WHERE FOUR-D ENDS...

Richard Wooller[1]

ABSTRACT

RTZ Consultants (RTZC) in its many guises has been using software to design open pits for many years. The earliest version of its Open Pit Design program (OPD) was developed during the 1970s.

The early stages of the process of pit design using OPD has parallels in Four-D. Starting from a block model of the orebody trials determine the best location for the initial pit. There then follows a stage of incremental analysis to determine ultimate pit. Finally a set of working pits is developed within the ultimate outline in order to generate a production schedule. Now RTZC uses Four-D to perform these tasks when first evaluating a project.

Used intelligently, rock codes and processing methods can model subtleties in pit design. Before Four-D commences, block models are built using RTZC's software. This standard format is the source for building Four-D models.

RTZC use Four-D optimization and analysis as the first stage in the pit design process. Where Four-D finishes RTZC's software - OPD and OGREPlus - takes over. Four-D pit shells are transferred to these systems as the basis for further design.

Some examples are presented of the application of Four-D by RTZC together with some lessons learned.

INTRODUCTION

Whittle Four-D pit optimizing software is used around the world as an open pit mine planning tool. However in many cases mining engineers, when presented with the output from the system, are unsure as to what to do with it. This is particularly the case in operating mines where the engineer has the task of producing detailed designs for pushbacks, access to the pit and production schedules over the life of the mine.

Engineers at RTZ Consultants Ltd (RTZC) have been performing these tasks over many years. In that time they have developed several software packages to assist them in this task. The combination of mining engineering skills and in-house software was the reason why the organisation was slow to adopt pit optimizing techniques such as the cone miner and Lerchs-Grossmann algorithms.

1. RICHARD WOOLLER
Qualifications: BSc (Hons) Mining, University of Leeds, UK.
MSc Computer Science, University of Bradford, UK.
Membership: Institution of Mining & Metallurgy, UK.
Experience: Nchanga Consolidated Copper Mines Ltd, Zambia. Rock Fall Company Ltd, UK. Irish Base Metals Ltd, Republic of Ireland. Compower Ltd, UK. Hamersley Iron Pty Ltd, Paraburdoo, Australia. ZC Mines, Australia. 6 years as a Mining Engineer on operations and mine planning; 14 years developing computer systems in the mining industry for geology and mine planning applications.
Currently: Senior Consultant Mining Engineer, RTZ Consultants Ltd, UK.

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The change came with the development by Whittle Programming of their Four-D pit optimizing package and the availability of fast cheap computer hardware. RTZC decided to purchase a licence to use the system for the evaluation of mining projects. The objective, as in all of RTZC's endeavours, was to ensure the maximization of the return from assets for their clients both within and external to the RTZ group.

When purchasing Four-D, RTZC realised that it was not a complete open pit mine planning package but a tool to complement its other systems. This has been reflected both in the way that Four-D has been applied to open pit design and in the software tools that have been developed in-house to integrate it with its own software.

This paper sets out to describe the use of Four-D at RTZC. The open pit mine planning philosophy is reviewed together with the systems developed in-house to implement it. The integration of Four-D into this process is explained. Additional topics include graphical presentation of Four-D pits, the effect of discounting on the ultimate shell and the effect of minimum cut widths. Finally some examples are given of its use by RTZC on projects.

A note on names. RTZ Consultants Ltd is a wholly owned subsidiary company of RTZ Technical Services Ltd (RTZ TSL) which in turn is ultimately owned by The RTZ Corporation PLC. RTZ TSL trade under the name of RTZC when supplying consultancy services to companies outside of the RTZ group. Also software produced by the company is owned through RTZC. Throughout this paper reference to RTZC can be taken as referring to both RTZC and RTZ TSL.

THE OREBODY MODEL

Probably the main reason why Four-D has been successfully integrated into the RTZC system is the degree of commonality between their deposit model formats. RTZC uses a standard regular block model throughout its systems. This is referred to as the OPD format from the Open Pit Design program in which it was first used.

