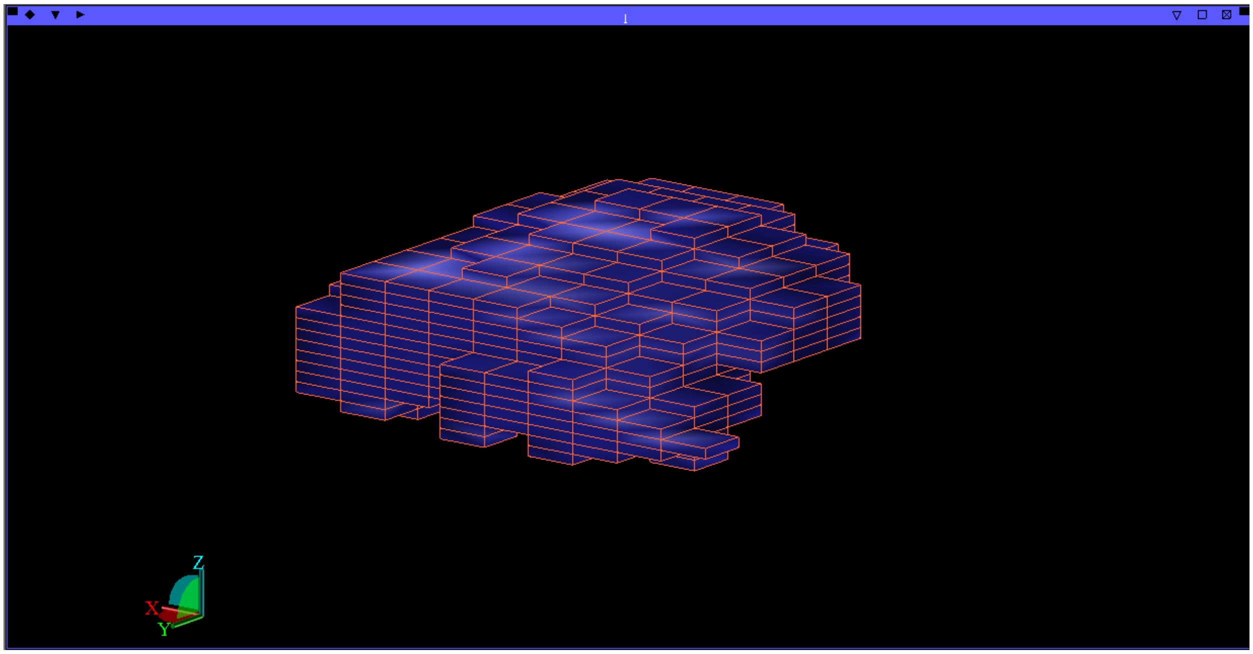


Figure 4.4 Display of constrained block model

Next task was to estimate the ore reserve for each block. It was achieved using three different methods (Nearest Neighbor, Inverse Distance with power 2 & 3 and Ordinary krigging). Estimation reports were generated after applying sufficient constraints.

4.4 Reserve estimation using Nearest Neighbor method

This is the simplest method of estimation. The search parameters are few. The parameters used in this project are given below:

Ellipsoid search parameters

Angles of rotation of the major axis

Bearing	0.00
Dip angle	0.00
Tilt angle	0.00

Anisotropy factors

Semi-major axis 1.00

Minor axis 1.00

Other interpolation parameters

Max search distance of major axis 78.000

Max vertical search distance 78.000

Maximum number of informing samples 1

Minimum number of informing samples 1

Then appropriate constraints were applied and the resultant blocks were taken into account for ore reserve estimation. The figures of constrained block models are provided below.

