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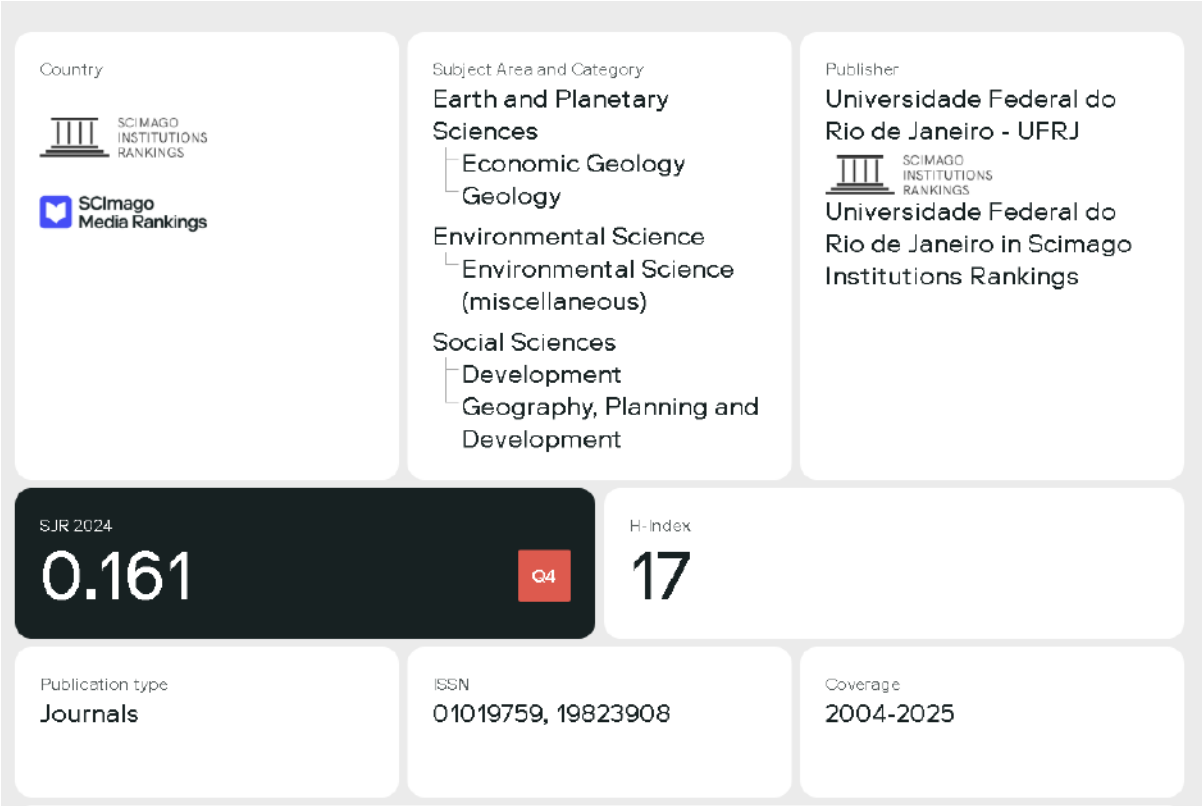
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GEOLOGY

Application of the Global Estimation Variance and Sill Variogram Methods in Determining the Optimum Drill Hole Distance for the classification of Measured Coal Resources

Aplicação dos Métodos de Variância de Estimativa Global e Variograma de Sill na Determinação da Distância Ideal Entre Furos de Perfuração para a Classificação de Recursos de Carvão Medidos

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Abstract

In the implementation of effective and efficient exploration of mineral and coal resources, it is required to carry out geostatistical analysis to determine the relative error value of the optimum spacing of the drilling and its thickness and quality distribution. This study uses the application of geostatistics with the sill variogram method and global estimation variance (GEV), based on the relative value of the error of the thickness of the coal seam. This research was conducted in the concession area of PT. Kaltim Prima Coal. Based on the case study, the coalfield consisted of two seams, namely the North BE and South BE seams, with moderate geological conditions. From the variogram analysis of the thickness of the northern BE layer, the range is 151, the sill is 0.65, and the Nugget Effect is 0.04, while the BE South has a range value of 209, the sill is 0.16, and the nugget effect is 0.26. Based on field data, the average drill hole distance in the North BE seam is 131 meters. The distance of 1/3 of the sill gets a value of 50 meters (measured resource), while for the South BE seam it is 126 meters. The distance of 1/3 sill gets a value of 60 meters (measured resource), the distance of 2/3 sill gets a value of 122 meters (resource indicated), and the distance of 3/3 sill gets a value of 210 meters (inferred resource). Based on global estimation variance analysis. For the North BE Seam, the drill hole spacing for the measured resource category was 350 meters with a total of 29 drills, while for the South BE Seam, the drill hole spacing for the measured resource category was 350 meters with a total of 104 drills. The results of this classification produce an area of influence that is smaller than the SNI standard of moderate geological complexity. By using the sill variogram analysis, the results of the drill hole spacing are dense when compared to the results of the GEV analysis. The results of this GEV classification produce an area of influence that is relatively like to the SNI standard of moderate geological complexity.

Keywords: Geostatistics; Geological Complexity; SNI standard

Resumo

Na implementação de uma exploração eficaz e eficiente dos recursos minerais e de carvão, é necessário realizar uma análise geoestatística para determinar o valor do erro relativo do espaçamento ideal da perfuração e sua distribuição de espessura e qualidade. Este estudo utiliza a aplicação da geoestatística com o método do variograma de soleira e a variância de estimativa global (GEV), com base no valor relativo do erro da espessura da camada de carvão. Esta pesquisa foi realizada na área de concessão da PT. Kaltim Prima Coal. Com base no estudo de caso, o campo de carvão consistia em duas camadas, nomeadamente as camadas BE Norte e BE Sul, com condições geológicas moderadas. A partir da análise do variograma da espessura da camada BE Norte, o intervalo é 151, o limiar é 0,65 e o efeito Nugget é 0,04, enquanto a BE Sul tem um valor de intervalo de 209, o limiar é 0,16 e o efeito Nugget é 0,26. Com base nos dados de campo, a distância média entre os furos de perfuração na camada BE Norte é de 131 metros. A distância de 1/3 do limiar obtém um valor de 50 metros (recurso medido), enquanto que para a camada BE sul é de 126 metros. A distância de 1/3 do limiar obtém um valor de 60 metros (recurso medido), a distância de 2/3 do limiar obtém um valor de 122 metros (recurso indicado) e a distância de 3/3 do limiar obtém um valor de 210 metros (recurso inferido). Com base na análise de variação da estimativa global.

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Para a camada BE Norte, o espaçamento entre os furos de perfuração para a categoria de recurso medido foi de 350 metros, com um total de 29 furos, enquanto que para a camada BE Sul, o espaçamento entre os furos de perfuração para a categoria de recurso medido foi de 350 metros, com um total de 104 furos. Os resultados desta classificação produzem uma área de influência menor do que o padrão SNI de complexidade geológica moderada. Ao usar a análise do variograma de soleira, os resultados do espaçamento entre furos de perfuração são densos quando comparados aos resultados da análise GEV. Os resultados dessa classificação GEV produzem uma área de influência relativamente semelhante ao padrão SNI de complexidade geológica moderada.

Palavras-chave: Geoestatística; Complexidade Geológica; Padrão SNI

1 Introduction

Most mining companies will try to get maximum profit with minimum costs; in this case, the cost of drilling is the one that must be incurred in large amounts. The factor that most influences resource classification is the distance of the drill holes. For economic reasons to get maximum profit with minimum cost, it means that the number of drill holes must be sufficient to guarantee classification results without additional costs that need to be incurred, which returns to management to determine the level of risk that they are willing to accept.

Generally, the determination of drill hole spacing is carried out to determine geological conditions and resources using a qualitative approach and assumption method, which only applies the descriptive analysis of the quantity parameters and thickness geometry, as well as the level of complexity of the geological structure, as the limiting criteria (Cornah, Vann & Driver, 2013). However, the use of these criteria has not been measured and is difficult to implement in prospective areas that tend to have varied characteristics (Silva & Boisvert 2014).

The use of the geostatistical method is an approach that can be used to gain an understanding of quantitative geology (David 1982; Isaaks & Srivastava 1989; Nas 1994). Analysis using variograms and kriging can be carried out for thickness geometric parameters; besides that, the addition of parameters in the form of quality can also be added. The kriging process that is carried out will produce a relative error value to determine the optimal drill hole distance (Vann 2003; Ramadhan *et al.* 2021).