• THE OPD MODEL

For open pit design three classes of attributes are included - rock types, mineral/metal grades and density. In addition to modelling the distribution of rock types throughout a deposit the rock model also serves to model topography, air being a special rock type.

The rock model is also used to describe a pit design by flagging blocks that have been mined with a pit number, similar to the logic used for the Four-D results file. Each block can also include the year in which it is scheduled to be mined.

Over the years several programs have been developed to load data into the OPD model format from sources such as ASCII files containing the co-ordinates and value for each block, and gridded seam data. In addition RTZC has developed systems for geological modelling which generate OPD models.

• BUILDING FOUR-D MODELS

This standard format is the source for building Four-D models. A software module takes as its input the OPD block model containing rock codes, one or more grade models and optionally a density model, and writes a Four-D model file. Each four character rock type code that identifies a parcel can be generated from the OPD rock code, a grade interval derived from the first (primary) grade model or a combination of these factors. Where the algorithm for determining the code is more complex, the program can be easily extended to include special methods for specific projects.

Used intelligently, rock codes and processing methods can model subtleties in pit design. Hanson (1994) has demonstrated one use with the modelling of differing reserve categories.

PIT DESIGN - INCREMENTAL ANALYSIS

The pit design philosophy used at RTZC has been described by Mathieson (1982). It involves a two stage approach - ultimate pit definition using incremental analysis and pit sequence planning to define a set of pit phases for scheduling ore and waste. For both these stages RTZC uses its Open Pit Design program (OPD). This software was first developed during the 1970s and has since undergone a continuous process of project driven enhancement, leading to the latest interactive version.

Incremental analysis is used to determine the ultimate pit limits (and therefore mining reserves). It gives an indication of the value of a project and forms the starting point for working pit designs for pit sequencing.

• THE TRADITIONAL APPROACH

Pits are designed using a process of trial and error. The engineer inspects plans and sections of the model showing the distribution of grades and the topography. From these he determines the best location for the base of the initial pit. This is digitised into OPD as a perimeter. OPD projects this perimeter, bench by bench, to surface through the block model of the deposit, evaluating the pit design as it goes. The slope angle applied at each point along the perimeter is determined by either the rock type at that point or the pit sector in which the bisector of its adjacent chords falls.

Evaluating a pit design uses concepts similar to those found in Four-D. The cost of mining a block can be varied by rock type and by depth, through haulage costs which can be specified by bench and the destination of material - ore, marginal or waste. Processing costs can be varied by rock type in a similar way to the processing methods in Four-D.

Starting bases can be moved vertically and horizontally in a set of iterative runs. This is in essence a manually driven cone-miner. OPD served this purpose before the advent of pit optimizing programs. Second and subsequent bases can be added to the pit to produce working extensions.

Once the starter pit has been determined the design is expanded incrementally. Each increment is evaluated for profitability. A crude discounting routine is available to evaluate each incremental pushback. An ultimate pit shell is developed which includes the starter pit and all the profitable increments.

The manual methods outlined above have served RTZC well. A competent mining engineer using these tools can arrive at a solution that is extremely close to those obtained using a pit optimizer. He can also take other factors into consideration that it may not be possible to model within a pit optimizer. Cases where Four-D has been applied following manual designs using the procedures outlined above have confirmed the engineer's designs. This serves to give confidence in both the competence of the engineers and in Four-D as a pit design tool.

The disadvantages with this method are twofold. It is a time consuming trial and error process. There is also the danger that profitable increments may include unprofitable material and likewise increments that are rejected as unprofitable may have included profitable zones. This can be overcome, to some extent, by using very small increments. However this adds to the time taken to arrive at the ultimate pit.

• THE APPLICATION OF FOUR-D

There are classes of deposit where the relationship of block grades and topography may lead to a solution that is not intuitive, needing a lot of trials to determine the best pit. No pit produced using OPD could ever be demonstrated as being optimal in that it might always be possible to improve the value of the design in some way. This is where Four-D comes into its own.

