An Evolutionary Solution for Coal Reserves Modelling and Production Scheduling

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ABSTRACT

Coal and other stratigraphic deposits consisting of multiple layers commonly require a lot of time and effort to produce a representative geological model that will allow accurate estimation of reserves and provide a solid basis for effective mine planning. The transition from such a 3D geological model of stratigraphy to an effective Run-Of-Mine model that can be used to calculate reserves is a critical part of this process. Approaches to achieve this transition range from one-dimensional mineable coal compositing of drillhole data to more effective three-dimensional aggregation of mineable coal seams based on an appropriate stratigraphic geological model. There are very few commercial software packages that integrate a complete stratigraphic modelling module, and even fewer that have the capability to take the process further into production scheduling. The solution presented in this paper is based on two commercial software packages part of the same family of products – Maptek Vulcan, a general mine planning package with advanced stratigraphic modelling capabilities, and Maptek Evolution, a mine scheduling package based on evolutionary algorithms. The examples presented in this paper show how the two packages together provide a complete solution for coal reserves modelling and production scheduling.

1 INTRODUCTION

Developing an effective coal resource model from drillhole data is a difficult and time-consuming process. In cases where the deposit consists of multiple coal layers, it becomes even harder as certain important steps like seam correlation require better understanding of the data in 2D (plans and sections) and 3D (complete derived model) and the overall process requires a lot more time. In such cases, proper geological software tools are essential in working with drillhole data to identify the correlation of seams in plans and sections and check the produced model in three dimensions. The visualisation and statistical analysis capabilities of the software become crucial. The amount of data and information is simply too large to handle with traditional methods of producing sections and plans.

Once seam correlation is complete, the drillhole database can be used to develop a complete structural and qualities model of stratigraphy. Seam extents, seam merging and splitting, faulting, and other aspects of geology need to be effectively addressed by the modeller and the software. The end result of this effort will be a stratigraphic model and a corresponding resource model commonly in the form of multiple grid models or an overall stratigraphic block model.

Prior to reporting coal reserves and moving to pit design and scheduling, it is necessary to convert the developed coal resource model to a coal reserve model by applying a number of parameters related to the mining method(s) applied and the coal quality targets. These parameters commonly include minimum mineable coal and waste thickness, maximum parting thickness when merging waste with coal to achieve minimum thickness, and maximum ash content for mineable coal. Roof and floor losses are also applied as well as mining dilution. The final coal reserves model should be the result of sound geological interpretation and solid mining factors application with increased confidence.

The procedure discussed in this paper, covers all aspects of generating a coal reserves model starting with a correlated drillhole database. Two closely interacting software solutions are presented in the discussion that provide all necessary functionality to develop a coal reserves model and proceed with the scheduling of the produced reserves. Maptek Vulcan and particularly the Integrated Stratigraphic Modeller provides all the necessary functionality to produce a coal resource model using drillhole, topographical and tectonic data (Section 2). Maptek Vulcan also provides the tools to output the resource model in a format readable by Maptek Evolution – the second software package discussed in this paper, responsible for the development of the coal reserve model (Section 3) and production scheduling (Section 4).

2 STRATIGRAPHIC MODEL DEVELOPMENT

2.1 Overview of Integrated Stratigraphic Modelling

Maptek Vulcan integrates one of the most complete Integrated Stratigraphic Modelling modules (ISM) providing a variety of modelling methods to develop stratigraphic, structural and grade/quality grid models using an automated modelling process. A unique stratigraphic block model structure, the HARP (Horizon Adaptive Rectangular Prism) model, gives further flexibility and capabilities in stratigraphic reserves modelling. HARP's non-rectangular block models easily handle reverse faults and very thin horizons, that can be reserved against complex 3D solid shapes such as pit cutbacks and mining blocks (Fig. 1) [1]. A single file contains all the structural, quality, faulting and associated data. Geological resolution and stratigraphic fidelity are preserved. The steps included in the development of a stratigraphic model using ISM are as follows [2]:

1. ***Database Validation***: the first step in the process is to validate the drillhole database in Vulcan and ensure all data entries are legitimate. This step allows *field-by-field validation* to check the contents of a specified field against a variety of possible entries for that field, for example, check if the logging codes are valid, if the data lies in certain ranges, and that data has been entered into a mandatory entry field. It also allows *global validation*, i.e. the contents of a field are checked against the contents of all other occurrences of that field in the database, for example, the hole name and/or Eastings and Northings for a hole will be checked against every other hole in the database.
2. ***Drillhole Data Interpolation (FixDHD)***: FixDHD is an option of ISM used to interpolate missing stratigraphic horizons in drillhole data to improve stratigraphic modelling. It ‘recognises’ that most drillhole data sets contain a number of problems and provides a range of interpolation options to best address these. If a horizon is missing in a drillhole, roof and floor positions are calculated using actual, logged, horizon intervals in drillholes surrounding the drillhole with the missing horizon. An inverse distance weighting method is applied to determine which intervals to use. Intervals which are both stratigraphically and geographically closest to the missing horizon receive the highest weight. Some typical data problems and the way FixDHD addresses these are outlined in the following paragraph (2.2).
3. ***Stratigraphy Structural Modelling***: at this stage, the fixed stratigraphic information of the database is used to model structurally the roof and floor (upper and lower boundaries) of all

horizons of interest as well as structural thickness, cropping and horizontal extents (masking). Faulting can be defined in four different ways:

- ***Zones*** and ***Crest and Toe*** methods are all purely grid-based methods, and as such are not suited to modelling reverse or thrust faults. In the Zones method of fault definition, a series of mutually-exclusive, polygonal limits are applied. The faults are typically applied to an individual surface.
- ***Blocks*** and ***Throw*** methods are suited to more complex faulting scenarios, including reverse and thrust faults.

Grid models are commonly used for structural modelling as they allow quick and straightforward application of mathematical equations and relationships between them. Paragraph 2.3 covers this step.

4. ***Compositing and Modelling of Qualities***: at this step ISM produces a composite for any specific interval down a hole. The composite interval (the structure) can be defined by geology, height, surfaces, or a combination of these. Analytical data can be extracted from multiple databases using depths or samples. This step is covered in Paragraph 2.4.
5. ***HARP Model Generation***: a HARP model represents an entire Integrated Stratigraphic Model in a single block model file. The HARP model is created directly from grids or faulted triangulations. All quality grids are automatically incorporated. The development of the HARP model is covered in Paragraph 2.5.
6. ***Run-Of-Mine (ROM) Model Generation***: ISM simulates the manner in which material is extracted from a stratigraphic deposit. Basic parameters are defined for extraction. The ROM model is constructed from the geological model using three rules. These rules are applied to the mine modelling process in the following order:
   - Minimum parting thickness
   - Minimum mining thickness
   - Minimum product to waste ratio

   The output of this process is a new ROM HARP model.
7. ***Strip Ratios Calculation***: at this final step, it is possible to calculate a ratio from a Stratigraphic Block model or HARP model. The stripping ratio is defined as the volume of waste material divided by the tonnage of product material.