Based on the explanation above, it can be an opportunity for researchers to conduct further investigation on the analysis of determining the optimum distance between drill holes. Thus, this work is expected to provide good information to academics and industry. In addition, it can be used as a reference and guideline in conducting exploration or making plans for groundwork and further development of mining areas. This study is intended to analyze the optimum drill hole distance to increase the level of confidence in the estimation of coal resources in the study.

2 Data and Method

Research was conducted in the coal mining area owned by PT Kaltim Prima Coal, to be precise, in the PIT J area of Sangata, East Kalimantan. This research is about a comparison between two methods of determining the optimum spacing of exploration drill holes, namely the Global Estimation Variance Method (GEV) and the sill variogram.

In this study, geological mapping was also carried out to determine aspects of geomorphology, geology, stratigraphy, and geological structures that developed in the study area. In addition, a geostatistical analysis was also carried out to determine the relative error value of the optimum spacing of the drilling (Nengovhela 2018). Drill hole spacing needs to be designed based on the direction of the geological conditions, whether the area belongs to simple, moderate or complex geological conditions. All of these conditions are determined based on the parameters of sedimentation variation, tectonics and quality, so to get the optimal distance between the borehole and the exploration area, it is necessary to determine the right geological conditions first Borehole spacing needs to be designed based on the direction of coal seam distribution (strike and dip), so to get the optimal distance between the borehole and the exploration area, proper calculations need to be done first (Heriawan *et al.*, 2020; Ramadhan *et al.*, 2021). The determination of these simple geological conditions is based on the condition of the coal seam, which is almost not deformed by faults, folds, or intrusions. For moderate geological conditions, it is based on the condition of the coal seam that has been deformed, but only slightly, while for complex geological conditions, the condition of the coal seam has been strongly deformed. The regulation of determining the geological conditions of an area is regulated in the Indonesian National Standard, "Guidelines for reporting coal resources and reserves" (SNI 5015: 2019, 2019, Badan Standar Nasional, 2011)).

2.1 Drill Hole Spacing Analysis (DHSA) Method

The calculation method used is the Global Estimation Variance shows the accuracy of the estimated average value of the data as a whole (Sianturi et al. 2021). GEV uses the extension variance to calculate the error when a block is estimated using one sample located in the middle of the block (Nengovhela 2018; Sianturi et al. 2020). The method used to determine the variance of estimates used to assess the level of confidence in resource estimates is known as Drill Hole Spacing Analysis (DHSA). Estimation variance associated with using a known average value for a small volume 'v', which will be used to estimate the value over a much larger area, 'V' (Journel & Huijbregts 1978; Deutsch & Journel 1992).

The steps taken are:

1. The calculation begins by finding the value of the extension/estimated variant (σ_k^2) point to square plane for the spherical model with a nugget variance value of 0, with the interpretation of the nugget variance for the variogram using a tolerance angle of 180, and a sill value of 1 by plotting on the nomogram the extension/estimated variant value, can be seen in Figure 1.

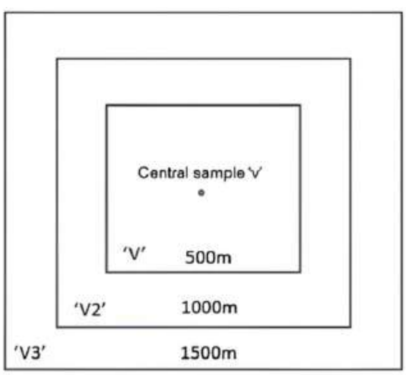

Figure 1 Calculation of the estimation variance of the regular square area V, with increasing sizes of V2 and V3 (Annels 1991).

2. Calculation of the variance of the point estimate of the plane (σ_k^2) must be adjusted to the nugget variance and sill values of each parameter (Equation 1) (Crozel & David, 1985):

$$\sigma_{E(r)}^2 = CO + (C * \sigma e^2) \qquad (1)$$

Global estimated variance value from the distribution of the estimated variance value to the number of blocks (N) (Equation 2) (Crozel and David, 1985).

$$\sigma_E^2(R) = \sigma_E^2(r) \,/\, N \qquad (2)$$

Calculation of the relative error value (Equation 3) (Crozel & David, 1985).

$$Relative\ Error = \pm 1.96\sigma_E . 100\%/mean \qquad (3)$$

3. Making a DHSA graph that displays a comparison between drill hole distances and relative errors according to the parameters.

The Nomogram of Extension/Point to Square Field Variance Values for Spherical Models is a graphical tool used in geostatistical analysis, useful for determining the accuracy of estimates and resource classification visually, to determine the extension variance (from a single sample point to its area of influence) and the estimation variance (from several sample points to a block or ore reserve) for a spherical variogram model. The nomogram graph can be seen in Figure 2 below.

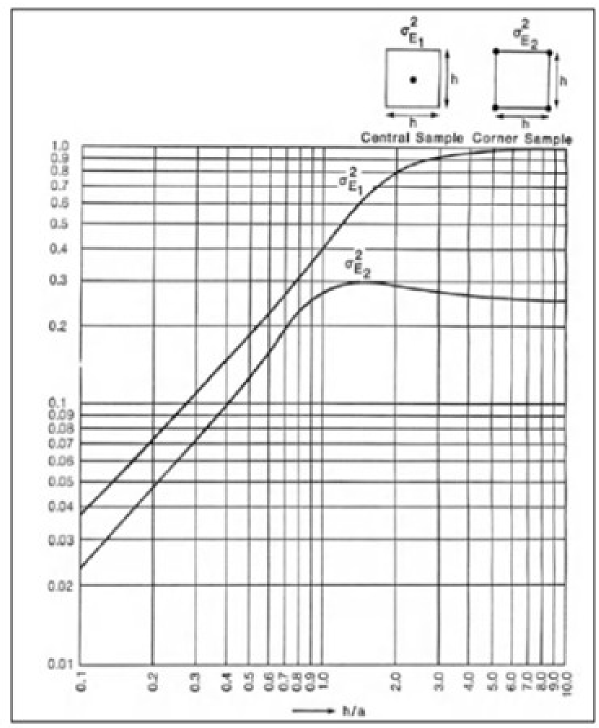

Figure 2 Nomogram of Point Extension/Estimation Variance Values to Square Planes for Spherical Models (Annels, 1991).

Before estimating and classifying coal resources, we need to consider the geological conditions. To see the comparison between geological conditions and the recommended drilling distance for coal resource classification, we can refer to various classifications, including SNI 5015:2019, the Australian Coal Guidelines for Coal Resource Estimation and Classification 2014, South African National Standard (SANS 10320:2004), along with the error tolerance values, as seen in Table 1 (Badan Standar Nasional, 2011; Cornah, Vann & Driver 2013; Marwanza et al. 2016).

Table 1 Comparison of recommended borehole distances for coal resource classification between SNI 5015:2019 and Australian Coal Guidelines for the Estimation and Classification of Coal Resources 2014, South Africa National Standard (SANS 10320:2004) and error tolerance values.

Resource Classification	SNI 5015:2019 Criteria for Distance of Information Points Based on Geological Conditions			Australian Coal Guidelines, 2014	South Africa Nations Standart (SANS 10320:2004)		Error Tolerance
	Simple	Moderate	Complex	Information Point Distance	Multile Seam	Thick interbed seam	
Measured	200<x≤400	100<x≤400	≤100	<500	<350	<350	0-10%
Indicated	500<x≤1000	250<x≤500	<250	<1000	<500	<1000	10-20%
Inferred	1000<x≤1599	500<x≤1000	≤500	<4000	<1000	<3000	>20%

2.2 Drill Hole Spacing Optimization Method with Sill Variogram

This session discusses techniques and parameter determination in making experimental variograms and fitting variogram models. The variogram is calculated using a simple algorithm, namely the average difference between two sample points with a certain distance (Bohling 2005; Srivastava 2013). For the difference to be positive, it is necessary to apply statistical calculations based on the squared difference.

