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Resource estimation for Alpagut-Dodurga coal field and determination of spatial distribution of coal quality parameters

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Abstract: In this study, coal seams of the Alpagut-Dodurga coal field, located in one of Anatolia's most important Tertiary-aged basins of the Çankırı-Çorum Basin, were modeled in 3 dimensions by using Netpro/Mine software and geostatistical methods for the estimation of resource amount. Additionally, the spatial distributions of coal quality parameters (lower calorific value, ash content, and moisture content) were determined using the same software and mapped thematically. Mining activities with inaccurate methods and planning lead to unacceptable reserve losses. The selection and planning of effective and economic production methods could be possible with three-dimensional modeling, accurate determination of spatial distributions of quality parameters, and resource estimation. As a result of this study, the present resources estimated from the geologic solid model using Netpro/Mine software was found to be 19.5 × 10^6 m^3. Modeling and 3-dimensional visualizations of resources in a scientific and rational manner with software provides mine planners with realistic production design and planning. These models have great importance in terms of providing quick and more reliable data to mine planners and managers during decision-making processes.

Key words: Coal resource estimation, geostatistics, 3D modeling, Alpagut-Dodurga coal field

1. Introduction

Coal is used in many areas like electricity production, iron-steel, and cement manufacturing and for steam production in industrial processes, and at the same time it is consumed as domestic fuel for heating purposes. Many countries meet a significant portion of their electricity production from coal. This rate is 53% in the USA and Germany, 69% in Greece, 75% in China, 77% in Denmark, 83% in Australia, 93% in South Africa, and 95% in Poland. In Turkey, this rate is at lower levels compared to the countries listed above at about 32%.[1] World coal production has nearly doubled in the last 30 years. The increase in coal production is mainly due to the demand for electrical energy from the continent of Asia, mainly China. The resource most intensely used for electricity production is coal (Aktan et al., 2018).

Mine resources are defined as the presence of a mineral or resource found in the crust in form and amount to allow for economic production. Estimation of mine resources includes estimation of the geology, continuity, tonnage, and mean grade of mine assets (Aktan and Tercan, 2016). Minerals are nonrenewable resources, making it necessary to extract and use them with the lowest losses. To obtain these resources at low cost and efficiency with highest benefit, it is necessary that they should be extracted in projects appropriate to modern mining science and technology. Selection and planning of an effective, efficient, and sustainable mining method can be possible using realistic determination of the spatial distribution of resource estimates and quality parameters with three-dimensional modeling. These studies require the use of user-friendly, rapid, and reliable software with the ability to visualize in 3 dimensions. Due to this software, many mine design alternatives can be rapidly evaluated and design errors can be minimized. The obtained data are used in every stage from operating the mine to pit design and production planning and for investment decisions about the future. Approaches paying attention to these data may determine the optimum point among the targeted production, product quality, and economy and thus reliably ensure continuation of operations. At the same time, these data have great importance in terms of allowing

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[1] Turkish Coal Enterprises. Energy and Coal [online]. Website http://www.tki.gov.tr/bilgi/komur/enerji-ve-komur/232 [accessed 15 October 2019].

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the possibility of selective mining implementation in line with new strategies that may develop in future periods. As a result of production without appropriate methods and planning, reserve losses may reach unacceptable proportions.

The process of modeling mineral deposits with the aid of computers first began at the beginning of the 1960s (Jiang, 1998). Later when all resources present in the mining sector were assessed, a variety of computer programs (Surpac, Micromine, Datamine, etc.) were developed with the aim of ensuring maximum benefit from minerals consumed and full identification of mine reserves. One of these programs was the Netpro/Mine computer program, developed through the cooperation of the Hacettepe University Department of Mining Engineering, Turkish Coal Enterprises (Turkish: TKİ), and the Netcad company, providing all technical designs from the stage of finding mineral deposits to completing production and the first domestic product in the field in Turkey (Tercan et al., 2013; Gharehoghlani, 2014).

Many researchers have completed Netpro/Mine-based studies about the creation of geologic solid and block models of mine resources, geostatistical resource and reserve estimation, pit project applications, three-dimensional imaging and thematic mapping, and production planning, and they have produced solutions with a variety of approaches (Arıöz, 2011; Tercan et al., 2011; Arıöz et al., 2012; Özdemir, 2013; Tercan et al., 2013; Gharehoghlani, 2014; Toptaş, 2015; Gharehoghlani et al., 2016).

This study, completed in light of the information mentioned above, used drilling data from the Alpagut-Dodurga coal field with the Netpro/Mine mining software and included three-dimensional modeling of the resources, geostatistical evaluation, creation of a block model, detailed reserve calculation, and thematic mapping of the distribution of coal quality parameters (lower calorific value (LCV), ash content (AC), and moisture content (MC)).

The Alpagut-Dodurga coal field has been known since 1938. The first geological research in the field was completed by Blumental (1938) and Pekmezciler (1948, 1955–1956) (Kara et al., 1990). In 1938, Blumental tested the Çorum-Çankırı lignites and performed geological mapping at 1/100,000 scale for a large area between Osmancık and Tosya and also around Dodurga (Kara et al., 1990). Pekmezciler (1948) geologically mapped the area at 1/5000 scale and exploration drilling began as a result of these studies. The first reserve estimation for the field was completed by Pekmezciler with a probable reserve of 30.5 × 10^6 t found with the isopach mapping method linked to drilling results from 1955–1956 (Kara et al., 1990). The final study about reserve estimation was completed by Kara et al. (1990). Apart from the reserve identification performed by Pekmezciler with drilling data from 1955–1956 (30.5 × 10^6 t probable reserve), although new drilling was performed in the process until the study by Kara et al. (1990), no reserve assessment was performed for the field. Kara et al. (1990) studied the geology of the Alpagut-Dodurga coal field in detail and revised the 1/5000 scale geological map. Within the scope of the study 29 boreholes were drilled (total quantity 10,319 m) and partial solutions were suggested for the structural geology of the field. The 29 boreholes completed in 1989 were evaluated together with the 35 boreholes from previous years and the field had a total of 24.22 × 10^6 t coal reserve identified with 21.76 × 10^6 t proven and 2.46 × 10^6 t probable reserve with the polygon method. In another study about the topic, Uğur (1994) evaluated 5 boreholes drilled in 1993–1994. The study researched whether the panels the operator wanted to enter were favorable in terms of geotechnical aspects and coal, and identified data that would be beneficial to the operator (coal thickness, distribution, and depth).

To date, there is no study revealing the three-dimensional study of the coal seams in the field with special mining software and no study about resource estimation with geostatistical approaches.

2. Material and methodology

2.1. Material

This study was completed in a coal field located near the village of Alpagut in Dodurga district, Çorum province. The field had 169 cored boreholes drilled from 1949 to the present by the General Directorate of Mineral Research and Exploration (Turkish: MTA), State Hydraulic Works (Turkish: DSİ), and TKİ. In order to evaluate data obtained from these drill cores for resource estimation, the three-dimensional mining software Netpro/Mine software has been used.

2.1.1. Study area and geology

The area of the study is located within one of the most important Tertiary-aged basins of Anatolia in the Çankırı-Çorum Basin. The coal field is located between the Tutuş and Alpagut villages, 5 km from Dodurga district, 21 km from Osmancık district, and 49 km from Çorum (Figure 1a). Geodynamically, the basin is within the Sakarya and Kırşehir continent within the İzmir-Eskişehir-Ankara-Erzincan ophiolitic suture belt. The Kırşehir massif, one of Central Anatolia's most important metamorphic massifs, is located south of the basin, while widespread rocks that are ophiolitic mélange products surround the basin to the north and west. Toward the southwest, a narrow zone links the Haymana-Polatlı and Tuzgölü basins. The subduction process beginning with the subduction of the northern branch of the Neotethys Ocean under the Sakarya continent in the Early Cretaceous ended with the closure of the ocean in the Late Eocene period. From the Late Paleocene to the Oligocene collision continued and basins representing continental environment products like Sivas, Çankırı-Çorum, and Haymana-Polatlı in Central Anatolia formed with the effect of the compressional regime. Units in the Çankırı-Çorum Basin formed in the interval from the Late Paleocene to the Pleistocene (Tüysüz and Dellaloğlu, 1992).