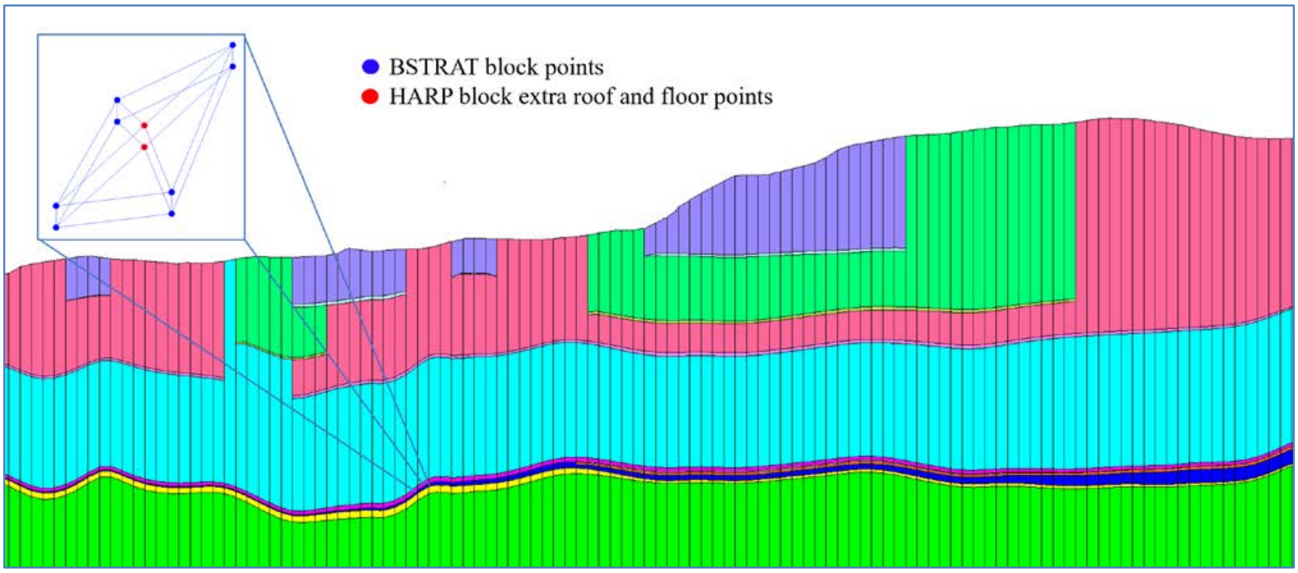


Figure 1. Example section through a Horizon Adaptive Rectangular Prism (HARP) model and detail of a HARP block showing the use of 5 points on the top and bottom side (see section 2.5).

Steps 6 and 7, i.e. the generation of the ROM model and calculation of strip ratios can now take place in Maptek Evolution. This leads to the development of a reserve ROM model, ready for scheduling, as opposed to the resource-based ROM model generated by ISM. However, the coal aggregation facilities in Maptek Evolution should not be considered as a direct replacement of the corresponding functionality of ISM, as the ROM model produced by ISM can be used in Maptek Vulcan to help design the mine and calculate resources before moving to the reserve model and scheduling in Maptek Evolution.

The purpose of stratigraphic modelling is to create an idealised representation of the stratigraphy in an area of interest. Such models allow comprehension of many useful characteristics. These include the geological processes affecting the stratigraphy, their three-dimensional inter-relationships and the accurate calculation of measurements (depth to horizons, fault locations, reserves etc). The following sections discuss the most important steps of the ISM modelling process in more detail.

2.2 Drillhole Stratigraphic Data Validation and Interpolation

Typically, data for coal resource modelling is collected in the form of drillholes in which the positions of horizons of interest are logged. Rarely, however, are the data so perfectly collected so as to provide information about all of the horizons to be modelled in every hole. As shown in Fig. 2, almost all drillhole data sets will contain holes where some of the horizons are not represented. The reasons for this are various; some inherent in the nature of the deposit being drilled, some introduced by the methods of the drilling program and some by poor logging practice or lost data. The reasons for the missing information fall into two main categories [1]:

1. Data that was not collected by the drilling program.
2. Data that was not available for collection because of pre and post -depositio processes.

The problems that can be caused by the first of these categories are:

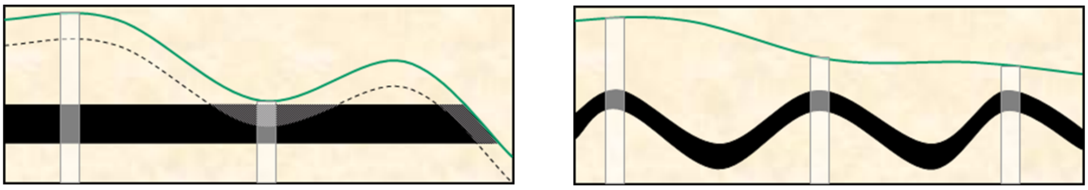
- Short holes which are not deep enough to include all horizons of interest.
- Problems determining the position of missing horizons that have thinned to zero thickness.
- Problems determining the position of the boundary of daughter horizons in their merged parent horizon.
- Lost core, lost data or poor logging.

The problems that can be caused by the second category are:

- Removal of horizons from the top of the sequence by erosion.
- Weathering of horizons blurring upper boundaries.
- Sub-cropping of horizons against other geological features.
- Washout by erosion processes at the time of deposition.

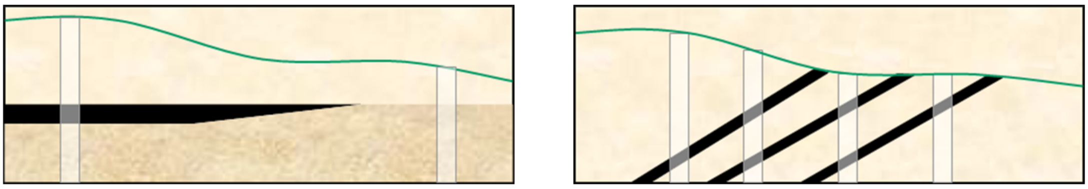
In addition to the above, drillholes may not be vertical, which compromises the modelling requirement that we know the vertical thicknesses and position at a given location.

These problems are resolved using various techniques provided by the FixDHD option of the ISM. FixDHD will attempt to fill in these gaps using statistical modelling techniques to determine the missing or unavailable data from the known data, and to manipulate the available data to meet the required criteria for modelling. An example of the FixDHD operation is shown conceptually in Fig. 3. Where there is insufficient data for the statistical techniques to be employed, less rigorous stacking methodologies are employed, full details of which are supplied to a process log for auditing purposes. Generally, where horizons pinch-out, zero thicknesses are applied, where horizons have been removed via post-depositional processes, they are restored, where data has not been sampled, it is interpolated and where merged seams are identified, the merged seam is re-identified as the relative component splits.



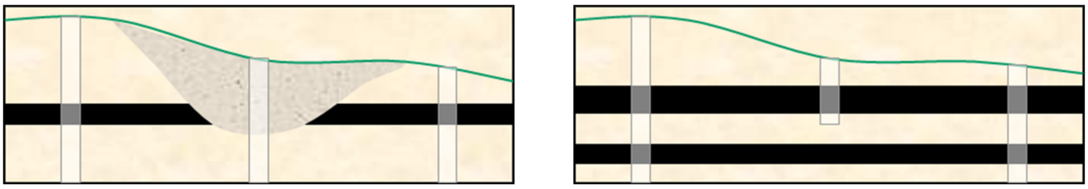
Weathering

Unfortunate drilling pattern



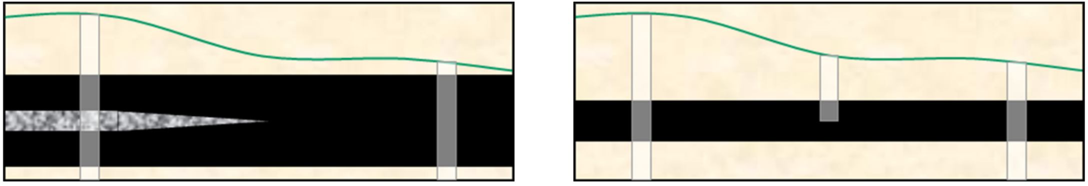
Syn-depositional

Steeply dipping strata



Post-depositional

Short drilling



Seam splits

Partial intersections

Figure 2. Potential issues with drillhole stratigraphic data that need to be addressed before structural modelling [3].