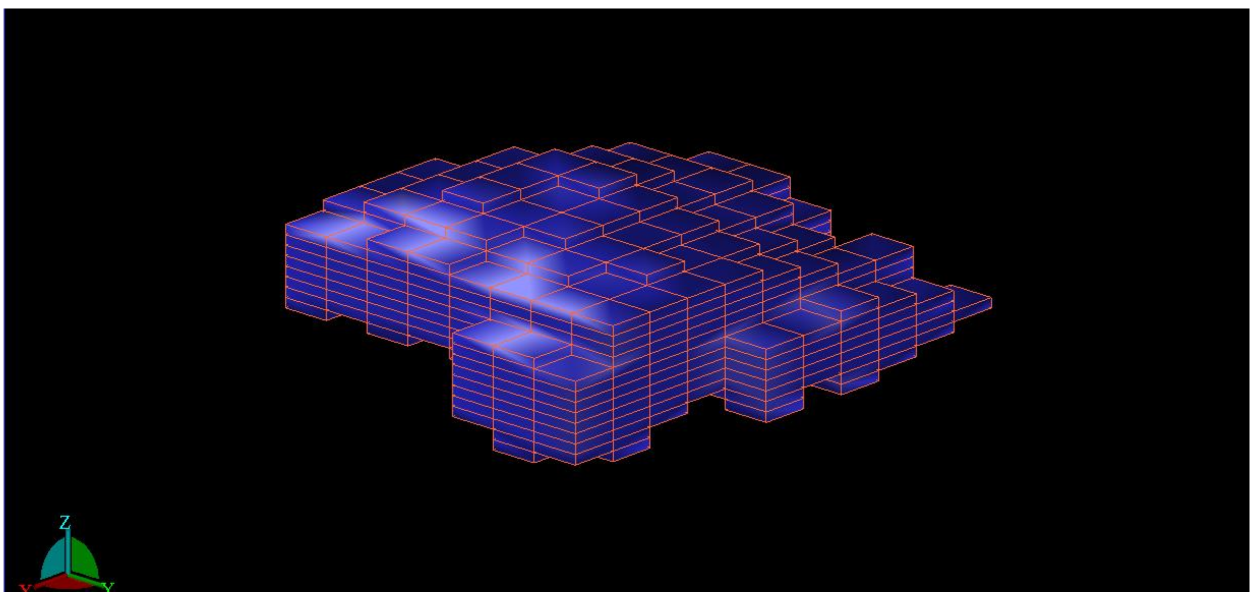


Figure 4.5 Block model after applying the solid model as constraint

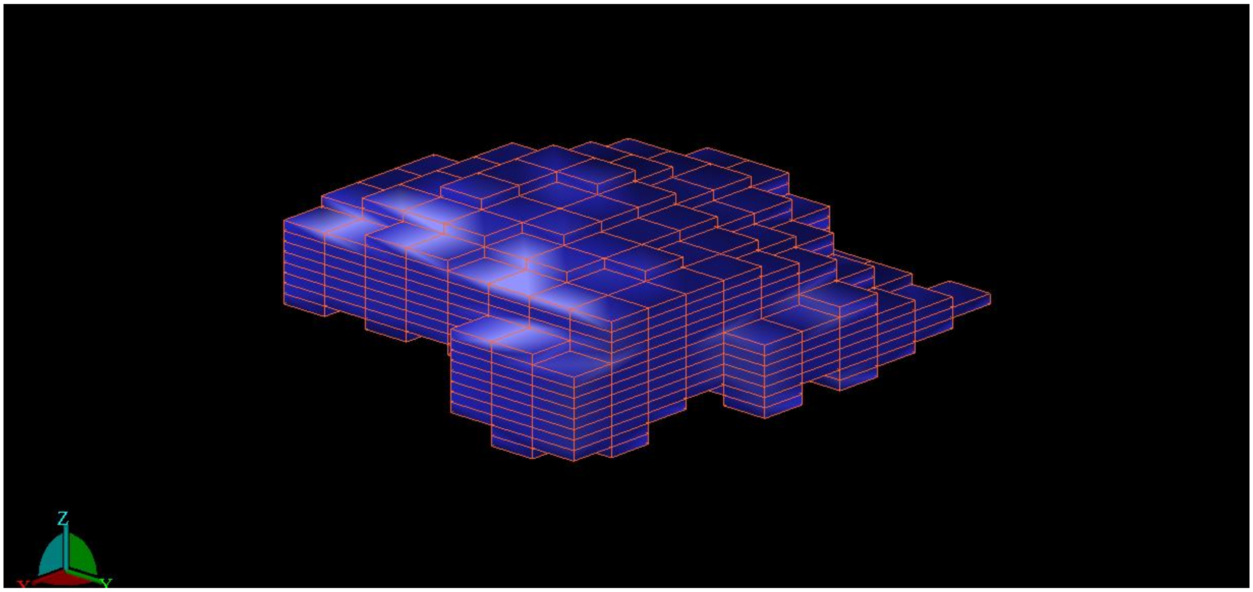


Figure 4.6 Block model after adding both solid model constraint and iron grade constraint (iron grade>50)

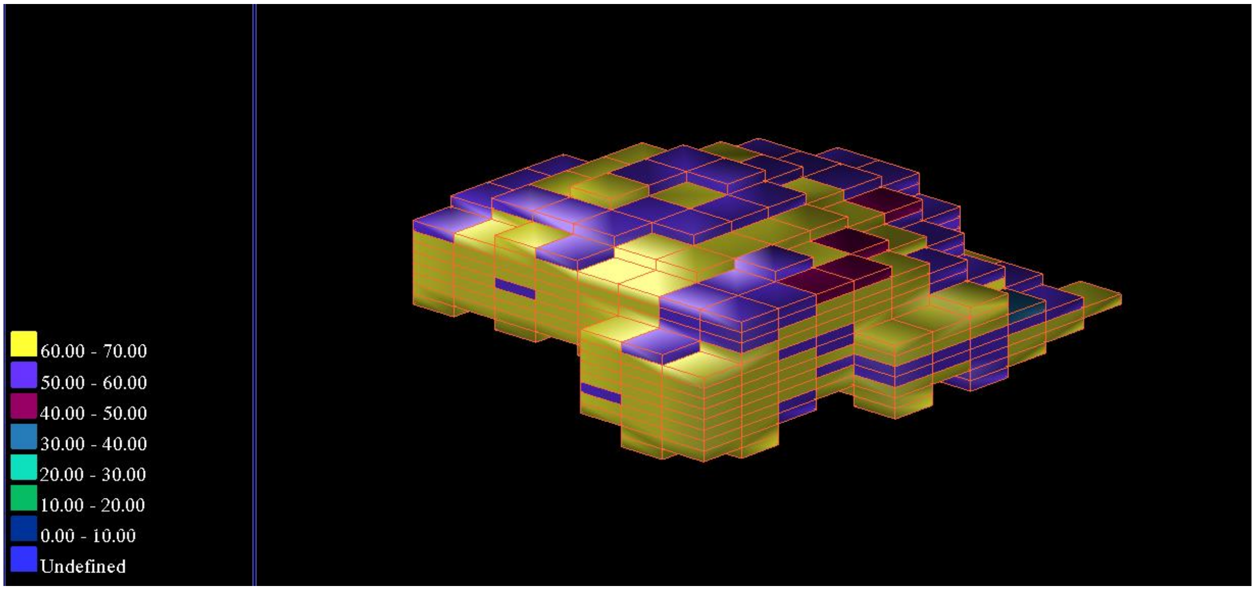


Figure 4.7 Constrained block model colored according to iron grade (blocks partially under constraints are included)

Estimation report:

Constraints used

a. Inside 3dm ore 2, where ore 2 is the solid model that we have created first

b. Iron grade of block > 50

Keep blocks partially in the constraint : false

Iron	Volume	Iron
50.0-55.0	675000	52.86
55.0-60.0	2000000	57.31
60.0-65.0	6725000	63.43
65.0-70.0	3500000	66.11
Grand total	**12900000**	**62.66**

4.5 Reserve estimation using Inverse Distance method (power 2 & 3):

For the reserve estimation using this method first we need to select the proper composite file. Large composite lengths may lead to easier calculation but result good estimation if the distribution of the mineral is continuous throughout the explored area. But if the distribution is not continuous then large composite lengths can result in erroneous estimation. It is because a large amount of mineral body is left and is not included in the estimation in case of large composite length. So, to overcome this drawback, in this project down the hole composites were created with different composite lengths and all were compared. The distribution of iron for different composite lengths is shown in terms of histograms.