By using Four-D at this stage, RTZC has eliminated the need to perform incremental analysis in order to obtain an indication of the size of the project, the likely shape of the pit and the project value. Depending on the objectives of the project in many cases this is sufficient. Should RTZC need to proceed to more detailed planning, the pit shells generated by Four-D provide the starting point for pit phase planning as described below.

PIT SEQUENCE PLANNING

Orebodies are normally mined in stages commonly called phases, working pits or pushbacks. These are the basic building blocks on which detailed production schedules are made. The objective of phasing is to produce a mining sequence that maximizes the net present value of the project. This is achieved by concentrating mining in high grade zones in the early years and by deferring some of the waste stripping.

Where a pit design cannot be divided into practical mining phases, all waste above the first ore bench must be stripped during the pre-production period. This is approximately equivalent to the 'Worst Case' scheduling option in the Four-D analysis program FDAN. If phasing is possible then some of the waste stripping and hence negative cash flow can be deferred until the production period. Phases are sequenced in order of declining cash flow to eventually reach the ultimate pit limits. At the extreme this approaches the FDAN 'Best Case' scheduling option.

• THE TRADITIONAL METHOD

One of the products of an OPD run is a mined-out rock model. For phase or working pit planning the mined-out model of the ultimate pit is 'inverted'. Blocks that were flagged as mined are restored to the unmined state and unmined blocks are flagged as air. In OPD pit perimeter points that occur in air are projected vertically. Thus any pit projected within this model is confined to the model.

Within this model a set of working pits is developed starting at the most profitable pit and expanding by practical increments to the ultimate pit shell. The system relies on the skill of the mining engineer to determine the best starter pit and sequence of pushbacks. At this stage practical considerations such as access and maintaining minimum working widths, an issue which is discussed later, assume importance. The strategy is usually to take the 'next best' ore. This does involve a certain amount of trial and error.

• FOUR-D AS A GUIDE

Four-D produces a set of nested pit shells, the innermost shells being the most profitable, the outermost the least profitable at any given metal price. By importing these shells into OPD they can be used as a guide in pit sequence planning. OPD is used to enhance the Four-D designs by:

- generating pits where the pit wall slopes are more complex than can be modelled in Four-D;
- generating pits with ramps;
- modifying the Four-D sequence to take cognisance of practical constraints that cannot be modelled in Four-D.

Several techniques exist for presenting the Four-D pits in OPD. Bases can be digitised from printer plots produced by FDPR. Once in OPD they can edited to produce smooth outlines, adjusted for practical constraints and ramps inserted where required.

Four-D results files can be processed to produce DXF files for importing into an AutoCAD drawing. Details of the various formats are given later. Pit phases can be designed interactively within AutoCAD and then exported to OPD for evaluation. Alternatively the AutoCAD drawing can be plotted and used as the basis for manually produced designs. These can be digitised into OPD for evaluation.

Some classes of DXF output produced for AutoCAD can be read and displayed in OPD as a guide to phase design along with displays of rock and grade models.

A rock model can be constructed using the Four-D pit codes as the rock type codes. This has two uses. The model can be presented visually to guide the engineer when designing pushbacks, each Four-D pit or group of pit shells being differently colour-coded.

• SMOOTHING FOUR-D PITS

It can also be used as a method for generating smoothed pit outlines that follow the Four-D shells. A technique exists in OPD which forces the pit outline to follow specified rock codes. This was originally developed for generating pits to mine deposits occurring in flat dipping seams. When applied to a rock model of Four-D pits each bench perimeter steps out to follow those blocks that are within a given pit shell. OPD's perimeter smoothing is then applied.

• THE NEXT STAGE

One of the products of pit sequencing is a set of phase data files for production scheduling. For each bench in a phase the file contains a breakdown of material in up to 30 grade intervals. This is passed to OGREPlus for pit scheduling and cut-off grade optimization.

OPEN PIT SCHEDULING

For long term open pit scheduling RTZC have developed a system called OGREPlus. It is based on the cut-off grade theories developed by Lane K.F. (1988). The OGRE (Optimum Grades for Resource Exploitation) program works on a set of sequential pit shells similar to those generated by Four-D. Given a set of parameters which include the grade distribution of the reserves, the mining, milling, transport and marketing costs, product prices and production constraints it generates an optimum cut-off policy for each mining period.

