Optimized Open Pit Mine Planning and Scheduling

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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.

I INTRODUCTION

1.I *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. I).
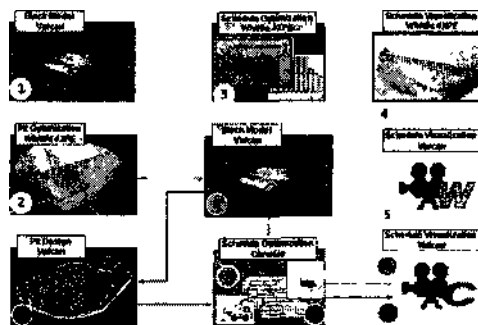

Figure I Optimized mine planning and scheduling model

1.2 *Software Components*

Three major software packages are discussed and illustrated here:

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) transfet to a Chronos scheduling workbook 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 eg OVB WST ORE HGR, LGR

3 Whittle 4X Multi Element does not require a Net $ Value Product element guides (eg Au Ag, Cu, Fe and Recovery) are passed directly from Vulcan to Whittle and used within the program to calculate 'block values

4 Ten element variables can be set up for just about 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), 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 Model Export to Whittle*

In this step we export pit optimization variables to Whittle MOD format The Formats tab in 4X shows the 10 elements 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)

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ELEMENTS	
WTRC = Product Wt Recov	
EXWR = Exploration Wt Recov	
SIO2 = Silica in Concentrate	
MGFE = Mag Suscept Crude	
SFER = Indication of Oxidation	
RATO = Indication of Oxidation	
KWHT = Grindability measure	
TACH = Ore Haul unit Cost	
WSTH = Waste Haul unit Cost	
ROYL = Royalty Cost	

Figure 2 Formats tab in Whittle 4X

Figure 1 The Summary tab shows the 14 rock types exported

2 3 *Pit Optimization in Whittle 4XPE*

Setting up of the relevant expressions, cost model and revenue factors is required to run pit optimization in Whittle 4X Proteus Environment Once the setup is complete optimization can take place in a step by step procedure that is displayed graphically in a tree-like graph (Fig 4)
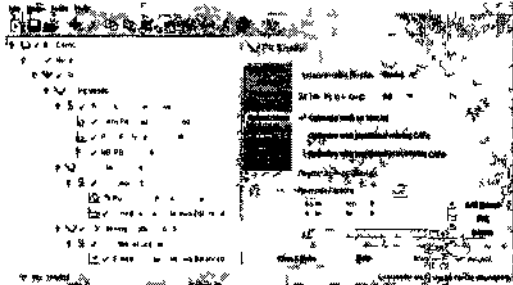
Figure 4 Optimization in 4X

Push Back)	Original Tonnage	Revised Tonnage	Variation	Percentage
	x1000	x1000		
1	148802	270093	121290514	61 8
2	244410	264073	19652842	8 t
3	272560	208783	-23776476	-10 2
4	321450	214346	117104150	-35 3
Total	957222	957294	72730	0 0

2 4 *Whittle Pit Design Selection*

This step constitutes the "conceptual" mine design sequence

I Ultimate Pit we select an Ultimate Pit from the Pit-by-Pit Giaph There are many ideas on how to achieve this Some include

- Max Best Case Value,
- Required Tonnage,
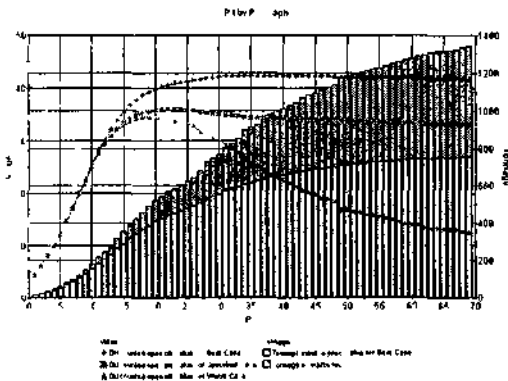- Product Price Point,
- Max Specified Case Value

