Why One Dimension is Not Enough – A Comparative Study of Lignite Resources Estimation Using Drillhole Mineable Lignite Compositing of Uncorrelated Seams and Mineable Lignite Compositing of Correlated Lignite Seams

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ABSTRACT

Lignite deposits in Greece of the type consisting of multiple thin lignite layers are traditionally estimated using a one-dimensional compositing approach that suffers from large error margins particularly in the presence of medium to large tectonism and uneven vertical distribution of lignite seams. Each drillhole is evaluated using mining and processing criteria leading to a number of mineable lignite “packages”, the sum of which is reported as the total mineable lignite at the drillhole horizontal location. The total minable lignite values from the various drillholes are interpolated horizontally leading to a two-dimensional model of the mineable lignite parameter. A more advanced version of this one-dimensional approach has been applied with improved results in the past. In this version, the one-dimensional approach was limited to a single mine bench and repeated separately for each bench, thus reducing the scale of potential errors and better approaching the vertical distribution of mineable lignite. In effect, each bench was approached as an isolated lignite “deposit”, reducing the effects of applying a one-dimensional approach to a 3D modelling problem but not making them completely disappear. Lignite deposits, such as the one examined in this paper, require the development of a thorough stratigraphic model to allow the reporting of accurate lignite resources and form the basis for solid mine planning and lignite reserves calculation. The evaluation of mineable lignite using mining and processing criteria can then be applied to modelled raw lignite seams leading to an overall three-dimensional model of the deposit that allows accurate lignite resources calculation even in the presence of tectonism. This paper presents all three modelling approaches through an extensive case study based on part of a real lignite deposit. The effects of using each of the approaches are analysed and the benefits of the three-dimensional approach are clearly demonstrated.

1 INTRODUCTION

1.1 The Modelling Problem and Solution Approaches

Thin layered lignite deposits (known as Zebra deposits) are commonly modelled using a one-dimensional compositing approach that suffers from large error margins particularly in the presence of medium to large tectonism and uneven vertical distribution of lignite seams. Each drillhole is composited using mining and quality criteria forming mineable lignite sections, the sum of which is reported as the total mineable lignite at the drillhole horizontal location. The total minable lignite values from the various drillholes are interpolated horizontally leading to a two-dimensional grid model of the mineable lignite parameter. This approach, even though capable of calculating global lignite resources with acceptable accuracy provided a high sample density, it is particularly prone to errors in calculating local lignite resources which are necessary for effectively planning and scheduling a continuous mining process. Another issue with this approach, is the sensitivity of the results to potentially incomplete or incorrectly interpreted drillholes that due to the one-dimensional nature of the modelling process can lead to significant errors in the local resource estimates. All this uncertainty has led to the use and experimentation with various interpolation algorithms like inverse distance and kriging and their parameters, in an effort to improve on the estimates produced by bringing the local estimate closer to the single value reported by the closest composited drillhole – but the real problem lies in what happens between drillholes.

Lignite deposits, such as the one examined in this paper, require the development of a thorough stratigraphic model to allow the reporting of accurate lignite resources and form the basis for solid mine planning and lignite reserves calculation. Such a stratigraphic model requires the painful but irreplaceable step of seam correlation in sections and plans before any compositing of mineable lignite takes place. The evaluation of mineable lignite using mining and processing criteria can then be applied to modelled raw lignite seams leading to an overall three-dimensional model of the deposit that allows accurate lignite resources calculation even in the presence of tectonism. This paper presents all three modelling approaches through an extensive case study based on part of a real lignite deposit. The effects of using each of the approaches are analysed and the benefits of the three-dimensional approach are clearly demonstrated.

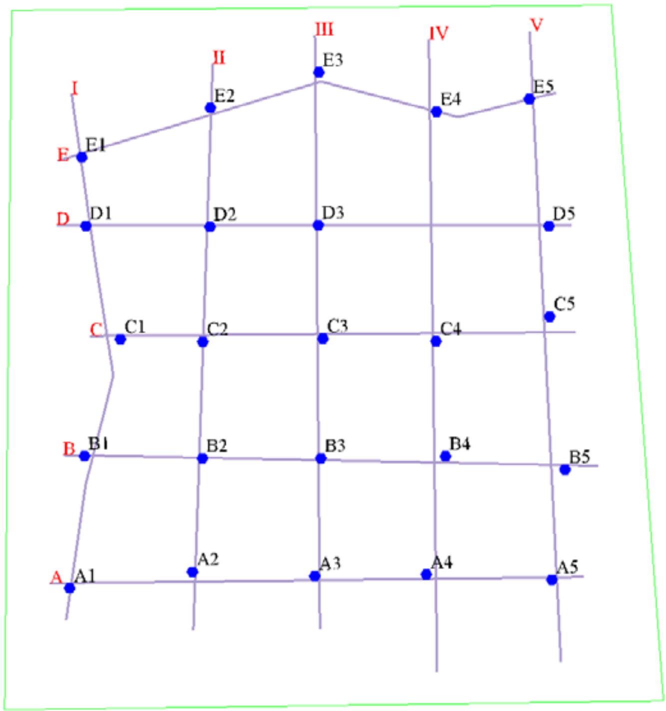

Figure 1. Location and naming of drillholes and sections used in the study.

1.2 Example Dataset

Data used to compare the lignite resource modelling approaches in this paper come from an exhausted lignite mine in NW Greece. A small area of the mine was selected and a total of 24 drillholes on a random grid of 5x5 (Figure 1). The model limits cover an area of 1.32km^2. The names and coordinates of the drillholes were changed for confidentiality purposes. The area topography was not used in the study for the same reason – the drillhole collar was taken as the top of overburden (excluding drillhole C5). Reported resources were limited only by the study area polygon – no pit surface was used in the study. Figure 1 shows the drillhole collar locations in plan view. Drillholes were named after their row and column number which correspond to the section names. For example, drillhole A1 appears in Section A and Section I. The 24 drillholes contained a total of 2,950 original (raw) intervals. The dataset was imported and validated in Maptek Vulcan.

2 ONE-DIMENSIONAL COMPOSITING OF TOTAL DRILLHOLE MINEABLE LIGNITE INTERVALS

2.1 Method Analysis

The method to composite drillhole mineable intervals described in this section is very similar to the one applied in Greek lignite deposits [1]. The method used in this paper is using the corresponding mineable intervals option in Maptek Vulcan software plus some extra steps before and after applying this option to make it more suitable for lignite seams. A comparative study has been performed in the past to prove the similarity of the results produced by this approach and the software traditionally used for compositing of Greek lignite deposits [2]. The method is applied using the following steps:

- **Pass 1:** The program looks at samples down the hole and classifies each sample as lignite or waste based on the ash cutoff value specified.
- **Pass 2:** The program combines adjacent samples of lignite and waste to produce runs of pure lignite and pure waste.
- **Pass 3:** Working from the top of the hole down, the program checks if the waste interval between the first lignite run and the subsequent lignite run is shorter than the waste absorption maximum length. If the waste length is longer than this limit, then the lignite runs are left as separate composites and the waste length from the second lignite run to the third is checked. If the waste length is shorter than the limit, then the first lignite run, the waste run and the second lignite run are added together, and the resulting ash value is computed. If the ash value is higher than the lignite/waste cutoff value, then the lignite and waste runs are left as individual composites and the process moves onto the second and third lignite runs. If the resulting ash value is lower that lignite/waste cutoff value, then the interval is accepted as a single lignite composite. The waste length between this new lignite composite and the subsequent lignite run is then checked, and the process described above is repeated.
- **Pass 4:** At this stage there are lignite runs that incorporate internal waste where possible and whose ash value is below the lignite/waste cutoff value. The procedure continues then to add upper and lower waste dilution to these lignite runs. It will add adjacent waste samples up to a dilution length specified. It should be noted that this step will not disqualify any lignite runs. Roof and floor losses area applied to lignite intervals and respective gains to waste intervals.
- **Pass 5:** The final pass checks all resulting lignite runs to see if they are longer than the minimum lignite run length. Lignite runs that are shorter than this limit, are reclassified as waste and absorbed into the surrounding waste runs. All quality calculations are length weighted.