The squared difference is assumed to be the expectation $[Z(x_i) - Z(x_{i+h})]$, so the definition of the variogram becomes (Equation 4) (Isaaks & Srivastava 1989):

$$2\gamma(h) = \text{var}\left[z_{(x_i)} - z_{(x_i+h)}\right] \quad (4)$$

Based on this function, an experimental variogram is defined by the following Equation (5) (Isaaks & Srivastava 1989).

$$\gamma(h) = \frac{1}{2N_{(h)}} \sum_{i=1}^{\mathbb{N}_{(h)}} \left[Z_{(x_i)} - Z_{(x_i+h)}\right] \quad (5)$$

where the notation Z(xi) and Z(xi+h) shows two data at points separated by a distance h, where h is a vector denoting the distance between two points according to the lag value for experimental variogram calculations, while N(h) is the number data pair (Bohling 2005).

Variograms can be used to analyze the degree of similarity/variability between each data (Soares, Nunes & Azevedo, 2017). An experimental variogram is made based on the data on coal thickness and quality. Variogram analysis for each variable uses a lag distance of 5 m and a lag tolerance of 2.5 m, where the aim is to obtain many variogram data pairs by paying attention to the data spacing in the horizontal direction according to the average borehole spacing of 25 m and the data spacing at vertical direction according to the assay sample drill spacing of 1 m. In addition, variogram analysis is made in various representative directions, namely 4 (four) main directions on the horizontal plane and 1 (one) direction on the vertical plane as follows:

- North – South (azimuth 0°, dip 0°)
- Southwest – Northeast (azimuth 45°, dip 0°)
- West – East (azimuth 90°, dip 0°)
- NW – SE (azimuth 135°, dip 0°)
- Vertical direction (azimuth 0°, dip 90°)

The theoretical variogram model used for fitting is the Spherical model or the Matheron model because based on the analysis of the experimental variogram (Isaaks & Srivastava 1989), the properties obtained are almost the same as the Spherical model and the behavior of the experimental variogram at the starting points tends to be linear. Experimental variogram calculations and variogram fitting have been carried out with predetermined parameters, both horizontally and vertically, so that the spatial characteristics of the data can be identified (Jeuken, Xu & Dowd 2020). To analyze the density of exploration data in the study area, the variogram modeling was carried out in 2D without a vertical direction for the variable thickness and quality of coal. The semivariogram fitting stage between the experimental semivariogram and the semivariogram model is carried out by try and error, meaning that in obtaining an accurate (valid) semivariogram model parameter value, it is carried out manually in the SGeMS software until it provides a good semivariogram parameter value (nugget effect, sill, and range).

Semivariogram parameter fitting is said to be valid if the results of the selected semivariogram model and its parameters overlap. The experimental semivariogram parameters are expected to have small nugget effect values, large sill, and large range. The results of semivariogram fitting in the form of semivariogram parameters that are considered accurate are then used in the estimation of the point kriging method.

3 Results

The research area is in a very geological sheet and is included in the Balikpapan Formation. The study area is located in Balikpapan Formation and Alluvial Deposits. The research is focused only on the Balikpapan Formation, which is a coal bearing formation. In this study, two coal seams will be analyzed, namely the North BE and South BE seams, which are dominant in the research area (Marwanza et al. 2016; Faidatulaila et al. 2023).

a. Seam BE

The results of field geological observations show that this coal seam is exposed with a strike of N111^0 – 125^0 E and a layered slope of 19^0 to the southwest. The BE seam has a relatively long northwest-southeast distribution. Based on outcrop data in the field (E 101126; N 195465), the thickness of the coal seam is 0.8 – 1.9 meters (see Figure 3), the general characteristics of the coal in this seam are black and shiny; there are cleats filled with clay that are sturdy with black streaks; and the coal seams have partings in the form of clay. The base layer (floor) is gray claystone, non-carbonate, layered, and soft, while the roof layer (roof) is claystone, gray, and non-carbonate.

3.1 Borehole Spacing Analysis Results

3.1.1. Sill Variogram Method

The analysis of the variogram model is focused on the thickness and quality of the coal. An analysis of the thickness variogram model is used to determine the relationship between the effect of the thickness of each zone and the distribution of each zone (Snowden 2021).

a. North BE seams

In making an experimental variogram with Try and Error, an experimental variogram is obtained that can be modeled with a Lag Spacing value of 30 and a Lag Tolerance of 10. Based on the modeling results, the range value is 151, the sill is 0.65, and the Nugget Effect is 0.04, as shown in Figure 4. The experimental variogram is then modeled to see the shape of the variogram, with the following results:

Classification of coal resources by looking at the variogram continuity can be done by calculating the distance based on the values of 1/3 sill, 2/3 sill, and 3/3 sill (Snowden 1996, 2021). This distance is used as a benchmark for resource classification to be inferred, indicated, or measured.

Based on field data, the average drill hole distance in the North BE seam is 131 meters. The distance of 1/3 sill gets a value of 50 meters, the distance of 2/3 sill gets a value of 80 meters, and the distance of 3/3 sill gets a value of 151 meters, as shown in Figure 5.

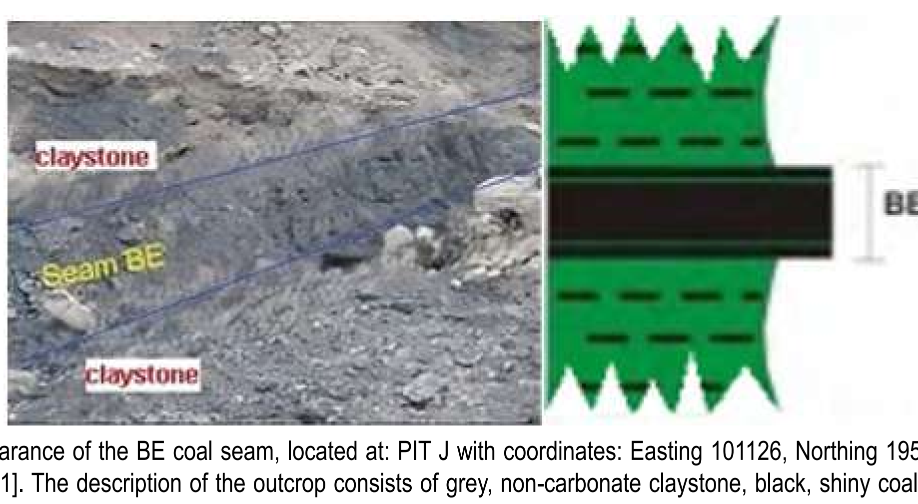

Figure 3 Appearance of the BE coal seam, located at: PIT J with coordinates: Easting 101126, Northing 195465, Seam N Position 1110E/190 [CA1]. The description of the outcrop consists of grey, non-carbonate claystone, black, shiny coal, filled with mud, black lines, 1.9 metres thick, and grey, non-carbonate claystone [IM2].

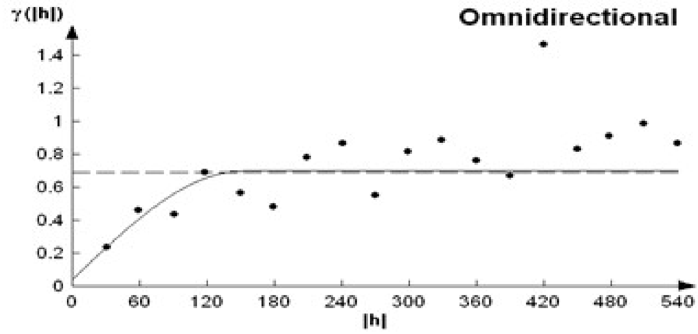

Figure 4 North BE seam thickness, variogram model

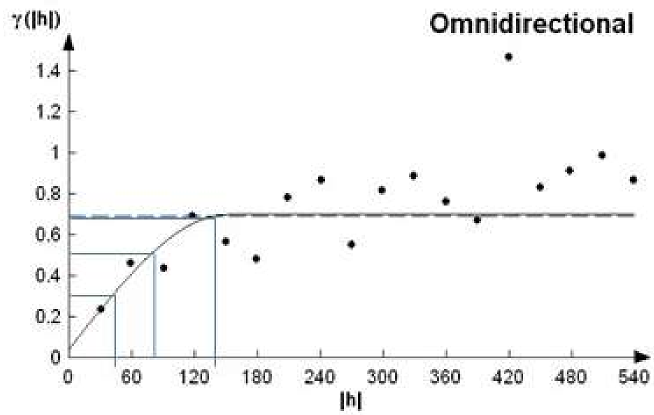

Figure 5 Determination of coal resource classification and drill hole spacing.

b. South BE seams

In making an experimental variogram with Try and Error, an experimental variogram is obtained that can be modeled with a Lag Spacing value of 110 and a Lag Tolerance of 15. The experimental variogram is then modeled to see the shape of the variogram, with the following results.