Fill sediments in the Çankırı Basin formed in five different sedimentation cycles and comprise rocks with more than 4 km of thickness. These cycles were investigated in detail by Kaymakci (2000). The sediment packet belonging to the oldest cycle comprises Late Cretaceous volcanoclastic and regressive shallow marine units with Paleocene-aged red sediments and carbonates. The second cycle is represented by Middle Eocene widespread nummulitic limestones overlain by Paleocene-Oligocene-aged sediments representing environments varying from regressive to debris. The Middle Miocene sediments overlying these units include occasional Oligocene-aged evaporate interlayers and pass into occasionally overlying Late Eocene-Oligocene red-colored sediments. The third cycle comprises fluvial-lacustrine sediments deposited in the Early-Middle Miocene period. The fourth sediment packet comprises fluvial-lacustrine sediments deposited in the Late Miocene. The Plio-Quaternary alluvial fan sediments and current alluvium overlie all units locally (Kaymakci et al., 2003).

The Tertiary coals located in the northwest of the basin are one of the resources meeting local energy requirements in the Central Anatolia region in spite of low calorie value and low and discontinuous reserves, similar to the other Tertiary-aged coals in Turkey. The coals studied formed within the Dodurga Formation deposited in a Miocene lacustrine environment in terms of regional geology. The Dodurga Formation comprises marl-clay intercalations, with economic coal seams at the base of the unit and abundant microfossil levels above the coals (Figure 1b). Above this formation are the Pliocene-aged Büyükşeyhefendi Formation and Quaternary sediments containing slope debris and alluvium (Figure 1c) (Toprak, 1996; Yalçın and Karslı, 1998; Yalçın Erik et al., 2018).

The sequence in the region of Alpagut where the coal mine is located begins with red-colored, angular, poorly sorted conglomerate comprising volcanic rock pebbles and red-blue claystone intercalations, with the coal zone above varying from low clay lignite-lignite claystone. Above the coal zone, layers begin with white dolomite and continue with plant traces and mollusk shells and green, gray, and black claystones. In upper sections again there is a level comprising gray, green, and black claystone and marl, shales, and a bituminous shale sequence, ending in yellowish-brown carbonate cherts (Figures 1b and 1c) (Yalçın and Karslı, 1998). Drilling studies completed by MTA in the region cut a single coal layer in the north and northwest of the field, with multiple coal layers cut in the south and southwest (Toprak, 1996).

In the Miocene period, sedimentation beginning in the Dodurga-Tutuş-Alpagut region was effective in creating the coal basin. As a result of this sedimentation, the basal section of the basin filled with pebble and block type large material. The filling of the base of the basin with large pebbles and blocks shows rapid sedimentation in this period. Later, the basin passed to a stable sedimentation stage and coal formation began within the basin. Following lignite formation, as a result of the deepening of the basin and increased water level, shale, claystone, clay, and marl type sediments formed (Kara et al., 1990).

The presence of coal in the basin was identified in 1938, with the first operating license given to the head of the village of Tutuş under the responsibility of the Çorum Provincial Special Administration. After 1964, the field was operated for 38 years by TKİ and passed to a private company in 2002. Today, there are two firms in the field. One operates an open-pit mine with a production capacity of 200,000–250,00 t, and the other one operates an underground mine with a capacity of 90,00–100,000 t annually. Due to depletion of the open-pit mine, future activities have been planned to continue with only underground operations.

2.1.2. Netpro/Mine software

Netpro/Mine is a Netcad module performing all stages of mine deposit modeling and mine operation (open pit and underground mining) together.[2] The program was developed to create a topographic field model and obtain a 3-dimensional ore model with the aid of drilling and geological research, and reserve estimation with geostatistical methods, and it uses field and ore models to determine which method will provide production in the most efficient, economical way with the least harm to the environment for the mineral deposit and allowing production plans to be completed (Arıöz, 2011; Özdemir, 2013; Gharehoghlani et al., 2016).

2.2. Methodology

The methodology for estimation of the coal resource in the Alpagut-Dodurga field with Netpro/Mine software and the evaluation and interpretation of results obtained are given as follows:

i. Based on core drilling performed in the study area, creation of a database using geological maps and reports from the field,

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[2] NETPRO/Mine. Help [online]. Website http://portal.netcad.com.tr/pages/viewpage.action?pageId=115802159 [accessed 15 October 2019].

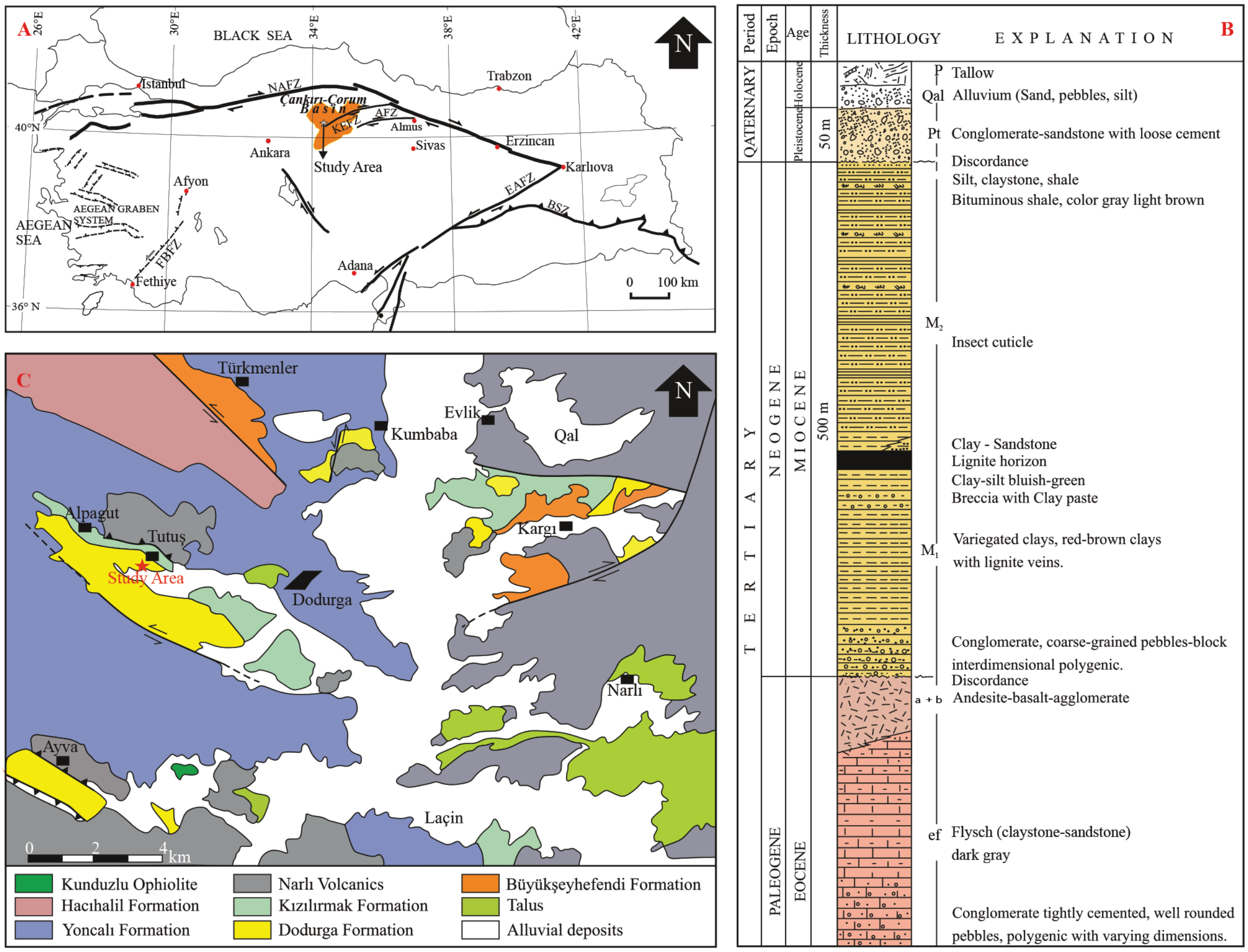

Figure 1. (A) The location of the study area in a simplified tectonic map of Turkey (Piper et al., 2006; Koçbulut et al., 2013). Tectonic lineaments are abbreviated: NAFZ, North Anatolian Fault Zone; EAFZ, East Anatolian Fault Zone; KEFZ, Kırıkkale-Erbaa Fault Zone; FBFZ, Fethiye-Burdur Fault Zone; AFZ, Almus Fault Zone; BSZ, Bitlis Suture Zone. (B) Generalized stratigraphic columnar section of study area (Kara et al., 1990). (C) Geological map of the study area (Yalçın Erik et al., 2018).

ii. Checking the accuracy of the database and making necessary corrections,

iii. Descriptive statistical analyses and determination of data distribution and behavior (histograms, relationships between coal quality variables),

iv. Geologic interpretation,

v. Obtaining geological solid models from cross-sections,

vi. Creation of a three-dimensional block model,

vii. Variogram analyses revealing the variations in distance and orientation of coal quality parameters (lower calorific value (LCV), ash content (AC), and moisture content (MC)),

viii. Applying cross-validation tests to the obtained theoretical variogram models and deciding about the validity of the model,

ix. Estimation of coal quality parameters for each block with the geostatistical approach of the kriging method,

x. Determination of distribution and proportions for coal quality variables (LCV, AC, and MC) and thematic mapping,

xi. Evaluation and interpretation of thematic maps and block model reports.

