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Using MIP for strategic life-of-mine planning of the lead/zinc stream at Mount Isa Mines

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Lead-zinc production at MIM, Mount Isa includes three mines, a lead concentrator, zinc filter plant and lead refinery. Lead production is vertically integrated with lead-silver bullion shipped from Australia to London for refining. Zinc is sold as a concentrate. All three mines have reached varying states of maturity mining a multitude of orebodies having significant variation in grades and metallurgical recovery for three metals.

Based on current levels of measured resources, the remaining project life is at least ten years. The objective is to schedule production over the life of all three mines so as to maximize the present value of the complex. Additional scheduling complexity arises out of the implementation of long-term schedules, capital expansion projects for both mining and processing, the presence of substantial inferred reserves and interactions with MIM copper production.

A large-scale, time-dynamic, life-of-complex Mixed Integer Program (MIP) production schedule was formulated to optimize lead/zinc cash flow based on a detailed life of project production scheduling study. The requirements for such a study are detailed herein. The operational feasibility of the MIP solution is compared against a non-optimal approach to strategic life-of-mine scheduling. The strategic planning emphasis placed on the MIP is compared to the implementation of a life-of-mine schedules at Mount Isa using spreadsheets and other popular commercial mine schedulers.

Introduction

Mount Isa Mine is in its 80th year of operation since the discovery of the carbonate lead and silver bearing gossan by John Campbell Miles. It is still one of the largest underground mining operations in Australia. Mount Isa Mines produced 3.5 million tonnes of silver-lead-zinc ore (at 128 g/t Ag, 5.3% Pb and 7.8% Zn) and 5.8 million tonnes of copper ore (at 3.6 % Cu) in the last financial year ending 30th June 2002.

Mount Isa is located in north-west Queensland about 900 kilometres west of the Townsville. Hilton and George Fisher orebodies of the George Fisher Mine are located 22 and 24 kilometres respectively north of Mount Isa (Figure 1). The Mount Isa Business Unit operates the Isa Copper (X41), Enterprise, Isa Lead and George Fisher Mines.

Geology

The Mount Isa, Hilton and George Fisher silver-lead-zinc orebodies are stratiform Proterozoic silver-lead-zinc deposits which occur in a dolomitic shale and siltstone sequence called the Urquhart Shale. The orebodies at Hilton and George Fisher are similar to the Mount Isa silver-lead-zinc orebodies but display much more structural complexity. Faulting associated deformation has affected the orebodies on all scales causing truncations, fault windows, thickening and thinning[1].

Isa lead orebodies

The Isa silver-lead-zinc deposit is composed of over 28 separate minable orebodies. These stratiform orebodies are contained within the top 600 metres of a 1 km thick Urquhart Shales (Figure 2). The regional dip of the Urquhart Shales in the lead mine is 65 to 70 degrees to the west with a consistent north-south strike[2]. The ore mineralization is mainly galena and sphalerite with associated pyrite and pyrrhotite in 1 mm to one metre thick sulphide beds. Wherever these beds are grouped together in sufficient density and grade they constitute an orebody[3].

The individual orebodies range between 100 m to 900 m in strike length, from 3 to 45 m in width and can exceed 800 m down dip. Separation between orebodies ranges from 4 to 80 m and all lie in a sequence up to 600 m thick. In plan they have an echelon arrangement with hangingwall orebodies extending further to the north in general.

Most of wide, high-grade orebodies in the lead mine were extracted over the past eight decades but substantial mining reserve is still available. The inclusive mineral resource of the Isa lead orebodies was 18.9 million tonnes at 152 g/t Ag, 6.3% Pb and 7.2% Zn and the total mining reserve was 7.2 million tonnes at 129 g/t Ag, 5.4% Pb and 6.7% Zn on 30 June 2001.

