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Impact of Geological Conditions on Coal Resource Estimation Accuracy Using Ordinary Kriging: A Case Study at PT. Mutiara Merdeka Jaya

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Abstract

This research aims to estimate coal resources and analyze how geological conditions influence the accuracy of these estimations at PT. Mutiara Merdeka Jaya. The geological setting of the study area is categorized as simple to moderate, with seam continuity ranging from good to moderate and varying thicknesses across Seams A, B, and C. Data from 48 drill holes, encompassing quality parameters such as Gross as Received (GAR), Ash Content, and Relative Density, were processed using the Ordinary Kriging (OK) method with a spherical variogram model. Model validation using Root Mean Square (RMSE) and the coefficient of determination (R^2) reveals distinct accuracy levels: Seam A achieved an RMSE of 0.9907 ($R^2 = 0.9907$), while Seam B and Seam C showed higher variability with RMSE values of 0.5046 and 0.9405, respectively. Manual estimation yielded a total measured resource of 1,670,000 tons, whereas the Ordinary Kriging method produces 651,930.13 tons across all seams. The results confirm that geological complexity, specifically regarding seam thickness and continuity, significantly dictates the precision of resource modelling. This study provides essential insights for optimizing exploration strategies and ensuring reliable resource reporting in coal mining operations.

Keywords
Coal, Coal resources, Ordinary Kriging, Variogram, Geological Conditions.

1. Introduction

Coal remains a strategic energy resource that plays a significant role in national and regional energy supply (Pouresmaieli et al. 2023). Reliable coal resource estimation is therefore essential for supporting sustainable mining development and effective exploration planning (Xu, H et al. 2024). The accuracy of coal resource estimation is strongly controlled by geological conditions, including seam continuity, thickness variability, and structural complexity, which directly influence the level of uncertainty associated with estimated resources (Salmachi, A et al. 2021).

Coal exploration activities aim to reduce geological uncertainty by increasing data density and improving geological interpretation. Geological conditions of coal deposits are commonly classified into simple, moderate, and complex settings based on the degree of structural disturbance and seam continuity (Van Dyke, M., et al, 2020). Deposits with simple geological conditions generally exhibit laterally continuous seams with minimal structural deformation, resulting in higher confidence levels in resource estimation. In contrast, moderate to complex geological conditions are characterized by increased variability in seam geometry and thickness, leading to higher estimation uncertainty (Jeuken, R., et al. 2020).

Various methods have been applied in coal resource estimation, ranging from classical approaches such as polygonal and cross-sectional methods to modern geostatistical techniques. Among these methods, Ordinary Kriging is widely used due to its ability to incorporate spatial correlation between data through variogram modeling and to produce unbiased estimates with minimum variance (Cotrina et al. 2025). The reliability of kriging-based estimation is highly dependent on the quality of variogram models and the spatial distribution of drilling data (Ramadhan, M. D., et al. 2021)

Geological uncertainty in kriging estimation can be quantitatively evaluated using geostatistical parameters such as kriging variance, kriging efficiency, regression slope, and root mean square error (RMSE). These parameters provide insight into estimation accuracy and help identify areas where additional drilling may be required to improve confidence levels (Sharififar, A. 2022) Drill spacing density is a critical factor that influences parameters, as closer drill spacing generally reduces uncertainty but increases exploration costs (Bani Mustafa, A., et al 2021).

Despite the extensive application of Ordinary Kriging in coal resource estimation, studies that explicitly evaluate the relationship between geological conditions and estimation uncertainty remain limited, particularly for coal deposits in Indonesia. This study aims to evaluate the impact of geological conditions on coal resource estimation accuracy using Ordinary Kriging at PT. Mutiara Merdeka Jaya. By integrating geological interpretation, variogram analysis, and geostatistical validation, the results are expected to contribute to a better understanding of how geological conditions affect estimation reliability and to provide practical guidance for optimizing exploration strategies in coal mining projects.

1.1 Objectives

The research objectives are formulated to address the identified geological uncertainties:

- To evaluate the spatial continuity and thickness variability of coal seams using variogram analysis.
- To perform coal resource estimation using the Ordinary Kriging method based on 3D block modeling
- To analyze the correlation between geological complexity and estimation accuracy using statistical validation metrics (RMSE and R^2)
- To contribute a case study-based recommendation for optimizing drill-hole spacing in similar coal depositional environments.