Figure 2 shows a simplified example of the input (raw) and output (composited) version of a drillhole using the mineable intervals compositing method. Lignite and waste raw intervals are combined to form mineable lignite or waste composited intervals based on criteria such as minimum lignite thickness, maximum waste absorption thickness, mineable lignite ash upper limit (cutoff) and mineable lignite roof and floor losses and dilution.

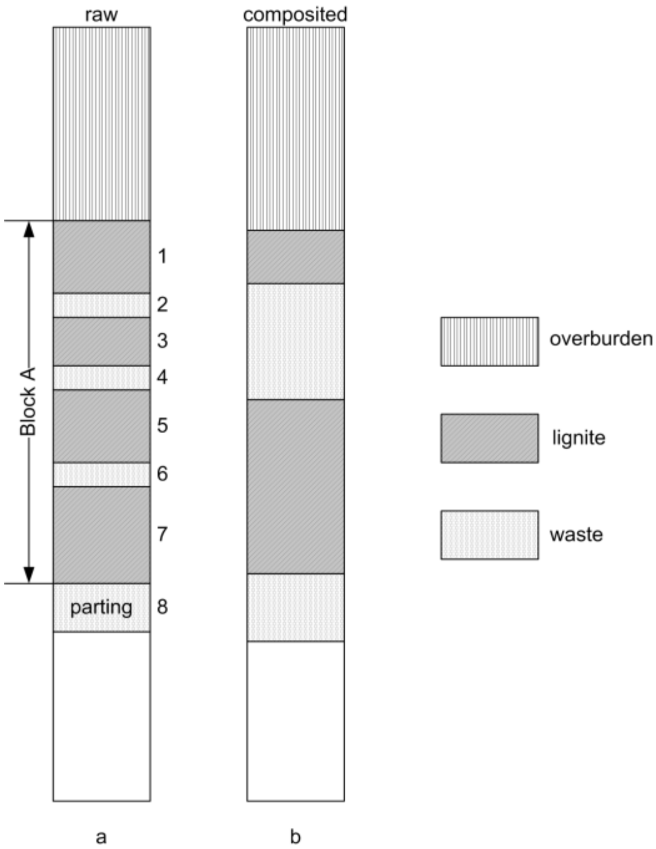

Figure 2. Simplified example of raw lignite and waste intervals (a) and composited mineable lignite and waste intervals (b).

2.2 Compositing

Applying this method to the 24 drillholes of the example dataset led to the generation of 1,016 composited mineable intervals of lignite and waste from the 2,950 raw intervals. The generated composites table was added to the original drillhole database. Figure 3 presents the output of each of the five passes of the mineable intervals compositing method on part of a drillhole from the dataset. Lignite intervals at each pass are coded as CO. Waste horizons are coded as WASTE after the first pass. Only part of the drillhole is shown due to space limitations. The total length (thickness) of mineable lignite per drillhole was calculated next. This was stored together with other information such as the top and bottom depth of mineable lignite in a formatted text file. The file contained information on the thickness and depths of overburden and midburden. These files were used to calculate and locate lignite resources within the study area limits. A 0.5m minimum mineable lignite thickness and 0.3m waste thickness was applied. The maximum ash content for lignite was set to 36% and the roof and floor losses for lignite were 0.1m.

2.3 Resource Modelling

Using the information contained in the formatted text files for the thickness, roof and floor of the mineable lignite and the corresponding values for overburden and midburden, grid models were generated using the inverse distance weighting method. The power of 1 for inverse distance was used for the roof and floor models, while the power of 2 was used to model thicknesses. Figure 4 shows section C – the overburden is clearly displayed as a single layer, while lignite and midburden are shown together. The absence of seam correlation means that it is not possible to display (and model) lignite seams as separate layers in section.

Original

Litho	Length	Ash
AL	3.70	100.00
CO	0.50	46.50
MR	0.60	100.00
AL	2.40	100.00
AL	0.60	100.00
CO	0.60	38.50
MR	0.80	100.00
CO	0.60	45.10
AL	1.00	100.00
MR	0.90	100.00
CO	0.40	36.20
MR	0.50	100.00
CO	1.20	30.90
MR	2.60	100.00
CO	0.40	35.80
CO	1.70	25.20
MR	0.70	100.00
CO	0.60	23.00
CO	0.60	22.70
MR	0.50	100.00
CO	1.40	36.00
MR	0.50	100.00
CO	1.60	40.90
MR	1.00	100.00
CO	0.40	40.60
AL	0.90	100.00
CO	1.30	34.40
MR	0.30	100.00
CO	0.50	35.90
CO	1.00	25.30
MR	1.30	100.00
MR	6.10	100.00
CO	0.60	23.30
MR	0.50	100.00
CO	0.50	28.60
CO	0.80	27.60
CO	1.20	39.60
CO	1.20	33.50
MR	0.40	100.00
CO	1.40	22.70
CO	0.20	17.80
MR	0.20	100.00
CO	0.25	18.00
MR	0.75	100.00
CO	0.80	21.20
CO	0.80	32.90
CO	0.40	25.80
MR	0.20	100.00

Pass 1

Litho	Length	Ash
WASTE	3.70	100.00
WASTE	0.50	46.50
WASTE	0.60	100.00
WASTE	2.40	100.00
WASTE	0.60	100.00
WASTE	0.60	38.50
WASTE	0.80	100.00
WASTE	0.60	45.10
WASTE	1.00	100.00
WASTE	0.90	100.00
WASTE	0.40	36.20
WASTE	0.50	100.00
CO	1.20	30.90
WASTE	2.60	100.00
CO	0.40	35.80
CO	1.70	25.20
WASTE	0.70	100.00
CO	0.60	23.00
CO	0.60	22.70
WASTE	0.50	100.00
WASTE	1.40	36.00
WASTE	0.50	100.00
WASTE	1.60	40.90
WASTE	1.00	100.00
WASTE	0.40	40.60
WASTE	0.90	100.00
CO	1.30	34.40
WASTE	0.30	100.00
CO	0.50	35.90
CO	1.00	25.30
WASTE	1.30	100.00
WASTE	6.10	100.00
CO	0.60	23.30
WASTE	0.50	100.00
CO	0.50	28.60
CO	0.80	27.60
WASTE	1.20	39.60
CO	1.20	33.50
WASTE	0.40	100.00
CO	1.40	22.70
CO	0.20	17.80
WASTE	0.20	100.00
CO	0.25	18.00
WASTE	0.75	100.00
CO	0.80	21.20
CO	0.80	32.90
CO	0.40	25.80
WASTE	0.20	100.00

Pass 2

Litho	Length	Ash
WASTE	12.60	100.00
CO	1.20	30.90
WASTE	2.60	100.00
CO	2.10	27.22
WASTE	0.70	100.00
CO	1.20	9.90
WASTE	6.30	100.00
CO	1.30	34.40
WASTE	0.30	100.00
CO	1.50	28.83
WASTE	7.40	100.00
CO	0.60	23.30
WASTE	0.50	100.00
CO	1.30	27.98
WASTE	1.20	39.60
CO	1.20	33.50
WASTE	0.40	100.00
CO	1.60	22.09
WASTE	0.20	100.00
CO	0.25	18.00
WASTE	0.75	100.00
CO	2.00	26.80
WASTE	0.20	100.00