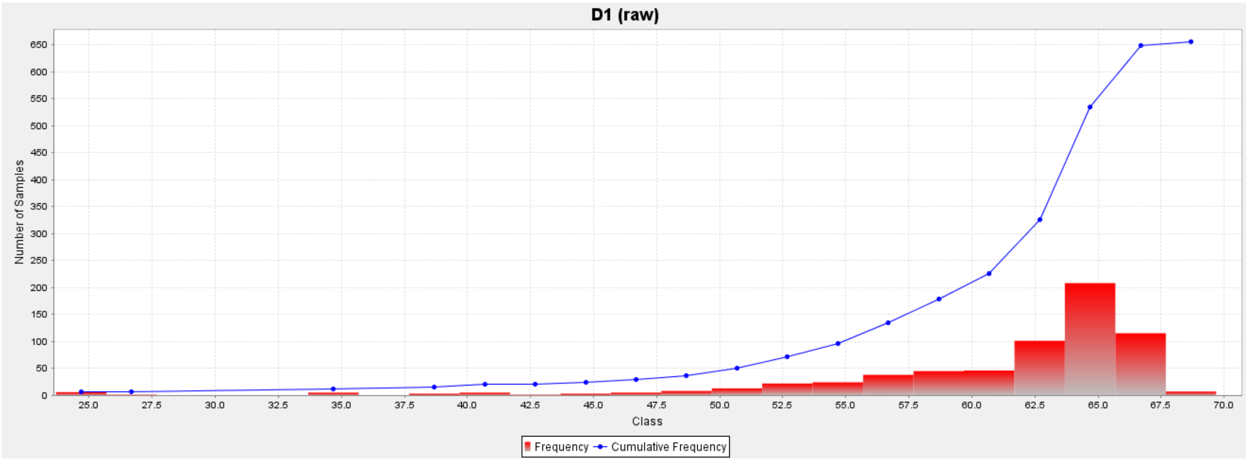


Figure 4.8 Histogram of iron grade with composite length 5

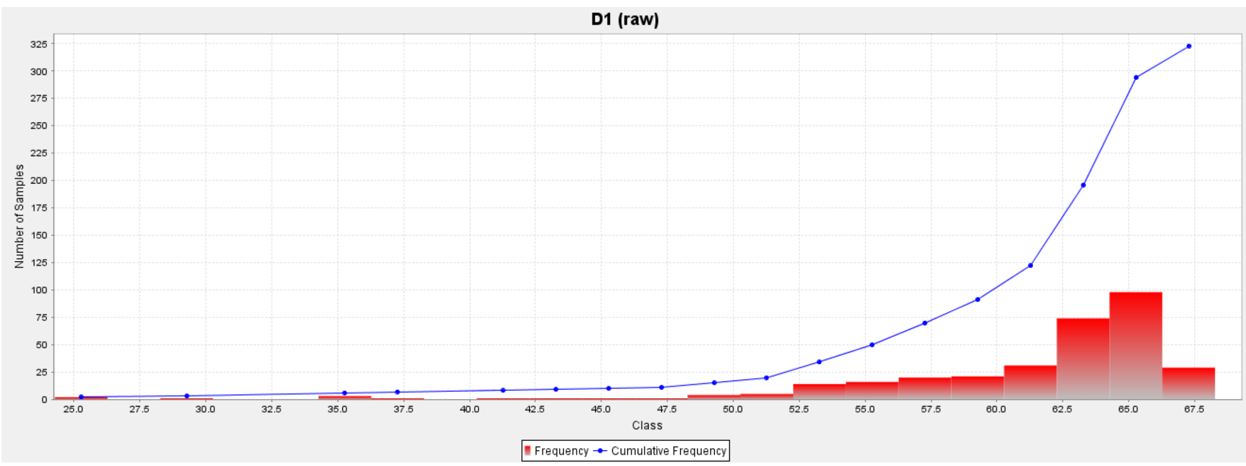


Figure 4.9 Histogram of iron grade with composite length 10

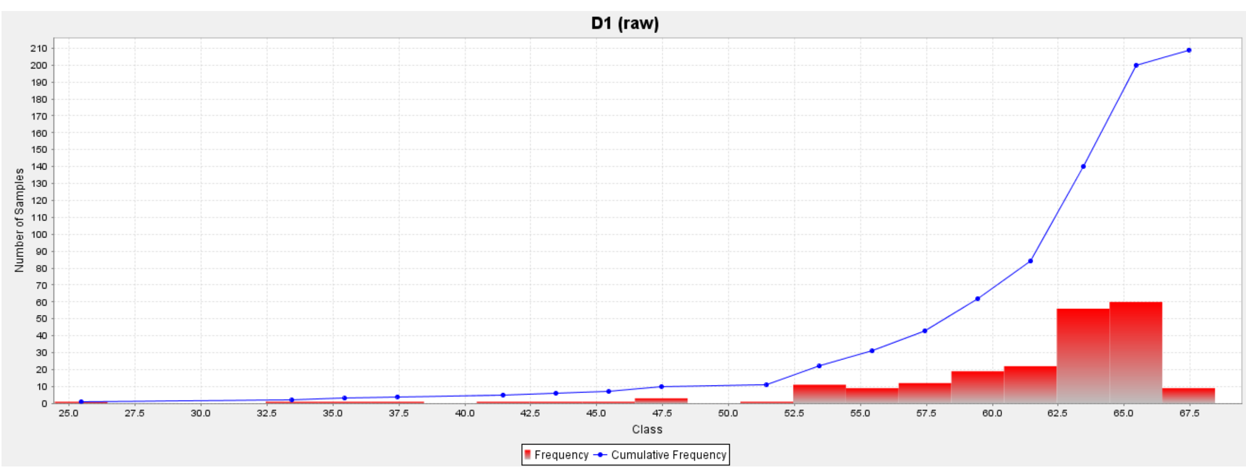


Figure 4.10 Histogram of iron grade with composite length 15

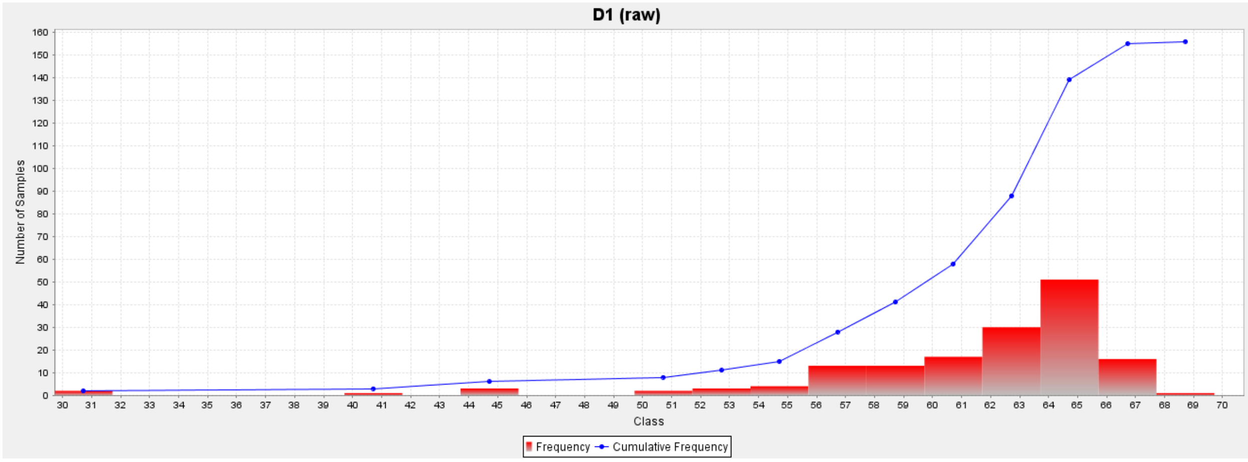


Figure 4.11 Histogram of iron grade with composite length 20

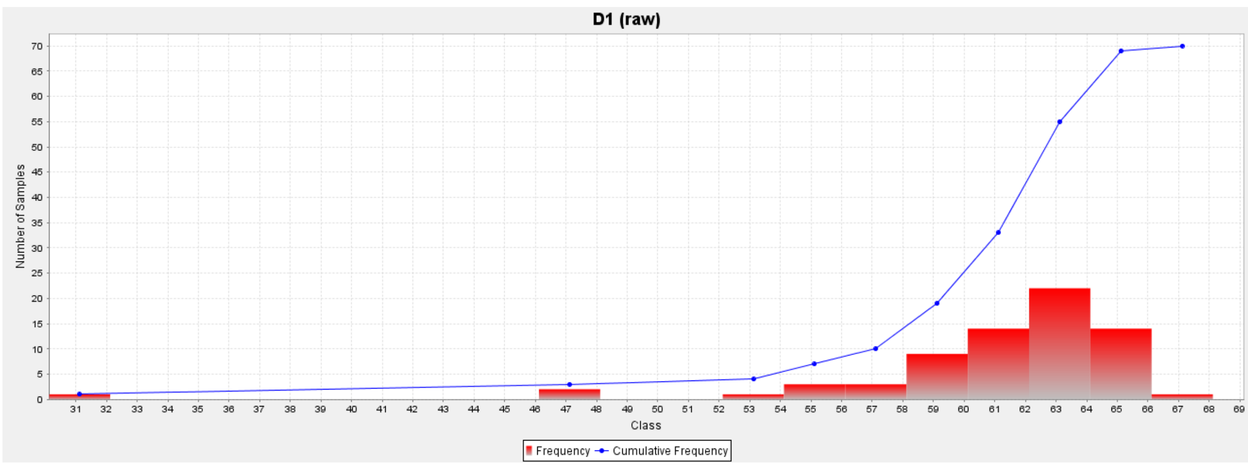


Figure 4.12 Histogram of iron grade with composite length 40

Comparison:

Composite length	Mean of iron grade
5	61.190147
10	61.244433
15	61.231958
20	61.178651
40	60.984257

Table 4.2 Comparison of different composite files

From the above table we can see that composite length 10 gives the best mean of iron grade among all the composite lengths. With larger composite lengths mean reduces continuously and it is also less with smaller composite length. Thus, composite length was taken to be 10.