Hilton orebodies

The zones of economic mineralization of the Hilton deposit have been subdivided into seven orebodies, numbered 1 to 7, starting at the hangingwall and moving east to the footwall (Figure 3). The Barkley shear zone, a bedding parallel fault that marks the end of the ore-bearing Urquhart shale unit to the east and the hangingwall fault zone truncates the orebodies to the west[4]. The inclusive mineral

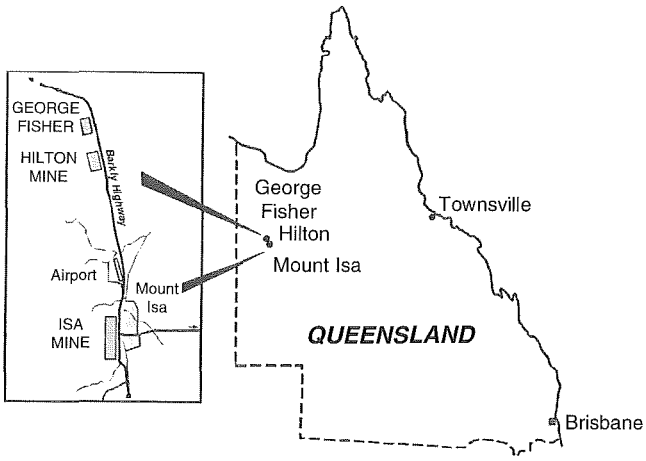

Figure 1. Location of Mount Isa and George Fisher Mines

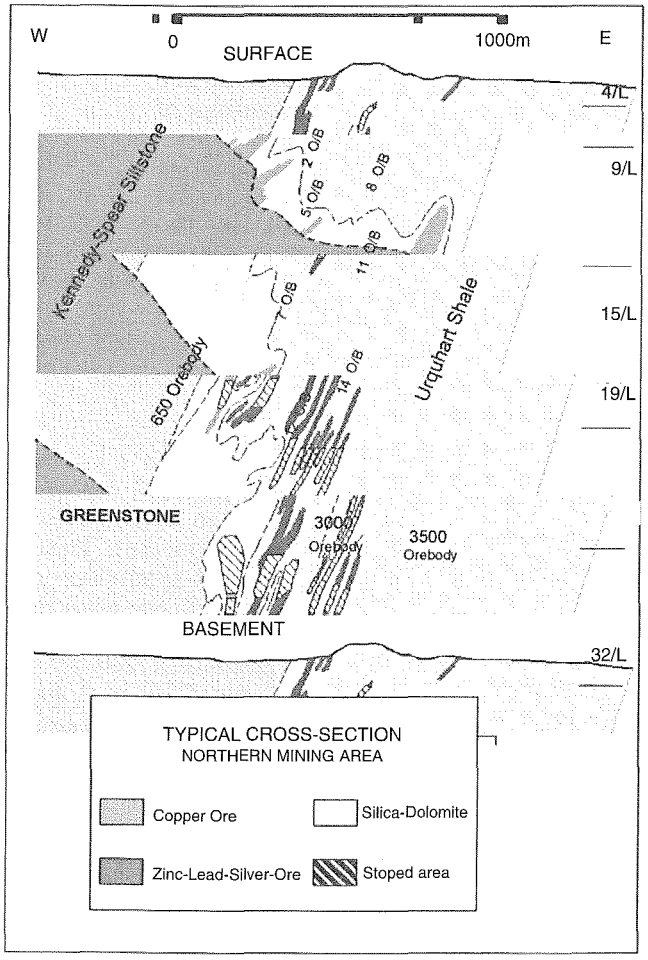

Figure 2. Typical east-west cross-section of Mount Isa Mines

resource of the Hilton orebodies was 37 million tonnes at 140 g/t Ag, 6.2% Pb and 8.9% Zn and the total mining reserve was 12.8 million tonnes at 130 g/t Ag, 5.9% Pb and 8.7% Zn on 30 June 2001.

George Fisher orebodies

The George Fisher orebody extends over a strike length of 1.2 kilometres to a known depth of approximately 1 kilometre. The hangingwall (west) economic mineralization