Pass 3

Litho	Length	Ash
WASTE	12.60	100.00
CO	1.20	30.90
WASTE	2.60	100.00
CO	2.10	27.22
WASTE	0.70	100.00
CO	1.20	9.90
WASTE	6.30	100.00
CO	1.30	34.40
WASTE	0.30	100.00
CO	1.50	28.83
WASTE	7.40	100.00
CO	0.60	23.30
WASTE	0.50	100.00
CO	1.30	27.98
WASTE	1.20	39.60
CO	1.20	33.50
WASTE	0.40	100.00
CO	2.05	29.19024
WASTE	0.75	100.00
CO	2.20	26.80
WASTE	0.2	100

Pass 4

Litho	Length	Ash
WASTE	12.70	100.00
CO	1.00	30.90
WASTE	2.80	100.00
CO	1.90	27.22
WASTE	0.90	100.00
CO	1.00	9.90
WASTE	6.50	100.00
CO	1.10	34.40
WASTE	0.50	100.00
CO	1.30	28.83
WASTE	7.60	100.00
CO	0.40	23.30
WASTE	0.70	100.00
CO	1.10	27.98
WASTE	1.40	39.60
CO	1.00	33.50
WASTE	0.60	100.00
CO	1.85	29.19
WASTE	0.95	100.00
CO	2.00	26.80
WASTE	0.30	100.00

Pass 5

Litho	Length	Ash
WASTE	12.70	100.00
CO	1.00	30.90
WASTE	2.80	100.00
CO	1.90	27.22
WASTE	0.90	100.00
CO	1.00	9.90
WASTE	6.50	100.00
CO	1.10	34.40
WASTE	0.50	100.00
CO	1.30	28.83
WASTE	8.70	100.00
CO	1.10	27.98
WASTE	1.40	39.60
CO	1.00	33.50
WASTE	0.60	100.00
CO	1.85	29.19
WASTE	0.95	100.00
CO	2.00	26.80
WASTE	0.30	100.00

Figure 3. Example of drillhole composited with the 5-pass mineable interval compositing method – interval type changes from one pass to another are shown in light green and interval length changes in light blue.

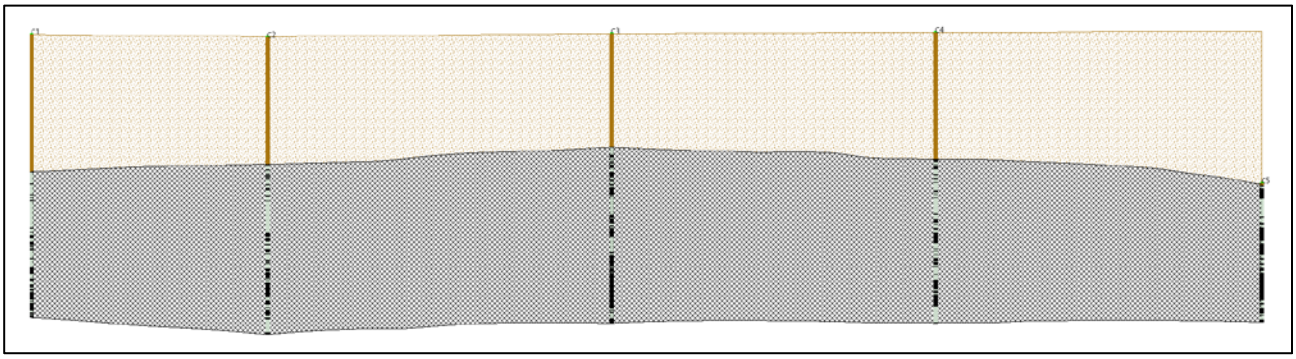

Figure 4. Section C showing composited drillholes and modelled overburden (brown), lignite roof and floor surfaces (black). Drillhole C5 is not used for the modelling of overburden roof and thickness.

As lignite seams are not correlated, we rely on the total mineable lignite thickness model for resource estimation. Stripping ratio is also calculated using the total overburden and midburden thickness models. Calculating lignite resources per bench is based on the total mineable midburden/lignite ratio and the thickness of their sum (lignite plus midburden) inside each bench. The same midburden/lignite ratio is effectively applied to all benches, with the only possibly varying parameter being the thickness of the mineable lignite plus midburden. For benches being totally enclosed in the area between the roof and floor of mineable lignite, this parameter is constant, leading to equal resources being reported in these benches.

3 ONE-DIMENSIONAL COMPOSITING OF DRILLHOLE MINEABLE LIGNITE INTERVALS PER BENCH

3.1 Method Analysis

The second approach considered is based on the 5-pass compositing method discussed in the previous section but adds an extra pass where the produced lignite and waste composite intervals are split and coded based on surfaces corresponding to mining benches (Figure 5). The height of the benches can be constant or different between benches, and essentially controls the vertical resolution of the calculation. As the interval splitting takes place after any quality and thickness-based classification to lignite or waste, the added sixth pass does not reduce the total mineable lignite of a drillhole produced by the previous method. It simply distributes the mineable lignite and waste to separate benches allowing the more accurate calculation of resources per bench. Mineable lignite or waste composite intervals vertically crossing the floor of a bench are split in two components, each coded according to the bench volume they belong to (e.g. CO560, CO570, etc.). This approach was used in the lignite resources estimation and mine planning study of the South Western Field (Public Power Corporation of Greece) in 2009 [3].

3.2 Compositing

The 1,016 mineable lignite and waste composite intervals from the previous method were intersected with bench surfaces every 10m vertically (pass 6). This led to the generation of 1,404 new composites that were stored in a separate table of the database. Figure 6 shows how this was done on the same part of the drillhole presented in Figure 3.

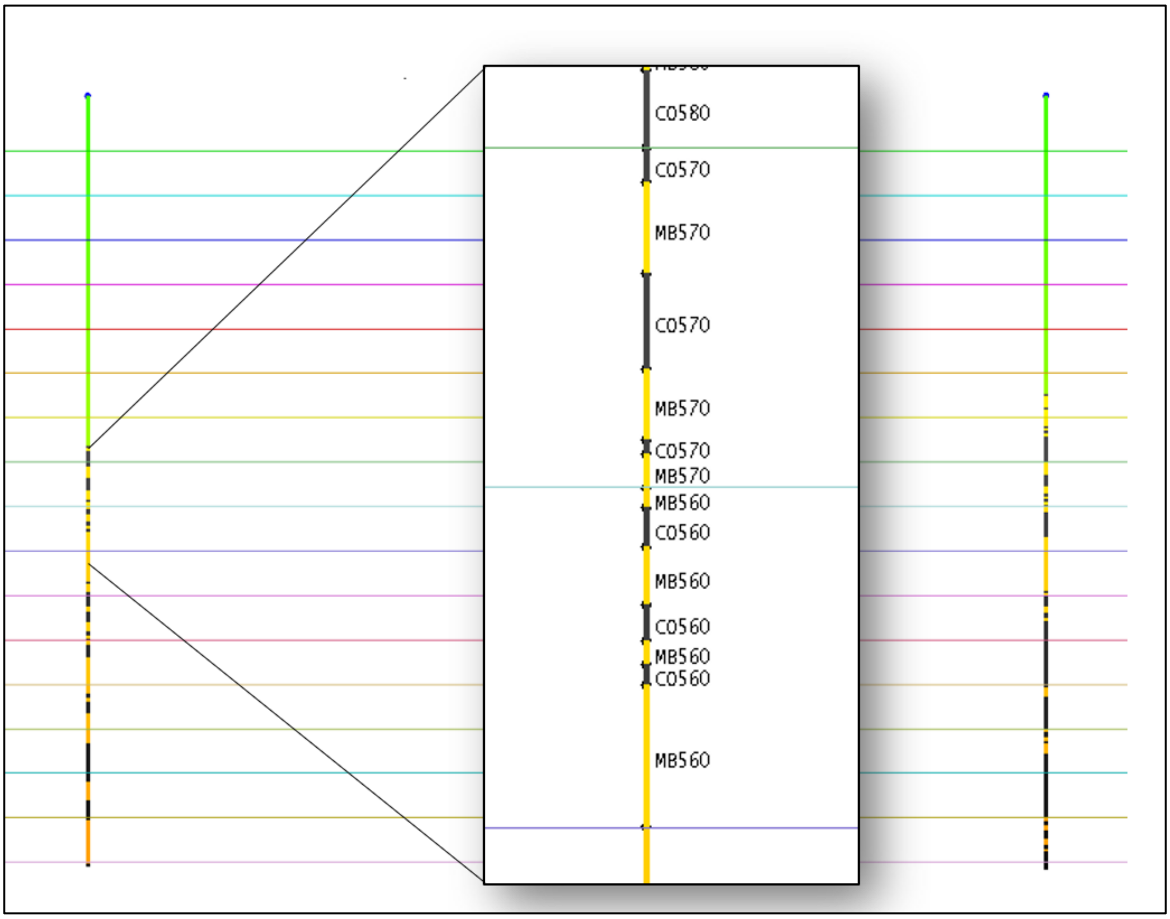

Figure 5. Splitting and coding of mineable lignite and waste intervals per bench.