Different parameters for ID

Ellipsoid search parameters

Angles of rotation of the major axis

Bearing	0.00
Dip angle	0.00
Tilt angle	0.00

Anisotropy factors

Semi-major axis	1.00
Minor axis	1.00

Other interpolation parameters

Max search distance of major axis	78.000
Max vertical search distance	78.000
Maximum number of informing samples	20
Minimum number of informing samples	2

Then appropriate constraints were applied (which is same as of the previous case, i.e. nearest neighbor method) and the resultant blocks were considered for ore reserve estimation. The figures of constrained block models are presented below (both for ID with power 2 & 3 respectively).

For Inverse Distance with power 2:

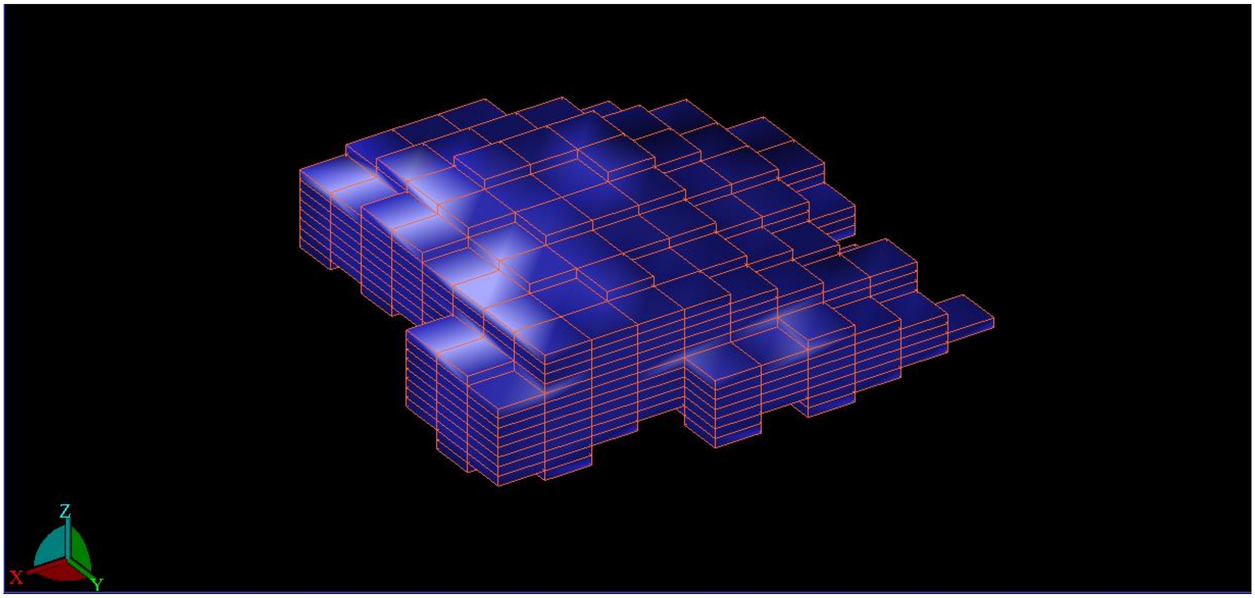


Figure 4.13 Block model after applying the solid model as constraint

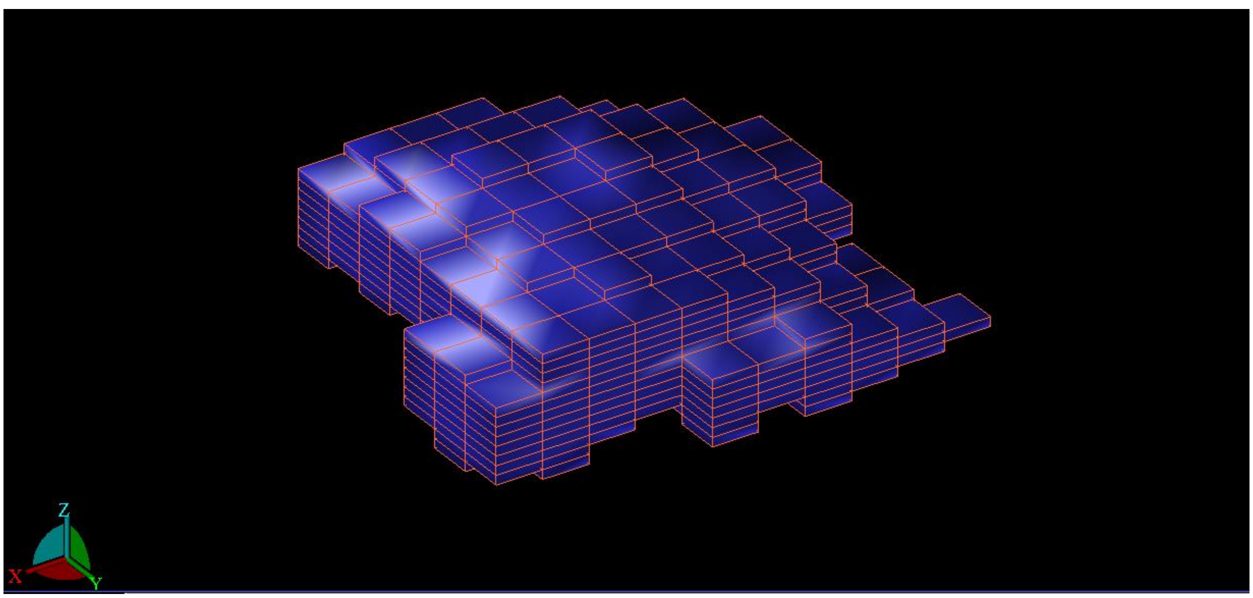


Figure 4.14 Block model after adding both solid model constraint and iron grade constraint (iron grade>50)

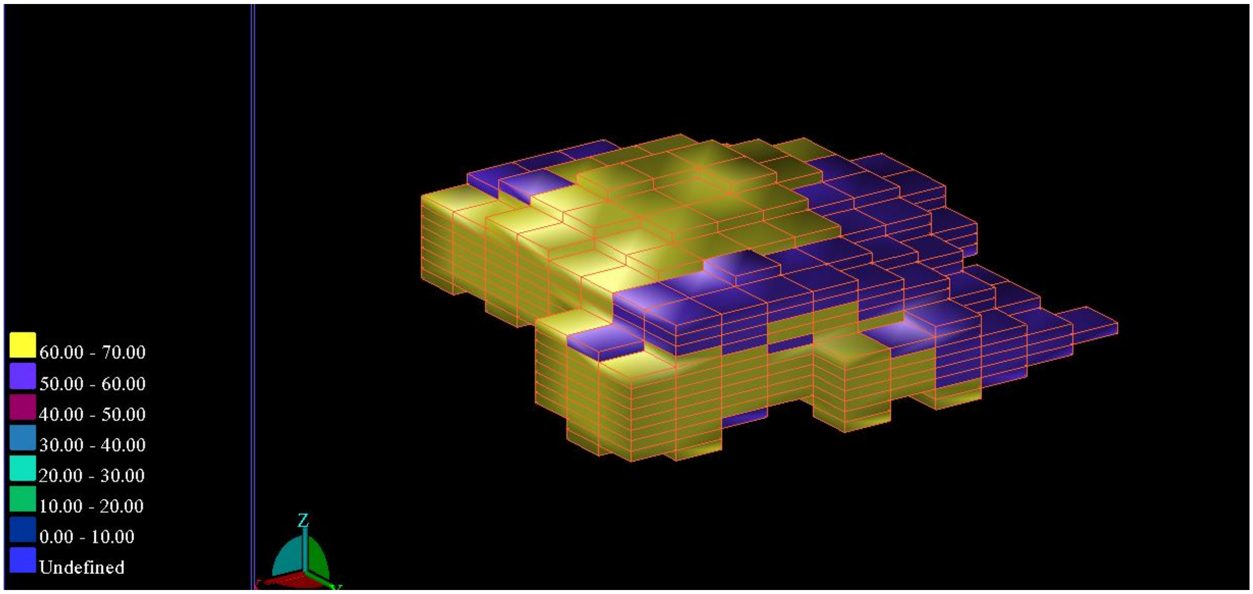


Figure 4.15 Constrained block model colored according to iron grade (blocks partially under constraints are included)