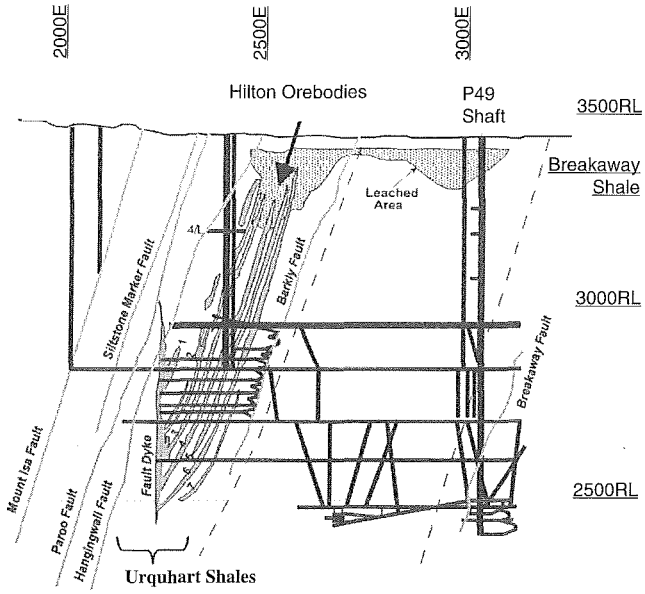

Figure 3. Typical east-west cross-section of Hilton orebodies with access infrastructure

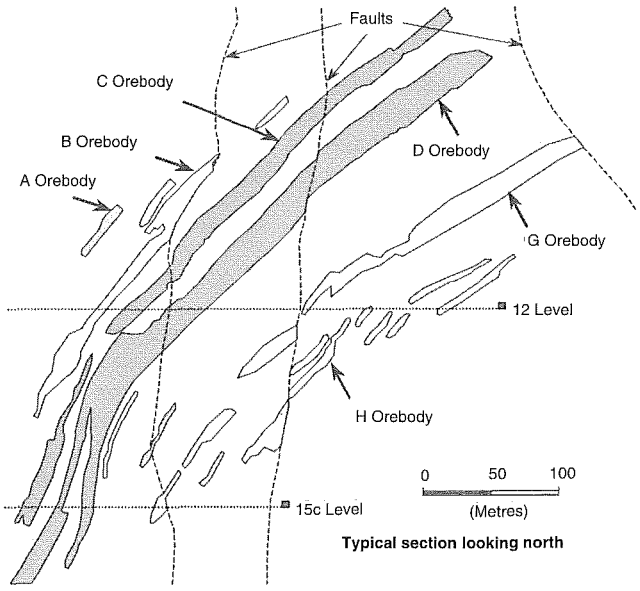

Figure 4. Typical east-west cross-section of George Fisher orebodies

of the deposit is truncated at depth by a hangingwall fault in a similar manner to Hilton. The George Fisher deposit is also bounded by the Gidyea Creek Fault to the south and the Spring Creek Fault to the north[4].

Even though eleven George Fisher orebodies have been named 1, 2 and 'A' through 'I' moving from hangingwall to footwall, only A, B, C, D, G and H orebodies satisfy the current reserve cut-off criteria (Figure 4; Typical east-west cross-section of George Fisher orebodies). D is the dominant orebody in the George Fisher deposit and it contains 46% of the tonnage and 49% of the value of the George Fisher mining reserve. C orebody follows next with 27% of the tonnage and 30% of the value.

The inclusive mineral resource of the George Fisher orebodies was 99 million tonnes at 82 g/t Ag, 4.1% Pb and

9.2% Zn and the total mining reserve was 22.4 million tonnes at 111 g/t Ag, 4.9% Pb and 9.3% Zn (30 June 2001).

Figures 3 and 5 show the main infrastructure associated with the Hilton and George Fisher orebodies in the George Fisher Mine.

Current practice

Effective production scheduling is only possible if geology, mining and processing are integrated: the deposit model must capture geologic uncertainty and the scheduling algorithm must account for this uncertainty while meeting complex mining and blending constraints and providing as close to an optimal mill feed as possible. The specification for an optimal mill feed depends on recovery for each ore type. However, in addition to the generalized feed properties provided earlier, various additional site-specific factors may be considered[5–8].

Mathematical Programming methods, especially Integer Programming, can be used to schedule production in this manner: variables represent the tons mined from various faces in each period, constraints ensure that any solution conforms to operational limitations imposed by mining, and an objective function drives the solution towards a production schedule that produces the least deviation in feed to the mill. In surface mining, there have been only a few applications of MIP-based production scheduling[9–11]. Goal Programming (GP) and MIP were applied to the short-term production scheduling problem in large surface mines[12] and for blending and inventory control in phosphate mining[13].