Figure 5 Pit by pit graph in Whittle 4X

2 Push Backs (Phases) we select a sequence ol Push Backs (Pit Phases) Irom the Pit-by-Pit graph (Fig 5)
3 Minimum Mining Width Whittle 4X allows the user to apply the concept ot 'Minimum Mining Width' (MMW) This has the effect ot "iedistiib-uting' tonnage between the chosen Push Backs m oidei to accommodate the MMW

Also, using MMW renames the Push Backs tiom Pit Number to Push Back numbei staiting from 1 (Fig 6)

The above leport shows the tonnages present in each Push Back - originally atter selecting the pits and atter 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 ot 300 tt 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 ot "covering" up exposed inventory present in operating benches
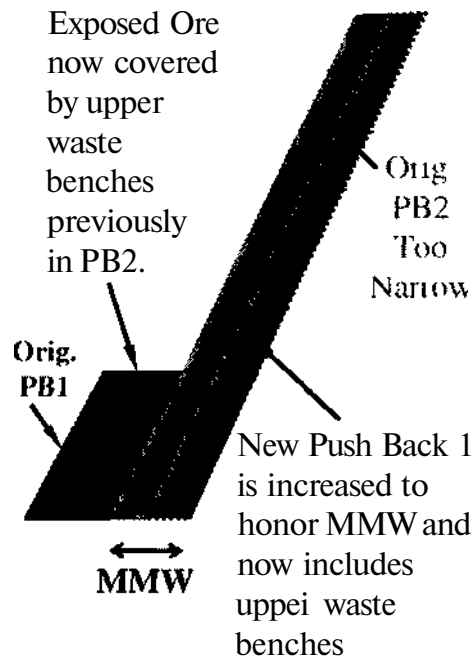
Redistribution to PB 1

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

Orig. PB1

MMW

Oiig PB2 Too Nariow

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

Figure 6 Pushback tonnage redistribution

Using the Push Backs (Pit Phases) selected trom Pit Optimization, schedule using three techniques available in Whittle 4X Analyser In the case ol the BIF Pioject scheduling objectives wete

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

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

I Fixed Lead

This schedule mines out the Phases sequentially, with a hxed 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 teimed Best Case' (Fig 7)
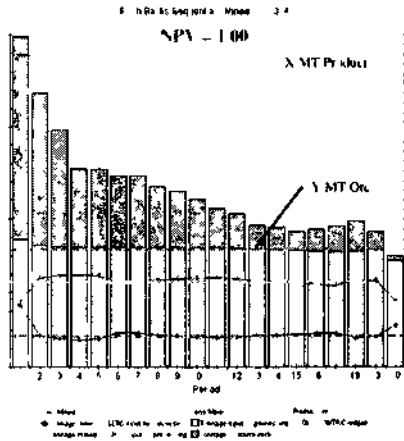

Figure 7 Fixed lead scheduling

2 Milawa NPV Maximizer Algorithm

This scheduling method mines die benches in an optimum sequence maximizing NPV Note the inuease over 'Best Case" is +36% (Fig 8)
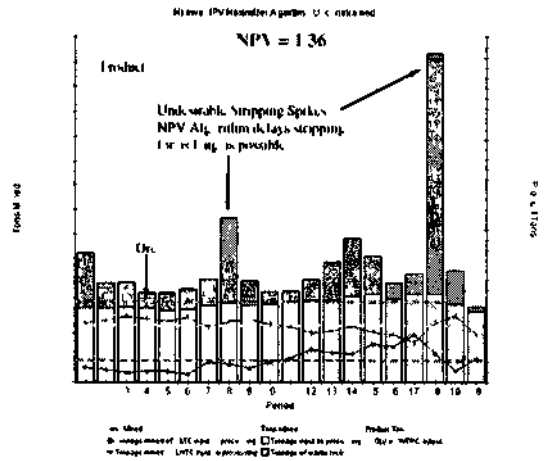