Estimation report

Constraints Used

a. Inside 3dm ore 2, where ore 2 is the solid model that we have created first

b. Iron grade of block > 50

Keep blocks partially in the constraint : False

Iron	Volume	Iron
50.0-55.0	375000	53.06
55.0-60.0	1700000	58.58
60.0-65.0	10800000	62.76
65.0-70.0	175000	65.16
Grand Total	**13050000**	**61.97**

For Inverse Distance with power 3:

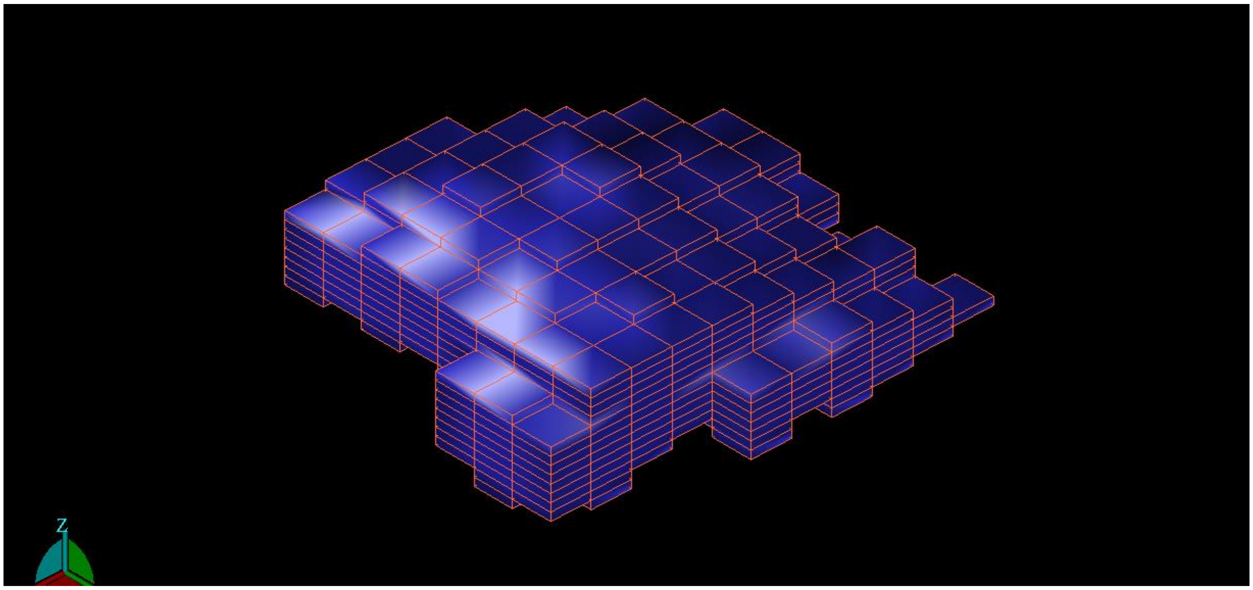


Figure 4.16 Block model after applying the solid model as constraint

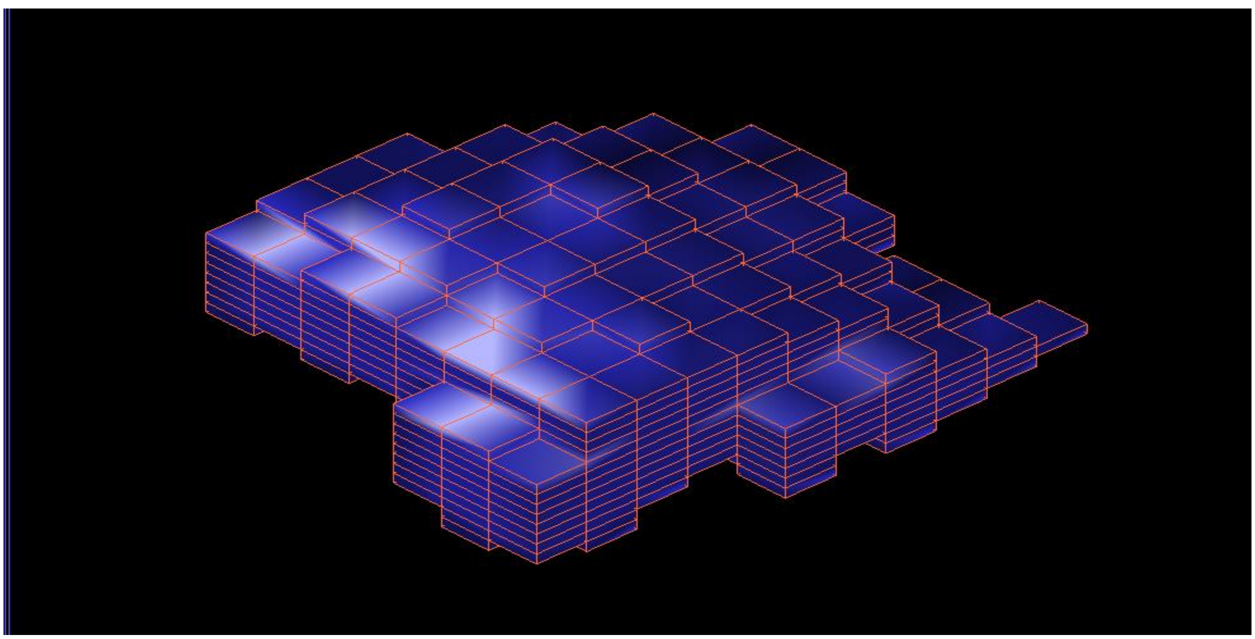


Figure 4.17 Block model after adding both solid model constraint and iron grade constraint (iron grade>50)