There are a few examples of underground mine production scheduling using Mixed Integer Programming (MIP) in the literature that illustrate this approach. Trout[14] scheduled production with an application at Mt. Isa Mines and with an emphasis on stope development and backfilling. Additional production constraints specified production targets for metal. At that time, Trout was unable to solve the MIP to optimality due to the large number of binary variables, but in a comparison the non-optimal Branch and Bound (B&B) solution outperformed MIM's manual scheduling solution by 123%. Almgren[15] used MIP as an aid in scheduling development and production at the Kiruna Mine, a large sublevel caving iron mine in Sweden. Almgren also ran into difficulties solving the large-scale MIP due to the time-dynamic (solving across all periods simultaneously) nature of his initial formulation but determined that a sequence of single period optimizations probably yielded as good a result due to uncertainty in production, development and geology. Like Almgren, Chandra[16] used a Goal Programming (GP) MIP formulation to schedule drawpoint production in block caving panel to minimize the deviation of production targets. Draw control and production scheduling applications have continued importance in underground mass mining.

Data requirements for UG scheduling

Regardless of the final scheduling methodology used, the input to the schedule and scheduling requirements will remain the same: ore reserve analysis, costing, economics including cutoffs, metallurgical recovery, mining rates and various constraints on capacity and sequencing. The lead/zinc stream production study was an opportunity to test and truly implement optimization-based scheduling since an immense body of work for a large complex was already under way.

Ore reserve estimation

During the first phase of the lead–zinc feasibility study all underground mineral resources were geologically re-

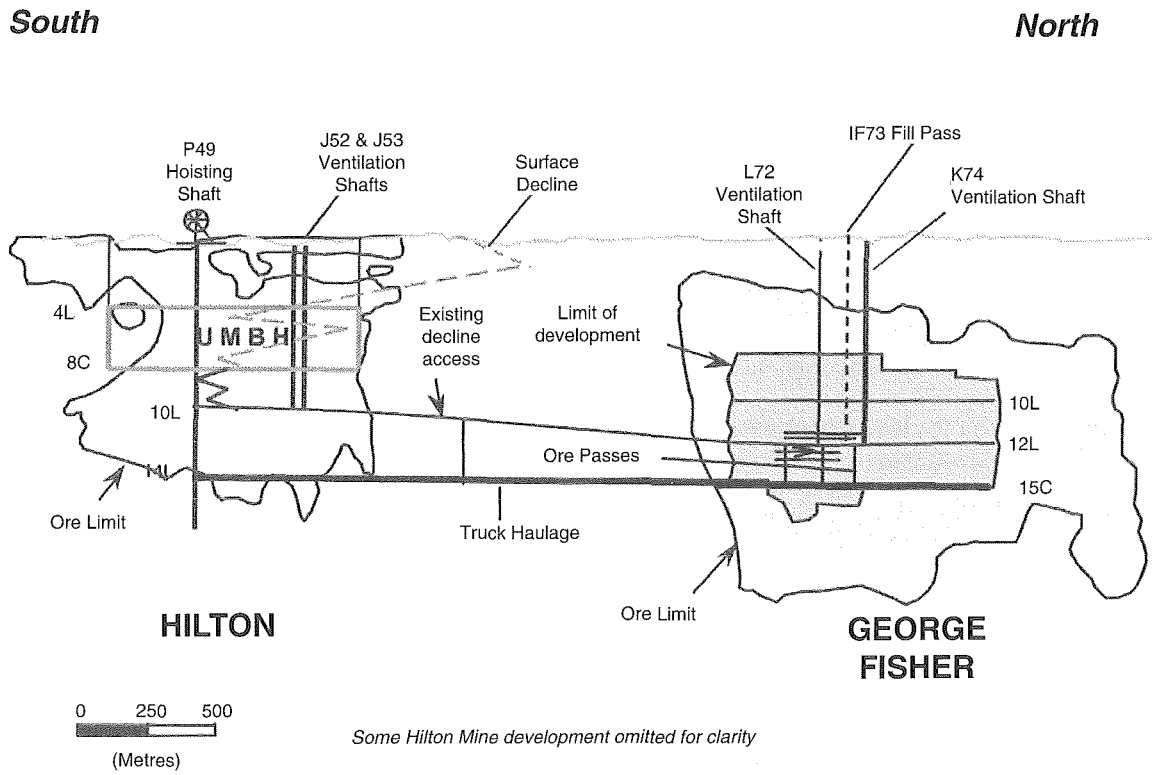

Figure 5. Longitudinal section looking west—Hilton and George Fisher deposits

evaluated by validating the diamond drill database, upgrading CAD software, constructing 3D structural/stratigraphical model, developing a 3D block model and revising the mineral resource cut-off model.