• OGRE

OGRE schedules a family of nested pit shells using a sequence similar to the Four-D 'Best Case' schedule, in that it mines the first pit before starting the second shell. However OGRE operates on a grade/tonnage curve for the phase as a whole and is unable to distinguish variations of the grade distribution bench by bench within a phase.

Stripping within a phase, ie the mining of overlying waste to expose the ore horizon, is normally scheduled in periods prior to mining ore in the phase. Waste stripping in later phases occurs concurrently with ore mining in earlier phases. Based on user defined horizons that mark the limit of stripping, ore from a pit shell is combined with stripping from the following shell to create a set of phase grade/tonnage curves for OGRE. This technique is used to generate an initial cut-off grade policy.

• THE PLUS PART

The next stage is to run the scheduler, the 'Plus' part in OGREPlus. This mines each phase following constraints such as the cut-off grade policy, waste and ore production rates, sinking limits etc. Once the limiting conditions of an inner phase have been reached the program mines ore, provided it has been exposed, from the next phase. Stripping follows the same logic. If the specified stripping base has not been exposed in the subsequent phase, scheduling stops. OGREPlus provides an indication of the limiting condition. The engineer can try to overcome it by calling for more waste, raising the base of stripping or sinking more benches.

The engineer adjusts these parameters until he arrives at a set which allow ore and waste to be continuously scheduled over the life of the mine.

From this schedule a set of annual pit increments is generated in the form of grade/tonnage curves. These are passed to the OGRE program to re-calculate the optimum cut-off grade strategy. This new strategy will be an improvement over the original, being based on pit phases which are annual increments.

As the previous schedule was based on a now outdated policy it is necessary to re-run it with the new policy. This is likely to generate a new set of annual increments which can be OGREed to generate a new cut-off grade policy. Although the scheduling is always one step behind, the optimum policy tends to converge.

Initially stripping rates are determined to ensure that ore in a phase is exposed just-in-time. The engineer smoothes stripping to match the capacity of the planned fleet to create an orderly equipment purchase policy. Although this is a trial and error process each run takes less than 30 seconds for a typical case. The scheduler reports a discounted cashflow enabling alternative strategies to be ranked.

- **FOUR-D AS THE SOURCE**

Phase data files for OGREPlus are generated by OPD following pit sequence planning. If, following inspection of the Four-D pit shells, there appear to be groups that can be combined to produce an adequate set of pit phases, these can be used as data for OGREPlus. A program reads the Four-D results file and generates phase data files in the required format.

GRAPHICAL PRESENTATION OF FOUR-D OUTPUT

In addition to producing a block model for OPD design RTZC has developed programs that convert a Four-D results file into DXF files suitable for importing into AutoCAD. The objectives are to help with visualising the results and to provide a guide for designing pits using RTZC's OPD software.

In order to provide maximum control of presentation within AutoCAD, layer names are generated based on the Four-D pit number and bench or section numbers as appropriate.

The techniques used are:

- **GRIDDED SURFACE**

  Used to represent the topography of a pit from a results file. This enables 3D views of the pit to be generated. Each pit is given a unique layer name enabling different characteristics to be selected in AutoCAD

- **MODEL SECTIONS**

  Long or cross sections can be generated for any given pit as 3D polylines. Giving each section line a layer name based on the pit and section numbers enables plots to be easily created for any section.

- **BLOCKS**

  Each block within the model file is output as a cuboid in AutoCAD comprising six 3D faces. Blocks are given layer names based on the pit and bench numbers. This enables bench plots to be generated with each Four-D pit, or group of pits, differently colour coded. These can be used as a guide for pit sequence planning.

- **PIT OUTLINES**

These are obtained by first building an OPD block model with pit numbers as the rock codes. A program then generates outlines for a given rock type and therefore pit number. A program to generate pit contours is currently under development.