3. Resource estimation

3.1. Database used in modeling and estimation

Logs from previous drilling in the study area, geological maps, and reports were used to create a database. In the field from 1949 to the present, a total of 169 boreholes were drilled by TKİ, MTA, and DSİ. Of the 169 boreholes, 109 were shallow surface holes directly on outcrops in relation to the open pit operation, rather than for estimation of the total resources in the field. The remaining 60 boreholes were deeper, performed by MTA with the aim of identifying and developing the underground resources, and 55 cut coal. The location map for the boreholes is given in Figure 2. The

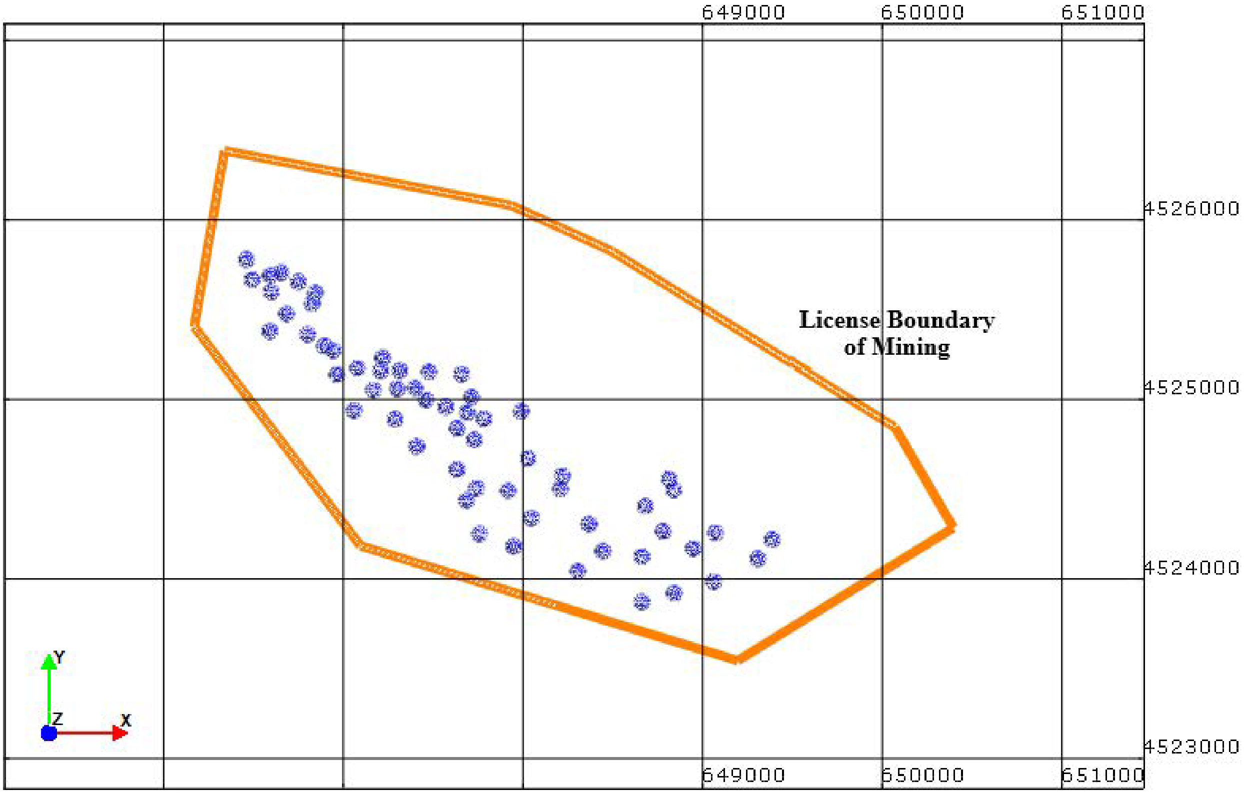

Figure 2. Drill hole locations.

mean distance between the boreholes in the field is 170 m and total length is 19,548 m. The average thickness of coal seams cut in boreholes is 13 m and it varies from 2.05 m to 47.45 m. The coordinates, drill length, and coal seams cut for each drill hole are given in Table 1.

In preparing the database, the 55 boreholes have been considered for the study. The Netpro/Mine software requires 4 data files (borehole, lithology, angle, raw sampling) that are created in .csv format[3] to form the basis for applications. The content of these files are given below:

- Borehole file: borehole number, hole depth, coordinates.
- Lithology file: borehole number, lithology beginning and end level, lithology definition.
- Angle: borehole number, depth, strike, dip.
- Raw sampling: borehole number, beginning level, end level, quality parameter values (LCV, AC, and MC).

After creating the database, accuracy was checked, erroneous data were determined, and necessary corrections were made. As drilling in the field was completed in several years (1955, 1967, and 1989) by different teams, inconsistencies were seen in lithology definitions. At this stage, production maps from previous years and control drilling during underground production activities were used to correct lithology definitions. When creating the database, intersections included in coal horizons reaching thickness of 1 m were included in coal; however, no quality parameter values were assigned. Black clay layers with calorific values lower than 1500 kcal/kg located at the bottom of the coal seam were not considered during the resource estimation.

3.2. Descriptive statistical analysis

Statistical analyses were based on analysis results of all samples (n = 258) taken from 55 boreholes cutting coal. With the aim of determining the frequency distribution of coal quality parameters, histograms (Figure 3) were drawn and scatter diagrams were created in order to define correlations between parameters (Figure 4). Statistical information for quality parameters obtained from histograms are summarized in Table 2. LCV varied from 1993 kcal/kg to 4685 kcal/kg (mean: 3350 kcal/kg), AC from 6% to 40% (mean: 21%), and MC from 11% to 34% (mean: 24%). When scatter diagrams were evaluated (Figure 4), a correlation was observed between LCV and AC (correlation coefficient r: 0.87). As AC increases, LCV decreases. Contrary to this, there were no correlations found between LCV and MC or AC and MC (Figure 4).

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[3] NETPRO/Mine. Catalog [online]. Website http://portal.netcad.com.tr/display/EN/Project+%7C+Read [accessed 15 October 2019].