The mineral resource cut-off grade revision was extended to the mining reserves. A number of new concepts were introduced in this process including Net Smelter Return (NSR) and Opportunity Cost. NSR was applied to allow a consistent measure of value between the operations. It represents the *in situ* value of ore in the ground less the downstream smelting, transport, refining and marketing costs. For the lead zinc orebodies at the Isa, one of the most important calculations included in the NSR is the metallurgical recovery estimate in the concentrator. A wide variation in recovery is experienced in mineral processing. This is related to mineral grain size and the proportion of pyrite in the ore. Sophisticated metal recovery equations relate head grade, grain size, pyrite content and target concentrate grades to estimate a recovery for each block of ore.

Opportunity Cost was applied to ensure an adequate return on shareholder investment. This was achieved by applying an impost on all ore reserves. This impost was determined based on the fixed assets used in the lead-zinc business. At the end of the cut-off determination process four new cut-offs for the George Fisher, Hilton, Isa Lead (Wide) and Isa Lead (Narrow) orebodies were derived and these were used for reserve modelling.

The measured and indicated mineral resources were converted to proven and probable reserves by modelling minable 3D wireframes and estimating the tonnes and grades. All reserve wireframes were modelled as single lifts between sublevels. Apart from the George Fisher D orebody, all other orebodies were modelled as benches between the fault blocks. The D orebody was modelled as 15 and 20 (along the strike) metre primary and secondary sub-level open stope lifts.

Historically, dilution was estimated by applying standard factors to the raw stope tonnage. To improve this process, a system utilizing volumetric estimation of the expected over-break was applied. This method allows the estimation of dilution for a stope based on measured geotechnical characteristics and stope geometry. In addition to the over/under break correction, several other factors were applied to allow for, design risk, development tonnage, rill and fill dilution and mining recovery.

All reserve tonnes and grade information and other stope parameters were collected in the ore reserve spreadsheet. Metallurgical recoveries of each individual source were built into the spreadsheet using the simplified metallurgical equations.

All ore reserves sources in the lead stream were grouped into 32 mining blocks in logical geographical regions where they are closely associated in terms of access, ventilation, ore and waste handling, filling and production sequence. These blocks are relatively independent in terms of scheduling and form the basis for life-of-mine planning.

In addition to the northing and sub-level limits, the ore zones were used to define the east and west boundaries of the George Fisher mining blocks. At George Fisher the prefix of the block name refers to the orebodies: e.g. 'ABC' in 'ABC-CMB' refers to A, B and C orebodies.

In the Isa Lead Mine the current production sources in some mining blocks were grouped together to maintain continuity with the short-term production schedule.

Mine layout

With the ore reserves location, tonnes and grade established the capital and operating development plan can be designed. For a complex mine with multiple orebodies this is critical to the strategic scheduling task. A basic layout of the mine is required to establish the sequential relationships between mining areas and the lead time required to develop into each mining area. This plan can change with subsequent mine scheduling, however, there must be a base case plan to start the iteration process.

The layout of development for the George Fisher Mine is given by way of example. Figure 6 shows the Central Mining Block of the George Fisher 10 level with the boundaries of the 'ABC-CMB', 'D-CMB', and 'GH-CMB' mining blocks. This layout also shows the major faults, B, C, D, G and H orebody mineralized zones, the plan outline of the B and C bench stopes and the D orebody primary and secondary stopes and all development required to extract the production sources within the mining blocks. These LOM plans are used to quantify the development required, specifically:

- Capital development that provides access and services to a number of different mining areas is treated as a time constraint for each of the mining areas affected
- Operating development that is internal to a particular mining area helps determine the production rate possible from each mining area.

Cash margin estimates

Operating and capital cost estimates are calculated for each stope in the ore reserve. Assumptions about the target concentrator and production rates are made at this stage. This is required for the distribution of nominally fixed operating costs (e.g. ventilation and administration costs). A total mining cost for each mining source is calculated from which the expected cash margin of each stope is calculated. This is commonly expressed both as a unit margin ($/tonne) and total stope cash margin. The cash margin is now available to use as the basis of production scheduling.

