Drill Holes Spacing Analysis for Estimation and Classification of Coal Resources Based on Variogram and Kriging

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Abstract. In detailed exploration, it is necessary to analyze optimal drill hole distance. Drill hole spacing analysis results in optimal drill hole spacing on each coal seam for the coal resources classification. Based on a case study in one of the coal mining companies in North Bengkulu, four coal seams have continuous seams and there is splitting from one seam to four seams. The sediment model generally has a direction of distribution of coal seams trending from northeast to southwest with gentle dip. This research uses geostatistical methods to determine the thickness distribution and variation of coal in the study area and to estimate and classify coal resources and determine the optimal distance from the borehole spacing. Estimation using kriging block results in the value of kriging relative error. Coal resource estimates and variability are determined based on kriging estimation with the relative kriging standard deviation (RKSD) method and the polygon method for classification based on sill distances. The number of drill holes used was 57 drill holes. Based on the calculation of the sill variogram, the coal measured resource is 150 meters, the coal indicated resource is 250 meters and the coal inferred resource is 500 meters. Based on the estimation and classification with relative kriging standard deviation (RKSD), the total coal measured resource is 1.8 million tons, the coal indicated resource is 3.2 million tons and the coal inferred resource is 2.5 million tons with total coal resources.

1. Introduction
The research location is currently conducting detailed exploration, by carrying out coring drilling and infill drilling, to obtain a certain level of estimation and classification of coal resources, as well as looking for new coal deposits. For this reason, several parameters need to be carried out, including analyzing the spacing of drill holes to optimize drilling and obtain exploration decisions. We can also see variations in the thickness of coal that the borehole cannot reach, so we need a method to estimate the parameters in places where the data is not known.

To classify and estimate coal resources, a method is needed that is suitable for the field conditions and the genesis of coal deposits. In this study, the geostatistical method is used, using "The Theory of Regionalized Variables" where the data from the sample points correlate with each other according to the distribution characteristics of coal deposits. The geostatistical method used is the kriging method. This method uses the correlation between points with Look at the value between spatial points to predict the value at an unknown location, where the prediction depends on the proximity to the sample location. This study aims to classify and estimate coal resources with geostatistics and determine the distribution of the level of variability in coal thickness, as well as to perform geological modeling and determine the optimal spacing of the drill holes.
2. Literature Review

2.1. Basic Statistics
Statistics is knowledge related to methods, techniques, or ways to collect data, process data, present data, analyze data, and draw conclusions or interpret data. Basic statistical analysis in geostatistics is used to determine that the data be calculated by the experimental variogram comes from a homogeneous population, because geostatistics assumes the data comes from a homogeneous population[1] The statistical analysis used is descriptive statistical analysis. Basic statistics provide information about the existence of such a distribution of data. The median, mean, and mode can give us information about where the distribution center is located. Variation and Standard deviation to describe the variability of data values. The shape of the distribution can be seen from the skewness and the coefficient of variation. [2] Before spatial analysis using geostatistical methods, all data must be analyzed in the form of basic statistics to determine the mean, standard deviation, coverage, COV, and other data as well as graphical forms, namely histograms and probability plots. If the CoV is less than 0.5, the data is considered to be normally distributed.[3] If the estimate is the end goal of the research, COV can provide a warning about upcoming problems. COV greater than one indicates the presence of several erratically high sample values that may have a significant impact on the final estimate. For the coefficient variance of the data, the data is normally distributed and tends to be homogeneous.