Figure 8 Milawa NPV maximizer .Ugonlhm

3a **Milawa Balanced**

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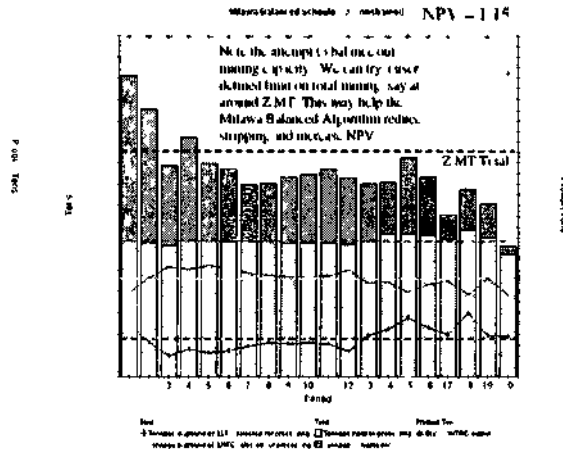

Figure 9 Milawa balanced scheduling algorithm

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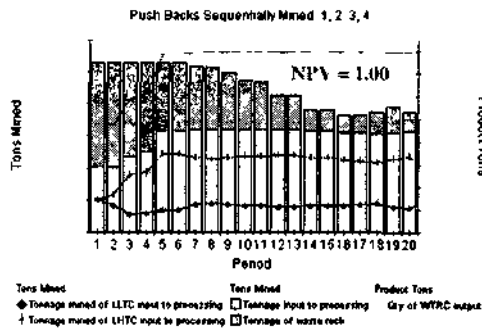
Apply a Total Mining Limit (Fig 10)

Figure 10 Milawa NPV and Sequential Lead schedules

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:
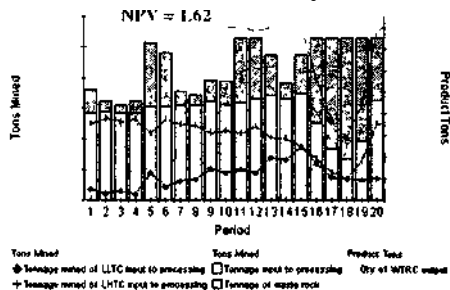- Unworkable in the critical early years.

Figure 11 Milawa NPV

Milawa NPV

- 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 ot making required product tons. Objectives #3 (ore mining) and #4 (ore type blend) are still off target (Fig. 12).
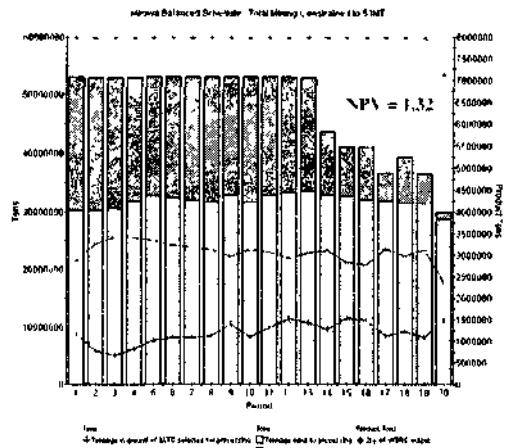

Figure 12 Milawa balanced with mining limit

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).
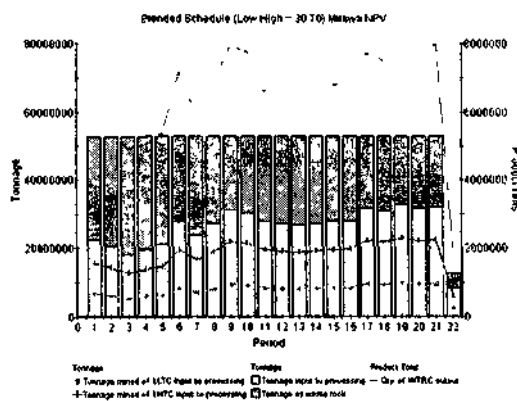
Figure 13 Blending in 4X