A conventional approach to long-term scheduling

There are approximately 1500 stopes in the lead/zinc ore reserves. The process described above has provided the information required to start the scheduling task. The problem is how to select which of these stopes to take first and at what rate while ensuring that the constraints on shaft and concentrator capacity are not exceeded.

Grouping stopes into blocks

The organization of the ore reserve and mineral resource data is critical to the production-scheduling task. This is particularly important with large complex systems such as the lead/zinc orebodies at Isa. It is achieved by subdivision of the mine into independent mining areas, referred to henceforth as a stoping block or simply as a block. A block consists of a group of dependent stopes. The group dependency is identified by the following criteria:

- Similar geological and metallurgical characteristics
- Supported by the same capital infrastructure (haulage system, ventilation, access development)
- Extraction by the same mining method
- Similar mining costs
- Similar production rates.

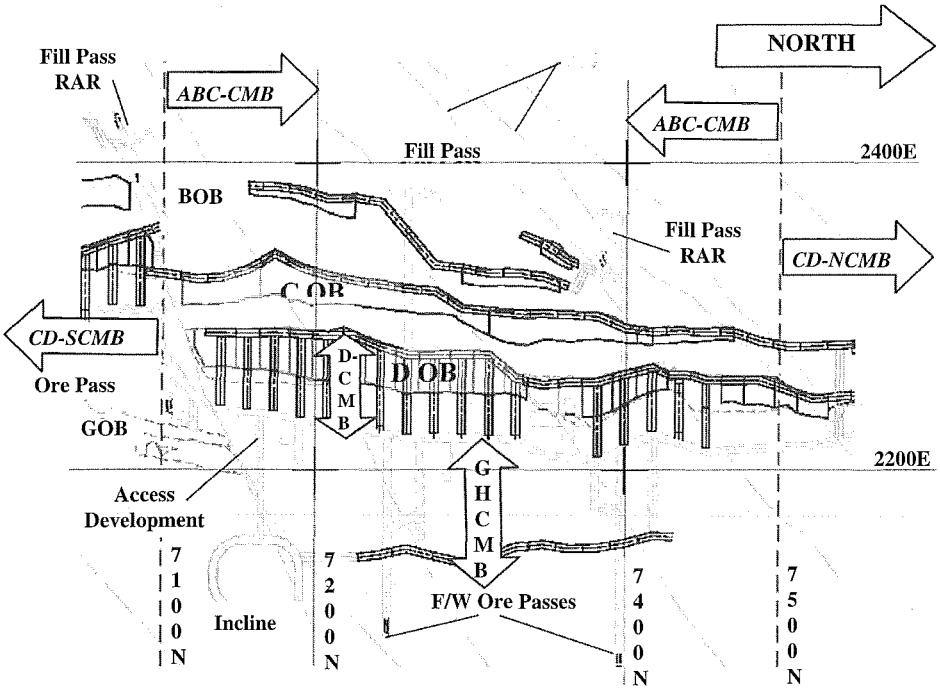

Figure 6. Typical life of mine development layout (George Fisher 10 level)

Most important in the selection of an independent mining area is that stopes should not interact with stopes outside the area. Sharing material movement (trucking or hoisting) infrastructure is permissible, but not interaction at the detailed stope level. All ore reserves sources in the lead stream were grouped into a number of mining blocks within a logical geographical region where they are closely associated in terms of access, ventilation, ore and waste handling, filling and production sequence. These blocks are relatively independent in terms of scheduling and form the basis for life-of-mine planning.

Stopes are considered to be dependent when they influence each others start times. Figure 6, showing a long section view of one of the George Fisher orebodies, illustrates the concept of dependent stopes.

The grouping of stopes into blocks for the Isa lead/zinc business reduces the scheduling problem from 1500 stopes to thirty four (34) sources to schedule.

Estimating block production limits

The production rate possible from any one independent mining area is determined by the complex interactions between the constituent inter-dependent stopes. A number of operational scheduling criteria are applied to estimate the production rate. The most important of these are the following:

- Mining method
- Equipment size and productivity
- Backfilling issues
- Rock mechanics sequencing rules
- Ventilation constraints
- Access constraints.

A detailed mining schedule of each stoping block, will give an estimate of the possible production rate. The upper and lower bound production rates of the blocks are determined by taking into account the past experience. Rules of thumb and industry standards are used to help estimate the upper and lower bound production rates.