Based on the modeling results, the value range is 209, the sill is 0.16, and the Nugget Effect is 0.26. Classification of coal resources by looking at the variogram continuity can be done by calculating the distance based on the values of 1/3 sill, 2/3 sill, and 3/3 sill, as shown in Figure 6.

This distance is used as a benchmark for resource classification to be inferred, indicated, or measured (Snowden 1996, 2021).

Based on field data, the average drill hole distance in the South BE seam is 126 meters. The distance of 1/3 sill gets a value of 60 meters, the distance of 2/3 sill gets a value of 122 meters, and the distance of 3/3 sill gets a value of 210 meters, as shown in Figure 7.

b. Global Estimation Variance (GEV) Method
i. Global Estimation Variance (GEV) Analysis

a. North BE seams

Based on the Table 2, the drill hole spacing for the measured resource category is 350 meters with a total of 29 drills.

The graph of Relative Deviation versus Distance (grid) from the Northern Layer BE is shown in Figure 8 below.

Based on the graph above, the drill hole spacing for the measured resource category is 420 meters, while for the indicated coal resource category, it is 800 meters.

b. South BE seams

Based on the Table 3, the drill hole spacing for the measured resource category is 350 meters, with a total of 104 drills.

To see the relationship between Relative Std Deviation and Distance (grid) of the Southern Layer BE, see Figure 9.

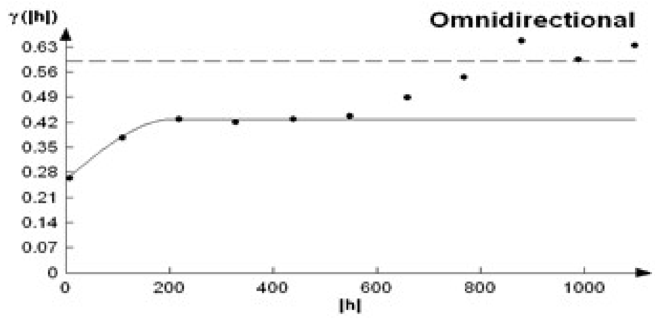

Figure 6 Variogram model of the southern BE seam thickness.

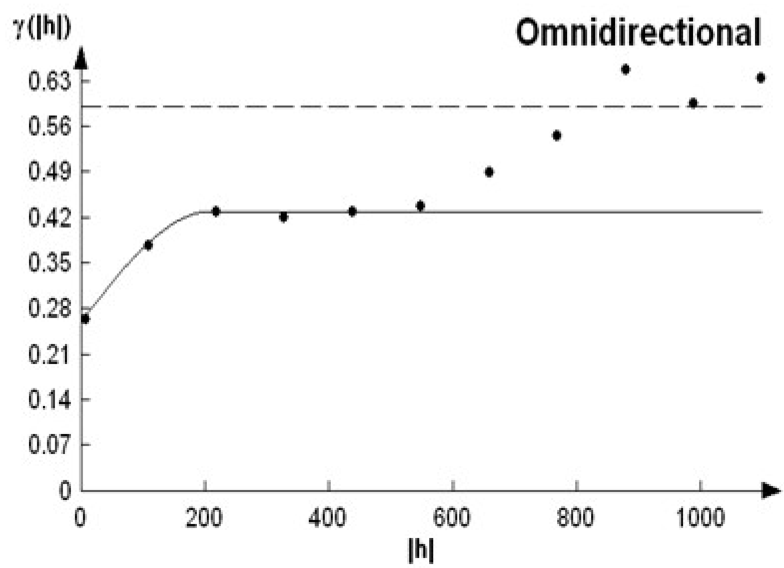

Figure 7 Determination of resource classification and drill hole spacing based on variogram analysis.

Table 2 Results of Global Estimation Variance Seam BE North.

Coal Thickness												
Means	**GRID**	**CO**	**C**	**a**	**Ha**	**Est Var**	**Functions e^2**	**N**	**GEV**	**std Dev GEV**	**St Dev GEV (99%)**	**St. Dev Relative**
2.79	100	0.04	0.65	151	0.662252	0.25	0.2025	114	0.001776	0.04214636	0.084292723	3.02
	100	0.04	0.65	151	0.662252	0.25	0.2025	410	0.000494	0.02222392	0.044447832	1.59
	200	0.04	0.65	151	1.324503	0.5	0.365	100	0.00365	0.06041523	0.12083046	4,33
	250	0.04	0.65	151	1.655629	0.6	0.43	66	0.006515	0.08071649	0.161432977	5.79
	300	0.04	0.65	151	1.986755	0.8	0.56	41	0.013659	0.11686974	0.233739484	8,38
	350	0.04	0.65	151	2.317881	0.85	0.5925	29	0.020431	0.14293717	0.285874339	10.25
	400	0.04	0.65	151	2.649007	0.9	0.625	22	0.028409	0.16854997	0.337099931	12.08
	500	0.04	0.65	151	3.311258	0.95	0.6575	12	0.054792	0.2340762	0.468152397	16.78

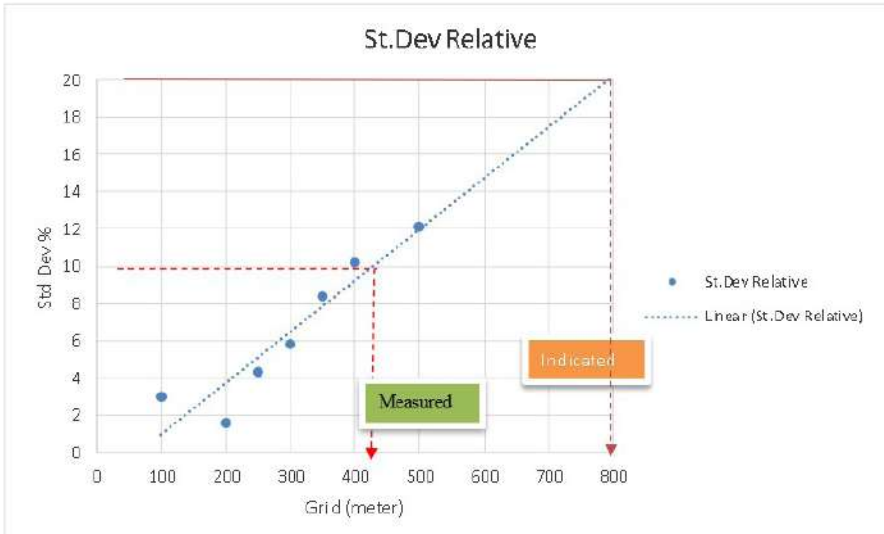

Figure 8 Graph of Std Dev Relative vs distance (grid) of North BE Seam.

Table 3 Results of Global Estimation Variance Seam BE South Analysis.

Coal Thickness												
Means	**GRID**	**CO**	**C**	**a**	**Ha**	**Est Var**	**function e^2**	**N**	**GEV**	**std Dev GEV**	**St Dev GEV (99%)**	**St. Dev Relative**
1.06	100	0.26	0.16	209	0.478469	0.18	0.2888	522	0.000553	0.02352141	0.047042819	4.438001793
	100	0.26	0.16	209	0.478469	0.18	0.2888	1487	0.000194	0.01393616	0.027872319	2.629464069
	200	0.26	0.16	209	0.956938	0.38	0.3208	365	0.000879	0.02964632	0.059292634	5.59364471
	250	0.26	0.16	209	1.196172	0.42	0.3272	240	0.001363	0.03692334	0.073846688	6.966668682
	300	0.26	0.16	209	1.435407	0.55	0.348	147	0.002367	0.04865539	0.097310779	9.180262192
	350	0.26	0.16	209	1.674641	0.62	0.3592	104	0.003454	0.05876943	0.117538864	11.0885721
	400	0.26	0.16	209	1.913876	0.8	0.388	78	0.004974	0.07052914	0.141058271	13.30738408
	500	0.26	0.16	209	2.392344	0.85	0.396	42	0.009429	0.09710083	0.194201662	18.32091156

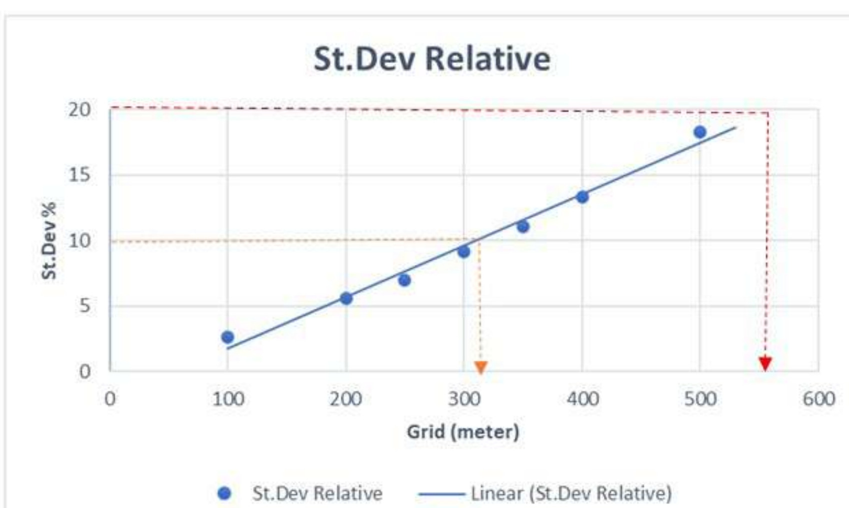

Figure 9 Graph of Std Cev Relative vs distance (grid) of South BE Seam.