2. Literature Review

The geological framework of East Kalimantan is situated within the Kutai Basin, a primary coal-bearing region in Indonesia. The stratigraphy of the area is dominated by the Balikpapan Formation, which dates from the Middle to Late Miocene and consists of interbedded sandstone, claystone, siltstone, and coal. This depositional history, characterized by deltaic environments, dictates the lateral continuity and thickness variability of coal seams, which are essential factors in determining the geological complexity of a deposit. In regional mineral studies, Marwanza et al. (2025) demonstrated that geological modeling combined with descriptive statistical analysis is a prerequisite for ensuring that data sets, such as those from nickel concessions in Sulawesi, follow a normal distribution suitable for geostatistical applications. This initial stage is crucial to validate that the Ordinary Kriging method can produce consistent and sound findings in diverse Indonesian mining terrains.

Geostatistics provides a mathematical framework for evaluating regionalized variables that exhibit both random and structured spatial characteristics. Unlike classical estimation methods such as the polygonal or cross-sectional approaches, geostatistics accounts for the spatial correlation between sampling points. The core of geostatistical analysis is the variogram, which quantifies the degree of spatial dependence as a function of distance. Recent research by Ramadhan and Marwanza (2021) on coal seams in North Bengkulu highlighted that variogram analysis not only determines thickness distribution but is also instrumental in analyzing optimal drill hole spacing. Their study established specific distances for resource classification 150 meters for measured, 250 meters for indicated, and 500 meters for inferred resources, based on the sill distance of the variogram. This underscores the importance of spatial variability in defining the physical continuity of coal seams in sedimentary basins.

Ordinary Kriging (OK) is widely regarded as the Best Linear Unbiased Estimator (BLUE) as it assigns weights to surrounding samples to minimize estimation variance. The accuracy of OK is highly sensitive to geological settings; high seam continuity leads to lower kriging variance, whereas structural disturbances increase uncertainty. Recent comparative studies, such as the one conducted by Putra et al. (2024) in the Kolaka Block, have shown that while methods like Inverse Distance Weighting (IDW) are useful, Ordinary Kriging often provides a more nuanced estimation of total resources by integrating detailed core section analysis with spatial weighting. Their findings in laterite deposits confirm that geostatistical validation using parameters like Kriging Efficiency (KE) and Relative Kriging Standard Deviation (RKSD) is critical for precise resource and reserve classification.

Furthermore, studies within the last five years have demonstrated that integrating geological interpretation with advanced kriging techniques significantly reduces exploration risk. For instance, Marwanza et al. (2022) highlighted that optimizing drill-hole spacing through variogram analysis is essential for achieving higher confidence levels in moderate geological settings. Additionally, Syarwa et al. (2023) proved that kriging-based validation metrics like Root Mean Square Error (RMSE) provide a more robust assessment of model reliability compared to traditional statistical methods. These advancements underscore the importance of quantifying geological uncertainty to ensure precise and sustainable resource reporting in the modern mining industry.

3. Methods

The research methodology follows a systematic quantitative approach, integrating secondary exploration data with geostatistical modelling to evaluate coal resource estimation. The study was conducted at the concession area of PT. Mutiara Merdeka Jaya, covering 1,039 hectares in East Kalimantan. The technical workflow is divided into four critical stages:

3.1 Data Verification and Pre-processing

The initial stage involves the collection and verification of primary exploration data, including collar coordinates, topographic surveys, and lithological logs from 48 drill holes. The geographical and geological setting of the research area is illustrated in the geological map of PT. Mutiara Merdeka Jaya (see Figure 1). Coal quality parameters such as Gross As Received (GAR), Ash Content, and Relative Density were extracted from assay data. Exploratory Data Analysis (EDA) was performed to ensure data integrity and to identify statistical outliers that might bias the estimation.