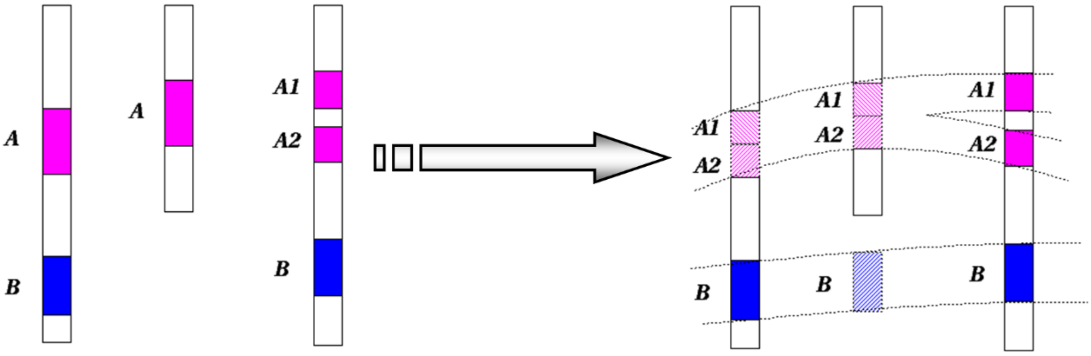


Figure 3. Concept of interpolating/fixing incomplete drillhole stratigraphic data (left) with FixDHD (right) [3].

If a drillhole is collared in a horizon, FixDHD does not consider the collar location as a reliable roof position for that horizon as it could be considerably higher in elevation. Therefore, the roof position for that horizon may be interpolated above the collar location using the surrounding, reliable intervals for the horizon in question. Similarly, a drillhole that terminates in a horizon does not reflect reliable floor positions for the horizon in which they terminate. This is because the horizon may extend deeper than what drilling indicates. Therefore, the floor position for that horizon may be interpolated below the drillhole terminus using the surrounding, reliable intervals for the horizon in question.

A major advantage of the FixDHD process over previous interpolation tools is that it works directly from the drillhole database. The fixed version of the stratigraphic data is kept together with the original, clearly marked to allow validation before modelling. After generating a consistent stratigraphic sequence in each drillhole, we can begin our structural modelling procedure.

2.3 Structural Modelling

There are three main methods of creating a structural model in ISM:

1. ***Stacking***: creates all horizon models based upon one selected structural surface. A selected surface becomes a reference for creating the rest of the grids in the model. The remaining surfaces are created by adding and subtracting thicknesses and midburdens from the reference surface. The reference surface is the horizon in which there is the most confidence. This is generally the horizon with the most, or most reliable, data. It is modelled using one of the available modelling algorithms: *triangulation*, *inverse distance weighting*, *kriging*, *spline*, *least squares*, and *trend surface*.
2. ***Structural Surfaces***: models individual roof and floor surfaces for each horizon using the available modelling algorithms mentioned above. As roof and floor surfaces represent the same type of data, a height above sea level, a single modelling method is used for both. After roof and floor models for each horizon are created, thickness grids are automatically generated between adjacent pairs of surfaces. Every node in each thickness grid is forced to a value of zero or greater, which insures that no horizons cross each other. Should a horizon cross its neighbour, either the floor is forced to the roof position, or the roof is forced to the floor position.
3. ***Hybrid***: is an enhanced Stacking method. The ability to include additional design CAD data for any roof, floor or thickness interval for any horizon adds extra control. It is possible to control the horizontal and vertical influence of defined design data. A Hybrid method offers many of the advantages of either the Stacking or Structural Surfaces method with few of the drawbacks.

Each method has advantages and drawbacks. Regardless of the method, the produced structural model needs to be visually checked and compared against the correlated drillhole intervals in sections and in three dimensions. Figure 4 shows the comparison of database and grid (model) correlation in a drillhole section view window. Figure 5 shows multiple coal grid models in three dimensions constituting part of the structural model of a coal deposit. Faulting and seam limits are evident.

2.4 Compositing and Quality Modelling

In addition to the structural models of the seams, it is necessary to model various coal quality parameters such as ash content, sulfur, insitu moisture, calorific value and density. As the original analyses on the drillholes do not necessarily follow the correlated and fixed stratigraphy after the application of FixDHD, it is necessary to composite these values to receive a single value for each parameter per correlated seam before modelling the parameter in two dimensions as a grid model. A special compositing function of ISM is used to generate formatted text files with all the composite values - one file per seam. The information contained in these files is then used to model quality parameters per seam, commonly using the inverse distance weighting method.

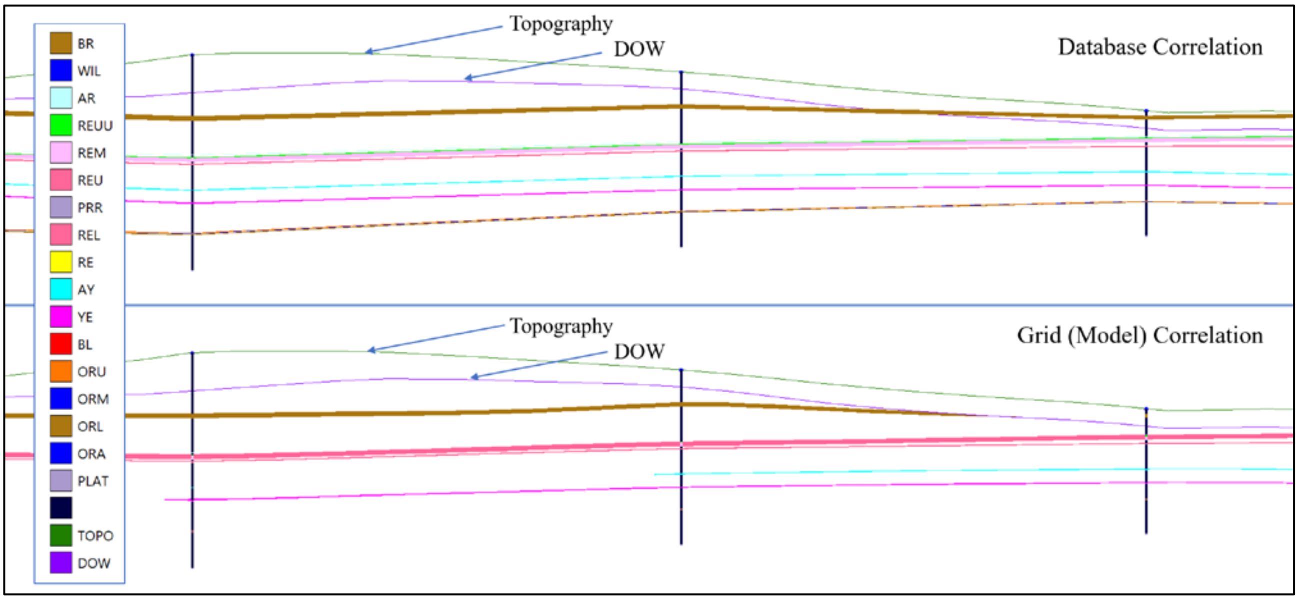


Figure 4. Comparison of database and grid model correlation in section view showing the effects of structural modelling and cropping of seams using topography and depth of weathering (DOW) surfaces.