Based on the graph above, the drill hole spacing for the measured resource category, is 320 meters, while for the indicated coal resource category it is 580 meters. Based on the Drill Hole Spacing Analysis (DHSA) chart that has been carried out with global variance estimation, the optimum hole spacing for each seam is obtained, namely: For the North BE seam, it can be seen that the distance of the influence area for measured, indicated, and inferred resources is 470 m, 780 m, and 1500 m, respectively, while the South BE seam for measured, indicated, and inferred resources is 200 m each. 400m, and 650m.

4 Discussion

In conducting drilling activities, the spacing between drill points is one of the main things that needs to be considered because the spacing of drill points will affect the confidence level of the estimation results and affect exploration costs. Choosing the right method is necessary. If you compare the calculations using the sill variogram and based on the Global Estimation Variance (GEV) analysis, the two methods do not show the same or significantly different results. Calculation of borehole spacing determination with the global estimation variance method, has the advantage of more precision, because the calculation of the relative error of each block can be directly calculated after the estimated variance value is obtained, while it is suitable for calculating borehole spacing with moderate to complex geological conditions. While the calculation of borehole spacing with the sill variogram method, although it is easier and the observation is only based on the observation of the sill variogram value, but the disadvantage is that there is no calculation of relative error for each block, so the results are less precise. The advantage is that the processing time is relatively faster and well used in layers with simple geological conditions for coal. For a comparison of the two methods can be seen in the Table 4.

Table 4 Comparison of advantages and disadvantages of sill variogram and GEV methods.

Parameters	Sill variogram method	GEV method
Data input	Simpler inputting, because the borehole spacing can be directly determined based on the sill variogram (1/3, 2/3 or 33 (range))	Slightly complicated, because the calculation of the relative error of each block can be directly calculated after the estimated variance value is obtained.
Time Duration	Relatively faster processing	Computationally time-consuming, with variogram model checking required.
Types of mineral deposits	Good for use in seams with simple geological conditions for coal	Good for deposits with simple to complex geology with high variability in coal quality.
Application of Calculation	The calculation results are local or applied to one study area with the same sediment homogeneity, and spatial continuity.	The calculation results are local or applied to one study area with the same sediment homogeneity, and spatial continuity.

5 Conclusions

Based on the analysis of determining the optimum borehole spacing using the GEV and Sill Variogram methods, it can be concluded that:

1. This method of determining drill hole spacing is necessary due to the confidence level of estimated resources and reserves and exploration costs.
2. DHSA using the Sill Variogram method is conceptually very simple and has a shorter processing time, but the results are less accurate because it does not take into error values and can be used in simple geological conditions.
3. The GEV method requires processing time, which is more complicated with regards to computation but can be applied to deposit conditions with high variability and moderate and complex geological conditions.

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Author contributions

Irfan Marwanza: conceptualization; formal analysis; methodology; validation; writing – review and editing; supervision. **Wiwik Dahani:** methodology; validation. **Subandrio Subandrio:** methodology; software; visualization. **Masagus Ahmad Azizi:** writing- review & editing. **Rhazes Eesha Gumay:** writing – original draft.

Conflict of interest

The authors have no conflict of interest to declare.
The paper has been reviewed and approved by all co-authors, and there are no financial conflicts of interest to disclose.

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GEOLOGY

Application of the Global Estimation Variance and Sill Variogram Methods in Determining the Optimum Drill Hole Distance for the classification of Measured Coal Resources

Aplicação dos Métodos de Variância de Estimativa Global e Variograma de Sill na Determinação da Distância Ideal Entre Furos de Perfuração para a Classificação de Recursos de Carvão Medidos

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Abstract

In the implementation of effective and efficient exploration of mineral and coal resources, it is required to carry out geostatistical analysis to determine the relative error value of the optimum spacing of the drilling and its thickness and quality distribution. This study uses the application of geostatistics with the sill variogram method and global estimation variance (GEV), based on the relative value of the error of the thickness of the coal seam. This research was conducted in the concession area of PT. Kaltim Prima Coal. Based on the case study, the coalfield consisted of two seams, namely the North BE and South BE seams, with moderate geological conditions. From the variogram analysis of the thickness of the northern BE layer, the range is 151, the sill is 0.65, and the Nugget Effect is 0.04, while the BE South has a range value of 209, the sill is 0.16, and the nugget effect is 0.26. Based on field data, the average drill hole distance in the North BE seam is 131 meters. The distance of 1/3 of the sill gets a value of 50 meters (measured resource), while for the South BE seam it is 126 meters. The distance of 1/3 sill gets a value of 60 meters (measured resource), the distance of 2/3 sill gets a value of 122 meters (resource indicated), and the distance of 3/3 sill gets a value of 210 meters (inferred resource). Based on global estimation variance analysis. For the North BE Seam, the drill hole spacing for the measured resource category was 350 meters with a total of 29 drills while for the South BE Seam, the drill hole spacing for the measured resource category was 350 meters with a total of 104 drills. The results of this classification produce an area of influence that is smaller than the SNI standard of moderate geological complexity. By using the sill variogram analysis, the results of the drill hole spacing are dense when compared to the results of the GEV analysis. The results of this GEV classification produce an area of influence that is relatively like to the SNI standard of moderate geological complexity.

Keywords: Geostatistics; Geological Complexity; SNI standard

Resumo

Na implementação de uma exploração eficaz e eficiente dos recursos minerais e de carvão, é necessário realizar uma análise geoestatística para determinar o valor do erro relativo do espaçamento ideal da perfuração e sua distribuição de espessura e qualidade. Este estudo utiliza a aplicação da geoestatística com o método do variograma de soleira e a variância de estimativa global (GEV), com base no valor relativo do erro da espessura da camada de carvão. Esta pesquisa foi realizada na área de concessão da PT. Kaltim Prima Coal. Com base no estudo de caso, o campo de carvão consistia em duas camadas, nomeadamente as camadas BE Norte e BE Sul, com condições geológicas moderadas. A partir da análise do variograma da espessura da camada BE Norte, o intervalo é 151, o limiar é 0,65 e o efeito Nugget é 0,04, enquanto a BE Sul tem um valor de intervalo de 209, o limiar é 0,16 e o efeito Nugget é 0,26. Com base nos dados de campo, a distância média entre os furos de perfuração na camada BE Norte é de 131 metros. A distância de 1/3 do limiar obtém um valor de 50 metros (recurso medido), enquanto que para a camada BE sul é de 126 metros. A distância de 1/3 do limiar obtém um valor de 60 metros (recurso medido), a distância de 2/3 do limiar obtém um valor de 122 metros (recurso indicado) e a distância de 3/3 do limiar obtém um valor de 210 metros (recurso inferido). Com base na análise de variação da estimativa global.

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Para a camada BE Norte, o espaçamento entre os furos de perfuração para a categoria de recurso medido foi de 350 metros, com um total de 29 furos, enquanto que para a camada BE Sul, o espaçamento entre os furos de perfuração para a categoria de recurso medido foi de 350 metros, com um total de 104 furos. Os resultados desta classificação produzem uma área de influência menor do que o padrão SNI de complexidade geológica moderada. Ao usar a análise do variograma de soleira, os resultados do espaçamento entre furos de perfuração são densos quando comparados aos resultados da análise GEV. Os resultados dessa classificação GEV produzem uma área de influência relativamente semelhante ao padrão SNI de complexidade geológica moderada.