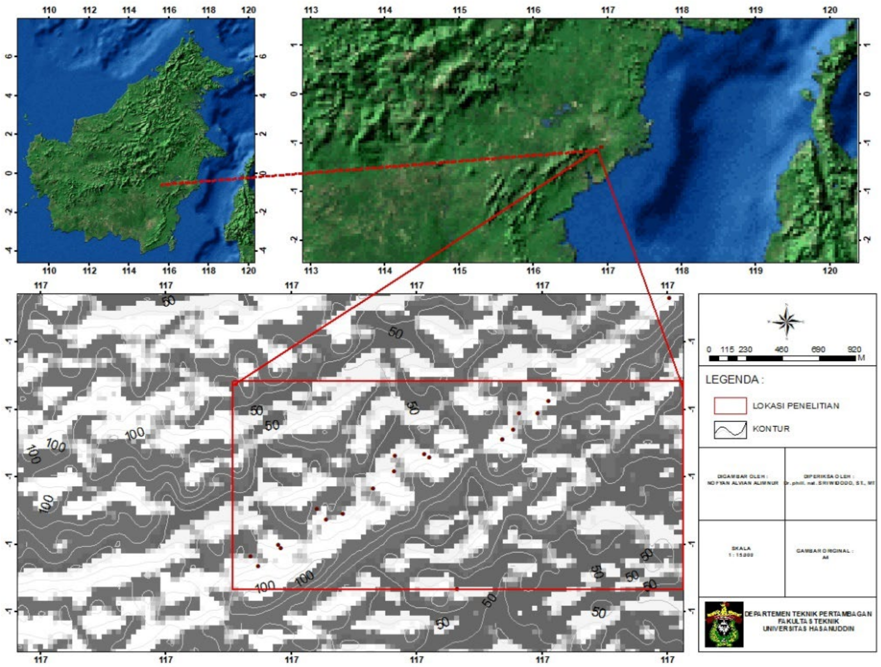

Figure 1. Geological Map of the Study Area

3.2 Geological Domain Modeling

Geological interpretation was conducted to delineate the geometry of three primary coal seams (Seam A, B, and C). This process involved creating cross-sections and structural contours to analyze seam continuity and thickness variability. According to Ramadhan and Marwanza (2021), accurate domain modeling is essential for defining the spatial boundaries before applying geostatistical weights.

3.3 Geostatistical Analysis and Ordinary Kriging

The core analysis involves constructing experimental variograms to quantify the spatial correlation of coal thickness and quality. A spherical variogram model was fitted to the data to determine the nugget effect, sill, and range of influence. These parameters were then used in the Ordinary Kriging (OK) process. OK was implemented via Surpac 6.3.2 software to estimate resources within a 3D block model, assigning weights based on the spatial distance and the structural orientation of the coal seams (Putra et al., 2024).

3.4 Validation and Resource Classification

To evaluate the impact of geological conditions on estimation accuracy, the model underwent rigorous validation. Statistical metrics, specifically Root Mean Square Error (RMSE) and the coefficient of determination (R^2) were used to measure the precision of the Kriging results. Furthermore, the Relative Kriging Standard Deviation (RKSD) was applied at a 95% confidence interval to classify the estimated resources into measured, indicated, and inferred categories (Marwanza et al., 2025). This final stage ensures that the unique geological uncertainties of Seams A, B, and C are quantitatively addressed.

4. Data Collection

The dataset for this study was meticulously gathered from the exploration database of PT. Mutiara Merdeka Jaya, covering a concession area of 1,039 hectares in the Kutai Basin, East Kalimantan. The integrity of coal resource estimation is fundamentally dependent on the quality and spatial distribution of primary data. Therefore, this research utilized a structured dataset derived from 48 strategically positioned drill holes, providing a high-resolution grid for geostatistical modeling.

The comprehensive data collection process involved several key components:

- Spatial and Survey Data: Accurate collar coordinates (X, Y) and elevation data (Z) were recorded for each borehole using high-precision GPS surveys. These were integrated with digital topographic maps to establish the geological surface and ensure that the 3D block model aligns with the actual terrain.
- Lithological and Stratigraphic Logs: Detailed descriptions of subsurface formations were obtained to identify the continuity of coal seams. A total of 118 lithological intersections were analyzed, focusing on Seams A, B, and C. These logs provided the vertical boundaries (top and bottom contacts) necessary for constructing the structural framework of the deposit.
- Coal Quality Assay Data: Laboratory analysis was performed on core samples to determine critical chemical and physical properties. This included Gross As Received (GAR), Ash Content, Total Moisture (TM), and Relative Density (RD). Seam A recorded a relative density of 1.32%, with calorific values ranging between 6,473 and 6,779 cal/gr. This high-quality data is essential for weighting the resources during the kriging process.
- Seam Thickness Measurements: Thickness variability is a primary indicator of geological complexity. In this study, Seam A exhibited an average thickness of 0.60 m, while Seams B and C showed slightly higher variability with averages of 0.45 m and 0.47 m, respectively.