The total length (thickness) of mineable lignite per drillhole and bench was calculated next. This was stored together with other information such as the top and bottom depth of mineable lignite inside each bench in separate formatted text files – one per bench. The files contained information on the thickness and depths of overburden and midburden in each bench. These files were used to calculate and locate lignite resources within the study area limits for each bench.

3.3 Resource Modelling

The same process followed in the previous method, was applied in the case of mineable lignite composites per bench. The formatted text files were used to generate grid models of the roof, floor and thickness of mineable lignite, overburden and midburden. This time, there were several models corresponding to the different benches, and resources were calculated per bench using the composited mineable thicknesses per bench. There was no need to use the waste to lignite ratio to calculate resources per bench, as the mineable overburden, midburden and lignite thicknesses were calculated directly for each bench using values related to each bench.

The horizontal extents of mineable lignite in each bench had to be considered during modelling. Vertical variations in lignite density meant that not all drillholes contained mineable lignite in each bench. This was addressed by applying polygonal masks to the grid models, limiting their horizontal extents as shown in Figure 7.

Original

Litho	Length	Ash
AL	3.70	100.00
CO	0.50	46.50
MR	0.60	100.00
AL	2.40	100.00
AL	0.60	100.00
CO	0.60	38.50
MR	0.80	100.00
CO	0.60	45.10
AL	1.00	100.00
MR	0.90	100.00
CO	0.40	36.20
MR	0.50	100.00
CO	1.20	30.90
MR	2.60	100.00
CO	0.40	35.80
CO	1.70	25.20
MR	0.70	100.00
CO	0.60	23.00
CO	0.60	22.70
MR	0.50	100.00
CO	1.40	36.00
MR	0.50	100.00
CO	1.60	40.90
MR	1.00	100.00
CO	0.40	40.60
AL	0.90	100.00
CO	1.30	34.40
MR	0.30	100.00
CO	0.50	35.90
CO	1.00	25.30
MR	1.30	100.00
MR	6.10	100.00
CO	0.60	23.30
MR	0.50	100.00
CO	0.50	28.60
CO	0.80	27.60
CO	1.20	39.60
CO	1.20	33.50
MR	0.40	100.00
CO	1.40	22.70
CO	0.20	17.80
MR	0.20	100.00
CO	0.25	18.00
MR	0.75	100.00
CO	0.80	21.20
CO	0.80	32.90
CO	0.40	25.80
MR	0.20	100.00

Pass 5

Litho	Length	Ash
WASTE	12.70	100.00
CO	1.00	30.90
WASTE	2.80	100.00
CO	1.90	27.22
WASTE	0.90	100.00
CO	1.00	9.90
WASTE	6.50	100.00
CO	1.10	34.40
WASTE	0.50	100.00
CO	1.30	28.83
WASTE	8.70	100.00
CO	1.10	27.98
WASTE	1.40	39.60
CO	1.00	33.50
WASTE	0.60	100.00
CO	1.85	29.19
WASTE	0.95	100.00
CO	2.00	26.80
WASTE	0.30	100.00

Pass 6

	Litho	Length	Ash
BENCH 570	WASTE 570	10.00	100.00
BENCH 560	WASTE 560	2.70	100.00
	CO 560	1.00	30.90
	WASTE 560	2.80	100.00
	CO 560	1.90	27.22
	WASTE 560	0.90	100.00
	CO 560	0.70	9.90
BENCH 550	CO 550	0.30	9.90
	WASTE 550	6.50	100.00
	CO 550	1.10	34.40
	WASTE 550	0.50	100.00
	CO 550	1.30	28.83
	WASTE 550	0.30	100.00
BENCH 540	WASTE 540	8.40	100.00
	CO 540	1.10	27.98
	WASTE 540	0.50	39.60
BENCH 530	WASTE 530	0.90	39.60
	CO 530	1.00	33.50
	WASTE 530	0.60	100.00
	CO 530	1.85	29.19
	WASTE 530	0.95	100.00
	CO 530	2.00	26.80
	WASTE 530	0.30	100.00

Figure 6. Example of drillhole composited with the 6-pass mineable interval per bench compositing method. In pass 6, the evaluated intervals or split and coded using bench surfaces.

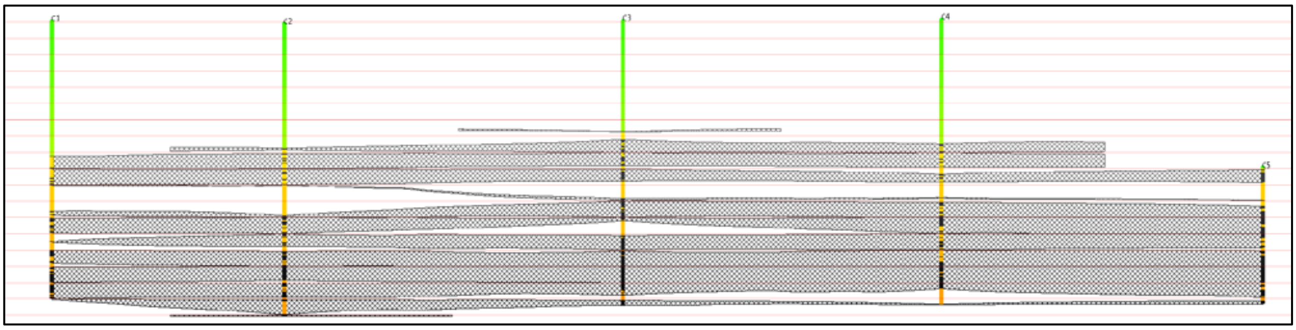

Figure 7. Section C showing composited drillhole intervals per bench and modelled mineable lignite roof and floor surfaces per bench (black).

4 THREE-DIMENSIONAL MINEABLE LIGNITE COMPOSITING OF CORRELATED LIGNITE SEAMS

4.1 Lignite Seam Correlation

The last method considered in our study was based on the geological analysis, correlation and modelling of the original (raw) lignite seams. The lignite seams were examined in cross sections and were manually correlated by selecting the drillhole intervals considered to belong to a particular seam and coding an appropriate seam field in the database. This was a fairly difficult and time-consuming process, the results of which were based to some degree on the geologist's interpretation. Figure 8 shows a drillhole section with the seam correlation stored in the database. This type of section helps to visualise the way correlation works before actual modelling of the seams. The software automatically links intervals with the same seam code between successive drillholes in a linear fashion aiding the user during correlation. A colour legend helps distinguish between seams as in our case there were so many that the section would become very confusing to the eye. Linking of correlated seams is not allowed through drillholes that don't contain them. Two characteristic marl horizons were used to group the lignite layers in upper and lower horizons. Upper horizons were numbered upwards (lowest one being U1) and lower horizons were named downwards (top one being L1). There was no particular reason for this convention other than the need to have a standard convention between drillholes. Horizon splits were named after the merging horizon, e.g. splits U8A, U8B and U8C merge to U8 (Table 1).