Table 1. Drill holes coordinates and coal seam cut

Borehole ID	Length (m)	Coordinates (ED-50, 6°)			From	To	Thickness (m)	Borehole ID	Length (m)	Coordinates (ED-50, 6°)			From	To	Thickness (m)
		X	Y	Z						X	Y	Z			
89/21	491.1	4525662.50	646497.40	793.63	435.80	464.60	28.80	88/1	262.0	4524886.65	647787.09	718.08	233.40	249.85	16.45
89/27	243.0	4525773.64	646463.94	769.82	225.50	229.10	3.60	67/40	310.0	4524770.00	647733.00	720.49	292.35	296.57	4.22
89/13	361.4	4525684.73	646598.64	782.85	316.75	327.70	10.95	55/8A	302.2	4524928.00	647994.00	734.90	98.80	112.65	13.85
88/4	442.0	4525593.93	646603.64	794.06	423.00	427.20	4.20	56/21B	461.8	4524500.00	647745.00	782.00	365.72	373.67	7.95
89/28	276.0	4525701.17	646658.62	774.05	236.25	263.35	27.10	67/41	452.9	4524431.00	647691.00	813.49	406.45	411.14	4.69
88/3	291.3	4525649.97	646754.47	764.47	240.20	282.00	41.80	55/14	272.4	4524666.00	648033.00	708.74	134.40	144.00	9.60
55/11	406.0	4525472.00	646688.00	804.62	331.35	340.20	8.85	89/18	313.5	4524485.90	647922.19	751.05	281.30	288.50	7.20
89/29	230.0	4525589.01	646847.85	758.50	206.00	216.70	10.70	56/32	614.5	4524246.00	647763.00	829.70	470.00	472.05	2.05
88/2	235.5	4525528.52	646830.62	767.49	209.50	217.10	7.60	67/54	149.7	4524570.00	648224.00	707.06	101.59	110.36	8.77
67/45	398.8	4525357.00	646805.00	790.30	319.75	329.80	10.05	67/39	198.2	4524496.00	648213.00	733.75	146.15	179.83	33.68
56/18B	700.0	4525375.00	646596.00	821.98	467.40	470.80	3.40	56/29	387.5	4524334.00	648051.00	796.86	311.73	327.45	15.72
89/25	298.3	4525291.42	646899.54	762.28	272.10	281.90	9.80	89/11	451.8	4524177.35	647953.07	841.47	428.30	439.00	10.70
89/8	279.0	4525267.77	646946.94	750.04	241.40	244.15	2.75	67/37	511.4	4524038.00	648310.00	835.04	418.88	426.96	8.08
55/15	481.1	4525133.00	646969.00	779.05	305.40	319.00	13.60	89/22	361.2	4524150.67	648449.87	775.01	319.00	321.30	2.30
89/9	290.5	4525169.01	647082.86	754.44	253.80	279.20	25.40	67/35	145.4	4524400.00	648685.00	706.11	109.00	114.52	5.52
89/3	256.0	4525155.03	647211.97	733.39	230.70	245.75	15.05	56/28A	445.1	4524120.00	648666.00	842.12	334.36	342.20	7.84
89/4	374.7	4525046.65	647172.03	741.42	335.75	343.80	8.05	67/36	457.0	4523867.00	648665.00	842.73	383.65	389.75	6.10
67/43	565.0	4524933.00	647066.00	797.48	514.08	520.05	5.97	89/19	289.0	4524259.68	648784.70	777.63	257.30	264.70	7.40
55/10A	253.0	4525226.00	647224.00	747.87	165.70	179.90	14.20	89/17	272.0	4524164.21	648951.59	761.35	211.40	224.50	13.10
89/7	322.5	4525054.81	647305.74	727.70	300.00	318.25	18.25	89/23	387.5	4523915.18	648846.57	824.52	340.70	363.50	22.80
55/12	478.5	4524884.00	647292.00	734.29	394.00	404.45	10.45	55/25	404.0	4523980.00	649066.00	786.86	253.00	255.25	2.25
89/1	283.0	4525148.54	647481.37	759.10	260.90	272.07	11.17	67/34	246.0	4524252.00	649076.00	717.43	176.45	189.15	12.70
89/6	359.8	4524993.54	647463.89	728.68	339.85	353.00	13.15	67/34B	133.8	4524108.00	649312.00	726.66	69.76	74.50	4.74
67/42	602.1	4524733.00	647413.00	761.23	547.40	594.85	47.45	93/2	288.0	4525007.73	647718.70	744.18	265.80	281.35	15.55
55/7	308.3	4525136.00	647663.00	755.29	226.25	241.00	14.75	93/3	276.0	4525155.76	647317.76	754.83	252.60	261.20	8.60
89/24	381.0	4524953.89	647574.39	731.60	355.80	372.00	16.20	94/1	332.0	4525058.92	647402.78	734.33	312.2	324.30	12.10
89/5	387.5	4524832.70	647638.75	715.74	346.40	372.10	25.70	94/2	321.2	4524922.00	647694.92	719.62	306.00	313.40	7.40
89/10	505.8	4524604.34	647637.14	780.65	448.30	482.45	34.15								

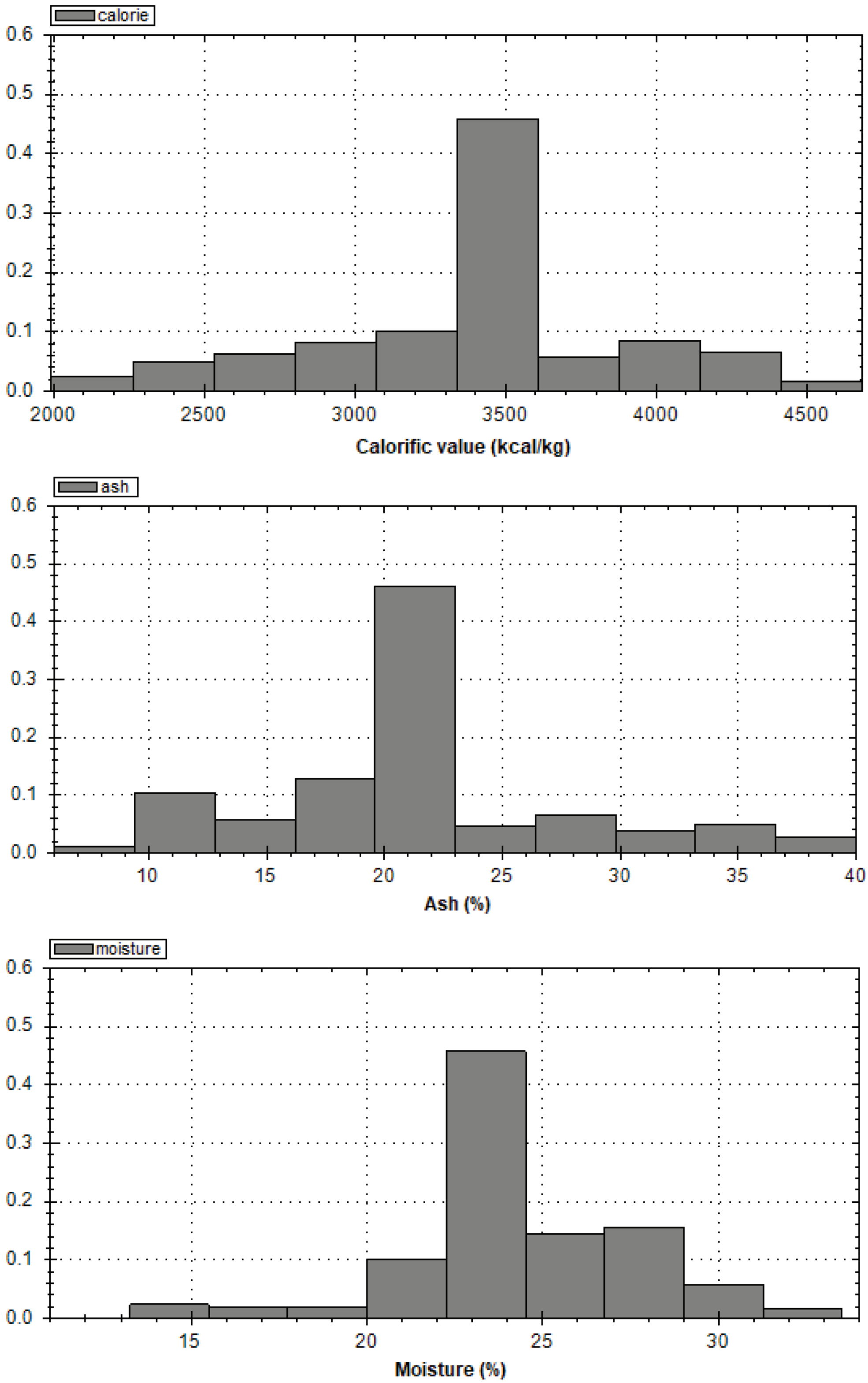


Figure 3. Histograms of coal quality variables.