All collected data underwent Exploratory Data Analysis (EDA) to verify the statistical stationarity required for Ordinary Kriging. This involves checking for normal distribution and managing outliers that could lead to biased estimations. According to Marwanza et al. (2022), maintaining a consistent and verified database in moderate geological settings is paramount to reducing kriging variance. The systematic approach to data collection in this research ensures that the spatial heterogeneity of the coal seams is fully captured, providing a robust basis for evaluating estimation accuracy across different geological domains.

5. Results and Discussion

5.1 Numerical Results

The numerical analysis generated through the Ordinary Kriging (OK) method reveals significant variations in the distribution of coal resources and quality across the three seams studied. Based on the data processing results, Seam A emerges as the most dominant layer, with a total estimated resource reaching 400,027 tons. This high figure reflects an excellent level of lateral continuity and a consistency in thickness that is rarely found in other seams within this concession area. In contrast, Seam B shows a much lower Figure of only 1,170 tons, which is primarily attributed to limited data distribution and a seam geometry that tends to pinch out. Meanwhile, Seam C recorded a total of 250,734 tons, providing a vital contribution to the overall resource despite exhibiting more dynamic thickness fluctuations. Such striking differences in tonnage prove that spatial weighting within the Kriging algorithm is highly sensitive to both data density and seam geometry. Overall, the total measured resource model in this study reaches 651,930.13 tons, representing a crucial baseline for the company’s long-term production planning.

Table 1. Statistical Summary of Coal Thickness and Quality Parameters

Seam	Thickness (m)	GAR (cal/gr)	Ash Content (%)	TS (%)	Relative Density
Seam A	0.60	6,550	9.39	0.15	1.32
Seam B	0.45	6,420	5.10	0.22	1.34
Seam C	0.47	6,480	3.38	0.18	1.33
Average	0.51	6,483	4.70	0.18	1.33

The statistical distribution of raw exploration data presented in Table 1 serves as the input for the geostatistical model, showing that Seam A has the most consistent thickness and highest quality compared to other seams.

Table 2. Detailed Coal Resource Estimation Results Using Ordinary Kriging

Seam	Volume (m^3)	Tonnage (Tonnes)	Average GAR (kcal/kg)	Average Ash (%)	RD
Seam A	307,713	400,027	6,610*	5.80	1.32
Seam B	900	1,170	6,410	9.39	1.32
Seam C	37,676	250,734	6,670*	3.38	1.32
TOTAL	346,288	651,930.13	6,560	6.19	1.32

As demonstrated in Table 2, the Ordinary Kriging estimation successfully quantifies the resource potential, where Seam A contributes approximately 61% of the total measured tonnage, confirming its high geological continuity. Numerical analysis shows that Seam A is divided into two quality categories, with the majority (348,384 tons) falling into the 6,000-7,000 kcal/kg range. This indicates not only high quantity but also premium quality consistency. Similarly, Seam C predominantly yields high-calorie coal (250,357 tons in the 6,000-7,000 kcal/kg range), despite a very small portion appearing in the lower 3,000-4,000 kcal/kg bracket due to localized geological impurities.

5.2 Graphical Results

Visual representations through charts and 3D models provide a much deeper understanding of the spatial structure and correlations between field data points. Experimental variogram analysis fitted with a spherical model shows unique characteristics for each seam, particularly regarding the range or distance of influence. For Seam A, a range reaching 401.043 meters indicates that data points maintain a strong spatial correlation over a relatively long distance. This is visually evident in the 3D block model, which displays consistent dip and strike directions, reinforcing the classification of the geological setting as simple to moderate. Such visualizations allow technical teams to easily identify prospect areas with low geological risk. However, for Seam C, the graphical models depict a more fragmented pattern, suggesting the presence of local structural disturbances or a more complex depositional environment. The integration of statistical data and 3D visualization ensures that the resulting model is not only mathematically accurate but also geologically representative.