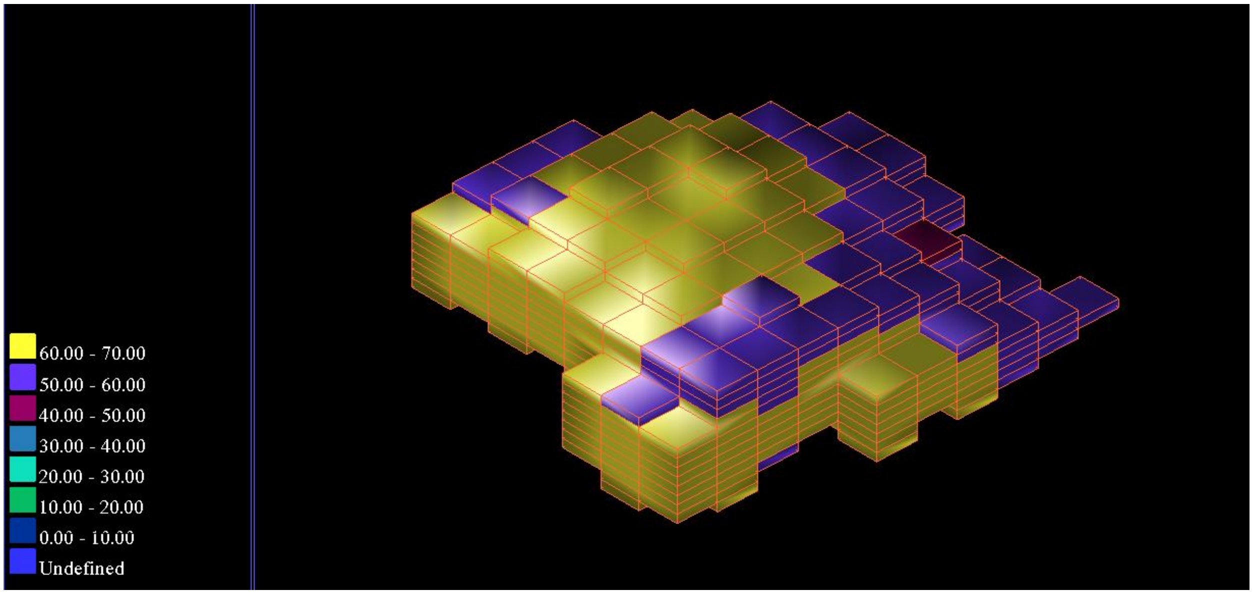


Figure 4.18 Constrained block model colored according to iron grade (blocks partially under constraints are included)

Estimation report:

Constraints Used

a. Inside 3dm ore 2, where ore 2 is the solid model that we have created first
b. Iron grade of block > 50

Keep blocks partially in the constraint : False

Iron	Volume	Iron
50.0-55.0	300000	52.56
55.0-60.0	1950000	58.41
60.0-65.0	10500000	62.88
65.0-70.0	275000	65.38
Grand Total	**13025000**	**62.03**

4.6 Reserve estimation using Ordinary Krigging method:

For ore reserve estimation using ordinary kriging method we need to decide suitable search parameters which are essential because a change in search parameter can result in misguided estimation. And for this first we need to design the variogram. Hence proper selection of variogram parameter is of much importance.

The variogram characterizes the spatial continuity or roughness of a data set. Ordinary onedimensional statistics for two data sets may be nearly identical, but the spatial continuity may be quite different. Refer to Section 2 for a partial justification of the variogram.

Variogram analysis consists of the experimental variogram calculated from the data and the variogram model fitted to the data. The experimental variogram is calculated by averaging onehalf the difference squared of the z-values over all pairs of observations with the specified separation distance and direction. It is plotted as a two-dimensional graph.

The variogram model is chosen from a set of mathematical functions that describe spatial relationships. The appropriate model is chosen by matching the shape of the curve of the experimental variogram to the shape of the curve of the mathematical function.

Mathematical function is defined as the variance of the difference between field values at two locations (x and y) across realizations of the field (Cressie 1993):

$$2\gamma(x,y) = \text{var}(Z(x) - Z(y)) = E\left(|(Z(x) - \mu(x)) - (Z(y) - \mu(y))|^2\right).$$

If the spatial random field has constant mean μ, this is equivalent to the expectation for the squared increment of the values between locations x and y (Wackernagel 2003)

(where x and y are not coordinates but points in space):

$$2\gamma(x,y) = E\left(|Z(x) - Z(y)|^2\right),$$

where $\gamma(x,y)$ itself is called the **semivariogram**. In the case of a stationary process, the variogram and semivariogram can be represented as a function $\gamma_s(h) = \gamma(0, 0 + h)$ of the difference $h = y - x$ between locations only, by the following relation (Cressie 1993):

$$\gamma(x,y) = \gamma_s(y - x).$$

If the process is furthermore isotropic, then the variogram and semivariogram can be represented by a function $\gamma_i(h) := \gamma_s(he_1)$ of the distance $h = \|y - x\|$ only (Cressie 1993):

$$\gamma(x,y) = \gamma_i(h).$$

Where ‘h’ is called lag distance.

Variogram calculation

The maximum lag distance is initially taken as the full span of the boreholes (i.e. 700 meters). Then from the experimental variogram the effect of the lag distance on the number of pairs of boreholes is studied. It is observed that with lag distance greater than 450 meter the number of borehole pairs are either zero or comparatively much less. Hence the maximum lag distance is set to 450m.

The best suited experimental variogram is selected based upon the following criteria:

- It should be smooth
- The variance should be minimum
- Range should be maximum for a given sill

Now whichever set of lag; bearing, azimuth and dip of search ellipsoid satisfies the above three criteria is selected to construct the experimental variogram.

In this project different lag values (5, 8, 10, 15) are used to construct the variogram. The generated variogram files are presented through the following figures respectively.