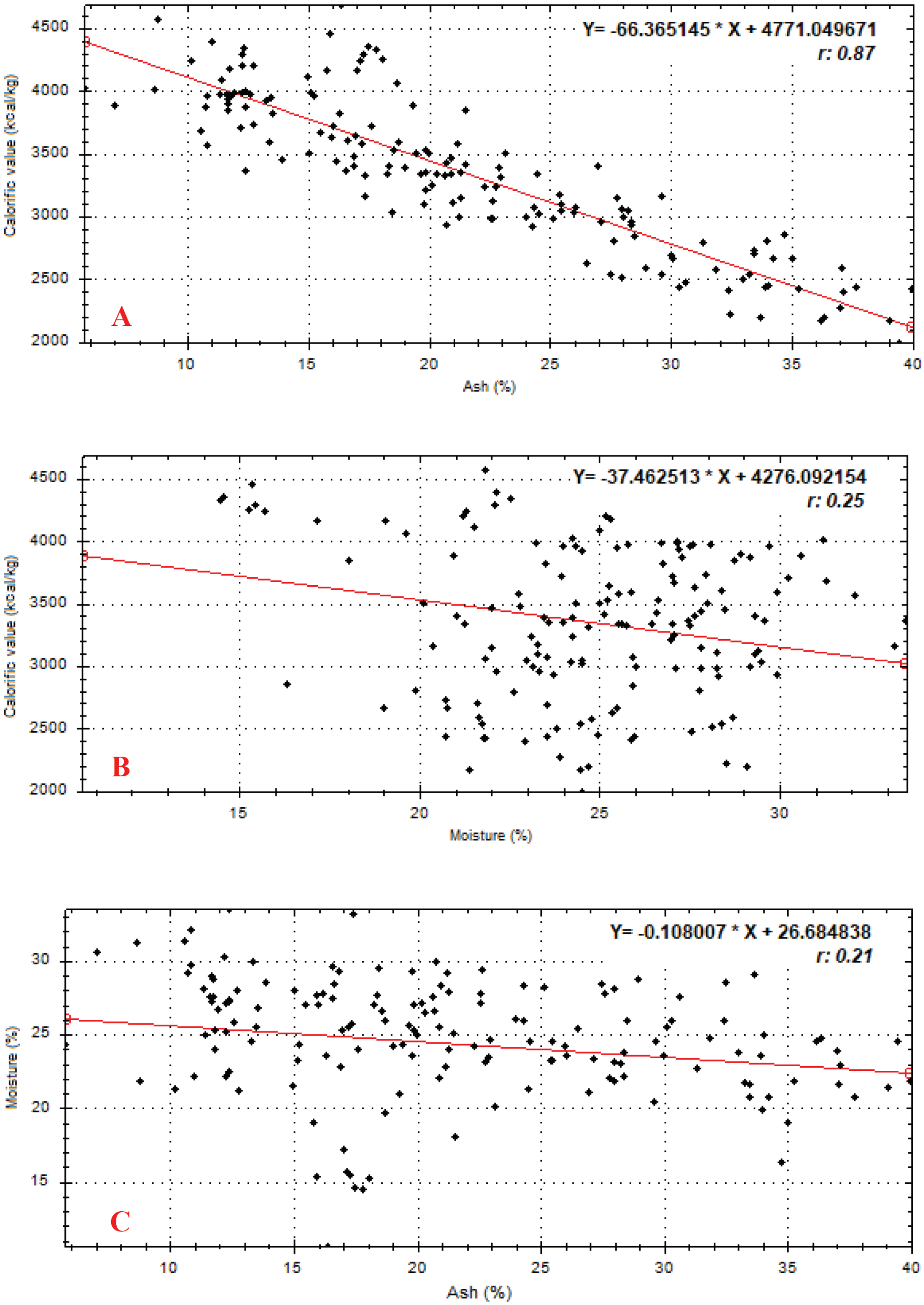


Figure 4. Relationships between coal quality variables: (A) calorific value vs. ash content, (B) calorific value vs. moisture content, (C) moisture content vs. ash content.

Table 2. The summary statistics of coal quality variables.

Variables	Lower calorific value, kcal/kg	Ash content, %	Moisture content, %
Number of data	258	258	258
Maximum value	4685	40	34
Upper quantile	3530	23	26
Median	3350	21	24
Mean	3362	21	24
Lower quantile	3154	17	24
Minimum value	1993	6	11
Variance	244667	40.7	9.6

3.3. Three-dimensional geological solid modeling

Solid models were created with the aid of 156 cross-sections with intervals of 27.31 m obtained with varying strikes from the NS, NE, and SW based on the layering in the field and coal seam distribution (Küçükkarasu and Gül, 2019). The cross-sections of the most appropriate strike were defined with the help of geological reports prepared by MTA in previous years (Kara et al., 1990; Uğur, 1994), isohypse maps, and investigating drill logs were used. The plan of cross-sections are given in Figure 5.

As a result of evaluating sections, as stated in the MTA reports (Kara et al., 1990; Uğur, 1994), the presence of a fault dividing the coal seam into two parts was observed. The coal seam in the modeling area is divided into two main parts by a north-south striking fault with ~55 m vertical slip, so the solid model was created in two parts (Figure 6). The first part is 165–547 m depth from the surface with average depth of 312 m, while the depth of the second part varies from 70 to 470 m depth with an average depth of 265 m. After confirming the fit of the boreholes to the solid model, the solid model volume for the first and second parts of the model were calculated as 12.7×10^6 m^3 and 6.8×10^6 m^3, respectively, for a total solid model volume of 19.5×10^6 m^3 (Küçükkarasu and Gül, 2019).

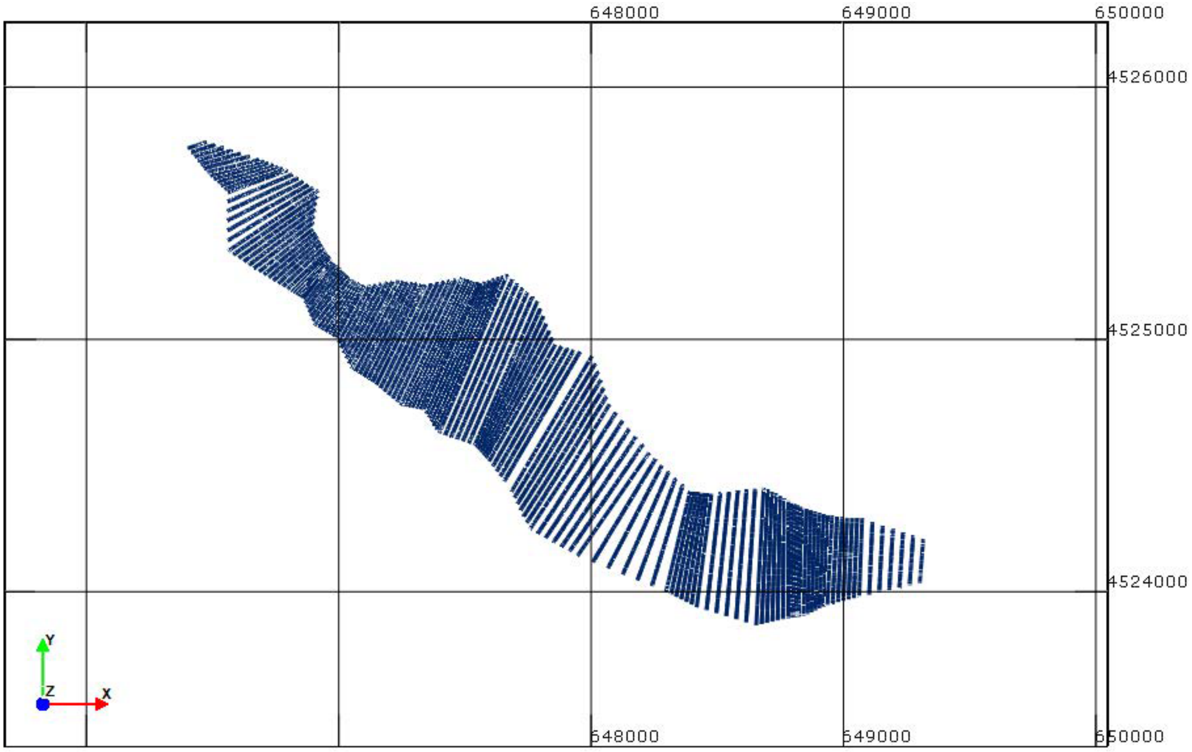


Figure 5. Plan view of the cross-section lines.

3.4. Block model

To represent the variations in coal quality parameters (LCV, AC, and MC), the solid model was divided into small conceptual blocks. When determining the block sizes, factors like data number and quality distribution, geological continuity, mining method, and size of excavation equipment have to be considered (Saydam, 1995; Mert, 2004; Nieto, 2011; Bascetin et al., 2011). It is necessary to determine the block sizes at the edge of the model in optimum shape in accordance with the volume of the solid model. In situations with small block sizes, the sensitivity of the model increases; however, the kriging estimation error reduces. In this framework, different block sizes were evaluated when creating the block model. The maximum block size (X, Y, Z) that will reduce estimation error to a minimum and best represent the solid model was determined as 20 m × 20 m × 10 m. When creating the block model, the block acceptance percentage is taken as 10% and the lower block coefficient is taken as 1. The block model created in accordance with the above conditions is given in Figure 7. The volume of the block model is 19.2 × 10^6 m^3 (Figure 7), with the volume of the block model being slightly lower than the volume of the geologic solid model (19.5 × 10^6 m^3) due to scarcity of data and the irregularity of drill locations.