All lignite seam codes and related splits were stored in a special database table and field to be used for structural modelling of the seams. A horizon list (table) was also stored for reference by other functions of the software. The horizon list should only contain stratigraphy that will be modelled. It is important to list the horizons in proper stratigraphic order with the first horizon being the uppermost deposit and the last horizon being the bottom of the modelling area of interest. The smallest split is defined in the Child Split column. Child splits are merged into larger horizons until the parent horizon is reached on the right side of the table. Horizons with no splitting are also listed in the Child Split column. Table 1 shows the horizon list and splits for our case study. The table is split in two parts – one for the upper horizons and one for the lower.

There were cases of very thin seams that existed in only one drillhole and a drillhole that was missing most of the upper lignite seams (C5). These and other stratigraphy issues were resolved using a special operation of Maptek Vulcan called FixDHD which we discuss in the following section. FixDHD is one of the first steps in the modelling procedure called Integrated Stratigraphic Modelling (ISM).

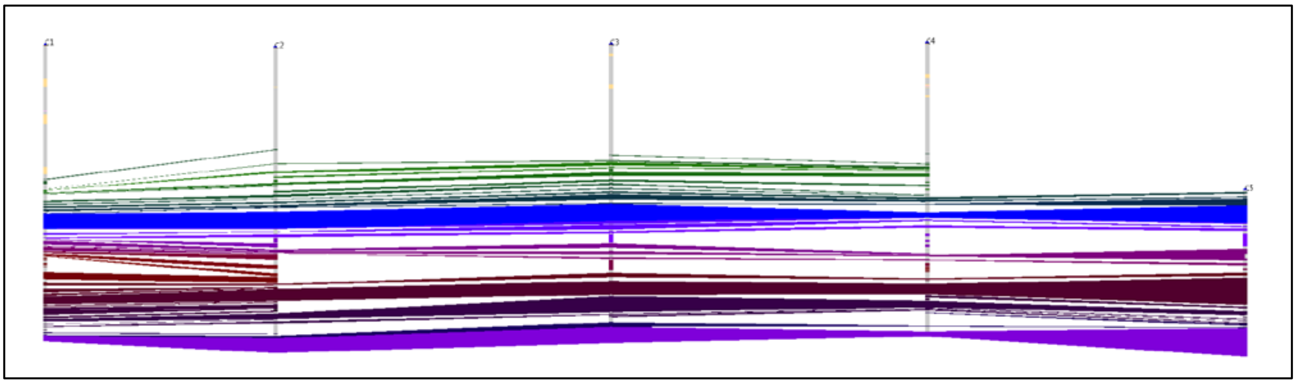

Figure 8. Section C showing drillhole database correlation – child splits are not shown linked to merge horizons.

4.2 Validating and Fixing Seam Correlation

Data for stratigraphic modelling, as in our case study, is provided from a drillhole database, with the horizons of interest noted. It is rarely possible to clearly identify all horizons in every hole. This may be due to:

- The geological nature of the deposit being drilled.
- Biases introduced when planning the drilling program.
- Poor logging practice.
- Lost data.

Our dataset, even though being limited to a small area of a much larger deposit and consisting of only 24 drillholes, presented the following data collection issues that need to be addressed:

- Short holes, which are not deep enough to include all horizons of interest or have a collar lower than the original topography surface.
- Difficulty determining the position of missing horizons that have thinned to zero thickness.
- Issues determining the position of daughter horizon boundaries within their merged parent horizon.

FixDHD was called to check the correlated lignite stratigraphy and fix possible problems. Several problems were initially identified that were stopping FixDHD from resolving the issues. These were problems related to the way correlation was coded (e.g. wrong seam sequence or seams existing in only one drillhole). In every trial run, FixDHD produced a detailed log file that explained the issues and suggested ways to resolve them. Once these problems were addressed, FixDHD produced a fixed version of the lignite stratigraphy table in the database. Table 2 shows how this table looks for drillhole C5.

The horizons are shown from top to bottom in the fixed table. As drillhole C5 was missing the top part of stratigraphy, several intervals were interpolated by FixDHD above its collar, shown with a negative *From* and *To* relative depth. Intervals interpolated or otherwise fixed by FixDHD are flagged with an F next to the column that was fixed (from, to, or thickness). Intervals unaltered by FixDHD are flagged DB. The final Flag column summarises the changes associated with an interval. For example, an interval with the original From value (column FF = DB) and a fixed To value (column TF = F) will have a final flag DBF (column Flag). Intervals with no changes are highlighted with light green colour in the table. FixDHD applies statistical modelling techniques to restore missing or unavailable data from the stored stratigraphy and manipulates the available data to meet required criteria for modelling. If the data is not enough to apply this techniques, less rigorous stacking methods are used. Similar changes to those shown for C5 took place in other drillholes, leading to a fixed correlation that could be effectively modelled.

Table 1. Finalised lignite horizon table showing how horizon splits are joined to form larger horizons based on the drillhole database correlation.

	Child	Merge Level 1	Merge Level 2
Upper Horizons	U14		
	U13		
	U12		
	U11		
	U10		
	U9C	U9	
	U9B	U9AB	U9
	U9A		
	U8C		
	U8B	U8	
	U8A		
	U7		
	U6		
	U5H2	U5H	
	U5H1		
	U5		
	U4		
	U3		
	U2		
	U1		

	Child	Merge Level 1
Lower Horizons	L1	
	L2	
	L3	
	L4A	
	L4B	L4
	L4C	
	L5	
	L6	
	L7	
	L8A	
	L8B	L8
	L8C	
	L9	
	L10A	L10
	L10B	
	L11A	
	L11B	L11
	L11C	
	L12A	
	L12B	L12
	L12C	
	L13A	
	L13B	L13
	L13C	
	L14	
	L15	
	L16	

4.3 Structural Modelling

Once the fixed lignite stratigraphic table was produced, structural modelling of the lignite seams could be performed. Seam existence limits were generated to control the horizontal area of the seams of the fixed lignite intervals. The same interpolation method was used (inverse distance weighting with a power of one) as in the previous methods discussed in this paper for consistency. Grid models for the roof, floor and thickness of each seam were generated and masked with the corresponding seam limits. Figure 9 shows Section C with the modelled seams. It should be noted that no minimum seam thickness or quality criteria have been applied up to this stage. After roof and floor models for each horizon were created, thickness grids were automatically generated between adjacent pairs of surfaces. Every node in each thickness grid was forced to a value of zero or greater, which insured that no horizons cross each other. Should a horizon cross its neighbour, either the floor was forced to the roof position, or the roof was forced to the floor position.

4.4 Compositing and Quality Modelling

For each of the modelled seams, it was necessary to generate corresponding quality grids, one for each of the quality parameters (ash, moisture, calorific value). Inverse distance weighting to the power of two was used to interpolate composited quality values (single value per seam and drillhole) to the respective grid models. Figure 10 shows ash contour maps from some lignite seams. Estimating quality parameters separately for each seam leads to a much more detailed quality model than the previous two methods and allows the application of quality mineability criteria in three dimensions instead of one.

Table 2. Fixed lignite stratigraphy of drillhole C5 – fixed intervals are flagged F, while original are flagged DB.