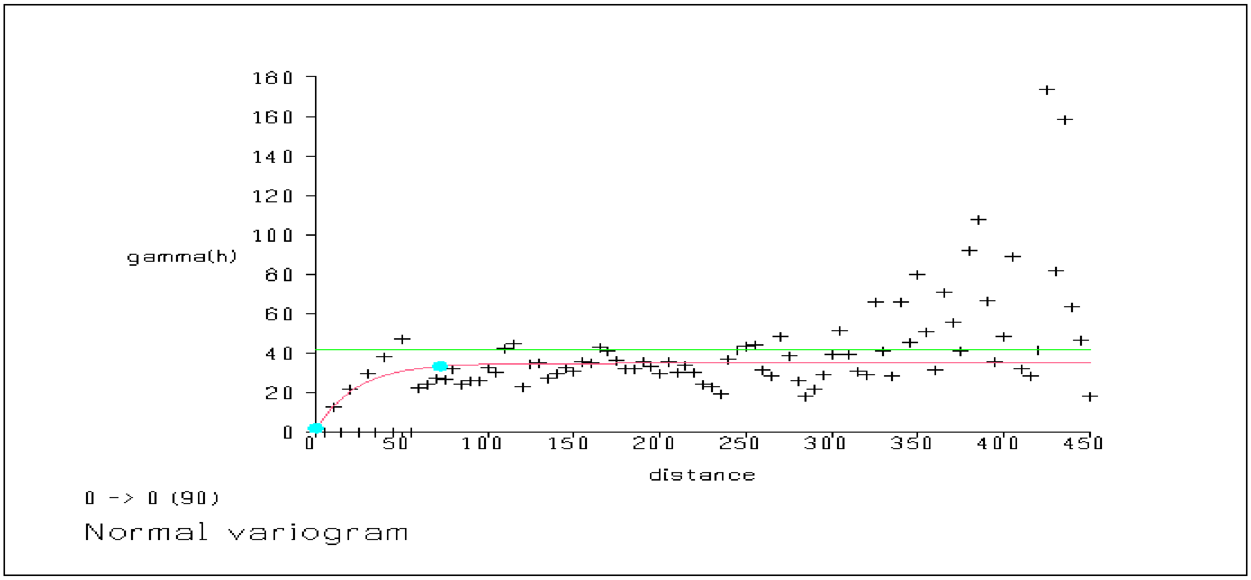


Figure 4.19 Variogram with lag 5

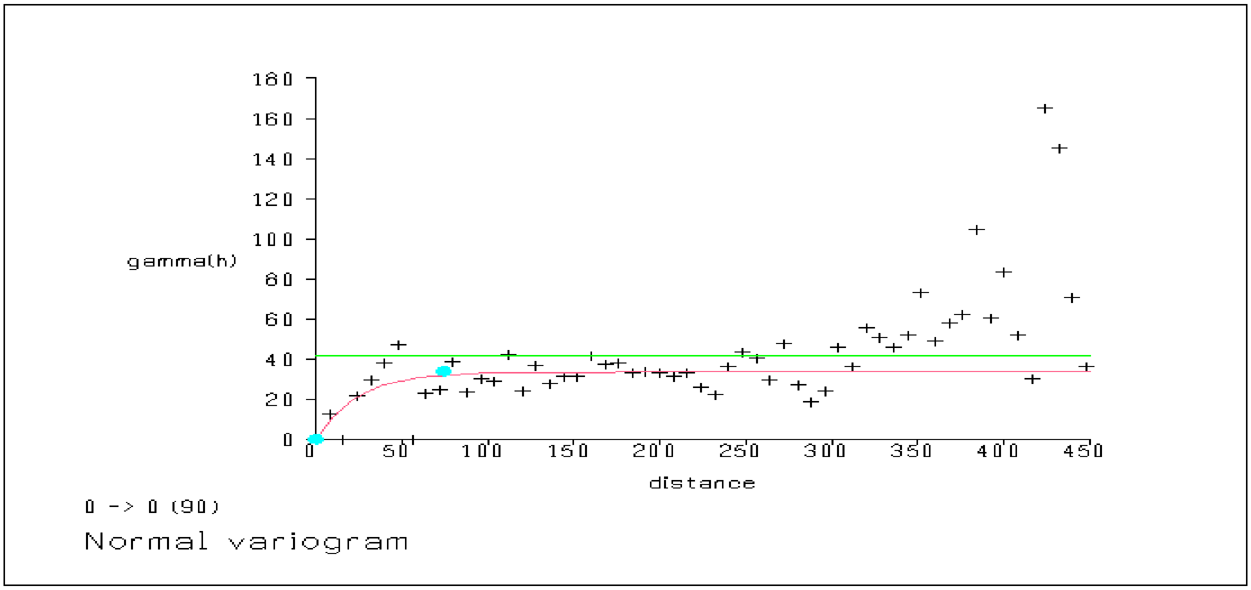


Figure 4.20 Variogram with lag 8

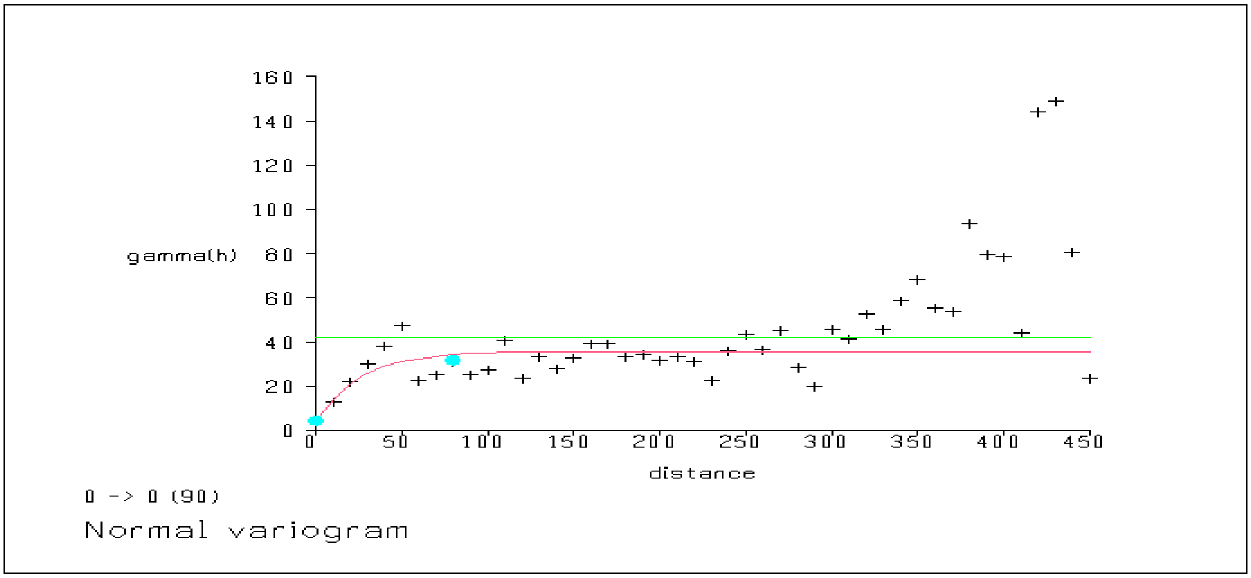


Figure 4.21 Variogram with lag 10

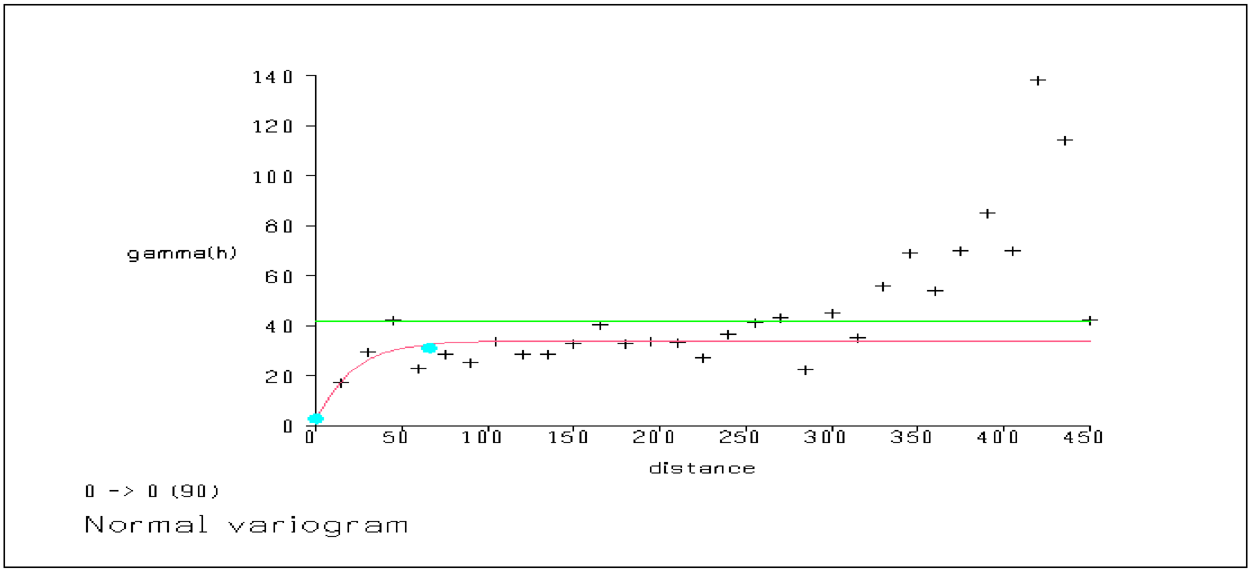


Figure 4.22 Variogram with lag 15

Lag value	Range	Variance
5	71.804	41.898
8	73.886	41.898
10	78.048	41.898
15	65.561	41.898

Table 4.3 Comparison of different lag values to determine the suitable variogram

The set of values which is observed to satisfy all the above criteria is given below:

1. Lag = 10
2. Bearing = 0
3. Azimuth = 0
4. Dip = 0

Then the selected experimental variogram is modeled and then saved for future use. The modeled variogram has the following attributes:

1. Nugget = 2.67
2. Sill = 32
3. Range = 78

Search parameters for ordinary kriging:

The important search parameters are max. search radius, max. vertical distance, bearing, azimuth, dip and anisotropy ratios. And these are decided based on the parameters of modeled variogram.