2.2. Geostatistics
The characteristics of the terrestrial data adopt spatial characteristics, which are spread over the spatial aspect of it can be said that the earth data is in a geographical position which has casting, northing, and elevation to the earth's space. Geostatistics in general understanding emphasizes or is focused on observing the distribution of data values in space [ Geostatistics is a statistical method used to see the relationship between variables measured at a certain point with the same variable, measured at a point with a certain distance from the first point (spatial data) and is used to estimate parameters where the data is not known. The use of geostatistics in mining has been widely used, one of which is used to estimate the total mineral and coal resources. The foundation of geostatistical learning is "The Theory of Regionalized Variables" [4], which contains:
   a. Data is random.
   b. Data are interconnected (dependence).
   c. The spatially adjacent variation of data is smaller than spatially distant data.
In its application, the geostatistical method can be optimal when the data is normally distributed and stationary (mean and variance do not change significantly concerning space)[5]. The data is stationary, if it has no trend or fluctuation the data is close to the average value or the variance that is constant concerning space. Significant deviations from data normality and data stationarity can cause problems[6].

2.3. Variogram
A variogram is a graph that displays spatial variations between data at a certain distance. In making a variogram, first, it is necessary to determine the direction of searching for data whether directional or omnidirectional by considering the spatial variations of the data are the same in all directions (isotropy) or different in each direction (anisotropy), then determine the distance tolerance, angular tolerance, and bandwidth[7],[8]. Based on the direction of searching the data, variograms are divided into two types: omnidirectional, where the direction of searching for data pairs in all directions or directions does not affect the search for data pairs, and directional, where the direction of searching for data pairs is focused on one move or direction separated by distance [2].
\[ \gamma(h) = \frac{1}{N} \sum_{i=1}^{N} (Z_i - \bar{Z})^2 \]  

\[ \text{Information:} \]
\[ \gamma(h) = \text{variogram value at interval } h \]
\[ N = \text{Number of data pairs.} \]
\[ Z_i = \text{value at point } i \]
\[ Z(i+h) = \text{the value of a point as far as } h \text{ from point } i \]

These calculations can then be plotted on a graph and produce experimental variograms which can then be modeled to obtain the parameters for estimating kriging. Based on the results of the experimental variogram modeling, the following parameters were obtained which would later be used in kriging estimation, including [6]:

a. Sill is a stable state of the variance value in which the data still has a correlation or relationship.
b. The Range is the limit of stationarity where the effect of a value will decrease over a distance greater than the range.
c. The nugget effect is a phenomenon present in many regionalized variables and represents short-scale randomness or noise in the regionalized variable.

Estimation using kriging requires parameters as described above. These parameters are obtained by modeling the experimental variogram into a line equation or better known as the variogram model. There are five variogram models often used [6]:

a. Spherical Model
   The form of this variogram is formulated as follows:
   \[ \gamma(h) = \begin{cases} c \left( \frac{3h}{a} - \frac{h^3}{2a^3} \right), & \text{for } h \leq a \\ c, & \text{for } h > a \end{cases} \]  

b. Exponential Model
   In the exponential model there is a very steep increase in the semivariogram and reaches the sill value asymptotically, formulated as follows:
   \[ \gamma(h) = c \left[ 1 - \exp \left( -\frac{h}{a} \right) \right] \]  

c. Gaussian Model
   The Gauss model is the quadratic form of the exponential so that it produces a parabolic form at close range. The Gauss model is as follows:
   \[ \gamma(h) = c \left[ 1 - \exp \left( -\frac{h^2}{2a^2} \right) \right] \]  

d. Power
   Power did not reach the sill value and did not have the appropriate covariance function. The power model is suitable for showing fractal behavior. It is commonly used for data that is not stationary and has a trend.
   \[ \gamma(h) = ch^\theta \text{ with } 0 < \theta < 2 \]  

e. Nugget
   \[ \gamma(h) = \begin{cases} 0, & \text{if } h = a \\ c, & \text{otherwise} \end{cases} \]
Information:
y (h) = variant value
c = sill (threshold)
h = log distance
α = practical range
β = shape parameter

2.4. Cross-Validation
After the experimental variogram has been modeled, it is necessary to carry out a variogram (validation) test to ensure that the experimental variogram that has been modeled can be used in kriging by using the cross-validation method[9]. This is done by comparing the true parameters with the estimated values at each sample point and generating a scatterplot and statistics.[10]

2.5. Kriging
Kriging is a method of estimating the value at a point or block that has no data value by utilizing a linear equation from the variogram modeling represented by the sill, range, and nugget effect values. The kriging method is a BLUE (Best Linear Unbiased Estimator)[11], which means:
a. Best, minimize error variance
b. Linear, the equation in the estimation is a linear function
c. Unavailable, ensure that the estimated value is unbiased (impartial).