In long-term scheduling we are primarily interested in the upper bound rate. There are an infinite number of possible slower production rates for the mining area, what is important is to select a lower bound on the rate for a period beneath which continuous production in the block would result in unacceptable production system utilization or excessively discontinuous stope production and moves. The problem is to select the optimum rate, considering all the external constraints and character of all other independent mining areas. It is the maximum possible production rate that is the boundary condition and this defines the range of possible outcomes.

Earliest start date and latest production finish and block precedences

The dates for the *earliest production start* and the *latest production finish* of a mining block determine the time frame that the block is in production. The time required for the pre-production activities such as diamond drilling, geological assessment, capital development, etc., has to be considered when the earliest production start date for a block is determined.

In some cases, the proximity of the orebodies and the location of access development, blocks associated with some orebodies may not be able to produce at the same time on the same horizon or may have to be sequenced, thus requiring the establishment of block precedence rules in the production schedule or delaying the start date. Use of a precedence rules is preferred to a hard coded date. This situation was applicable to the George Fisher blocks, as most of the George Fisher footwall access and the ore passes were located very close to the G and H ore zones. The production of G and H orebody stopes in the 'GH-CMB' block had to be delayed till the 'ABC-CMB' and 'D-CMB' blocks were extracted.

Cash margin and simple NPV ranking

The conventional approach to long-term scheduling in the

lead/zinc orebodies has been to rank individual ore sources on a combination of net cash margins and estimated Net Present Value. Net cash margins are calculated for individual stopes, while NPV estimates are made for the independent mining areas containing a number of related stopes. Ranking of production sources allows the manual selection of the order of extraction. Highest value ranked sources are scheduled for earliest production. At a crude level this should result in the highest NPV for the total project.

A typical cash margin ranking result for the 1500 lead/zinc ore sources at Isa is shown in Figure 7 (y axis values have been changed). It demonstrates the characteristic of a few high value sources and a larger tonnage of similar value low margin sources. Selecting the high margin sources for early production is apparently simple. Selecting from amongst the bulk of the lower margin material is not so simple. As discussed previously the simplification applied is to group sources into mining areas. The effect of this for 34 blocks is shown in Figure 8.

The problem with ranking is that it is an un-discounted approach. It cannot take the production rate or the pre-production set up time into account. Blindly following the ranking could result in a sub-optimal solution. The cash margin for each mining area can be converted to a very simplistic NPV. However, a large number of assumptions are required to make these NPV calculations. The most important of which is usually that the area should be extracted at the upper bound production rate. With large numbers of mining areas having similar, modest net cash margins the impact of changes in the production schedule on NPV estimates for each source are significant. Small changes in the assumptions of production rate and sequence change the NPV ranking. Attempting to make selection on NPV ranking then becomes difficult and time consuming.

Processing constraints

The lead/zinc business at Isa has two important products: a lead bullion that contains both the lead and silver metal and a zinc concentrate. Lead bullion production is constrained by the capacity of the lead smelter and the concentrator. Zinc concentrate is constrained only by the concentrator capacity. Balancing competing production targets set by marketing in such a system becomes complex. Different constraints on the two products results in some difficult mine scheduling problems. The constraints mean that simple mine sequencing based only on cash margin or NPV ranking is difficult. This is best illustrated by an example illustrating the impact of lead smelter capacity.

Selecting the highest margin ore for earliest production frequently means taking the ore with the very highest lead grade and the best metallurgical performance. In this schedule, the lead smelter capacity is quickly filled. Both mine production and concentrator throughput are low as a result. Estimates of operating costs, made on the assumption of near full capacity utilization, are then too low and margin and NPV ranking will change. Hence the original sequence selection is potentially no longer valid.

The practical operating problems of such a schedule are a major difficulty. Large swings in mine production rate and concentrator throughput can result, resulting in an unrealistic scenario for a large integrated business.

Experience combined with a trial and error approach is applied to balance the competing needs of the two product streams. Searching for the best solution is time consuming. In practice, time and people resource restrictions result in only a few schedules being investigated. The net result is frequently a sub-optimal schedule.

Infrastructure capacity constraints on production

Capacity constraints apply to each component of major ore movement (haulage and hoisting) infrastructure and each downstream mineral processing plant. It is frequently found that the combined maximum production rate from all the independent mining areas will exceed several of the infrastructure capacity constraints. In this case, a choice must be made from among the possible ore sources using a combination of experience, trial and error and NPV ranking of sources.