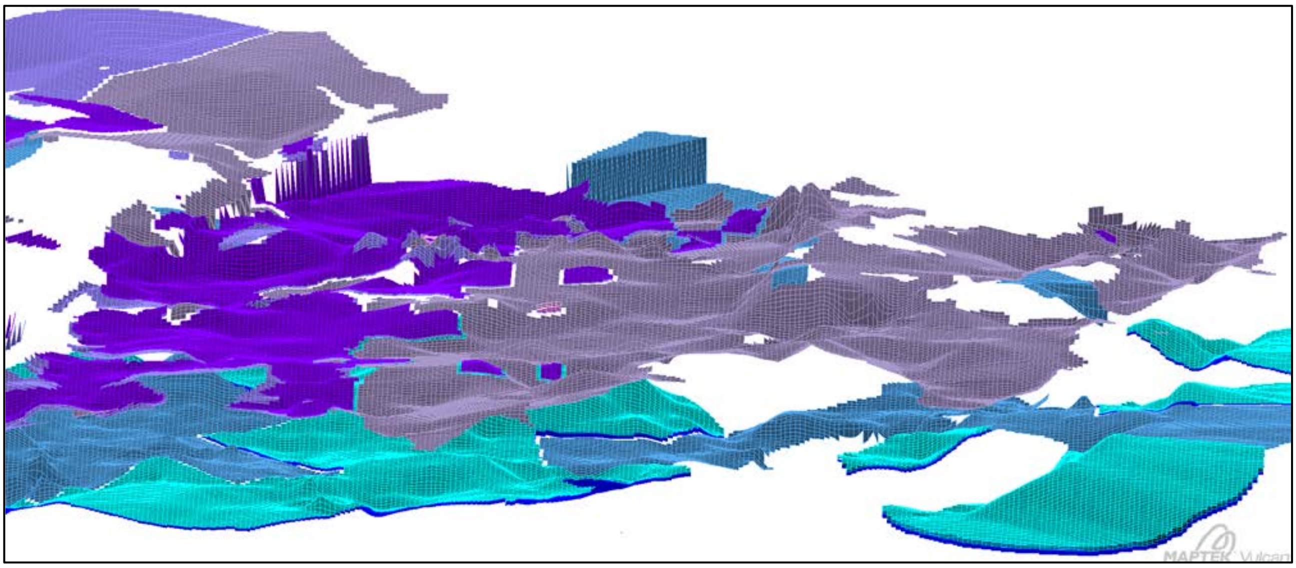


Figure 5. Grid models of coal seams floor developed with ISM showing the effect of seam limits and faulting.

In the situation where the deposit contains split horizons, one must consider how to treat qualities. There are a few strategies to consider:

a. Quality information for the parent seam and any child horizons is considered and modelled entirely separately. Grid masks are used when reserving to ensure that only the parent qualities are used for the extent of the parent, and child qualities for the extent of the child horizon.

b. The entire envelope of a split horizon is considered when compositing qualities. This means that the region from the top of the uppermost split to the base of the lowermost split is used across the extent of the parents and children. This involves compositing in partings between splits.

c. Only child horizons are composited. A weighting method is used where parent seams exist to artificially split them –into child quality values. If there is no breakdown of quality sampling within a parent horizon, then each child is given the full quality value of the parent seam.

d. The methodology in part c is combined with a Run of Mine (ROM) horizon compositing exercise to produce ROM grids. These grids combine and split on mining rules, not geological logging.

2.5 HARP Model Development

Traditional stratigraphic block models (known as BSTRAT models) were used prior to Maptek Vulcan version 8.0 to represent stratigraphic deposits. Like all traditional block models, each block was formed by a cuboid. As each vertex of the cuboid is formed with right angles, the blocks could not adequately represent roof and floor structures. A HARP model block contains 5 points in the roof of the block and 5 points in the block floor. These points allow vertex angles to fluctuate, which allows the block to conform to structure roof and floor grids (Fig. 1). 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. HARP non-rectangular block models easily handle reverse faults and very thin horizons and can be reserved against complex 3D solid shapes such as pit cutbacks and mining blocks. The benefits of using HARP models for coal resource and reserve modelling have been presented in various case studies in the past ([4], [5]).

Development of the HARP model is basically a single step in the ISM process. All structural and quality grid models are combined to form a single stratigraphic block model using the 10-point block geometry of the HARP model that allows it to match exactly the shape of the structural grids. All quality grid models become block model variables and their node values are transferred to the corresponding blocks. As grids are named with the standard naming convention during the ISM process, the appropriate quality grid value is automatically associated with the relevant block in the HARP model based on the horizon variable. The grid value is populated into the HARP block vertically above the grid cell. The produced HARP model becomes a complete database of coal resources for the project. As HARP block sizes vary along the Z axis, it would be necessary to run a regularisation step to a standard block size to allow running a pit optimisation algorithm and derive optimum pit limits from such coal resource model.

3 RUN-OF-MINE MODELLING WITH MAPTEK EVOLUTION

3.1 Overview

With the latest version, Maptek Evolution can work with a reserve model based on solid triangulations – this allowed ~~allows~~ the development and integration of a new coal seam aggregation module that takes an in-situ model and produces practical run-of-mine reserves within a flexible, yet automated, step-based workflow system [6]. Getting seam aggregation right is critical for accurate estimation of tonnages, and easy and efficient scheduling for stratigraphic mines.

The coal transformation module in Maptek Evolution is designed to take the reserved insitu solids from a mine planning package and calculate step by step coal qualities and quantities for each stage of the mining and beneficiation process. The result of these calculations is the construction of a Coal Reserves Model. It uses a 'pipeline' calculation process that applies a series of pre-built or custom scripted transforms in order to perform these calculations. The module has been designed to be labour saving, while still offering flexibility.

3.2 Basic Concepts

An Evolution coal model consists of a collection of 3D solids with associated variables. For example, a solid may represent a coal seam in a mining block, with variables for volume, density, thickness and various coal qualities. Each solid or block model cell is referred to by Evolution as a *row*, while the variables associated with that row are called *columns*. When dealing with coal models specifically, a row can also be called a horizon. A horizon is represented by a three dimensional solid and is the smallest user selectable unit within the model.

In Evolution, a *material* is a way to classify a horizon as product or waste. Each horizon has a material, which indicates whether that horizon should be considered worth mining or not. For example, there might be a material named coal that signifies this is the material we wish to mine for profit. Additionally, there might be a material called waste that informs Evolution that the material is waste and generates no profit. There might be several product material types – for example thermal, PCC, and coking coal. There might also be several waste types such as spoil, free dig and fresh. Most of the time, we are only interested in whether it is product or waste but defining multiple product or waste types can be useful for filtering, calculations for product washes, or equipment allocations.

While a given horizon may have only one material type – either waste or product – it may consist of some product material and some waste material. These form the product component and waste components respectively. However, when considered as a whole, these two components are aggregated into a total that when considered against product specifications, will dictate the material type of the total as either product or waste. This concept is particularly important during aggregation or loss and dilution. Even if the original imported horizons were completely waste or completely product, there will eventually be some mixing during the mining process.

When two horizons are aggregated into one larger horizon, the original horizons are not forgotten – they are stored as ancestors of the final horizon. The coal module considers these original ancestors and their location within the final aggregated horizon when calculating loss and dilution. This ensures that the qualities associated with any loss material is representative of the ancestors that were present in the region of the loss.

In our example, Maptek Evolution received the stratigraphic model of a coal deposit through a number of solid triangulations - each solid having a unique ‘address’ in the pit. This was achieved by defining a series of address ‘levels’ that identify its unique position within the mine. No two solids should share the same value for all address levels. For a typical coal mine, the levels might be:

- Pit – individual pit code
- Strip – strip number or code
- Block – block number or code in a strip
- Seam – seam code the block belongs to
- Material – type of material (e.g. coal, overburden, midburden)

These solid models were created in Maptek Vulcan and assigned a number of attributes related to structural and quality resource parameters. During the process of coal reserves model development in Maptek Evolution, the user can formulate a procedure of coal aggregation to convert the coal resources associated with the imported solids to coal reserves using the available coal database transformation options shown in Fig. 6. In other words, the user can create a customised aggregation procedure that suits the targeted coal deposit and the mining method(s) used to extract it.

A transform is a self-contained calculation that transforms incoming data, and then passes the result to the next transform. For example, a transform might import attributed Vulcan triangulation files into the program as horizons, while the next might calculate the effects of Loss and Dilution on that horizon. A later transform might account for moisture changes on the ROM stockpile by recalculating new tonnages and qualities at ROM moisture. Pre-built transforms can perform many standard calculations such as aggregation, seam wasting, and loss and dilution. Custom scripted transforms can also be created. The following paragraphs discuss the main coal database transformation options available. An example of a complete procedure is also provided at the end of this section.

