ABSTRACT: A complete Mine Planning solution often requires the integration of different "specialist" packages. It is necessary to understand what each package brings into a system and how they relate to each other in the mine planning and scheduling process. In isolation, each package may fall short of the final solution. However, when integrated with strategy, they form a powerful Mine Planning and Scheduling system. A step-by-step procedure is presented as a "model" for the mining engineer to follow in arriving at an optimized mine plan. The optimization process presented in the paper is capable of achieving all possible schedule objectives given the limitations in design and deposit. Obviously, as the deposit is depleted, the possibility that certain constraints can be met is reduced. This requires careful consideration in the scheduling optimization cycle.

1 INTRODUCTION

1.1 The Concept

In recent years, it has become a common approach in mine planning to use multiple software packages to achieve better results. The approach described in this paper consists of a general mining package and two mine scheduling and optimizing packages that operate on different stages of the optimization and scheduling process (Fig. 1).

Vulcan’s Envisage program is used as the General Mining Package (GMP). This software is used in basic block model preparation, manipulation, as a data transfer medium, and for schedule visualization; Pit Optimization and first-pass Schedule Analysis is performed using Whittle 4X Multi-Element (Analyzer). Various features are showcased including the user friendly Proteus GUI and the new Blending Module. The Milawa Scheduling algorithm is used in an example case study.

Final Schedule optimization and blending is performed in Vulcan’s Chronos Scheduling and Optimization package.

1.3 The Model

There are three "streams" in the mine planning and scheduling model:

Conceptual Design and Scheduling in Whittle: This involves block model preparation, variable export/import, pit optimization, mine design, scheduling and visualization;

Optimizing and Scheduling the Conceptual Whittle Design in Chronos: This involves passing the pit design back to Vulcan through push-back variables, reserving the block model against these variables, building a Chronos scheduling workbook in Chronos, and scheduling using the Chronos Optimization module. Results are transferred back to Vulcan for visualization.
Final Pit Design in Vulcan and Final Schedule Optimization in Chronos. This is the most detailed and time consuming stream in the model. It involves the use of all previous results to i) create a final phased pit design in Vulcan, ii) transfer to a Chronos scheduling workbook in iii) optimize and schedule in Chronos and iv) visualization in Vulcan.

In the following paragraphs these streams will be discussed in detail using an example case study from a Banded Iron Formation (BIF) deposit in the US (Slade 2001).

2 CONCEPTUAL DESIGN AND SCHEDULING IN WHITTLE

2.1 Preparation of the Block Model in VULCAN

Whittle requires a number of variables to exist in the VULCAN block model. These variables necessary for pit optimization are the following:

1. A pit slope variable containing 'slope zone' numbers can be used. Alternatively, slopes can be set by rock type.
2. A lock type variable is necessary for the different material types e.g. OVB, WST, ORE, HGR, LGR.
3. Whittle 4X Multi Element does not require a Net $ Value Product element guide (e.g., Au, Ag, Cu, or Recovery). These are passed directly from Vulcan to Whittle and used within the program to calculate block values.
4. Ten element variables can be set up to suit any function you require. The obvious product elements might include Au, Ag, Cu, or Fe. Less obvious elements might include PIT (used for haulage calculations), ROYL (used to calculate loyalty costs), and RECV (recovery variable used to determine recovered product). The advantage of this Multi-Element feature is that it is easy to perform what-if and sensitivity variations without having to go back to the original block model.

2.2 Vulcan Mode I Export to Whittle

In this step, pit optimization variables are exported from Vulcan (Fig 2).

In our BIF example, the primary product grade is WTRC and is described as recovered product tons divided by processed ore tons. Rock types LLTC and LHTC correspond to the mineable low-grade and high-grade ores respectively. UHTC and ULTC are un-leased ore grade material and therefore excluded from the ultimate pit and scheduled mining. All other rock types are waste material (Fig 3).