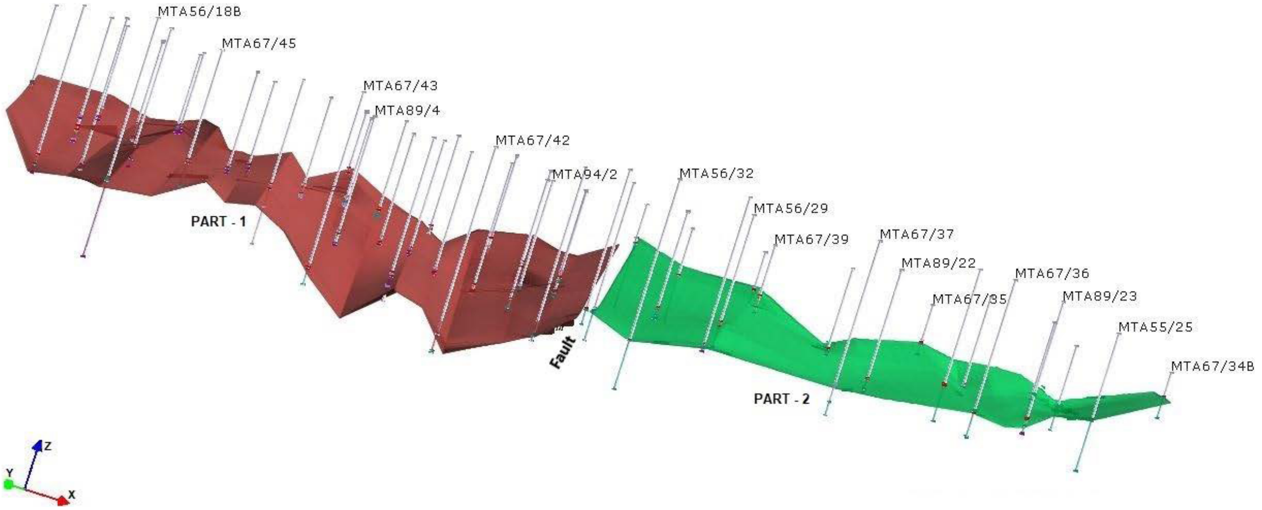
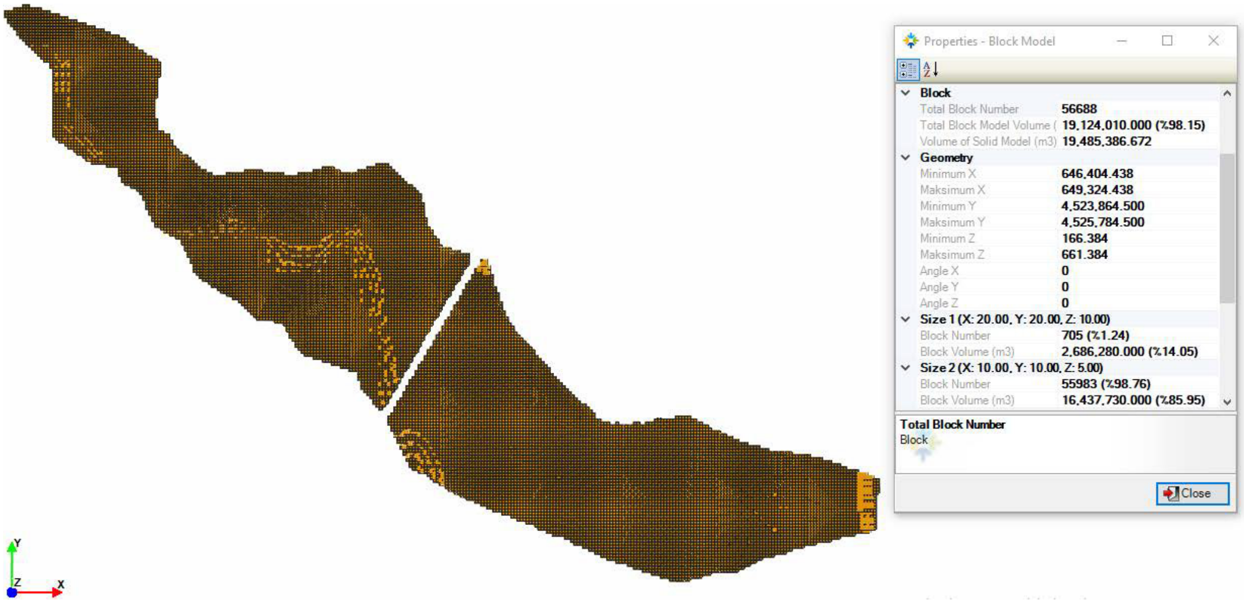


Figure 6. Solid model of the coal seam.



Block	
Total Block Number	56688
Total Block Model Volume (	19,124,010.000 (%98.15)
Volume of Solid Model (m3)	19,485,386.672
Geometry	
Minimum X	646,404.438
Maksimum X	649,324.438
Minimum Y	4,523,864.500
Maksimum Y	4,525,784.500
Minimum Z	166.384
Maksimum Z	661.384
Angle X	0
Angle Y	0
Angle Z	0
Size 1 (X: 20.00, Y: 20.00, Z: 10.00)	
Block Number	705 (%1.24)
Block Volume (m3)	2,686,280.000 (%14.05)
Size 2 (X: 10.00, Y: 10.00, Z: 5.00)	
Block Number	55983 (%98.76)
Block Volume (m3)	16,437,730.000 (%85.95)

Total Block Number
Block

Figure 7. Block model of the coal seam.

3.5. Compositing

As the core samples taken from boreholes do not have equal lengths, the compositing procedure was applied to cores of different lengths to lower the error in resource assessment and estimation of quality variables. Compositing is the procedure for transforming core samples of different lengths into samples of equal length linked to drill logs and seam thickness and ensures the most appropriate geostatistical value assignment to blocks previously created for geological estimation. To determine the composite length, statistical analysis was performed for core sample lengths and the composite length was determined as 3 m (Table 3). Composite data were obtained by dividing the borehole log into intervals of 3 m.

Table 3. Statistic of compositing.

Number of samples	258
Minimum	0.250
Mean	2.966
Median	1.850
Maximum	47.450
Variance	20.768
Standard deviation	4.557
Skewness	6.267

3.6. Variogram analysis

In order to determine variation in coal quality parameters based on distance, experimental variograms were calculated and modeled for each quality parameter (Figure 8). Within the scope of the analysis, quality parameters are grouped in terms of distance and angle tolerance and the oriented (0°, 90°, 45°, 135°) variogram analysis of the variables was performed with the anisotropy test. Generally, the variation in the range (a) of variogram functions according to orientation shows geometric anisotropy, while if the range is fixed and only the sill value (C) changes, it shows zonal anisotropy. The variogram model parameters for the quality variables are given in Table 4. The experimental variograms show that quality variables for the coal bed do not have geometric and zonal anisotropy. Stated differently, the quality variables for the coal bed do not show a tendency or difference within a certain orientation or distance.

In order to determine the correlation between quality variables in samples with each other linked to distance and orientation, a theoretical variogram model was fitted in contrast to the experimental variogram model. It appeared that correlations in horizontal and vertical directions were best represented by the correlations of pairs in a spherical model (Figure 8). The ranges in the horizontal-vertical direction on variogram functions obtained for LCV, AC, and MC were 13–500 m, 12–1000 m, and 18–500 m (Table 4). These values indicated that samples with distances from each other within these limits have a correlation defined by global functions. As a result, the use of estimations for samples at greater distances will increase errors. Within the scope of this study, the kriging estimations were completed according to the global type of theoretical variogram modeling as mentioned above.

3.7. Cross-validation

The accuracy and validity of the models obtained as a result of variogram analysis were tested with the cross-validation technique. Cross-validation deletes 1 true value and uses neighboring parameters and variogram model parameters to estimate that point. At the end of this procedure performed for every point, the true values are compared with the estimated values and the difference between them is stated as mean error. If all estimations coincide with true values, the mean error is zero. As this value approaches zero, it shows that the coincidence of the true values with the estimated values has a high level. The scatter diagrams for true and estimated values for quality variables are given in Figure 9, with mean errors given in Table 5.

As can be seen in Figure 9, the true and estimated values are very close to each other. The mean error percentage for true and estimated values of LCV, AC, and MC were 1.93, 0.84, and 2.51, respectively (Table 5). These results show that the selected variogram models represent the variation in quality parameters linked to distance from the coal bed.

3.8. Kriging estimation of quality parameters

As is known, geostatistics is a separate branch of statistical science developed for geological events used for estimation of mine resource amounts and determination of distributions in the field of data in terms of mine assessment. Estimation is defined as the process of calculating a mean value for an unsampled point or block using available composite data. The value of the point to be estimated is calculated by taking the mean weights for composite data used for estimation.