3.3 Wasting Options

Wasting transforms (quality or thickness based) can be used to turn the material type of a coal reserve solid from what it is originally prior to importing to either overburden or midburden. In the case of quality-based wasting, the criteria are, as expected, based on quality variables. It can be used, for example, to turn solids of coal material type to waste if ash is greater than an applied limit.

Thickness based wasting allows the application of minimum mining thicknesses to the coal reserve solids. A different thickness can be applied to different seams reflecting the possible use of different mining methods to extract them. Solids with a thickness smaller than the applied minimum have their material type changed to either overburden or midburden.

Coal forced wasting can be used to change the material type of any solid to overburden or midburden and at the same time assign new values to its variables. This allows wasted seams to have variable values overridden with new values in case those quality values (density, moisture, ash, etc.) need to be changed to typical waste values. Variable value switching is also possible allowing wasted seams to have the values of variables swapped with other variables. Typical usage might be to transfer the values for product quantities (coal thickness, coal tonnage, etc.) to waste quantities.

3.4 Aggregation

This is the main step in the development of the coal reserves model in Maptek Evolution. The aggregation transform is designed to merge horizons too thin to practically mine into larger horizons. Aggregation can be limited so that it does not cross in pit benches. Aggregation occurs within groups of seams called *passes*. A horizon table is provided that allows for the definition of passes and their member horizons. Selecting a pass, or a horizon in the table will allow the following aggregation logic to be set for each pass:

- ***Pass name*** – all solids will have a new variable/column added that includes this pass name.
- ***Minimum product thickness*** – any product horizons less than this thickness will be aggregated to a neighbouring horizon.
- ***Minimum waste thickness*** – any waste horizons less than this thickness will be aggregated to a neighbouring horizon.
- ***Set all product as*** – if after aggregation a horizon still qualifies as product (based on the rules set), then its material will be set to this value.
- ***Set all waste as*** – if after aggregation a horizon does not qualify as product (based on the rules set), then its material will be set to this value.

The variables (or columns in Evolution terminology) that will be available for further transforms after the aggregation step need to be specified in this step. The columns are grouped in four categories: *Standard, Quantity, Quality and Other columns*. Standard columns include the total, product and waste component columns that relate to volume, density, moisture, tonnage and thickness that must be selected. Quantity columns (qualities) represent amounts that are proportional to the thickness of the solid, such as volume or tonnage. When solids are merged, the columns listed in this table will be summed to determine the value for the new aggregated solid. Quality columns (qualities) represent values that are homogeneous throughout the solid, such as density or ash. The following aggregation methods are available:

- ***Minimum*** – the value for the aggregated solid will be equal to the least value held by any of the solids being merged.

- ***Maximum*** - the value for the aggregated solid will be equal to the highest value held by any of the solids being merged.
- ***Average*** – the value for the aggregated solid will be the numerical average of the solids being merged.
- ***Average (Non Zero)*** - the value for the aggregated solid will be the numerical average of the solids being merged, excluding any solids with zero values.
- ***Copy Top-most*** - the value for the aggregated solid will be the same as the top most solid in the group being merged.
- ***Copy Bottom-most*** - the value for the aggregated solid will be the same as the bottom most solid in the group being merged.
- ***Weighted Average*** - the value for the aggregated solid will be the weighted average of the solids being merged. The weighting is given by the column specified in the Weight field of the table.

Other columns can also be defined that represent values that don't fit into the quantities or qualities categories. These values would categorise solid, such as a name, ID, or strip number. When solids are merged, the aggregated solid will have its value set equal to the top most solid in the aggregation group (Copy Top-most) or bottom most solid (Copy Bottom-most), depending on the aggregation method selected in the table.

The product definition of the aggregation step allows for setting rules to define whether a solid should be considered coal or waste. During aggregation, rows (blocks) that were initially coal may be diluted with waste to an extent that they are no longer suitable for sending to a wash plant. Every time solids are aggregated by this transform operation, the resultant merged solid will be checked against the conditions in this table. If all conditions are met, the solid will be turned to the product defined in settings for that pass. If any of the conditions fail, then the merged solid will be set to the waste defined in pass settings. Solids that have not been aggregated will not be changed.

3.5 Loss and Dilution

The Loss and Dilution transform can optionally add the effects of roof, floor and edge loss and dilution. If this transform runs after an aggregation transform, the loss and dilution will still reflect the qualities of the original pre-aggregated horizons in the regions of the loss (when specifying loss by thickness only). Roof and Floor loss and dilution can be specified in the following ways:

- *Thickness* – the specified thicknesses are lost from the roof and floor and report to the horizons above and below respectively as dilution. The basal seam will experience dilution from the seam below (underburden) as specified by the underburden dilution thickness and the area column selected.
- *Percent* – the volume of roof and floor loss is specified as a percentage of the original horizon's volume. The roof and floor loss become the roof and floor dilution for the horizons above and below respectively. The basal seam will experience dilution from the seam below (underburden) equal to the volume of material lost.

Edge loss and dilution can be specified similarly.

3.6 An Example of an Aggregation Procedure and Coal Reserves Model

The example presented in this paper consists of multiple coal layers that have been modelled from drillhole data and converted to solid triangulations with associated resource attributes. A typical section through the deposit is shown in Fig. 7 (top). Over 5000 solids were imported into a Maptek Evolution coal database and aggregated using a straightforward procedure based on the following criteria:

- Minimum product thickness: 0.3m
- Minimum waste thickness: 0.3m
- Maximum product ash content: ~~0.6~~0.6 (fraction)
- Roof and floor loss and dilution: 0.1m

An aggregated version of the imported coal database was created. The effect of aggregation is shown in Fig. 6. The aggregated coal database, representing the coal reserves, was then used to produce a coal production schedule in Maptek Evolution.