Palavras-chave: Geoestatística; Complexidade Geológica; Padrão SNI

1 Introduction

Most mining companies will try to get maximum profit with minimum costs; in this case, the cost of drilling is the one that must be incurred in large amounts. The factor that most influences resource classification is the distance of the drill holes. For economic reasons to get maximum profit with minimum cost, it means that the number of drill holes must be sufficient to guarantee classification results without additional costs that need to be incurred, which returns to management to determine the level of risk that they are willing to accept.

Generally, the determination of drill hole spacing is carried out to determine geological conditions and resources using a qualitative approach and assumption method, which only applies the descriptive analysis of the quantity parameters and thickness geometry, as well as the level of complexity of the geological structure, as the limiting criteria (Cornah, Vann & Driver, 2013). However, the use of these criteria has not been measured and is difficult to implement in prospective areas that tend to have varied characteristics (Silva & Boisvert 2014).

The use of the geostatistical method is an approach that can be used to gain an understanding of quantitative geology (David 1982; Isaaks & Srivastava 1989; Nas 1994). Analysis using variograms and kriging can be carried out for thickness geometric parameters; besides that, the addition of parameters in the form of quality can also be added. The kriging process that is carried out will produce a relative error value to determine the optimal drill hole distance (Vann 2003; Ramadhan *et al.* 2021).

Based on the explanation above, it can be an opportunity for researchers to conduct further investigation on the analysis of determining the optimum distance between drill holes. Thus, this work is expected to provide good information to academics and industry. In addition, it can be used as a reference and guideline in conducting exploration or making plans for groundwork and further development of mining areas. This study is intended to analyze the optimum drill hole distance to increase the level of confidence in the estimation of coal resources in the study.

2 Data and Method

Research was conducted in the coal mining area owned by PT Kaltim Prima Coal, to be precise, in the PIT J area of Sangata, East Kalimantan. This research is about a comparison between two methods of determining the optimum spacing of exploration drill holes, namely the Global Estimation Variance Method (GEV) and the sill variogram.

In this study, geological mapping was also carried out to determine aspects of geomorphology, geology, stratigraphy, and geological structures that developed in the study area. In addition, a geostatistical analysis was also carried out to determine the relative error value of the optimum spacing of the drilling (Nengovhela 2018). Drill hole spacing needs to be designed based on the direction of the geological conditions, whether the area belongs to simple, moderate or complex geological conditions. All of these conditions are determined based on the parameters of sedimentation variation, tectonics and quality, so to get the optimal distance between the borehole and the exploration area, it is necessary to determine the right geological conditions first Borehole spacing needs to be designed based on the direction of coal seam distribution (strike and dip), so to get the optimal distance between the borehole and the exploration area, proper calculations need to be done first (Heriawan *et al.*, 2020; Ramadhan *et al.*, 2021). The determination of these simple geological conditions is based on the condition of the coal seam, which is almost not deformed by faults, folds, or intrusions. For moderate geological conditions, it is based on the condition of the coal seam that has been deformed, but only slightly, while for complex geological conditions, the condition of the coal seam has been strongly deformed. The regulation of determining the geological conditions of an area is regulated in the Indonesian National Standard, "Guidelines for reporting coal resources and reserves" (SNI 5015: 2019, 2019, Badan Standar Nasional, 2011)).

2.1 Drill Hole Spacing Analysis (DHSA) Method

The calculation method used is the Global Estimation Variance shows the accuracy of the estimated average value of the data as a whole (Sianturi et al. 2021). GEV uses the extension variance to calculate the error when a block is estimated using one sample located in the middle of the block (Nengovhela 2018; Sianturi et al. 2020). The method used to determine the variance of estimates used to assess the level of confidence in resource estimates is known as Drill Hole Spacing Analysis (DHSA). Estimation variance associated with using a known average value for a small volume 'v', which will be used to estimate the value over a much larger area, 'V' (Journel & Huijbregts 1978; Deutsch & Journel 1992).

The steps taken are:

1. The calculation begins by finding the value of the extension/estimated variant (σ_E^2) point to square plane for the spherical model with a nugget variance value of 0, with the interpretation of the nugget variance for the variogram using a tolerance angle of 180, and a sill value of 1 by plotting the nomogram the extension/estimated variant value, can be seen in Figure 1.

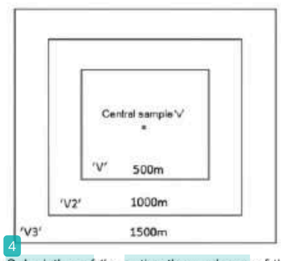

Figure 1 Calculation of the estimation variance of the regular square area V, with increasing sizes of V2 and V3 (Annels 1991).

2. Calculation of the variance of the point estimate of the plane (σ_E^2) must be adjusted to the nugget variance and sill values of each parameter (Equation 1) (Crozel & David, 1985):

$$\sigma_{E(r)}^2 = CO + (C * \sigma e^2) \qquad (1)$$

Global estimated variance value from the distribution of the estimated variance value to the number of blocks (N) (Equation 2) (Crozel and David, 1985).

$$\sigma_E^2(R) = \sigma_E^2(r) \ / \ N \qquad (2)$$

Calculation of the relative error value (Equation 3) (Crozel & David, 1985).

$$Relative\ Error = \pm 1.96\sigma_E . 100\%/mean \qquad (3)$$

3. Making a DHSA graph that displays a comparison between drill hole distances and relative errors according to the parameters.

The Nomogram of Extension/Point to Square Field Variance Values for Spherical Models is a graphical tool used in geostatistical analysis, useful for determining the accuracy of estimates and resource classification visually, to determine the extension variance (from a single sample point to its area of influence) and the estimation variance (from several sample points to a block or ore reserve) for a spherical variogram model. The nomogram graph can be seen in Figure 2 below.

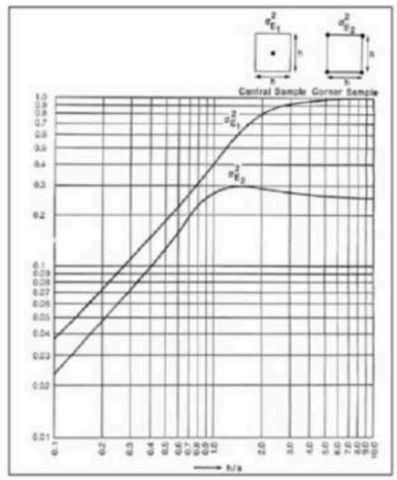

Figure 2 Nomogram of Point Extension/Estimation Variance Values to Square Planes for Spherical Models (Annels, 1991).

Before estimating and classifying coal resources, we need to consider the geological conditions. To see the comparison between geological conditions and the recommended drilling distance for coal resource classification, we can refer to various classifications, including SNI 5015:2019, the Australian Coal Guidelines for Coal Resource Estimation and Classification 2014, South African National Standard (SANS 10320:2004), along with the error tolerance values, as seen in Table 1 (Badan Standar Nasional, 2011; Cornah, Vann & Driver 2013; Marwanza et al. 2016).

Table 1 Comparison of recommended bore hole distances for coal resource classification between SNI 5015:2019 and Australian Coal Guidelines for the Estimation and Classification of Coal Resources 2014, South Africa National Standard (SANS 10320:2004) and error tolerance values.

Resource Classification	SNI 5015:2019 Criteria for Distance of Information Points Based on Geological Conditions			Australian Coal Guidelines, 2014	South Africa Nations Standart (SANS 10320:2004)		Error Tolerance
	Simple	Moderate	Complex	Information Point Distance	Multile Seam	Thick interbed seam	
Measured	200<x≤400	100<x≤400	≤100	<500	<350	<350	0-10%
Indicated	500<x≤1000	250<x≤500	<250	<1000	<500	<1000	10-20%
Inferred	1000<x≤1599	500<x≤1000	≤500	<4000	<1000	<3000	>20%

2.2 Drill Hole Spacing Optimization Method with Sill Variogram

This session discusses techniques and parameter determination in making experimental variograms and fitting variogram models. The variogram is calculated using a simple algorithm, namely the average difference between two sample points with a certain distance (Bohling 2005; Srivastava 2013). For the difference to be positive, it is necessary to apply statistical calculations based on the squared difference.