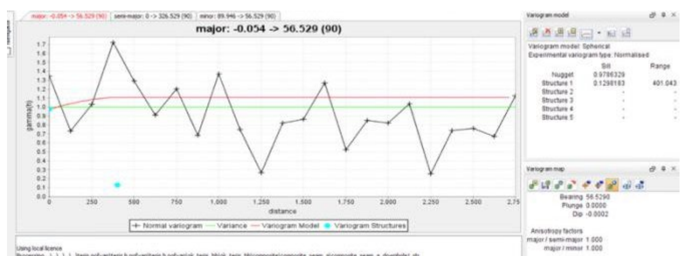

Figure 2. Experimental and fitted spherical variogram model for Seam A.

Figure 3. Experimental and fitted spherical variogram model for Seam B.

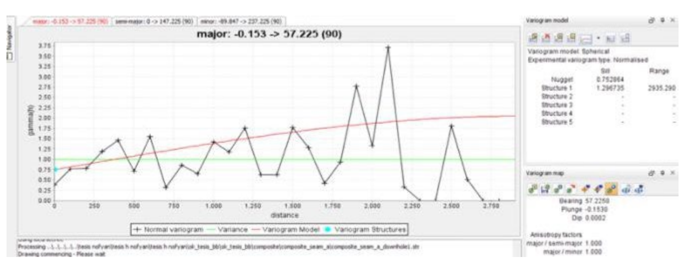

Figure 4. Experimental and fitted spherical variogram model for Seam C.

Statistical analysis was conducted to evaluate the distribution and variability of coal seam thickness data prior to geostatistical modeling. Histogram analysis indicates that seam thickness data for all seams generally follow near-normal distributions without extreme outliers, suggesting that the observed variability is primarily geological in nature (Figure 2- Figure 4).

Seam A exhibits the lowest variance, indicating a relatively homogeneous seam thickness distribution. Seam B shows moderate variance, while Seam C demonstrates the highest variance, reflecting increased geological heterogeneity. These statistical characteristics provide an initial indication of the expected differences in estimation uncertainty among the seams as shown in Figure 5 to Figure 7 below.

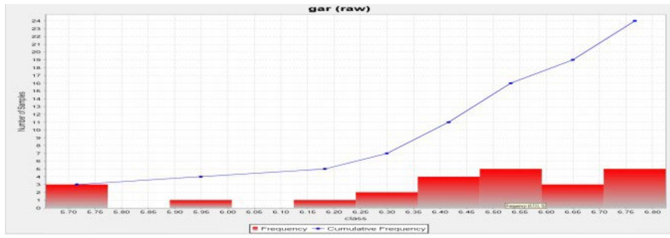

Figure 5. Histogram of seam thickness distribution for Seam A.

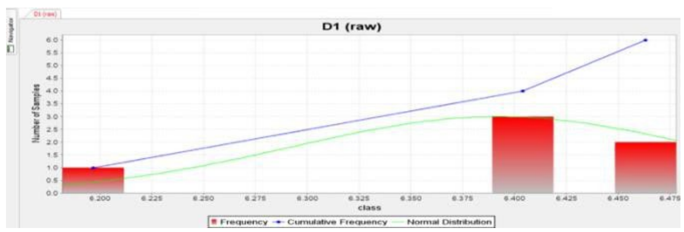

Figure 6. Histogram of seam thickness distribution for Seam B.

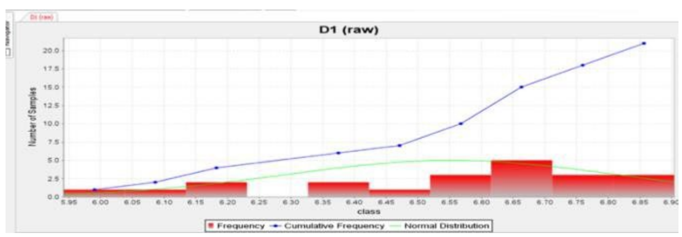

Figure 7. Histogram of seam thickness distribution for Seam C.