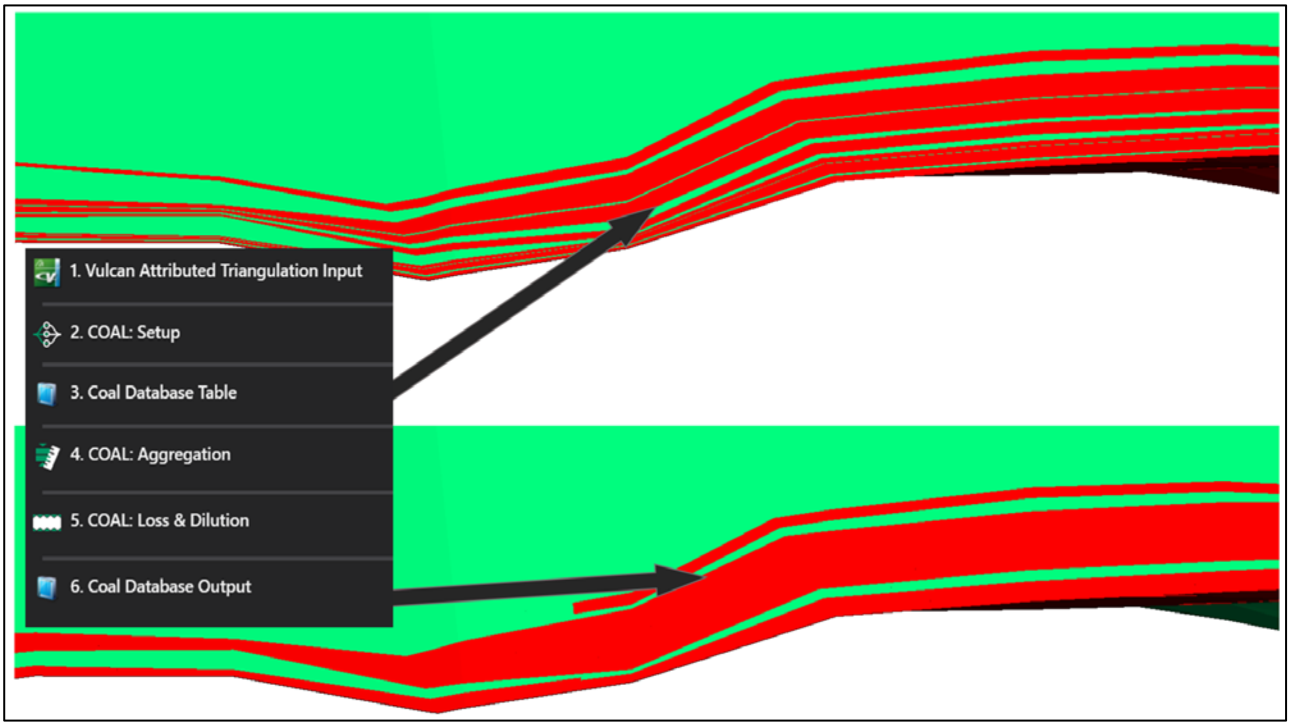

1. Vulcan Attributed Triangulation Input
2. COAL: Setup
3. Coal Database Table
4. COAL: Aggregation
5. COAL: Loss & Dilution
6. Coal Database Output

Figure 6. Example of imported coal seams (top) and aggregated coal seams (bottom) and associated steps in Maptek Evolution. Coal seams are shown in red while midburden is shown in green.

4 COAL PRODUCTION SCHEDULING WITH MAPTEK EVOLUTION

4.1 Overview of Evolution

Maptek Evolution is one of the most advanced scheduling systems commercially available and probably the only one based on evolutionary algorithms. The scheduling and optimisation functionality of Evolution is cloud-based – the reserve model and schedule setup are transmitted to a cloud facility for processing. The scheduling solutions found are transmitted back to the user for further analysis and approval.

Evolution consists of two main modules, *Strategy* and *Origin*. Strategy is a high-level scheduling solution focusing on value maximisation through the use of cutoff grade optimisation but allows for detailed constraint modelling as well (including blending). Origin is a tactical level scheduling system which allows the user to develop detailed mining schedules ready for medium term planning.

Optimisation in Strategy is based on a hybrid system consisting of a *core evolutionary algorithm*, a *local search evolutionary algorithm* and a *linear programming algorithm*, each with different responsibilities (Fig. 7). The main steps of scheduling operation are as follows [7]:

1. Creation of the initial population including a geometrically correct extraction sequence. (Graph Theory)
2. Calculation of the fitness of each individual and ranking of the population based on fitness. (Master and Local Search Evolutionary Algorithms)
3. Iteration through successive generations by generating an offspring population where each child competes with the parents for the privilege to progress to the next generation. (Master Evolutionary Algorithm)
4. The master algorithm calls on the secondary local search algorithm to boost the best individual found so far, by manipulating the threads through cut-off grade space whilst keeping the extraction sequence static. The improved individual is then sent back to the master where it replaces or upgrades its old self (analogue to exploring the local neighbourhood). (Local Search Evolutionary Algorithm)
5. Steps 2 to 4 are repeated until no improvement is registered, in other words when the population loses diversity and converges on a single high fitness value.

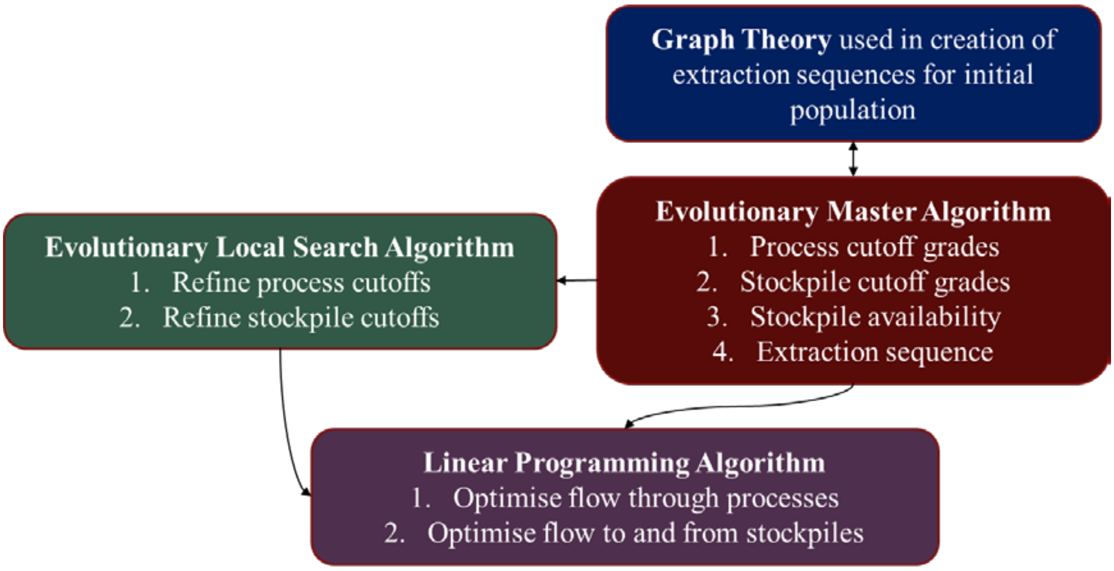


Figure 7. Maptek Evolution Strategy scheduling engine components.

4.2 Coal Production Schedule Setup

Setting up a schedule in Maptek Evolution involves a number of steps including the definition of the *flowchart, dependencies, calendar, objectives*, and *constraints*. The flowchart is used to select and define the reserve source models, number of mills, stockpiles and waste dumps to be used in the schedule. It highlights the relationship between the reserve models (block or solid models) and the mills, stockpiles and dumps, by indicating the direction of material flow (Fig. 8). All individual elements of the flowchart have parameters that need setting up.