In addition to the sill, range, and nugget effect values, according to, the accuracy of the estimation is influenced by several factors [1]:
a. Number of samples and data quality for each point
b. Position or location of data samples
c. The distance between the sample and the estimated point
d. Spatial continuity of data

Kriging which is known for estimating or estimating is divided into several types, namely based on the type and method[12]. Based on the type, kriging can be divided into point kriging (estimation of the point) and block kriging (estimation of blocks).

Kriging is divided into several types:
a. Ordinary kriging (OK), the simplest method and is commonly used when the mean is unknown.
b. Simple kriging (SK), used when the mean is known.
c. Universal kriging is an estimate of data that has a certain trend or trend.

Universal kriging is sometimes referred to as kriging with the trend. Resource estimation using the ordinary kriging method uses the weight as a control of the points around the location to be estimated, where the sum of these weights will amount to 1.

Kriging gives more weight to the sample with the closest distance compared to the sample with a farther distance, General equation of the kriging function according to[13]:

\[ Z(v) = \sum \lambda_i Z(x_i) \] \hspace{1cm} \text{to[13]}

Where:
- \( Z(x) \) = Measured value at location i
- \( \lambda_i \) = Weight of the measured value at location i
- \( Z(v) \) = Predicted Location

The weight (\( \lambda_i \)) used in the kriging function is obtained from the results of experimental variogram modeling, namely the range, sill, and nugget effect values entered in the Spherical model formula.

Information:
- \( \hat{Z}_o \) = Estimated point value
- \( \lambda_i \) = Weight factor from point i
- \( Z_i \) = Value of the estimating point
2.6. Classification Based on RKSD
The resource classification is based on Blackwell (1998), the measured, indicated, and inferred resource relationships based on the Relative Kriging Standard Deviation (RKSD) value are formulated as follows [14,15]:
\[
\text{RKSD} = \pm 1.96 \left( \frac{\sigma_z}{\sigma} \right) \tag{8}
\]
Information:
\[
\sigma = \text{Kriging standard deviation}
\]
\[
z^* = \text{Kriging value}
\]
Based on the RKSD value, resources are grouped as follows:
a. Measured Resources are when a block has an RKSD value <0.3.
b. Indicated Resources are when the block has a value of 0.3≤RKSD≤0.5.
c. Inferred Resources are when blocks have RKSD value> 0.5.

The calculation of the number of resources with the block model by multiplying the dimensions of the box in the kriging results by the thickness and density results in the tonnage of a deposit which is calculated as follows[5]:
\[
\text{Tonnage} = \sum_{i=1}^{n} A_i \times T_i \times D_i \tag{9}
\]
Where :
\[
A_i = \text{area of block i}
\]
\[
T_i = \text{thickness of coal in block i}
\]
\[
D_i = \text{density of coal in block i}
\]

2.7. Polygon Method (Area of Influence)
The polygon method is also called the area of influence method. In this method, all factors are determined for a particular point in the mineral deposit, extended as far as half the distance from the surrounding point forming an area of influence. The boundary of the outer area of influence of this polygon can only reach the outermost drill points (included area), or be extended to half the distance (extended area)[16]