DISCOUNTED ULTIMATE PITS

As part of an exercise to study the effects of discounting on project evaluation a technique was developed to optimize pit shells based on discounted block values. Following the initial pit optimization a schedule was developed using OGREPlus. An OPD rock model was built which included for each block the Four-D pit number in which it was mined. From the OGREPlus schedule the year in which each block was mined was added.

The Four-D model file was then processed against the OPD model, each block's rock, ore and metal tonnages being discounted by the factor in effect for the year. This model file was then used as the source for a Four-D run. The final stage was to process the results file against the OPD model increasing each block's rock, ore and metal tonnage's by the reciprocal of its discount factor.

A word of warning for those trying this technique. Present values for the discounted pit will inevitably show an improvement because the intermediate pit shells will have shrunk. This effect will be particularly noticeable if the early pit shells were originally too large. The importance of this effect is discussed in the next section.

The change in pit size could alter the mining sequence. This could lead to the delay of stripping at the limits which would tend to increase the size of the pit. The technique described only allows pits to be shrunk.

MINIMUM MINING WIDTHS

The necessity of maintaining a minimum mining width for the final pushback can affect the ultimate pit shell. The need to schedule stripping in advance affects the value of the final pit increments. Consider the example, illustrated in Figure 1, of two pit shells, B and C, generated by Four-D. Both shells have one year waste stripping and one year ore mining.

Scheduling them using the Four-D analysis 'Best Case' method results in a positive present value of 20.9 (Case 1). This is reduced to 11.4 when waste stripping is scheduled in the previous year to the ore in each pit shell as would occur using a just-in-time scenario (Case 2).

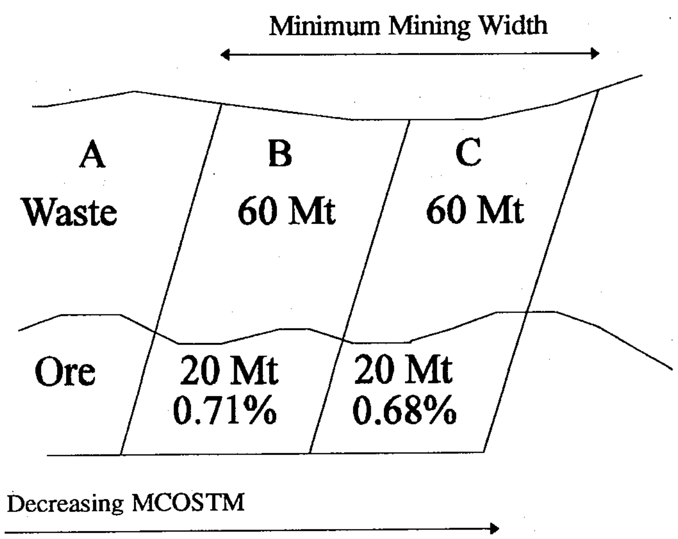

Figure 1 - Effect of Minimum Mining Widths

Table 1 - Operating Parameters

	Waste	Ore
Annual Capacity	60 Mtonnes	20 Mtonnes
Cost/tonne	$1.00	$6.00
Recovery	100%	90%
Revenue/tonne	$1543	
Discount Rate	10%	

Table 2 - Pit Shell Parameters

Pit	**B**	**C**
Waste	60 Mt	60 Mt
Ore	20 Mt	20 Mt
Grade	0.71%	0.68%
Costs	$180 M	$180 M
Revenue	$197 M	$189 M

Table 3 - Present Value of Schedule Alternatives

	Schedule Cases - See Text			
	1	**2**	**3**	**4**
Pit B	14.2	9.2	3.6	-2.5
Pit C	6.7	2.2	-2.9	0
Total	20.9	11.4	0.7	-2.5

If the minimum mining width involved taking B and C together, both shells would be mined over a period of 4 years, two years stripping followed by two years ore mining (Case 3). The contribution to the present value is still positive but reduced to 0.7. A reduction in revenue could cause a negative contribution from the pushback, eliminating it from the mine plan.