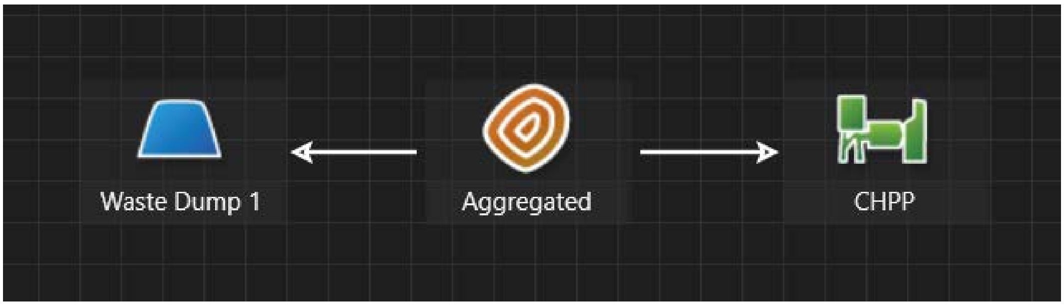
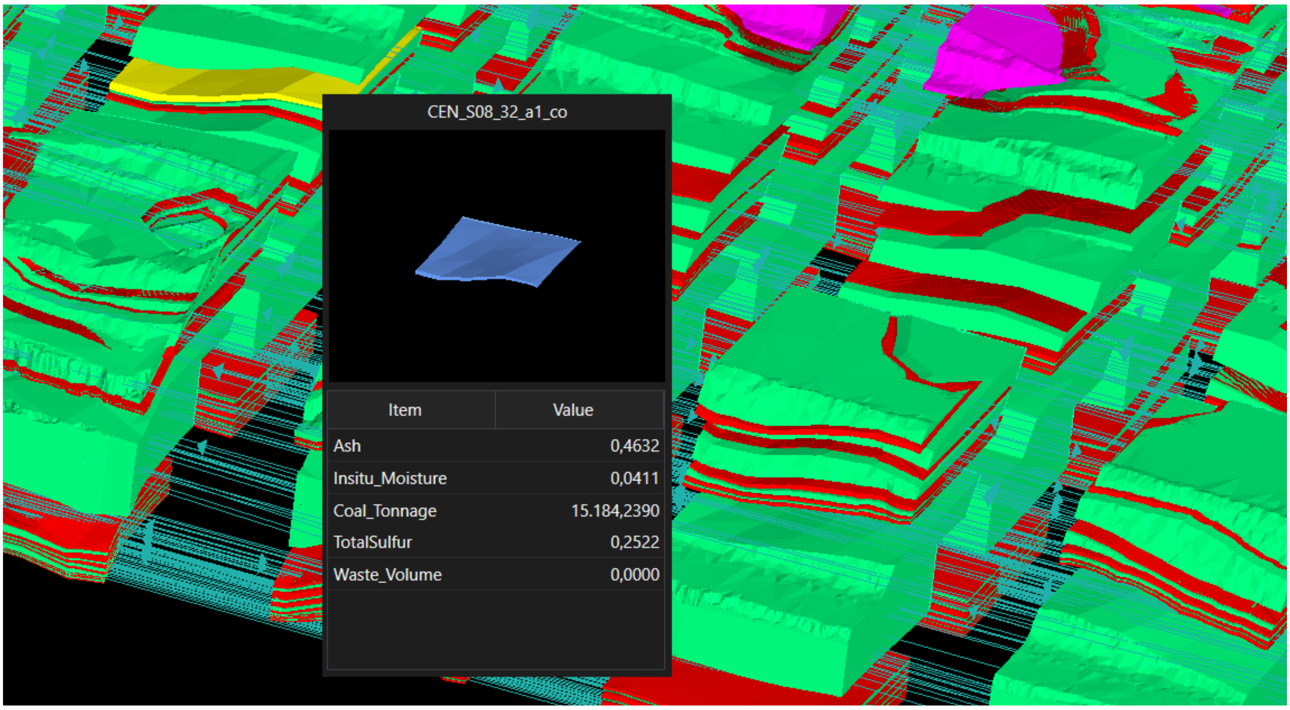


Figure 8. A simple schedule flowchart in Maptek Evolution.

In the case where the reserve model is based on solids, as in our example, Evolution allows the definition of dependencies – mining sequence controls that define the feasible sequence of extraction. Dependencies also provide the ability to allocate specific equipment for each sequence. There are three types of dependencies: *geometric* (vertical dependencies) automatically generated to prevent under-cutting in an open pit environment, *generated* dependencies based on certain rules defined by Stage, Bench, Block ID, or any other attribute, and *manual* dependencies defined interactively by the user. Dependencies can be displayed graphically in the Viewer tab (Fig. 9).


CEN_S08_32_a1_co

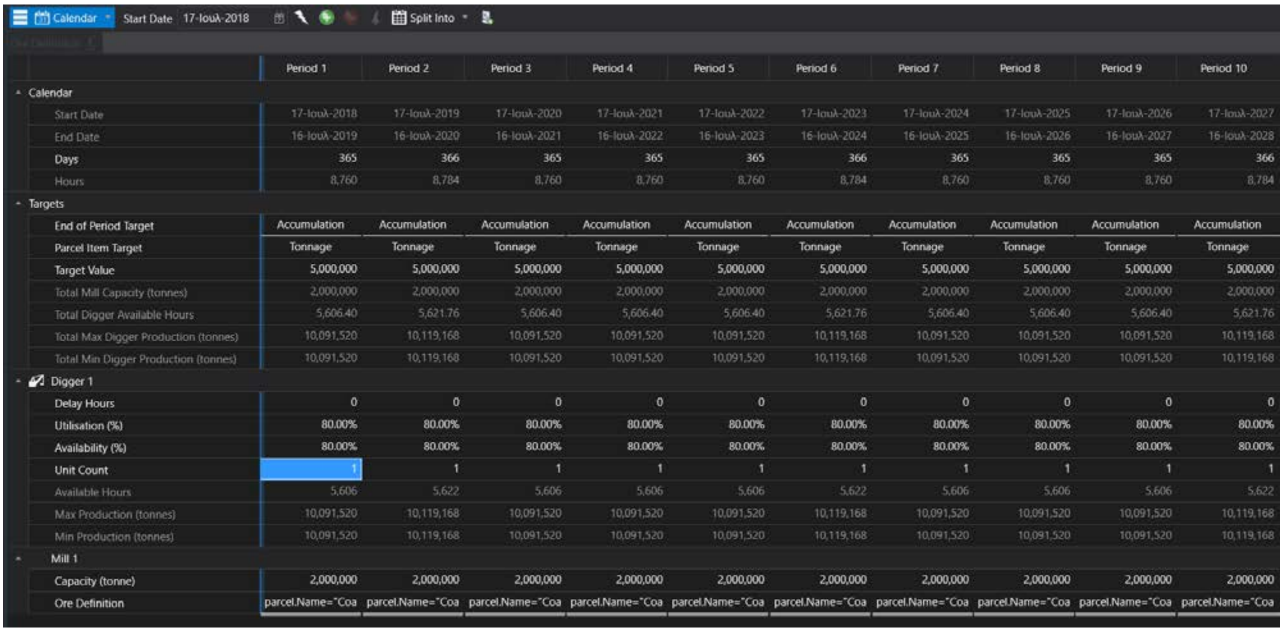
Item	Value
Ash	0,4632
Insitu_Moisture	0,0411
Coal_Tonnage	15.184,2390
TotalSulfur	0,2522
Waste_Volume	0,0000

Figure 9. Graphical display of block dependencies (arrows) and popup block details window.

The calendar is used to define the number and length of periods in the schedule. Periods can be of different lengths, capacities, and utilisation. Setting up the calendar includes defining the number of periods and their length, defining the equipment resources and target and defining the end of period flag. Figure 10 shows an example of a calendar.

Depending on the type of schedule (material movement or equipment based) the user can define how much material will be moved in each period or fix equipment production rates and hours. Material objectives are used to control the waste variance tolerance for each period of the schedule. Evolution utilises the waste tolerance to control how hard the scheduler must work on each period to achieve the movement target. A higher percentage number will generate a lower fitness, whereas a lower percentage variance will result in the scheduler refining the result based on a higher fitness value. Equipment productivity for the different parcels (e.g. coal and waste) included in each block can also be defined here.

Evolution provides a number of ways to constrain the produced schedule, including constraints such as sink rate and stage sink rate, stage availability, stage bench turnover, waste area and stockpile availability, waste area dependency and required tonnage, accumulations (stage, model, global, global process and process), and global and process blend. In our example, the stage availability constraint was applied to control the strips available in each period.