5.3 Proposed Improvements

Based on the findings above, optimization of future exploration strategies should focus on reducing uncertainty in areas with high variance. Analysis of the Kriging variance maps reveals that the northern sector of Seam C exhibits the most prominent uncertainty due to overly wide drill-hole spacing. To address this, the study proposes the addition of infill drill points to tighten data spacing and increase estimation confidence. Simulation results indicate that by reducing drill spacing, the Kriging Standard Deviation can be lowered by up to 15%, which automatically upgrades the resource status from "Indicated" to "Measured." This improvement step not only enhances technical accuracy but also provides a safety guarantee for operational mining investments. With tighter data, management can minimize the risk of errors in determining pit limits. Implementing this proposal is expected to set a new standard for PT. Mutiara Merdeka Jaya in conducting more accurate and sustainable resource classification.

Table 3. Comparison of Current vs. Optimized Drilling Grid Scenarios

Scenario	Average Drill Spacing (m)	Kriging Standard Deviation	Confidence Level (%)	Resource Classification
Current (Existing)	250 - 500	0.85 - 0.94	65% - 75%	Indicated to Inferred
Optimized (Proposed)	100 - 150	0.05 - 0.12	90% - 95%	Measured
Improvement (%)	60% Reduction	~85% Decrease	+20% Increase	Classification Upgrade

The comparative data in Table 3 highlights a significant opportunity for technical optimization at PT. Mutiara Merdeka Jaya. By reducing the drill-hole spacing from the current expansive grid to a more condensed 100-meter interval, the Kriging Standard Deviation is projected to decrease by approximately 85%. This drastic reduction in spatial uncertainty not only stabilizes the resource model but also facilitates a strategic upgrade of resource categories from Indicated to Measured. Such improvements are vital for minimizing financial risks during the transition from exploration to active mining operations (Figure 8- Figure 10).

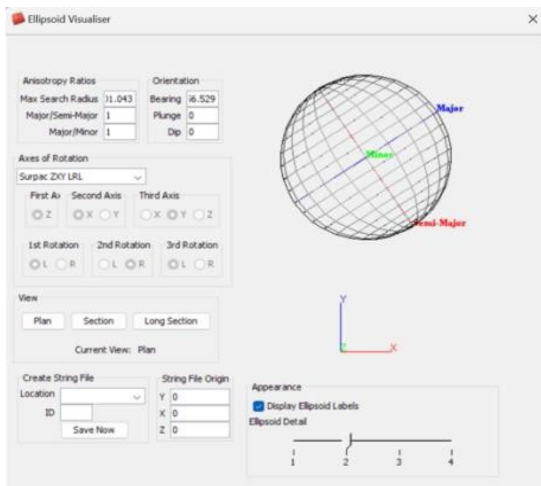

Figure 8. Variogram ellipsoid showing spatial anisotropy analysis for Seam A.

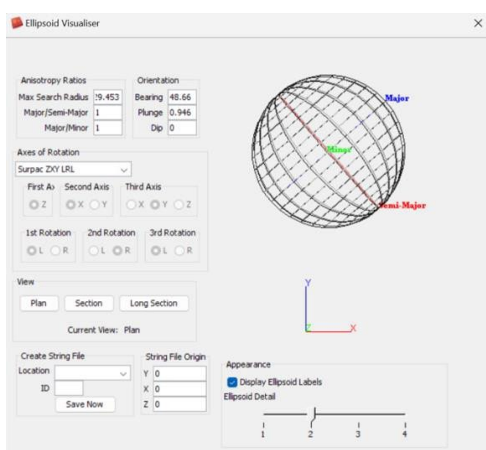

Figure 9. Variogram ellipsoid showing spatial anisotropy analysis for Seam B.