<table>
<thead>
<tr>
<th>ELEMENTS</th>
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<tbody>
<tr>
<td>WTRC = Product Wt Recovery</td>
</tr>
<tr>
<td>EXWR = Exploration Wt Recovery</td>
</tr>
<tr>
<td>SI02 = Silica in Concentrate</td>
</tr>
<tr>
<td>MGPE = Mag. Suscept., Chude</td>
</tr>
<tr>
<td>SPER = Indication of Oxidation</td>
</tr>
<tr>
<td>RATO = Indication of Oxidation</td>
</tr>
<tr>
<td>KWHT = Grindability measure</td>
</tr>
<tr>
<td>TACH = Ore Haul unit Cost</td>
</tr>
<tr>
<td>WSTH = Waste Haul unit Cost</td>
</tr>
<tr>
<td>ROYL = Royalty Cost</td>
</tr>
</tbody>
</table>

Figure 2: Formats tab in Whittle 4X
2.4 Whittle Pit Design Selection

This step constitutes the "conceptual" mine design sequence:
1. Ultimate Pit: We select an Ultimate Pit from the Pit-by-Pit Graph. There are many ideas on how to achieve this. Some include:
   - Max Best Case Value,
   - Required Tonnage,
   - Product Price Point,
   - Max Specified Case Value

2. Push Backs (Phases): We select a sequence of Push Backs (Pit Phases) from the Pit-by-Pit graph (Fig 5).
3. Minimum Mining Width: Whittle 4X allows the user to apply the concept of 'Minimum Mining Width' (MMW). This has the effect of "redistributing" tonnage between the chosen Push Backs in order to accommodate the MMW.

Also, using MMW renames the Push Backs from Pit Number to Push Back number starting from 1 (Fig 6).

The above report shows the tonnages present in each Push Back - originally after selecting the pits and after the MMW is applied. It is a "juggling" act to apply MMW and find a balance between the Push Backs. In this case, a balance was found using Pits 9, 16, 25, and 37. A MMW of 300 t was used in this instance.

Care must be taken when applying the MMW function, especially when optimizing existing pits. Re-distributing tonnages can have the unexpected result of "covering" up exposed inventory present in operating benches.

Redistribution to PB 1

Exposed Ore now covered by upper waste benches previously in PB2.

New Push Back 1 is increased to honor MMW and now includes upper waste benches.

Figure 6 Pushback tonnage redistribution
Using the Push Backs (Pit Phases) selected from Pit Optimization, schedule using three techniques available in Whittle 4X Analyser. In the case of the BIF Project scheduling objectives were:

1. Must achieve stated product output - X MT,
2. Minimize and balance total mining (eliminate stripping spikes)
3. Limit the ore throughput to a maximum of Y MT
4. Blend the High Low grade ores to 70% W%.
5. Maximize NPV

Whittle allows the scheduling of the conceptual mine design inherent in the Push Backs and Benches. The physical problem is set up, with all the spatial integrity of pit slopes and Bench-Push Back Precedence automatically in the Whittle model.

1. **Fixed Lead**
   This schedule mines out the Phases sequentially, with a fixed lead between benches in adjacent Push Backs (PB). A zero lead specified in Whittle mines out and completes each PB sequentially. This technique is often termed 'Best Case' (Fig 7).

2. **Milawa NPV Maximizer Algorithm**
   This scheduling method mines the benches in an optimum sequence maximizing NPV. Note the increase over 'Best Case' is +36% (Fig 8).

3a. **Milawa Balanced**
   This technique mines the benches in an optimum sequence, attempting to balance out mining requirements, while trying to maximize NPV. Note that this has come at a cost of 21% in NPV compared with the Milawa NPV method (Fig 9).

3b. **Milawa NPV and Sequential Lead Schedules with a Mining Limit**
   Apply a Total Mining Limit (Fig 10).

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Figure 7 Fixed lead scheduling

Figure 8 Milawa NPV maximator algorithm

Figure 9 Milawa balanced scheduling algorithm
Sequential Lead

- Fails to meet Product tons in early years;
- Fails to meet ore tons in early years;
- Fails to blend ore types in early years;
- Unworkable in the critical early years.

Milawa NPV Maximizer Algorithm

- Stripping minimized in early years;
- Fails to meet ore production in later years;
- Fails to meet Product tons in later years;
- Ore type blend is very poor;
- Basically unworkable - yet makes the most money? (Fig. 11).

3c. Milawa Balanced with Mining Limit

Limit total mining to Z MT. Note that we now have a "balanced schedule" which meets the #1 objective of making required product tons. Objectives #3 (ore mining) and #4 (ore type blend) are still off target (Fig. 12).

2.6 Blending in Whittle

In 4X Version 2.2, Whittle have added a new blending module. The parameters for the example BIF problem were entered and the module applied. We are able to make the 30:70 Low:High grade ore blend. However, it is at the expense of other schedule objectives, i.e., Product and Ore Tonnage targets (Fig. 13).