On studying the B+C combination (Case 3) we note that B makes a positive contribution of 3.6 while C a negative contribution of 2.9. Could the project value be improved by increasing the size of pushback A to include B? Given that A has been designed to the minimum width and could not be divided, the new pushback would include 180 Mtonnes of waste and 60 Mtonnes of ore. This would be mined over a six year period, in which case the contribution of B to the project would be negative (Case 4). The present value of the original material in A would also be reduced.

It is possible to envisage situations where material lying outside of the optimum pit limit is included in a pushback in order to provide the necessary working space to enable economic material to be mined, providing overall it makes a positive contribution a project.

This serves to demonstrate the interaction of the minimum mining widths with the position of the ultimate pit shell. The effect is more acute the shorter the project and the fewer the number of pushbacks. This also serves to reinforce the policy of doing the minimum amount of stripping to expose ore and delaying it till the last moment (just-in-time).

APPLICATION OF THE SYSTEM

Since acquiring Four-D RTZC has used the system on several projects involving a variety of minerals and locations around the world. Copper is by far the predominant mineral as would be expected in a company such as RTZ. South America is the predominant location, reflecting the general interest in mining projects in that region.

The following list includes a brief description of the projects and points of significance, such as special techniques developed, noted.

- **COPPER - CHILE**

  Studies have been performed on several prospective copper projects in the country.

  RTZC used Four-D as the initial stage in expansion studies at an operating mine. The pit shells generated were used as the basis for pushback designs using OPD. Finally these were scheduled using OGREPlus. Engineers at the mine are continuing to use Four-D as the basis for the detailed design of the pit.

- **COPPER - PERU**

  The project consisted of an existing open pit. Studies were undertaken to compare the alternatives of continuing with the open pit or moving to an underground operation. The project included several satellite orebodies which provided scheduling problems. Amalgamating them into a single pit was studied as a possible option.

- **COPPER - ARGENTINA**

  Studies have been performed on a prospective copper project.

- **GOLD - PNG**

  Four-D was used as the basis for studying the effects of different production rates on the economics and size of the project.

- **GOLD - CIS**

  Used in the initial evaluation of the project to estimate the size of the resource.

- **TITANIUM - CANADA**

  Following a programme of exploration drilling which indicated an extension to the resource, RTZC were involved in the creation of a new model of the deposit. Four-D was used to generate an ultimate pit to determine the size of the mineable reserve and a set of pit shells that were subsequently used as the basis for producing a long term mine plan.

- **COAL - VENEZUELA**

  Four-D was used to estimate the possible size of the coal resource in a gently dipping multi-seam deposit. In all some 20 seams were modelled with average thickness from 1 metre to greater than 10 metres.

  The block model was generated from gridded seam data. Five metre high benches were used. Blocks in the model were either coal or waste. The tonnages of coal in each block were adjusted to compensate for the seam thickness eg for 1 metre seams the tonnage was given by the formula:

block volume × coal density × 1.0 / 5.0

In the OPD model it was the density model that was adjusted. Similar adjustments were made to overburden and interburden blocks.

- TIN - BRAZIL

As part of an evaluation exercise Four-D was used to generate a set of pit shells to study the effect of different tin prices on the project size. From some 40 shells three were chosen to represent the phases in the development of an open pit. From these a production schedule was generated.

CONCLUSION

Over a number of years RTZC has built up a library of software tools to assist the mining engineer in open pit design. The key feature of these systems has been the maintenance of transparency. This philosophy has been followed in the use of Four-D.

Integrating Four-D into the system has proved relatively easy, principally because of the commonality of the model formats used by it and OPD. The system has brought benefits, particularly in the savings in time at the early stages of the evaluation of a project.

The systems complement each other. Four-D provides tools for quick evaluation of deposits and for performing what-if studies. The results are passed to RTZC's systems for the engineer to refine the design, taking into consideration practical constraints.

Four-D has also served as an independent audit for manually produced designs. As confidence and experience builds in its use more reliance is being placed in its results.

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