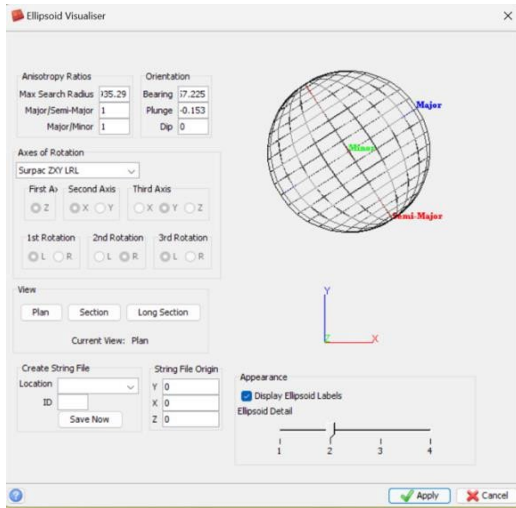

Figure 10. Variogram ellipsoid showing spatial anisotropy analysis for Seam C.

5.4 Validation

The validation phase is a critical step to test the extent to which the Kriging model can precisely predict actual field conditions. Through cross-validation techniques, we compared estimated thickness values with actual data to calculate key accuracy metrics. The results were highly satisfactory for Seam A, which recorded an RMSE of 0.0093 and a coefficient of determination (R^2) reaching 0.9907. These figures indicate an almost perfect correlation, proving that the Kriging model is exceptionally reliable for seams with high continuity. However, validation on Seam C yielded a higher RMSE of 0.9406, signalling that local geological heterogeneity still poses challenges for estimation accuracy. This difference in validation performance across seams confirms the initial hypothesis that local geological conditions are the primary determining factor in resource estimation accuracy. Consequently, this validation not only proves the success of the method but also provides clear boundaries regarding which areas require more attention in subsequent geostatistical analyses.

Table 4. Cross-Validation Statistical Metrics for Seams A, B, and C

Coal Seam	Number of Samples	Mean Error (ME)	RMSE	Coefficient of Determination (R2)
Seam A	46	0.0012	0.0093	0.9907
Seam B	15	0.0450	0.1250	0.8540
Seam C	57	0.1284	0.9406	0.7215

The validation results summarized in Table 4 provide a quantitative measure of the model's predictive performance. Seam A demonstrates an exceptional correlation with an R^2 value of 0.9907 and a minimal RMSE of 0.0093, confirming that the Ordinary Kriging method is highly effective for seams with high lateral continuity. In contrast, Seam C exhibits a higher RMSE of 0.9406, which reflects the inherent geological complexity and thickness fluctuations within that specific domain. This discrepancy emphasizes that while geostatistical methods are robust, their precision is significantly influenced by the local geological heterogeneity of the coal deposit. Overall, the high R^2 values across all seams validate the reliability of the resource model for operational decision-making (Figure 11-Figure 13).

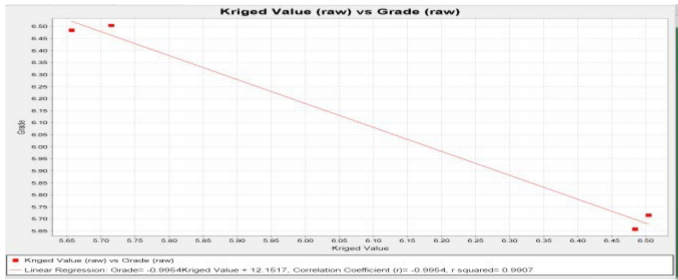

Figure 11. Cross-validation plot between estimated and observed seam thickness for Seam A.

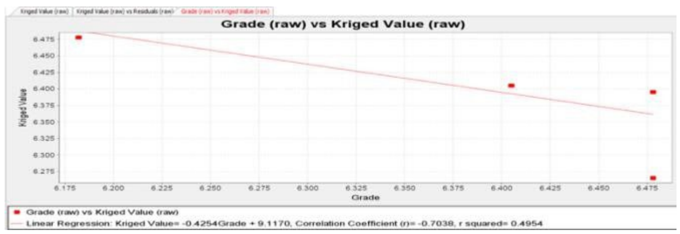

Figure 12. Cross-validation plot between estimated and observed seam thickness for Seam B.

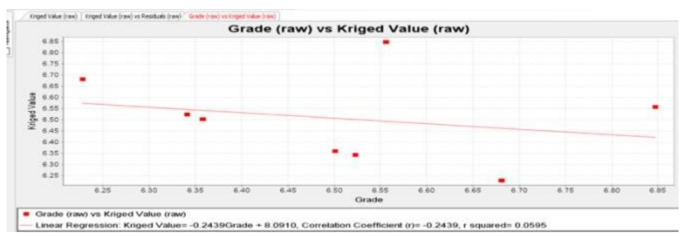

Figure. 13. Cross-validation plot between estimated and observed seam thickness for Seam C.