Start Date 17-Ιουλ-2018

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10
Calendar										
Start Date	17-Ιουλ-2018	17-Ιουλ-2019	17-Ιουλ-2020	17-Ιουλ-2021	17-Ιουλ-2022	17-Ιουλ-2023	17-Ιουλ-2024	17-Ιουλ-2025	17-Ιουλ-2026	17-Ιουλ-2027
End Date	16-Ιουλ-2019	16-Ιουλ-2020	16-Ιουλ-2021	16-Ιουλ-2022	16-Ιουλ-2023	16-Ιουλ-2024	16-Ιουλ-2025	16-Ιουλ-2026	16-Ιουλ-2027	16-Ιουλ-2028
Days	365	366	365	365	365	366	365	365	365	366
Hours	8,760	8,784	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784
Targets										
End of Period Target	Accumulation	Accumulation	Accumulation	Accumulation	Accumulation	Accumulation	Accumulation	Accumulation	Accumulation	Accumulation
Parcel Item Target	Tonnage	Tonnage	Tonnage	Tonnage	Tonnage	Tonnage	Tonnage	Tonnage	Tonnage	Tonnage
Target Value	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000
Total Mill Capacity (tonnes)	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000
Total Digger Available Hours	5,606.40	5,621.76	5,606.40	5,606.40	5,606.40	5,621.76	5,606.40	5,606.40	5,606.40	5,621.76
Total Max Digger Production (tonnes)	10,091,520	10,119,168	10,091,520	10,091,520	10,091,520	10,119,168	10,091,520	10,091,520	10,091,520	10,119,168
Total Min Digger Production (tonnes)	10,091,520	10,119,168	10,091,520	10,091,520	10,091,520	10,119,168	10,091,520	10,091,520	10,091,520	10,119,168
Digger 1										
Delay Hours	0	0	0	0	0	0	0	0	0	0
Utilisation (%)	80.00%	80.00%	80.00%	80.00%	80.00%	80.00%	80.00%	80.00%	80.00%	80.00%
Availability (%)	80.00%	80.00%	80.00%	80.00%	80.00%	80.00%	80.00%	80.00%	80.00%	80.00%
Unit Count	1	1	1	1	1	1	1	1	1	1
Available Hours	5,606	5,622	5,606	5,606	5,606	5,622	5,606	5,606	5,606	5,622
Max Production (tonnes)	10,091,520	10,119,168	10,091,520	10,091,520	10,091,520	10,119,168	10,091,520	10,091,520	10,091,520	10,119,168
Min Production (tonnes)	10,091,520	10,119,168	10,091,520	10,091,520	10,091,520	10,119,168	10,091,520	10,091,520	10,091,520	10,119,168
Mill 1										
Capacity (tonne)	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000
Ore Definition	parcel.Name="Coa	parcel.Name="Coa	parcel.Name="Coa	parcel.Name="Coa	parcel.Name="Coa	parcel.Name="Coa	parcel.Name="Coa	parcel.Name="Coa	parcel.Name="Coa	parcel.Name="Coa

Figure 10. Schedule calendar showing period setup, targets, mining and processing capacities.

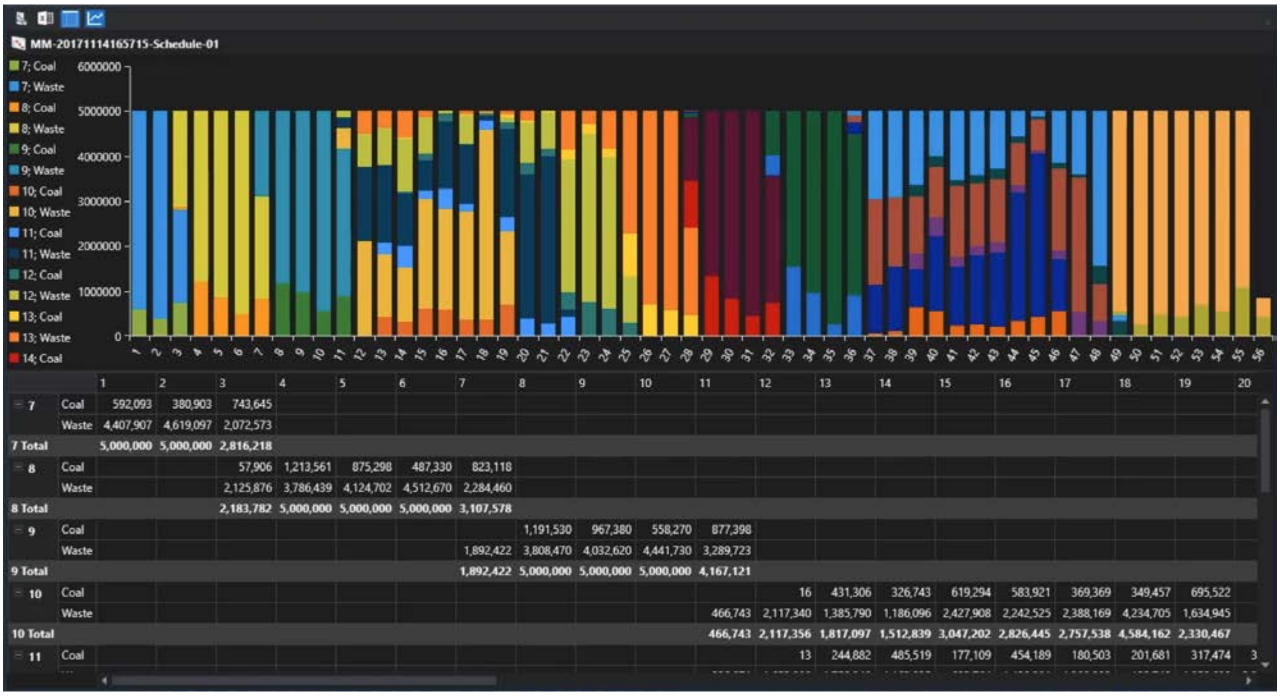
4.3 Coal Production Scheduling and Reporting

Once the schedule setup is complete and validated, Evolution goes online with the cloud servers to submit the schedule setup and reserves information for processing. Once scheduling is complete, the schedule solution(s) found is returned for further analysis and reporting. The user can decide which solution to choose depending on scheduling targets. Once the schedule sequence has been chosen, the fitness values of the scheduling targets can be viewed. Special charts are available that help identify in which periods the violations have occurred and assist the scheduler in making corrections and assessments before further processing is required. A violation within Evolution refers to the percentage difference between the target object and the schedule sequence results. These violation differences indicate to the user, the periods of the schedule requiring modification where the objectives are not being met.

A selected schedule can be viewed as a table and graphically as an animated sequence in Evolution or exported in CSV format (Fig. 11). Special reporting tools are available for quickly generated pivot tables and any other reports based on reserves and schedule information.

5 CONCLUSIONS

Coal reserves modelling and production scheduling is a procedure full of challenges. Effective use of available geological and mining data and information requires advanced software solutions with the right tools to build realistic models of coal geology and produce solid mining scenarios. Development of a sound coal resource model should be based on maximum usage of available sampling data, while converting the resource model to a reserve should be based on proper application of mining factors. Maptek Vulcan and its Integrated Stratigraphic Modelling module provide all necessary functionality to build an in-situ model of coal resources from drillhole data. Maptek Evolution takes the in-situ model and produces practical run-of-mine reserves in a flexible, yet automated, step-based workflow system which allows users to define relevant parameters. The use of evolutionary algorithms to optimise the produced schedules adds extra value and flexibility. As explained in this paper, the solution based on Maptek Vulcan and Evolution provides a complete environment for coal reserves modelling and production scheduling.



		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
− 7	Coal	592,093	380,903	743,645																	
	Waste	4,407,907	4,619,097	2,072,573																	
7 Total		**5,000,000**	**5,000,000**	**2,816,218**																	
− 8	Coal			57,906	1,213,561	875,298	487,330	823,118													
	Waste			2,125,876	3,786,439	4,124,702	4,512,670	2,284,460													
8 Total				**2,183,782**	**5,000,000**	**5,000,000**	**5,000,000**	**3,107,578**													
− 9	Coal								1,191,530	967,380	558,270	877,398									
	Waste							1,892,422	3,808,470	4,032,620	4,441,730	3,289,723									
9 Total								**1,892,422**	**5,000,000**	**5,000,000**	**5,000,000**	**4,167,121**									
− 10	Coal												16	431,306	326,743	619,294	583,921	369,369	349,457	695,522	
	Waste											466,743	2,117,340	1,385,790	1,186,096	2,427,908	2,242,525	2,388,169	4,234,705	1,634,945	
10 Total												**466,743**	**2,117,356**	**1,817,097**	**1,512,839**	**3,047,202**	**2,826,445**	**2,757,538**	**4,584,162**	**2,330,467**	
− 11	Coal												13	244,882	485,519	177,109	454,189	180,503	201,681	317,474	3

Figure 11. Schedule graph and table showing coal and waste tonnages per period and strip.

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