Horizon	Merge	From	FF	To	TF	Thickness	TKF	Sthickness	Flag
CO_U14	CO_U14	-28.812	F	-28.444	F	0.368	F	0.368	FF
CO_U13	CO_U13	-25.098	F	-24.712	F	0.386	F	0.386	FF
CO_U12	CO_U12	-23.462	F	-22.913	F	0.548	F	0.548	FF
CO_U11	CO_U11	-21.004	F	-20.104	F	0.901	F	0.901	FF
CO_U10	CO_U10	-18.983	F	-18.61	F	0.372	F	0.372	FF
CO_U9C	CO_U9	-18.61	F	-18.489	F	0.121	F	0.121	FF
CO_U9B	CO_U9	-18.197	F	-17.676	F	0.521	F	0.521	FF
CO_U9A	CO_U9	-17.204	F	-16.629	F	0.575	F	0.575	FF
CO_U8C	CO_U8	-15.355	F	-14.961	F	0.393	F	0.393	FF
CO_U8B	CO_U8	-14.961	F	-14.765	F	0.197	F	0.197	FF
CO_U8A	CO_U8	-14.765	F	-13.388	F	1.376	F	1.376	FF
CO_U7	CO_U7	-12.563	F	-11.367	F	1.196	F	1.196	FF
CO_U6	CO_U6	-8.944	F	-7.807	F	1.137	F	1.137	FF
CO_U5H2	CO_U5H	-6.112	F	-4.753	F	1.358	F	1.358	FF
CO_U5H1	CO_U5H	-3.258	F	-2.392	F	0.866	F	0.866	FF
CO_U5	CO_U5	-1.86	F	-1.86	F	0	F	0	FF
CO_U4	CO_U4	-1.347	F	-0.523	F	0.823	F	0.823	FF
CO_U3	CO_U3	1	DB	2	DB	1	DB	1	DBDB
CO_U2	CO_U2	3.8	DB	4.4	DB	0.6	DB	0.6	DBDB
CO_U1	CO_U1	5	DB	9.3	DB	4.3	DB	4.3	DBDB
CO_L1	CO_L1	20.1	DB	20.8	DB	0.7	DB	0.7	DBDB
CO_L2	CO_L2	22.1	DB	23	DB	0.9	DB	0.9	DBDB
CO_L3	CO_L3	23.8	DB	25.4	DB	1.6	DB	1.6	DBDB
CO_L4A	CO_L4	26.8	DB	29.518	F	2.718	F	2.718	DBF
CO_L4B	CO_L4	29.518	F	30.963	F	1.445	F	1.445	FF
CO_L4C	CO_L4	30.963	F	35	DB	4.037	F	4.037	FDB
CO_L5	CO_L5	36.25	DB	39.5	DB	3.25	DB	3.25	DBDB
CO_L6	CO_L6	42.6	DB	43.5	DB	0.9	DB	0.9	DBDB
CO_L7	CO_L7	45	DB	46.5	DB	1.5	DB	1.5	DBDB
CO_L8A	CO_L8	48.4	DB	48.659	F	0.259	F	0.259	DBF
CO_L8B	CO_L8	48.659	F	49.351	F	0.692	F	0.692	FF
CO_L8C	CO_L8	49.351	F	49.5	DB	0.149	F	0.149	FDB
CO_L9	CO_L9	49.786	F	49.786	F	0	DB	0	FF
CO_L10A	CO_L10	51	DB	51	F	0	F	0	DBF
CO_L10B	CO_L10	51	F	53	DB	2	F	2	FDB
CO_L11A	CO_L11	54	DB	56.8	DB	2.8	DB	2.8	DBDB
CO_L11B	CO_L11	56.8	DB	59.6	DB	2.8	DB	2.8	DBDB
CO_L11C	CO_L11	59.6	F	59.6	F	0	DB	0	FF
CO_L12A	CO_L12	59.6	DB	67.909	F	8.309	F	8.309	DBF
CO_L12B	CO_L12	67.909	F	70.284	F	2.375	F	2.375	FF
CO_L12C	CO_L12	70.284	F	71	DB	0.716	F	0.716	FDB
CO_L13A	CO_L13	72	DB	73	DB	1	DB	1	DBDB
CO_L13B	CO_L13	73.76	F	73.76	F	0	DB	0	FF
CO_L13C	CO_L13	73.76	F	73.76	F	0	DB	0	FF
CO_L14	CO_L14	75	DB	77.5	DB	2.5	DB	2.5	DBDB
CO_L15	CO_L15	82.7	DB	84	DB	1.3	DB	1.3	DBDB
CO_L16	CO_L16	85	DB	85.4	DB	0.4	DB	0.4	DBDB

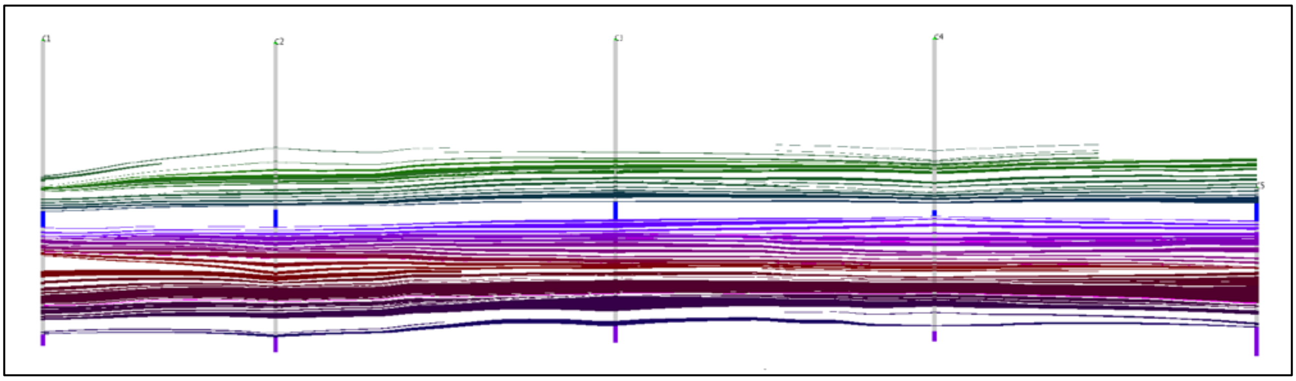

Figure 9. Section C showing modelled lignite seams – note the interpolated seams above C5 collar.