The search parameters set for this project are:

1. Maximum search radius = range of variogram = 78m
2. Maximum vertical distance = range = 78m
3. Bearing = 0
4. Azimuth = 0
5. Dip = 0
6. Major/minor axis ratio = 1
7. Major/semi-major axis = 1

The above parameters are set to the search ellipsoid and ordinary krigging of the block containing the mineral is performed for interpolation of iron grade. Then the appropriate constraints are applied to find the resulting ore reserve.

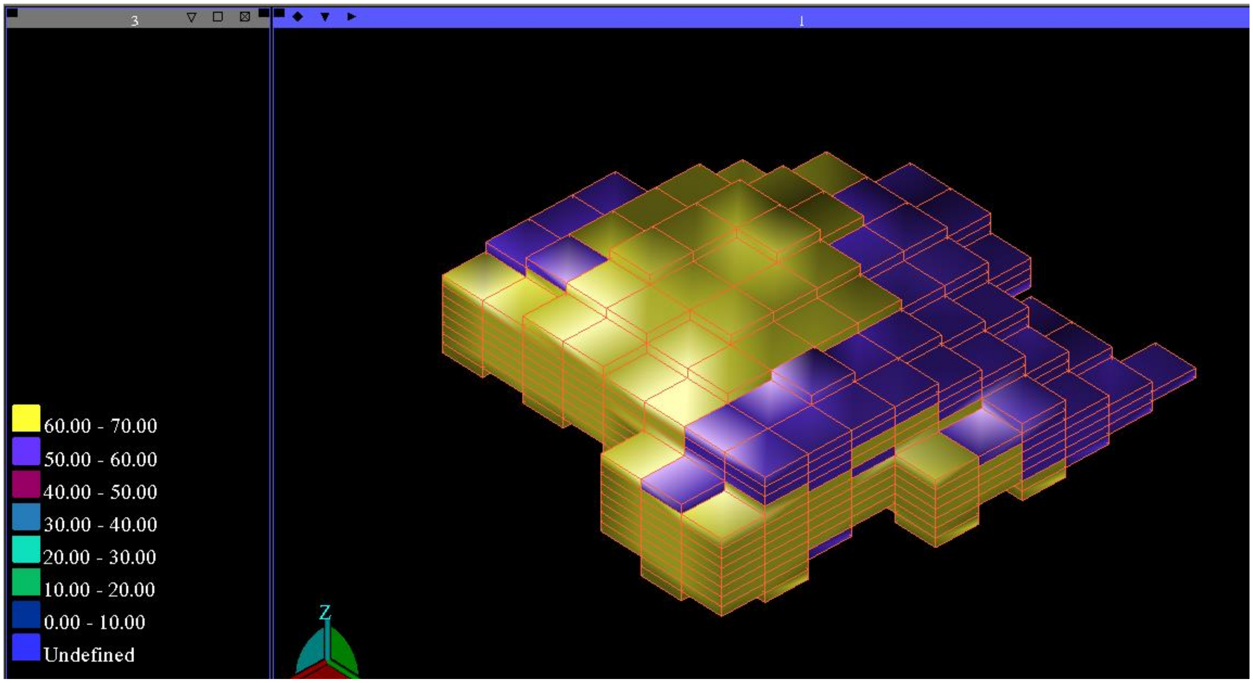


Figure 4.23 Constrained block model colored according to iron grade (Ordinary Krigging)

Estimation report:

Constraints Used

a. Inside 3dm ore 2, where ore 2 is the solid model that we have created first

b. Iron grade of block > 50

Keep blocks partially in the constraint : False

Iron	Volume	Iron
50.0-55.0	525000	53.22
55.0-60.0	2125000	58.12
60.0-65.0	9825000	62.78
65.0-70.0	500000	65.50
Grand Total	**12975000**	**61.74**

Chapter 5 :

COMPARISON & CONCLUSION

5.1 Comparison:

Here we have assumed ordinary krigging to be the best estima834tor which is also concluded in section 2. Now the comparison of reserve estimation of other estimators is carried out following the steps given below:

1. The variogram that has been used in the ordinary krigging estimation was cross validated.
2. Then the results of other estimators were compared with the result of ordinary krigging.

Cross validation of variogram:

Cross validation allows us to compare estimated and true values using only the information available in the sample data set. Thus it gives the statistics of krigging errors. The cross validation of the concerned variogram resulted the following:

- Number of assays = 352
- Mean of errors = 0.3508
- Variance of errors = 20.7834

The following figure explains the distribution of krigging errors.

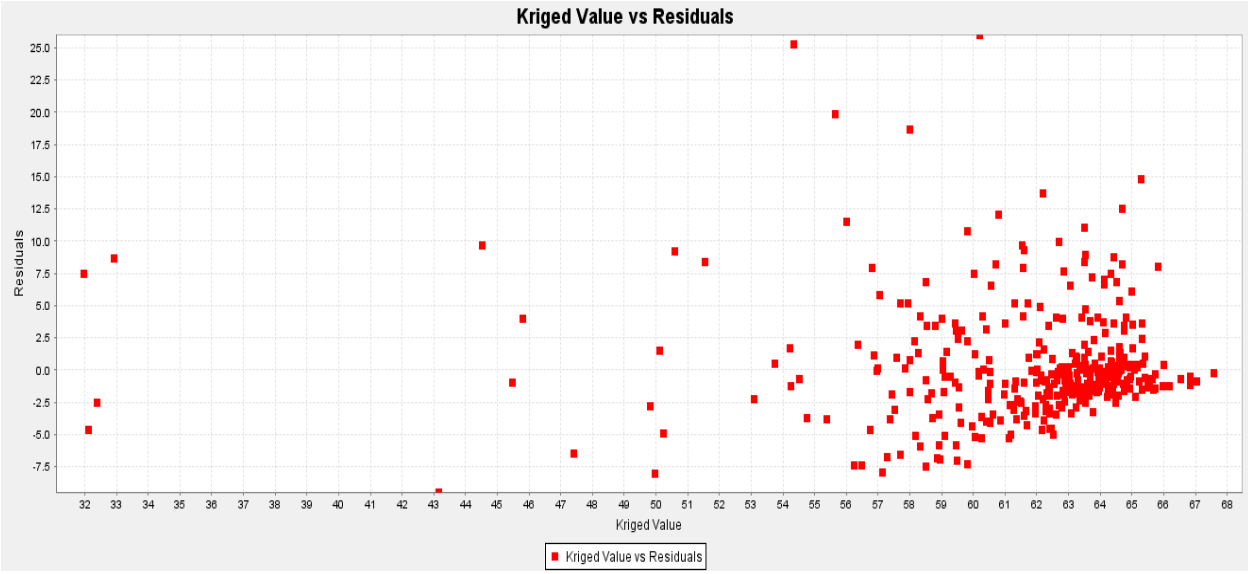


Figure 5.1 Distribution of Krigging errors

5.2 Conclusion:

The error in estimation in case of Ordinary Krigging was computed and the efficiency of reserve estimation using Nearest Neighbor and Inverse Distance (with power 2 & 3) method was compared with Ordinary Krigging method assuming it to be the best linear unbiased method.

From the obtained estimation results it was concluded that Nearest Neighbor method overestimates the iron percentage and underestimates the volume of the reserve while Inverse distance (with power 2 & 3) method overestimates both attributes in comparison to Ordinary Krigging.

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