3. Research Methodology
The method used in this research is a descriptive method and a quantitative method. The descriptive method is the observation method using secondary data, in the form of a description of the facts in the field, which will later be used in the analysis[5]. This method is also used to examine data on the distribution of coal thickness in the study area. The quantitative method is to determine the spread of the drill holes, create a geological model of coal, to see the area of coal distribution at the research location. Furthermore, estimating and classifying coal resources using geostatistical methods, the result is the determination of the optimal distance from the drill hole spacing.
The research location is in a coal mining area in North Bengkulu, Bengkulu Province. The first stage is to collect actual information using field conditions represented by pictures and graphs. Presentation of approach information on quantitative equations with geostatistical methods. Primary data in the form of drill data was used with a total of 57 drill holes data. The research stages are as follows:
a. Collecting coal exploration drill data. The drilling location is determined based on the mining plan.
b. Database creation and data evaluation
c. Test Statistics use Matlab to find out the data distribution
d. Variogram Modeling by using coal thickness data, the resulting variogram model, and the model produced optimally using the Variowin software.

e. Perform Cross-Validation Test

f. Estimating coal resources using the kriging (RKSD) using SGems software and polygon methods using Minescape software

g. Comparing the estimated coal resources from the polygon and kriging (RKSD) methods

4. Results And Discussion

4.1. Data
The data used is secondary data for coal exploration drilling in the research area which is used to model the spread of coal seams, classify coal resources, and estimate the tonnage of coal resources. Drill hole data for the whole area were 57 drill holes with an average spacing of ± 100 meters. The drilling depth varies up to 84.5 meters with touch coring and full coring drilling methods and has varying lithologies. Each drill hole has data in the form of Hole ID, easting, northing, elevation, top, and bottom for each lithology and the total depth of the hole and there are two geophysical well logging logs from the drill hole. The data collected to meet the objectives of this research are also lithology maps, geological maps, crop line maps, and drilling maps. Drilling to search for coal seams is carried out with the lowest borehole depth of 17.05 meters and the largest is 84.5 meters. In drilling in 57 drill holes, the thickness of the coal obtained varies according to the seam of each coal consisting of 4 seams. The thickness of coal for seam 1 to seam 4 from the largest and smallest thickness is as follows:

Seam 1: 5.57 meters and 0.4 meters
Seam 2: 3.2 meters and 0.15 meters
Seam 3: 3 meters and 0.2 meters
Seam 4: 2.95 meters and 0.35 meters

4.2. Geological Modeling of Coal Deposit
Geological modeling of a coal deposit is used to see coal crop lines, modeling coal seams, and the direction of their distribution. Coal modeling is done by correlating data from the database by creating survey data and lithology data. The survey data consisted of Hole ID, coordinates, elevation, drilling depth. The lithology data consists of Hole ID, Top, and Bottom of the lithology. Modeling of coal deposits using MineScape software is carried out using the Stratmodel module application. The general principle of Stratmodel is based on the general principles of stratigraphy, especially the sequence of layers deposited in a certain period that is continuous or aligned. The order of layers that are aligned in the Stratmodel is known as a conformable sequence. A conformable sequence is a part that shows deposits that have the same structural and structural characteristics. Stratmodel can make a geological model that consists of several conformable sequences which are in tune or not in harmony with one another. By obtaining a model of continuous coal deposits towards the northeast-southwest with a general strike and dip N 141° E/3° - 10°.