Using the variogram functions and kriging search ellipsoid parameters determined within the scope of this study, the quality parameters in blocks within the created solid model were estimated with the kriging method (Royle, 1982; Chaoudai and Fytas, 1991; Knotters et al., 2010; Tercan, 2011; Heuvelink, 2014; Bostan, 2017)

4. Spatial distribution of quality parameters

The spatial and proportional distributions of quality parameters in the field were determined from the final block model estimated with the kriging method for quality parameters in each block. Within this scope, each quality parameter (LCV, AC, MC) was thematically mapped with

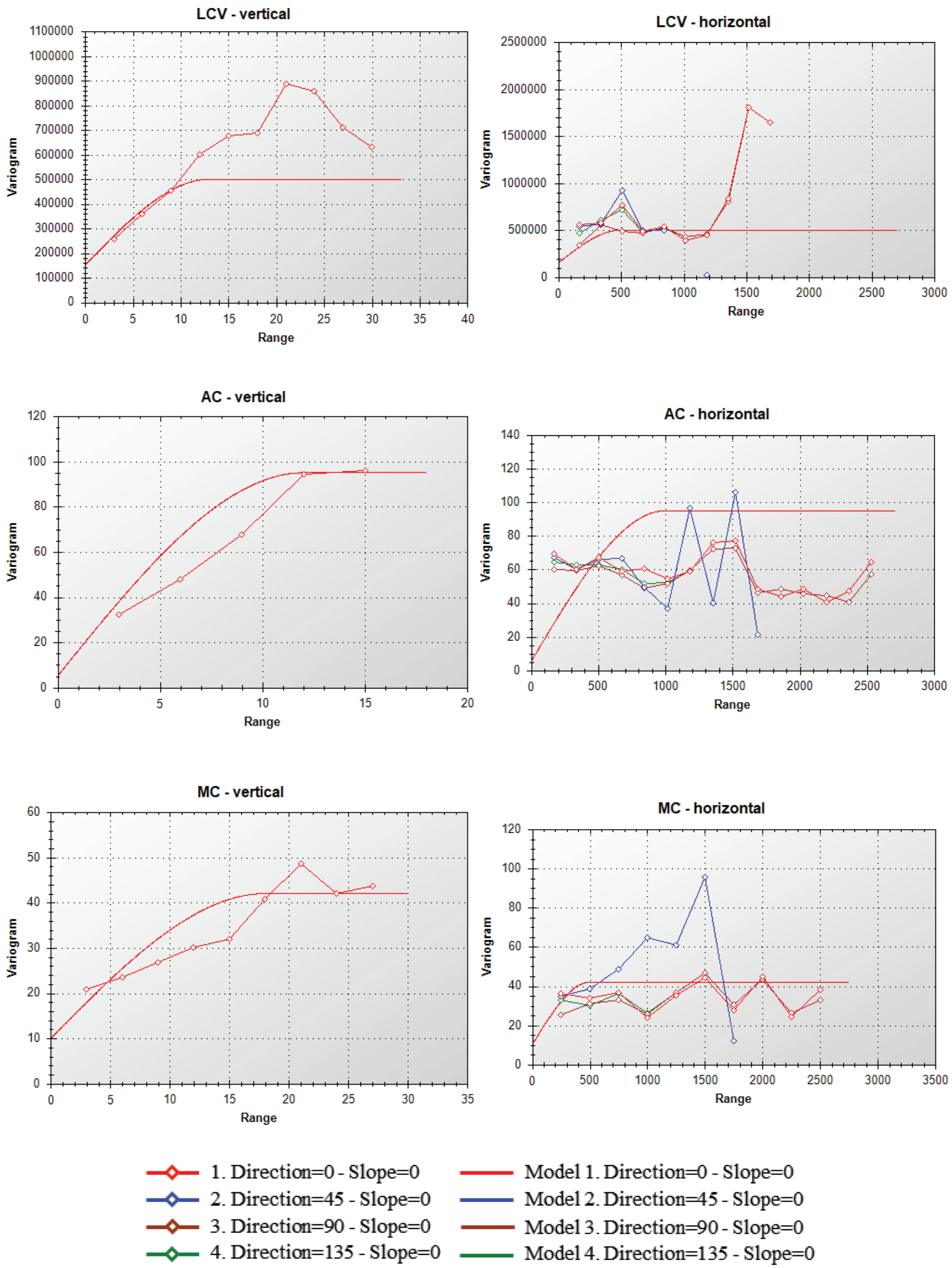


Figure 8. Variogram models of coal quality parameters.

Table 4. Variogram model parameters for quality variables.

Parameters		Lower calorific value, kcal/kg	Ash content, %	Moisture content, %
Nugget effect, C_0		150000	5	10
Sill value, C		350000	90	32
Range, a	Vertical	13	12	18
	Horizontal	500	1000	500
Model		Spherical	Spherical	Spherical

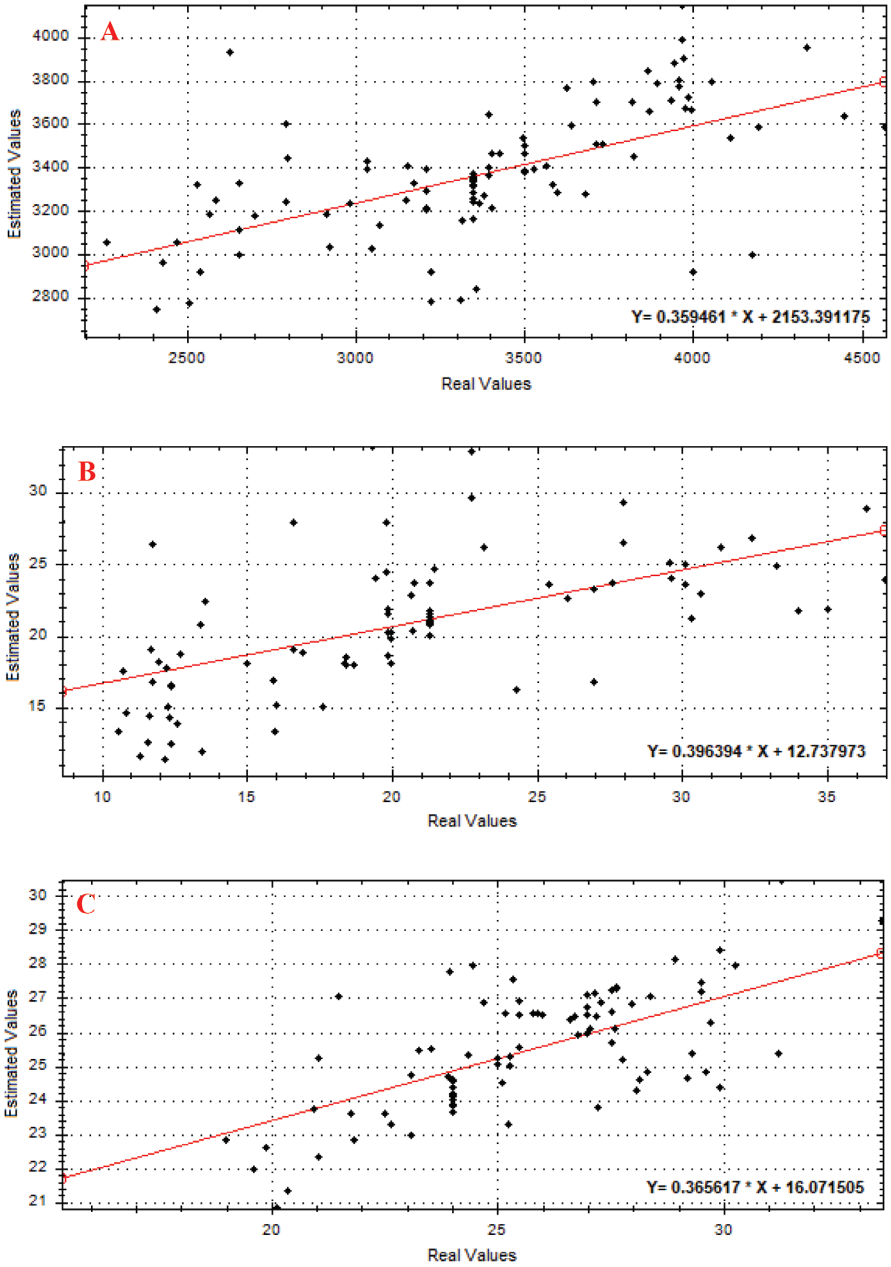


Figure 9. Scatter diagrams of real and estimated values: (A) lower calorific value, (B) ash content, (C) moisture content.

Table 5. Cross-validation results.

Parameters	Mean error value*	Mean error percentage (%)**
Lower calorific value, kcal/kg	64.24	1.93
Ash content, %	0.17	0.84
Moisture content, %	0.63	2.51

* Error value = Real value – Estimated value.
** Error percentage = (Error value / Real value) × 100

different colors representing certain value intervals (Figure 10). Additionally, the resource amounts in the varying value intervals created from the thematic maps were calculated separately for each block model. The resource amounts and proportional percentages calculated for various intervals on the basis of coal quality parameters are given in Table 6.