2.7 Visualization in Whittle

Whittle 4X Proteus Environment includes a 3D Visualization module. A "Mining Sequence and 3D Visualization file" is specified on the Definition tab for Whittle Schedule graphs.

The mining sequence file produced (.MSQ) can be read by the 3D Visualization module. A pit shell representing the mining progress to the end of each scheduled period is displayed and can viewed inter-
actively. It is also possible to display colored block model slices along with the pit shell surface (Fig. 14).

Once the import is complete, the engineer can contour (Grade Shell) the "first touch" blocks variable. This shows the first period in which a block is "touched" by mining and gives the engineer some idea of the sequential order of "bench by bench" mining (Fig 15).

2.8 Whittle Schedule Visualization in Vulcan

The Mining Sequence File (MSQ) generated in Whittle contains all the information necessary to create a Vulcan Animation. However, currently the relevant information must be extracted using CShell and other programming utilities. Pre-processing is as follows:

1. Export the MSQ file from Whittle 4XPE.
2. Remove all the "parcel" records using GREP with a reverse search on the PROCESSING path held (last field).
3. Run the "pendxtpl.pl" PERL script on the "PP37_MW300.rep" tile to produce a series of mining "touch" files: "file01.rep", "file02.rep", "file03.rep", "file04.rep". The number of files produced, which contain data, represents the maximum number of bench/block "mining touches" found in the schedule (benches mined over a series of production periods). This procedure only handles up to 4 mining "touches" per bench.
4. Run the "convert_ijk.csh" CShell script which executes the "schedule.awk" AWK script to convert the $ijk$ coords to xyz coords. The "schedule.awk" is customized to the translation implied in the Block Model header used and adjusted for the $ijk$ offsets to block centroids.
5. Import the ASCII files into the GMP block model. You will need 2 block model variables per "touch" file. One to contain the period in which a block is first touched (eg, msq01), another to contain the % mined in that period, and so on, for touch 2, 3, and 4.

2.9 Conclusions

Whittle is a very powerful tool when the LG pit optimization tools are combined with the outstanding time-value-of-money (DCF) and scheduling analysis routines. They are very easy to set-up and use within the new Proteus Environment.

Many different types of schedules can be run on the chosen conceptual pit design (Push Backs or Phases). These allow the user to focus on the various scheduling objectives. The execution of the various schedules is so fast that a user can run as many as necessary to draw initial conclusions on the value of the prospect in hand.

The "Milawa Balanced" schedule has been shown to get closest to the schedule objectives for our example Banded Iron Formation project. Whittle 4X now provides a simple, yet powerful method for visualizing the Pit design and Schedule.

The scheduling output from Whittle can be imported into Vulcan for animation.

Whittle's new blending routine enables the user to quickly establish the effect of blending on the schedule.

Whittle scheduling does not provide a final solution to multi-variable scheduling constraints. Therefore, the next Model Stream is to export the Whittle design to Chronos where it is possible to apply constraints to multiple variables, divide the conceptual design up into multiple pits, and solve complex blending problems.
3 OPTIMIZING AND SCHEDULING THE CONCEPTUAL WHITTLE DESIGN IN CHRONOS

3.1 Preparing the Vulcan Block Model for Chronos

This step provides Chronos more choices as it seeks an optimum solution to the multiple constraints applied. The actions included are:

1. Import the Whittle Pit Optimization results into the Vulcan model. This constitutes the Conceptual Mine design.
2. Add other "key" variables (in addition to pushback) required by Chronos for reserve block location. These variables are pit and bench. This will allow the engineer to separate the logical pits and allocate blocks to the benches identified in whittle.
3. Divide the deposit into pits using solids flagging in Envisage.
4. Add the block "value" variable (Cash Flow). Use the same formulation as that used in Whittle 4X. This must be verified.
5. Generate a Reserve Inventory for Chronos using Block - Reserves Advanced. This will include the key breakdown fields: Pit, Pushback, Bench, the products to be scheduled, the grades to be reported, and the cashflow resulting from the mining of each bench.

3.2 Set up a Chronos Scheduling Workbook

A brief outline of the steps required in setting up a workbook follows:

1. Start Chronos and open a new Workbook.
2. Import the Vulcan Reserve Dump file (.DMP) into a Reserve Sheet.
3. Insert derived columns into the Reserve Sheet.
4. Format the inserted columns and set the type and weighting fields.
5. Generate a Period Calendar and set the scheduling periods.
6. Create a single Chronos Destination called MINE. This is a key step in that all mission critical variables must be defined here.
7. Create a single Chronos Process called EXCAVATE.
8. Create a Process Lookup Table called TABLE.
9. Create a Push Back Ratio table called RATIO. This table sets, i) the minimum proportion of any one bench to be mined in any one period, ii) the proportion of the bench above to be mined in advance of the current bench.
10. Create a General Sheet and populate the lower half with an automatic Period Summary.