Figure 1. Structure contour map
4.3. Basic Statistical Analysis

Based on the results of the basic statistical analysis of the coal thickness value data. The basic statistical analysis data are as follows: The variance value is 4.123 as one of the parameters to see the sill limit of the variogram model. The coefficient variance obtained is 0.491. If the CoV is less than 0.5, the data is considered to be normally distributed [3]. The results of skewness are used to measure the asymmetry of data distribution, for coal thickness data which shows a value of -0.70, the curve will be skewed to the left (negative curve). The kurtosis value is a value that measures the degree of tapering or the peak height of the data distribution, the coal thickness data shows the kurtosis value, which is -0.51 meaning that the data is blunt or tends to be flat (platikurtis curve). For histogram graph analysis on coal thickness, the visible data can be useful to see the size of the location, the size of the spread and the size of the...
The data has met the criteria for normal distribution, seen from the high frequency approaching the mean data and the graph is symmetrical according to the distribution. The Probability Plot graph contains data that is not on the line and does not approach the diagonal line, but there is also data that is on and close to the diagonal line. The normality of a probability plot graph is not always the most important step in determining the distribution of the data, so it is not a priority if the probability plot does not fit the diagonal line. Data that is not on the diagonal line does not mean the estimation is good, data that is not on the diagonal line also cannot be ruled out looking at the distribution approach to determine the estimate. For this reason, the data can be continued to model the variogram and estimate using kriging.

| Basic Statistics | Coal Thickness |
|------------------|----------------|
| **Mean**         | 4,953          |
| **StDev**        | 2,031          |
| **Variance**     | 4,123          |
| **CoV**          | 0,409          |
| **Minimum**      | 0,400          |
| **Median**       | 5,460          |
| **Maximum**      | 7,970          |
| **Skewness**     | -0.70          |
| **Kurtosis**     | -0.51          |

**Figure 5.** Histogram Graph of Coal Thickness

**Figure 6.** Coal Thickness Probability Plot Graph
4.4. Spatial Statistical Analysis
In making the Experimental Variogram, coal drill data were used and processed with variowin software for the thickness of the coal. The parameter used is the 125-meter lag spacing, the lag tolerance is half of the lag spacing and the number of lag is 10. Experimental this variogram uses an angular tolerance of 90°, with the direction of searching for data pairs in all directions (Omnidirectional).

![Figure 7. Experimental Omni Directional Variogram of Coal Thickness](image)

The experimental variogram is then modeled so that three parameters are obtained for the resource estimation process using the kriging method. This study using a spherical model. The parameters obtained are the nugget effect (Co), (C) sill, and range as follows:

![Figure 8. Variogram Modeling of Coal Thickness](image)

The variogram parameters are range 630 meters, sill 3.173, and nugget effect 1.655. The values obtained must be tested with the cross-validation method, to be used in kriging, resulting in BLUE kriging or not[19]. Cross-validation compares the estimation results with the actual thickness data of the coal. This test shows that the correct variogram model produces BLUE kriging, if the variogram model is not correct then the kriging is invalid.

![Figure 9. Cross-Validation Of Coal Thickness](image)

The results of the cross-validation model show the distribution of data points, some points are close to the linear line and those that are not. This indicates that there is an error. Furthermore, the error calculation is carried out by comparing the estimated value with the actual thickness data of the coal from each point of the borehole. All error values are averaged so that an average value is obtained. The result of the error value of the thickness of the coal is 54.89%. This error may be due to errors in
exploration drilling activities in both technical terms and drill log descriptions. This error value can later cause the estimation process by kriging to not run optimally.

4.5. Classification of Coal Resources Based on The Distance Between Drill Hole Spacing

Classification of coal resources based on the distance between drill hole spacing can be seen from the continuity of the variogram, which is to calculate the distance between drill hole spacing based on the sill [20]. At the research location, the average distance between boreholes is ± 100 meters with the sill values that have been obtained from the variogram model. Based on the variogram continuity classification it is obtained from the sill value [21]. One-third of the sill value of a measured resource, two-thirds of the sill is the indicated resource and the value of three-thirds of the sill is the inferred resource. From this classification, the measured resource is 150 meters, the indicated resource is 250 meters, and the inferred resource is the value range of 500 meters.

![Figure 10. Classification Based On Variogram Continuity](image)

Based on the results that have been obtained, the classification at the research location is included in the measurable classification. The benefits of determining the minimum borehole spacing for resource classification are the possibility of reducing drilling costs by using a wider drilling distance, determining whether it is necessary to increase the drilling distance, and determining whether increasing the drilling distance will provide meaningful additional information. To see how to model the classification area and to ensure that the research area includes measured resources, a polygon model is made. Furthermore, knowing the number of coal resources with polygons in Minescape and as a comparison for estimation with geostatistics.