Figure 10 and Table 6 were evaluated together and the following identifications were made:

- As a result of modeling the mean lower calorific value of the coal resources was 2885.66 kcal/kg, ash content 18.24%, and mean moisture content 20.6%.
- LCV was higher in the north-northwest.
- Of the total 19.1 × 10^6 m^3 coal resources, nearly 65% was changing from 2999 to 3999 kcal/kg.
- Ash distribution was relatively lower in the north-northwest of the field, but showed variability within the area.
- Nearly 55% of the coal resources had ash amounts varying from 19% to 29%.
- Moisture content increased toward the north-northwest of the field and reduced toward the south-southeast.
- Nearly 79% of the coal resource had moisture content varying from 19% to 29%.

5. Conclusions and recommendations

Within the scope of this study, the coal mine in the Alpagut-Dodurga field was modeled in 3 dimensions using Netpro/Mine mining software and coal resources were estimated. Additionally, the spatial distribution and proportions of coal quality parameters (LCV, AC, and MC) were determined and also thematic maps were created. The results of the study are summarized as given below.

i. Characteristic features of quality variables were determined using descriptive statistical values from drill data. According to data analysis, the mean LCV, AC, and MC were 3350 kcal/kg, 21%, and 24%, respectively.

ii. The result of a variety of block size trials determined that the maximum block size with low estimation error and best representing the field was 20 m × 20 m × 10 m and a block model was created accordingly.

iii. With the aim of identifying the variation of the coal seam in the field and how each quality parameter varies linked to distance, horizontally and vertically (four orientations of 0°, 45°, 90°, and 135°) oriented variogram analyses were performed. The results of this analysis did not indicate geometric or zonal anisotropy.

iv. The performance of models and parameters obtained from variogram analyses were tested with cross-validation. The test results of mean error percentages were found as 1.93%, 0.84%, and 2.51% for LCV, AC, and MC, respectively. These results showed that the variogram model and parameters represent the quality variation linked to distance from the coal bed.

v. Using the reliability-tested variogram parameters, the quality parameters for each block in the coal block model were estimated with the kriging method.

vi. The coal resource amount estimated from the block model results was 19.1 × 10^6 m^3. The coal bed was determined to have mean LCV of 2885 kcal/kg, AC of 18.24%, and MC of 20.6%. These values are lower than the geologic solid model resource amount (19.5 × 10^6 m^3) and the drill sampling histogram analysis results (LCV: 3350 kcal/kg, AC: 21%, MC: 24%), as expected. This situation is due to the scarcity of data and irregularity of drill locations and is linked to the limitations of the block model created by the program. Calculations did not include blocks where quality parameters could not be estimated. Additionally, the other numerical sizes and identifications determined according to the final model of the coal bed are given below:

- LCV was higher in the north-northwest. Nearly 65% of the total 19.1 × 10^6 m^3 coal resources was varying from 2999 to 3999 kcal/kg.
- The ash distribution was relatively lower in the north-northwest of the field, but it showed variability in the field. Nearly 55% of the coal resources had ash contents varying from 19% to 29%.
- The moisture content increased toward the north-northwest and reduced toward the south-southeast. Nearly 79% of the coal resources had moisture contents varying from 19% to 29%.

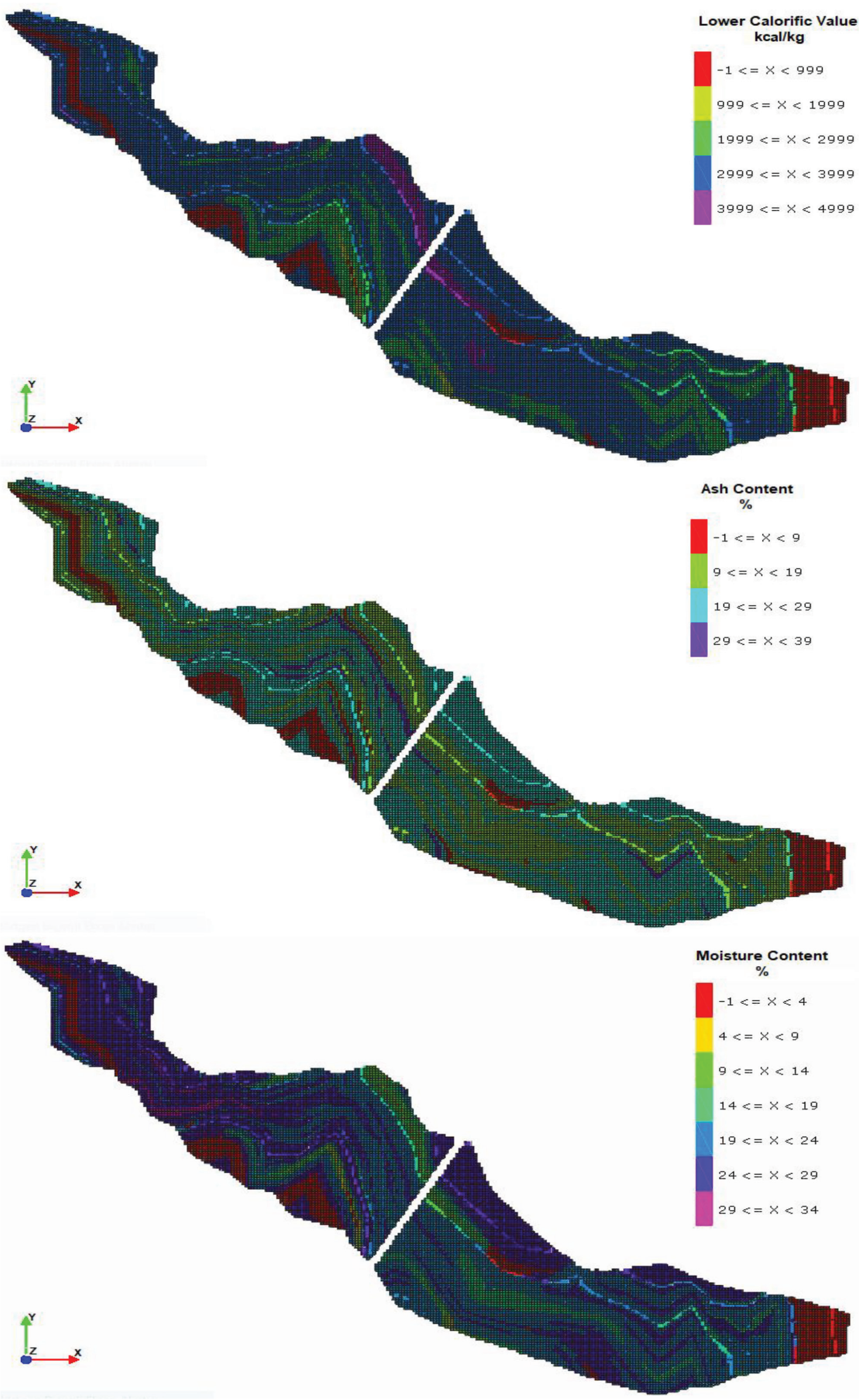


Figure 10. Spatial distribution maps of coal quality parameters.

Table 6. Distribution of coal quality variables.

Parameters	From (≤)	To (>)	Volume (m^3)	Tonnage (t)*	Number of blocks	Volume (%)	Average grade
Lower calorific value (kcal/kg)	–1	999	1,997,850	2,796,990	5737	10.45	2885.66
	999	1999	204,070	285,698	481	1.07	
	1999	2999	3,980,160	5,572,224	10,609	20.81	
	2999	3999	12,352,790	17,293,906	37,962	64.59	
	3999	4999	589,140	824,796	1899	3.08	
	Total		19,124,010	26,773,614	56,688		
Ash content (%)	–1	9	2,223,880	3,113,432	6302	11.63	18.24
	9	19	5,708,590	7,992,026	17,752	29.85	
	19	29	10,567,775	14,794,885	30,890	55.26	
	29	39	623,765	873,271	1744	3.26	
	Total		19,124,010	26,773,614	56,688		
Moisture content (%)	–1	9	2,131,750	2,984,450	6021	11.15	20.6
	9	19	1,674,555	2,344,377	5010	8.76	
	19	29	15,024,990	21,034,986	44,844	78.57	
	29	39	292,715	409,801	813	1.53	
	Total		19,124,010	26,773,614	56,688		

* Coal density: 1.4 g/cm^3 (Kara et al., 1990).

Considering the created geological model as a result of this study, it is beneficial to drill new boreholes in NE and/or SW directions as a priority with the aim of developing resource. Risks related to production should be reduced to acceptable levels by carefully modeling both coal geometry in three dimensions and parameters related to coal quality. Taking into account the block model and quality parameters, production plans can be created and applied more rapidly and efficiently.

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