The squared difference is assumed to be the expectation $[Z(x_i) - Z(x_{i+h})]$, so the definition of the variogram becomes (Equation 4) (Isaaks & Srivastava 1989):

$$2\gamma(h) = \mathrm{var}\left[z_{(x_i)} - z_{(x_i+h)}\right] \quad (4)$$

Based on this function, an experimental variogram is defined by the following Equation (5) (Isaaks & Srivastava 1989).

$$\gamma(h) = \frac{1}{2N_{(h)}} \sum_{i=1}^{N(h)} \left[Z_{(x_i)} - Z_{(x_i+h)}\right] \quad (5)$$

where the notation Z(xi) and Z(xi+h) shows two data at points separated by a distance h, where h is a vector denoting the distance between two points according to the lag value for experimental variogram calculations, while N(h) is the number data pair (Bohling 2005).

Variograms can be used to analyze the degree of similarity/variability between each data (Soares, Nunes & Azevedo, 2017). An experimental variogram is made based on the data on coal thickness and quality. Variogram analysis for each variable uses a lag distance of 5 m and a lag tolerance of 2.5 m, where the aim is to obtain many variogram data pairs by paying attention to the data spacing in the horizontal direction according to the average borehole spacing of 25 m and the data spacing at vertical direction according to the assay sample drill spacing of 1 m. In addition, variogram analysis is made in various representative directions, namely 4 (four) main directions on the horizontal plane and 1 (one) direction on the vertical plane as follows:

- North – South (azimuth 0°, dip 0°)
- Southwest – Northeast (azimuth 45°, dip 0°)
- West – East (azimuth 90°, dip 0°)
- NW – SE (azimuth 135°, dip 0°)
- Vertical direction (azimuth 0°, dip 90°)

The theoretical variogram model used for fitting the Spherical model or the Matheron model because based on the analysis of the experimental variogram (Isaaks & Srivastava 1989), the properties obtained are almost the same as the Spherical model and the behavior of the experimental variogram at the starting points tends to be linear. Experimental variogram calculations and variogram fitting have been carried out with predetermined parameters, both horizontally and vertically, so that the spatial characteristics of the data can be identified (Jeuken, Xu & Dowd 2020). To analyze the density of exploration data in the study area, the variogram modeling was carried out in 2D without a vertical direction for the variable thickness and quality of coal. The semivariogram fitting stage between the experimental semivariogram and the semivariogram model is carried out by try and error, meaning that in obtaining an accurate (valid) semivariogram model parameter value, it is carried out manually in the SGeMS software until it provides a good semivariogram parameter value (nugget effect, sill, and range).

Semivariogram parameter fitting is said to be valid if the results of the selected semivariogram model and its parameters overlap. The experimental semivariogram parameters are expected to have small nugget effect values, large sill, and large range. The results of semivariogram fitting in the form of semivariogram parameters that are considered accurate are then used in the estimation of the point kriging method.

3 Results

The research area is in a very geological sheet and is included in the Balikpapan Formation. The study area is located in Balikpapan Formation and Alluvial Deposits. The research is focused only on the Balikpapan Formation, which is a coal bearing formation. In this study, two coal seams will be analyzed, namely the North BE and South BE seams, which are dominant in the research area (Marwanza et al. 2016; Faidatulaila et al. 2023).

a. Seam BE

The results of field geological observations show that this coal seam is exposed with a strike of N111° – 125° E and a layered slope of 19° to the southwest. The BE seam has a relatively long northwest-southeast distribution. Based on outcrop data in the field (E 101126; N 195465), the thickness of the coal seam is 0.8 – 1.9 meters (see Figure 3), the general characteristics of the coal in this seam are black and shiny; there are cleats filled with clay that are sturdy with black streaks; and the coal seams have partings in the form of clay. The base layer (floor) is gray claystone, non-carbonate, layered, and soft, while the roof layer (roof) is claystone, gray, and non-carbonate.

3.1 Borehole Spacing Analysis Results

3.1.1. Sill Variogram Method

The analysis of the variogram model is focused on the thickness and quality of the coal. An analysis of the thickness variogram model is used to determine the relationship between the effect of the thickness of each zone and the distribution of each zone (Snowden 2021).

a. North BE seams

In making an experimental variogram with Try and Error, an experimental variogram is obtained that can be modeled with a Lag Spacing value of 30 and a Lag Tolerance of 10. Based on the modeling results, the range value is 151, the sill is 0.65, and the Nugget Effect is 0.04, as shown in Figure 4. The experimental variogram is then modeled to see the shape of the variogram, with the following results:

Classification of coal resources by looking at the variogram continuity can be done by calculating the distance based on the values of 1/3 sill, 2/3 sill, and 3/3 sill (Snowden 1996, 2021). This distance is used as a benchmark for resource classification to be inferred, indicated, or measured.

Based on field data, the average drill hole distance in the North BE seam is 131 meters. The distance of 1/3 sill gets a value of 50 meters, the distance of 2/3 sill gets a value of 80 meters, and the distance of 3/3 sill gets a value of 151 meters, as shown in Figure 5.

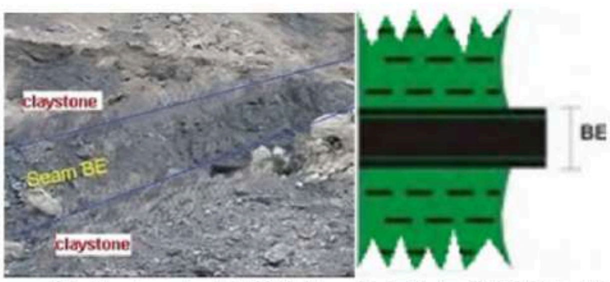

Figure 3 Appearance of the BE coal seam, located at: PIT J with coordinates: Easting 101126, Northing 195465, Seam N Position 1110E/190 [CA1]. The description of the outcrop consists of grey, non-carbonate claystone, black, shiny coal, filled with mud, black lines, 1.9 metres thick, and grey, non-carbonate claystone [IM2].

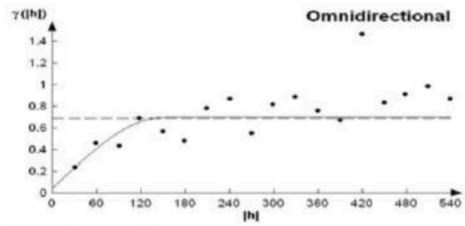

Figure 4 North BE seam thickness, variogram model

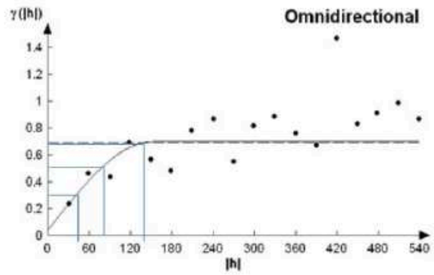

Figure 5 Determination of coal resource classification and drill hole spacing.

b. South BE seams

In making an experimental variogram with Try and Error, an experimental variogram is obtained that can be modeled with a Lag Spacing value of 110 and a Lag Tolerance of 15. The experimental variogram is then modeled to see the shape of the variogram, with the following results.

Based on the modeling results, the value range is 209, the sill is 0.16, and the Nugget Effect is 0.26. Classification of coal resources by looking at the variogram continuity can be done by calculating the distance based on the values of 1/3 sill, 2/3 sill, and 3/3 sill, as shown in Figure 6.

This distance is used as a benchmark for resource classification to be inferred, indicated, or measured (Snowden 1996, 2021).

Based on field data, the average drill hole distance in the South BE seam is 126 meters. The distance of 1/3 sill gets a value of 60 meters, the distance of 2/3 sill gets a value of 122 meters, and the distance of 3/3 sill gets a value of 210 meters, as shown in Figure 7.

b. Global Estimation Variance (GEV) Method
i. Global Estimation Variance (GEV) Analysis

a. North BE seams

Based on the Table 2, the drill hole spacing for the measured resource category is 350 meters with a total of 29 drills.

The graph of Relative Deviation versus Distance (grid) from the Northern Layer BE is shown in Figure 8 below.

Based on the graph above, the drill hole spacing for the measured resource category is 420 meters, while for the indicated coal resource category, it is 800 meters.

b. South BE seams

Based on the Table 3, the drill hole spacing for the measured resource category is 350 meters, with a total of 104 drills.