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-

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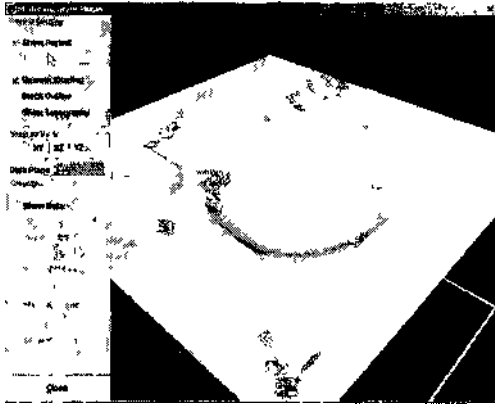actively. It is also possible to display colored block model slices along with the pit shell surface (Fig. 14).

Figure 14 Visualization in Whittle 4X

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 "penodspht.pl" PERL script on the "PP37_MW300.rep" tile to produce a series of mining "touch" files: "fileOl.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, msqOl), another to contain the % mined in that period, and so on, for touch 2, 3, and 4.

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).
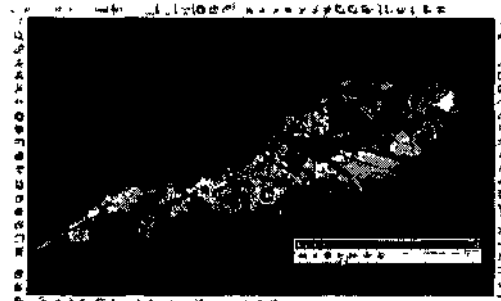

Figure 15 Visualization of Whittle schedule in VULCAN

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.

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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 he 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.
11. Set Block Precedences and check in the Reserve Sheet. Convert Precedences to Block Ordering Numbers.

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)
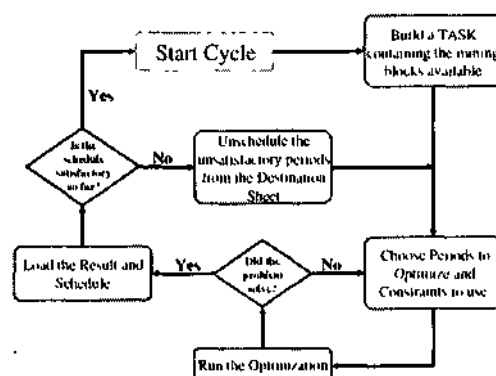

Figure 16 Chronos schedule optimization cycle

It appeared that there was further potential to reduce the upper mining constraint, thereby increasing NPV. The only constraints used on this schedule are

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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 mns, using constraint variations, is a set of Total Mining constraints which solve. The illustration below shows the Optimized Schedule 02 (Fig. 17).
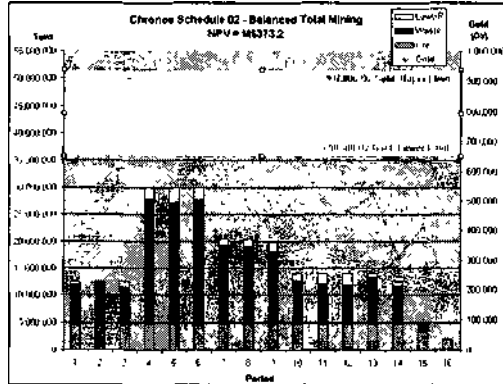

Figure 17 Balanced schedule in Chronos. Using Chronos Optimization the schedule can be balanced for only 0.3% loss in NPV

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,** triangulations 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#>_<pb#>_<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

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Rodriguez. F.. 2001. Implementing Whittle results to Pit Design. Long Term Scheduling and Maximizing NPV using Chronos Optimization Package. *VI Vulcan Users Conference.* Maptek South America.

Slade. R.. 2001. Optimized Open Pit Mine Planning and Scheduling using Vulcan. Whittle, and Chronos. *VI Vukim Users Conference.* Maptek South America.

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