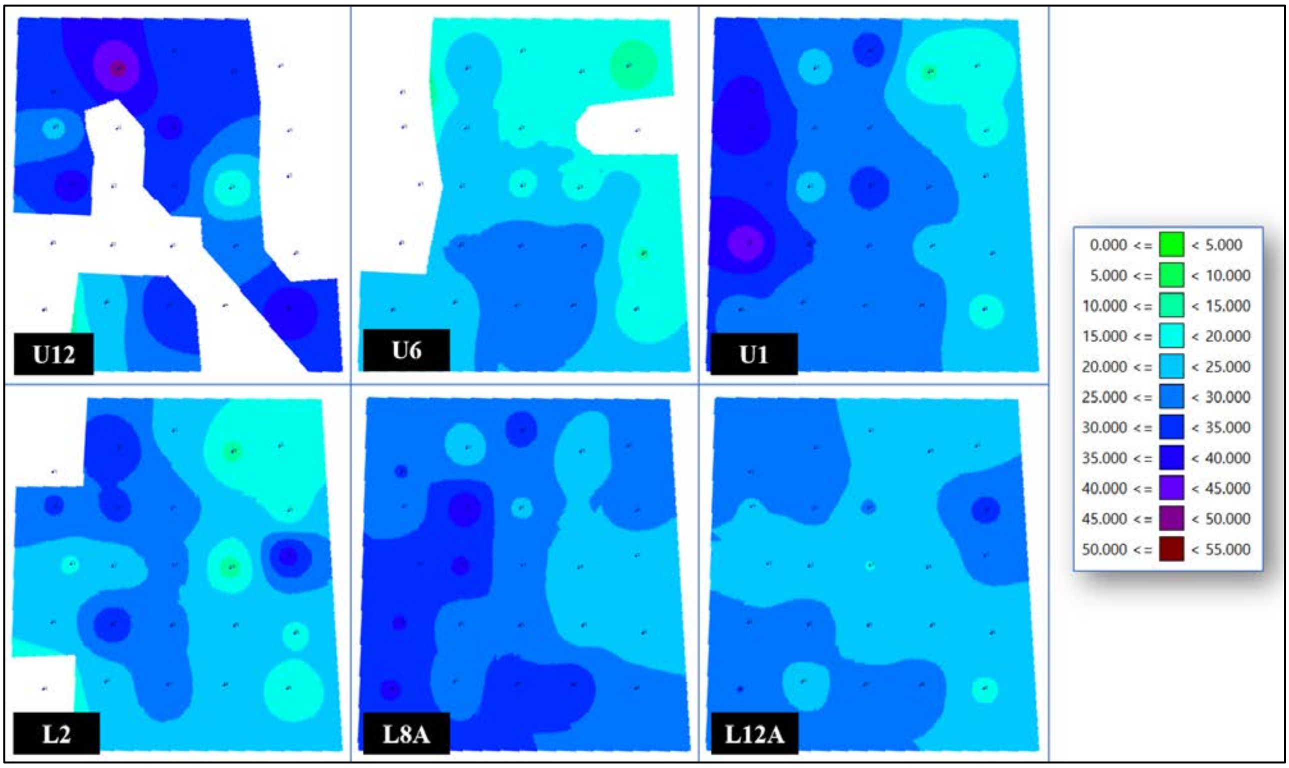

Figure 10. Estimated ash maps from some characteristic upper and lower lignite seams.

4.5 Resource Model Development

The resource model was based on the HARP (Horizon Adaptive Rectangular Prism) structure – a type of block model that represents an entire Integrated Stratigraphic Model. The HARP model is created directly from grids or faulted triangulations. All quality grids are automatically incorporated. A HARP model block contains 5 points in the roof of the block and 5 points in the block floor [4]. These points allow vertex angles to fluctuate, which allows the block to conform to structure roof and floor grids. HARP models accurately resolve horizons down to a few centimetres of thickness without the need to make huge models with extremely small Z sub-blocking.

All structural and quality grids generated for the modelled lignite seams of our study were used to construct a HARP model using the horizontal extents of the considered area. Each HARP block was initially coded as lignite or waste and received a seam code based on the formulated horizon list. Waste block seam codes had a prefix added to distinguish them from lignite (e.g. BD_L7 for burden block above L7). Figure 11 shows two sections through the produced HARP model coloured by ash estimates. It is quite clear that the HARP structure allows it to follow precisely the modelled stratigraphy.

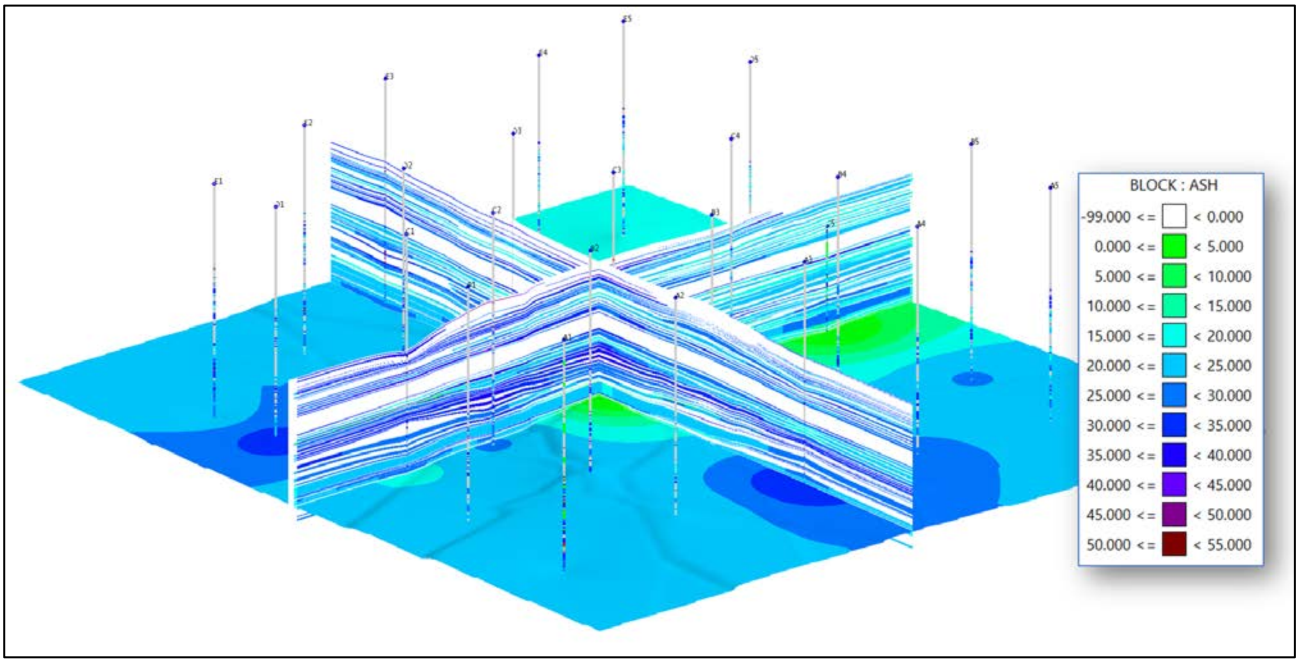

Figure 11. Vertical sections through lignite HARP model and floor of seam CO_13C coloured by ash – vertical scale was set to twice the horizontal to show more details.

4.6 Generation of Run-Of-Mine Model

Run of Mine (ROM) modelling in Maptek Vulcan simulates the way in which material is extracted from a stratigraphic deposit. Basic parameters are defined for extraction. The ROM HARP model is constructed from the geologic HARP model using three rules, applied to the mine modelling process in the following order [5]:

1. **Minimum mining thickness:** Any horizon less than this thickness is not mined by itself.
2. **Minimum parting thickness:** Any waste material between seams less than this thickness is mined with the next seam, resulting in composited seams. Waste material becomes a parting in the composited seam. The assumption when using this option is that burden material less than this thickness cannot be separated in the pit, so it is mined with the product. However, compositing only takes place if the Minimum product to waste ratio is met.
3. **Minimum product to waste ratio:** The total product to total waste ratio in a working section must be greater than or equal to this ratio. Total waste is defined as all in-seam partings plus all between-seam parting.

In our study, the minimum mining thickness was set to 0.5m and the minimum parting thickness was set to 0.3m. A 0.1m roof and floor loss was also applied. The following figure compares two sections of the original (resource) and ROM HARP model showing the effect of applying mining criteria to lignite seams in three dimensions. Parts of seams disappear due to thickness and others get combined to form thicker mineable sections.

5 CONCLUSIONS - METHOD COMPARISON

The three methods compared in this paper were applied to the same dataset, using the same mine planning software package. Timewise, the first and simplest method of the three, the compositing of mineable of total drillhole mineable lignite intervals, was the fastest to implement (couple of hours). The number of drillholes used plays almost no role to the time required by this method. It was also very easy to setup and run. The produced models and information take the smallest amount of hard disk space.