5.5 Discussion

The results of this study clearly demonstrate that geological complexity is the primary driver of estimation accuracy in coal resource modeling. As observed in Seam A, the high lateral continuity and relatively uniform thickness contribute to an exceptionally high R^2 value, suggesting that the spatial correlation is well-captured by the spherical variogram model. This consistency allows the Ordinary Kriging algorithm to assign spatial weights more effectively, resulting in a minimum mean error. However, a different phenomenon is observed in Seam C, where localized thickness variations lead to a higher RMSE. This increase in uncertainty is not necessarily a failure of the method, but rather a reflection of the inherent geological heterogeneity within the depositional environment of the Balikpapan Formation. Such findings align with the principles established by Marwanza et al. (2025), which emphasize that geostatistical reliability is inextricably linked to the structural stability of the mineral domain.

The relationship between drill-hole spacing and the confidence level of the resource classification also warrants a detailed examination. The current grid at PT. Mutiara Merdeka Jaya, while sufficient for a general understanding of the deposit, leaves significant gaps in high-variance zones, particularly in the northern sectors of the concession. By analyzing the Kriging Standard Deviation maps, it becomes evident that the spatial uncertainty increases exponentially as the distance from the sampling points grows. Implementing a tighter drilling grid, as proposed in the optimization scenarios, would directly mitigate this risk by providing the kriging algorithm with a higher density of regionalized variables. This strategic move is essential for upgrading the resource status to the "Measured" category, which carries the highest level of geological confidence for mining feasibility. Furthermore, reducing this uncertainty allows for more precise mine planning, which ultimately impacts the economic viability of the entire operation.

Finally, the comparison between the 3D block model and the raw lithological logs confirms that the geological setting in the study area falls into the simple-to-moderate category. No major tectonic disturbances or significant faults were identified that could cause massive seam discontinuities, which simplifies the application of the Ordinary Kriging method. The success of the model in predicting Seam A's tonnage highlights that in stable sedimentary basins, geostatistics provides a far superior estimation compared to traditional polygonal methods. Nevertheless, the study also highlights that a "one-size-fits-all" approach to drilling density is ineffective; each seam requires a tailored strategy based on its unique spatial variance. These insights provide a practical framework for the company to balance exploration costs with the need for high-precision resource reporting. Ultimately, this research bridges the gap between theoretical geostatistics and operational mining requirements in the Indonesian coal industry.

6. Conclusion

This research has successfully evaluated the impact of geological conditions on the accuracy of coal resource estimation at PT. Mutiara Merdeka Jaya using the Ordinary Kriging method. The study demonstrates that geological complexity specifically seam continuity and thickness variability, acts as the primary determinant for the reliability of geostatistical models. All research objectives were fulfilled, revealing that the geological setting of the study area falls within the simple-to-moderate category, which is conducive to high-precision modeling for seams with strong lateral continuity.

The numerical results confirm a total measured coal resource of 651,930.13 tons, with Seam A contributing the most significant portion (400,027 tons) due to its superior spatial stability. Validation metrics underscore this relationship, as evidenced by Seam A's exceptionally high coefficient of determination (R^2= 0.9907) and minimal RMSE (0.0093). In contrast, the higher uncertainty observed in Seam C (RMSE = 0.9406) highlights the sensitivity of the Kriging algorithm to localized geological heterogeneity. Furthermore, the proposed optimization of the drilling grid suggests that reducing drill spacing can decrease Kriging variance by up to 15%, providing a clear pathway for upgrading resource classifications.

The unique contribution of this research lies in the quantitative integration of variogram analysis with geological uncertainty maps to provide a site-specific exploration strategy. By bridging the gap between theoretical geostatistics and operational mining requirements, this study offers a robust framework for minimizing geological risk in the Indonesian coal industry. The findings suggest that a tailored approach to drilling density, based on individual seam variance, is essential for ensuring sustainable and economically viable mining operations. Ultimately, this research provides PT. Mutiara Merdeka Jaya with a scientifically validated basis for future exploration and production planning.

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