3.3 Run Optimization and Schedule the Results

The secret of successful Optimization and Scheduling in Chronos is to approach it as an iterative "hands on" procedure. It is a cyclical process in which the engineer:

1. Identifies a set of schedule constraints, according to the schedule objectives, and saves them in named Constraint Sheets.
2. Builds a list of available mining benches in a Chronos Task.
3. Sets up the problem, specifying the periods to be optimized, the constraint tables to be used in each period, and other conditions on the optimization, eg, whether to allow partial mining, Push Back Ratio tables to be used, etc.
4. Creates the "bei" and "bco" optimization files which contain the problem (bei) and provide a file to record the result (bco).
5. Solves the optimization.
6. Loads the result (bco) into Chronos Result Tables (CRT).
7. Schedules the result (from the CRT) and observes the schedule in the Summary General Sheet.

Schedule Optimization in Chronos is an iterative process. The engineer needs to be constantly reviewing and testing the result while optimizing. Rarely is the problem solved by pushing a button and walking away. (Fig. 16)

Figure 16 Chronos schedule optimization cycle

It appeared that there was further potential to reduce the upper mining constraint, thereby increasing NPV. The only constraints used on this schedule are
the range of Gold Metal production, and Ore less than 4.75Mt. The objective is to test what the project can theoretically create in NPV.

Attempt to balance the Total Mining tons by carefully reviewing the existing schedule and finding the "hurdle" points of the schedule. The result of some trial and error optimization runs, using constraint variations, is a set of Total Mining constraints which solve. The illustration below shows the Optimized Schedule 02 (Fig. 17).

Figure 17 Balanced schedule in Chronos. Using Chronos optimization the schedule can be balanced for only 0.3% loss in NPV

3.4 Create an Animation in Vulcan for Schedule Visualization

VULCAN provides functionality for creating schedule sequence animations. In our example we need to grade shell each individual mining bench per pit, pushback, and bench. Because the Chronos reserve was taken directly from the block model, keying off the three variables: pit, pushback, and bench, trian-
gulations do not exist for the scheduled entities. A CShell script can be used to batch the Grade Shelling routine which creates the triangulations all in one step.

The next step is to rename the Pit-Pushback-Bench triangulations resulting from the Grade Shelling process to conform to the key field naming convention in the Chronos Reserve Sheet. The naming convention used on the BIF project is: P<pit#>_P<pushback#>_B<bench#> e.g., P01_01_01.00t.

Finally we run a Perl script which builds a Vulcan animation file by matching the Chronos Reserve Sheet keys with the triangulation and displaying it in the period in which it was mined. The Display Attributes option in Chronos is used to color the bench triangulations by Period.

3.5 Conclusions

Using the designs generated in Whittle and the schedules generated in 4X Analyser, schedules can be optimized using any number of constraints in Chronos. The up-front scheduling work in Whittle is invaluable in setting the scene for the final optimization work in Chronos.

Vulcan provides powerful tools for easily subdividing the Whittle Push Backs into Multiple pit models. This provides more alternatives for optimization as illustrated in the BIF project.

The Chronos Optimization-Scheduling process is cyclic and should be viewed as an iterative process. Chronos Optimization is capable of achieving all of the Schedule objectives given the limitations in design and deposit. Obviously, as the deposit is depleted, the possibility that certain constraints can be met is reduced. This requires careful consideration in the Scheduling Optimization cycle.

Vulcan provides the engineer many ways in which to animate schedules from Chronos for visualization, checking and presentation.

4 FINAL PIT DESIGN IN VULCAN AND FINAL SCHEDULE OPTIMIZATION IN CHRONOS

All the previous schedule optimization is done to give the engineer an understanding of the problem, the possibilities, and the result to expect once this "stream" is complete. The results illuminate the path ahead so the detail design work can follow previous work based on sound principles (Rodriguez, 2001).

The user can maximize NPV (Net Present Value) and at the same time it can follow blending constraints, keeping stripping ratio at a constant rate until the later years in the life of the mine where it drops off and keep positive cash flow.

Figure 18 Graphical display of schedule in VULCAN

REFERENCES