![Figure 11. Polygon Area Model For Classification Based On Continuous Sill Variogram](image)
Table 2. Estimation Results of Coal Resources With Polygons Based on Continuous Sill Variogram

| Coal Resource Classification | Drill hole spacing (meter) |
|-----------------------------|---------------------------|
| Measured (0 - 1/3 sill)     | 150                       |
| Indicated (1/3 – 2/3 sill)  | 150 – 250                 |
| Inferred (2/3 – 3/3 sill)   | 250 – 500                 |

Kriging analysis was performed using SGeMS software, using a block size of 100 meters x 100 meters. The kriging method used is the ordinary kriging method. From the estimation results obtained kriging the thickness of the coal and kriging the variance. Following are the results of kriging and kriging variance:

Based on the estimation results, it can be seen the distribution of the thickness of the coal from the estimation results of the kriging and the distribution of the variation of the thickness of the coal from the variant kriging. The results of the spread of the thickness estimation by kriging and the spread of the variance kriging can be useful for knowing areas that have a high thickness and small variations, and there is no need to drill in adjacent spots, also to find out areas that have sweet spots, as a consideration and a basis for determining exploration drilling and subsequent decision making, to minimize costs incurred and gain high geological confidence. From the results of kriging and kriging variance, resources can be classified using the relative kriging standard deviation (RKSD) formula.
Table 3. Estimation and Classification of Coal Resources Based on RKSD

| Coal resource classification | Total Resources (tonnes) |
|-----------------------------|--------------------------|
| Measured                    | 1,837,483                |
| Indicated                   | 3,205,816                |
| Inferred                    | 2,518,963                |
| Total                       | 7,562,261                |

The estimation results and classification of coal thickness are for coal resources measured as 1.8 million tons, indicated coal resources 3.2 million tons, and inferred coal resources 2.5 million tons. The total coal resource in the study area is 7.5 million tons. Based on the comparison of the estimation results from the classification method using a continuous sill variogram and the RKSD method, it is known that the total estimated coal resource has a difference of 390 thousand tons. The significant difference in the results of the estimated resource based on measured, indicated and estimated classifications is seen in the estimation results obtained, including measured coal resources which have a difference of 460 thousand tons, while for indicated and estimated coal resources, the overall estimate is almost the same. Based on the comparison of the estimation results of the RKSD method and the polygon method based on the continuity of the sill variogram, the calculation results are almost the same and the comparison is not too far away. Judging from the classification and estimation of coal resources using the polygon method, it can be seen that the optimal distance obtained is to be measured, namely 150 meters, indicated as 250 meters and inferred is 500 meters. After obtaining the classification from the calculation results with the RKSD method, a classification map is then made to see the classification areas that have been estimated. It can be seen that the classification map from the polygon method with continuity of sill variogram is almost the same as the RKSD method, as follows:

Figure 14. Map of Resource Classification with RKSD

Information:
Dark blue (1) = Measurable source
Light green (2) = Designated resource
Red (3) = inferred resource

5. Conclusion

From the results of the research that has been done, the following conclusions can be drawn:

a. Optimal distance from borehole spacing, namely: For coal resources, the measured, indicated, and inferred are 150 meters, 250 meters, and 500 meters. Resource classification is a measured coal resource.

b. The coal seam model is according to the geological model, the coal is continuous, has 4 coal seams which are splitting from one layer to four coal seams. It has a general distribution direction from the northeast to the southwest with a gentle dip.

c. From the estimation and classification of coal resources based on the ordinary kriging method based on RKSD, the estimated measured coal resource is 5 million tons, the indicated coal resource is 2.3
million tons and the inferred coal resource is 120 thousand tons with a total coal resource of 7.5 million tons.

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