To see the relationship between Relative Std Deviation and Distance (grid) of the Southern Layer BE, see Figure 9.

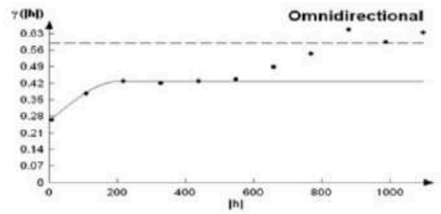

Figure 6 Variogram model of the southern BE seam thickness.

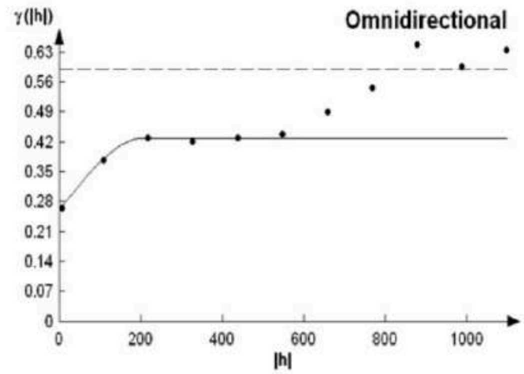

Figure 7 Determination of resource classification and drill hole spacing based on variogram analysis.

Table 2 Results of Global Estimation Variance Seam BE North.

Coal Thickness												
Means	**GRID**	**CO**	**C**	**a**	**Ha**	**Est Var**	**Functions e^2**	**N**	**GEV**	**std Dev GEV**	**St Dev GEV (99%)**	**St. Dev Relative**
2.79	100	0.04	0.65	151	0.662252	0.25	0.2025	114	0.001776	0.04214636	0.084292723	3.02
	100	0.04	0.65	151	0.662252	0.25	0.2025	410	0.000494	0.02222392	0.044447832	1.59
	200	0.04	0.65	151	1.324503	0.5	0.365	100	0.00365	0.06041523	0.12083046	4.33
	250	0.04	0.65	151	1.655629	0.6	0.43	66	0.006515	0.08071649	0.161432977	5.79
	300	0.04	0.65	151	1.986755	0.8	0.56	41	0.013659	0.11686974	0.233739484	8.38
	350	0.04	0.65	151	2.317881	0.85	0.5925	29	0.020431	0.14293717	0.285874339	10.25
	400	0.04	0.65	151	2.649007	0.9	0.625	22	0.028409	0.16854997	0.337099931	12.08
	500	0.04	0.65	151	3.311258	0.95	0.6575	12	0.054792	0.2340762	0.468152397	16.78

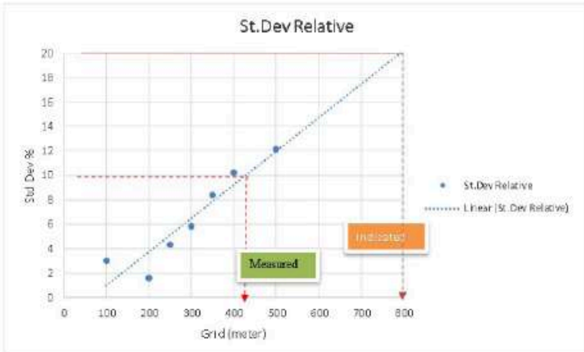

Figure 8 Graph of Std Dev Relative vs distance (grid) of North BE Seam.

Table 3 Results of Global Estimation Variance Seam BE South Analysis.

Coal Thickness												
Means	**GRID**	**CO**	**C**	**a**	**Ha**	**Est Var**	**function e^2**	**N**	**GEV**	**std Dev GEV**	**St Dev GEV (99%)**	**St. Dev Relative**
1.06	100	0.26	0.16	209	0.478469	0.18	0.2888	522	0.000553	0.02352141	0.047042819	4.438001793
	100	0.26	0.16	209	0.478469	0.18	0.2888	1487	0.000194	0.01393616	0.027872319	2.629464069
	200	0.26	0.16	209	0.956938	0.38	0.3208	365	0.000879	0.02964632	0.059292634	5.59364471
	250	0.26	0.16	209	1.196172	0.42	0.3272	240	0.001363	0.03692334	0.073846688	6.966668682
	300	0.26	0.16	209	1.435407	0.55	0.348	147	0.002367	0.04865539	0.097310779	9.180262192
	350	0.26	0.16	209	1.674641	0.62	0.3592	104	0.003454	0.05876943	0.117538864	11.0885721
	400	0.26	0.16	209	1.913876	0.8	0.388	78	0.004974	0.07052914	0.141058271	13.30738408
	500	0.26	0.16	209	2.392344	0.85	0.396	42	0.009429	0.09710083	0.194201662	18.32091156

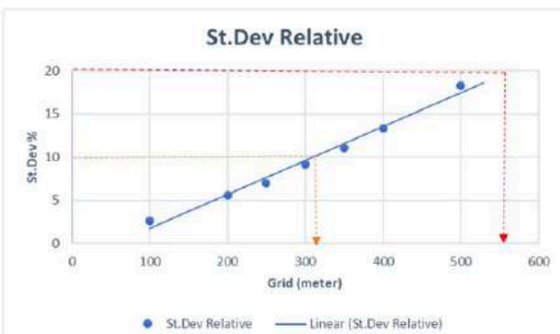

Figure 9 Graph of Std Cev Relative vs distance (grid) of South BE Seam.

Based on the graph above, the drill hole spacing for the measured resource category, is 320 meters, while for the indicated coal resource category it is 580 meters. Based on the Drill Hole Spacing Analysis (DHSA) chart that has been carried out with global variance estimation, the optimum hole spacing for each seam is obtained, namely: For the North BE seam, it can be seen that the distance of the influence area for measured, indicated, and inferred resources is 470 m, 700 m, and 1500 m, respectively, while the South BE seam for measured, indicated, and inferred resources is 200 m each. 400m, and 650m.

4 Discussion

In conducting drilling activities, the spacing between drill points is one of the main things that needs to be considered because the spacing of drill points will affect the confidence level of the estimation results and affect exploration costs. Choosing the right method is necessary. If you compare the calculations using the sill variogram and based on the Global Estimation Variance (GEV) analysis, the two methods do not show the same or significantly different results. Calculation of borehole spacing determination with the global estimation variance method, has the advantage of more precision, because the calculation of the relative error of each block can be directly calculated after the estimated variance value is obtained, while it is suitable for calculating borehole spacing with moderate to complex geological conditions. While the calculation of borehole spacing with the sill variogram method, although it is easier and the observation is only based on the observation of the sill variogram value, but the disadvantage is that there is no calculation of relative error for each block, so the results are less precise. The advantage is that the processing time is relatively faster and well used in layers with simple geological conditions for coal. For a comparison of the two methods can be seen in the Table 4.

Table 4 Comparison of advantages and disadvantages of sill variogram and GEV methods.

Parameters	Sill variogram method	GEV method
Data input	Simpler inputting, because the borehole spacing can be directly determined based on the sill variogram (1/3, 2/3 or 33 (range))	Slightly complicated, because the calculation of the relative error of each block can be directly calculated after the estimated variance value is obtained.
Time Duration	Relatively faster processing	Computationally time-consuming, with variogram model checking required.
Types of mineral deposits	Good for use in seams with simple geological conditions for coal	Good for deposits with simple to complex geology with high variability in coal quality.
Application of Calculation	The calculation results are local or applied to one study area with the same sediment homogeneity, and spatial continuity.	The calculation results are local or applied to one study area with the same sediment homogeneity, and spatial continuity.

5 Conclusions

Based on the analysis of determining the optimum borehole spacing using the GEV and Sill Variogram methods, it can be concluded that:

1. This method of determining drill hole spacing is necessary due to the confidence level of estimated resources and reserves and exploration costs.
2. DHSA using the Sill Variogram method is conceptually very simple and has a shorter processing time, but the results are less accurate because it does not take into error values and can be used in simple geological conditions.
3. The GEV method requires processing time, which is more complicated with regards to computation but can be applied to deposit conditions with high variability and moderate and complex geological conditions.

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Author contributions

Irfan Marwanza: conceptualization; formal analysis; methodology; validation; writing – review and editing; supervision. **Wiwik Dahani:** methodology; validation. **Subandrio Subandrio:** methodology; software; visualization. **Masagus Ahmad Azizi:** writing- review & editing. **Rhazes Eesha Gumay:** writing – original draft.

Conflict of interest

The authors have no conflict of interest to declare.
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