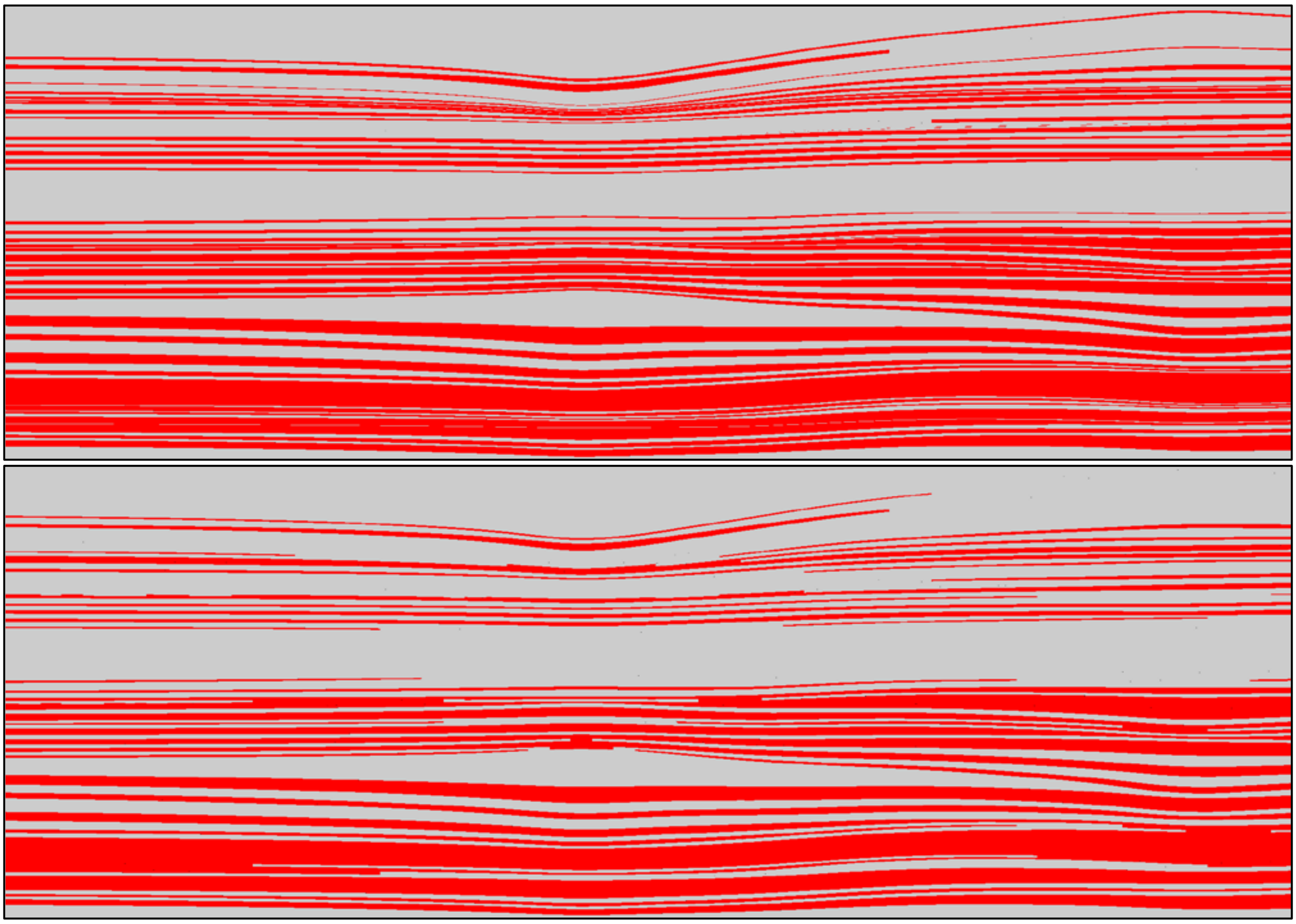

Figure 12. Original resource HARP model section (top) and ROM HARP model section (bottom) showing the changes in lignite seams after the application of mining criteria.

The second method, compositing of drillhole mineable lignite intervals per bench, required more time than the first method as the process was repeated for each bench considered (4-5 hours altogether). It required an extra compositing step to split the composites of the previous method by bench, and the development of a more complex reserve model based on sets of grids per bench. As all steps are fully automated, this method was still very easy to setup and run.

The third and most complex method, mineable lignite compositing of correlated seams, required correlation of lignite seams between drillholes – a step that took a couple of days to complete for the 24 drillholes of our case study dataset. It is quite impossible to estimate how much time it would take to correlate 100 drillholes or more as it would depend on other factors such as faulting which was not affecting the area considered in this study. Once correlation was complete, the other steps took little time to setup and run – a total of 4 hours to get the final ROM HARP model after correlation.

Table 3 below summarises the reserves calculated using each of the three methods. The reserves are split by bench, with the waste quantities given in m^3 while lignite is given in tonnes assuming a $1.2 t/m^3$ specific gravity. Looking at the totals, it is clear that the higher the resolution of the calculation (going from method 1 to 3) the lower the reported total lignite. However, looking at the individual benches, the only real comparison can be made between method 2 and 3, as the first method has no real control of what is reported as bench quantities. Calculating bench reserves using method 1 is essentially applying the same stripping ratio on a different lignite plus midburden total to derive the individual values. Only overburden can be directly calculated from its modelled floor.

Both methods 2 and 3 report reasonably distributed quantities per bench, but we can still see differences between them. The effect of artificially grouping lignite intervals into bench mineable sections leads to a slight overestimation in the lower benches and some underestimation of the upper ones compared to the number reported by method 3. These differences would have been much larger in the presence of faulting. Comparison of quality parameters estimations gave similar differences.

Overall, it became quite clear during this exercise that the time spent in building a complete stratigraphic model based on lignite seam correlation is time well spent as it provides all the necessary quantity and quality information in three dimensions and to the highest resolution possible based on the available data. Any efforts to replace seam correlation and compositing with one-dimensional compositing of each drillhole separately, lead to over-simplification of geology and significant reduction of the effectiveness of mine planning.

Table 3. Summary of bench reserves produced by the three compositing methods.

	1. Total Mineable Thickness Compositing			**2. Mineable Thickness Compositing per Bench**			**3. Compositing of Correlated Lignite Seams**		
Bench	**OB**	**CO**	**MB**	**OB**	**CO**	**MB**	**OB**	**CO**	**MB**
650	14,577,846	-	-	14,577,846	-	-	14,577,846	-	-
640	13,185,074	-	-	13,185,074	-	-	13,185,074	-	-
630	13,185,074	-	-	13,185,074	-	-	13,185,074	-	-
620	13,185,074	-	-	13,185,074	-	-	13,185,074	-	-
610	13,185,074	-	-	13,185,074	-	-	13,185,074	-	-
600	13,175,050	5,675	5,295	13,055,385	61,243	78,653	13,102,556	31,679	56,119
590	11,289,779	1,073,032	1,001,102	9,812,684	708,640	2,781,857	9,668,205	764,268	2,879,979
580	5,184,748	4,529,428	4,225,803	5,001,697	4,646,698	4,311,129	5,129,774	4,260,537	4,504,853
570	1,325,006	6,714,642	6,264,533	1,592,875	4,864,147	7,538,743	1,508,645	5,063,741	7,456,645
560	69,358	7,425,533	6,927,771	504,643	4,623,182	8,827,779	498,204	4,839,959	8,653,571
550	-	7,464,801	6,964,407	-	2,092,204	11,441,571	-	2,162,843	11,382,705
540	-	7,464,801	6,964,407	-	7,802,640	6,682,874	-	7,884,321	6,614,807
530	-	7,464,801	6,964,407	-	8,664,512	5,964,648	-	9,472,897	5,290,994
520	-	7,464,801	6,964,407	-	7,465,063	6,964,188	-	7,836,396	6,654,744
510	-	7,464,801	6,964,407	-	9,209,149	5,510,783	-	9,691,051	5,109,199
500	-	7,464,801	6,964,407	-	12,940,138	2,401,625	-	12,230,637	2,221,503
490	-	6,726,605	6,275,695	-	6,531,122	2,979,474	-	4,900,503	2,928,823
480	-	1,425,875	1,330,293	-	1,393,525	1,013,852	-	731,332	993,575
470	-	161	150	-	106,621	29,975	-	53	11
Total	***98,362,083***	***72,689,757***	***67,817,083***	***97,285,426***	***71,108,884***	***66,527,152***	***97,225,526***	***69,870,216***	***64,747,527***

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