Limitations of conventional scheduling

Once the mine planners have assembled all of the necessary scheduling data, decisions can be made on the actual sequence and production rates. In summary, the assembled data will include the following:

- Ore reserve estimates for individual stopes
- Grouping of stopes into blocks to give tonnes, grade and metallurgical recovery estimates with area size sufficiently large to be useful in long-term scheduling
- Maximum or upper bound production rate estimates developed from detail scheduling inside each stoping block
- Operating cost estimates developed for each block
- Capital cost and development time ahead of first production estimated for each block
- Simple NPV estimates for each block (note that these are notoriously inaccurate due to the number of assumptions that must be made in the calculation)
- Global precedence and sequence relationships established between the blocks

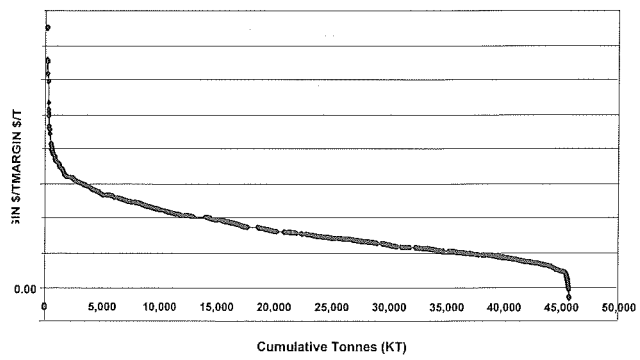

Figure 7. Cash margin curve for 1500 stopes

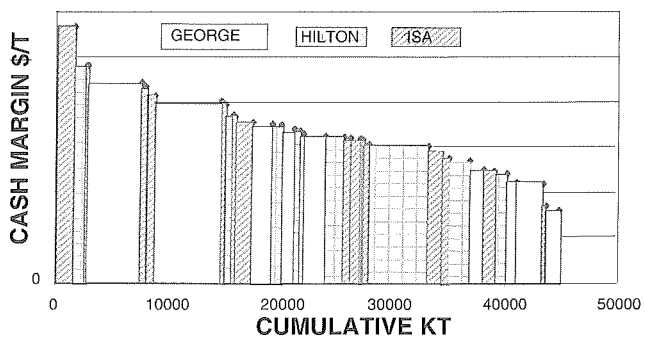

Figure 8. Cash margin curve for 34 mining blocks

- The capacity of each infrastructure and processing plant constraint.

On the basis of the above information the independent mining areas can be ranked on cash margins or simplified NPV.

In conventional scheduling all the data are loaded to an Excel spreadsheet. Manual manipulation is applied on a trial and error basis to develop viable production plans. In a complex system with more than a few capacity constraints and or mining areas this rapidly becomes a complex task. Attempting this with 1500 stopes would be close to impossible. The reduction of the problem to 34 mining areas makes the problem easier but still daunting. It is possible to iterate towards the optimum schedule solution. However, in practice the limited time and very few experienced people available means only a few iterations are conducted. As a result, a sub-optimal schedule solution is generally accepted. The time-consuming and subjective process of selecting the mining sequence results in a reluctance to review more than a very few production schedules. It is difficult to keep searching for the best and the net result is frequently sub-optimum mine plans.

A whole range of software tools have been developed in recent years to speed the scheduling task of the mine planner. The majority of these tools rely on the long-range production sequence having already been decided upon. For some mines this is relatively straightforward, and these new tools are very useful. At Mount Isa these tools are used to develop the detailed short-term mine schedules. They have helped with, but not solved the long-term strategic scheduling problem.

Other scheduling packages used at MIM, Mount Isa

Two commercial scheduling packages are used at Mount Isa, MWP and XPAC. MWP is used for short-term scheduling, principally of development and production resource utilization. While MWP does have a Linear Programming-based production scheduling module, at Mount Isa MWP is used for complex GANNT charting and production resource scheduling. MWP provides a detailed development schedule providing start, durations, and latest end dates for all major tasks associated with development and production down to the level of individual stope specific headings. These schedules are then used for crew and equipment scheduling and projections of supply consumption. While MWP can be applied at much coarser levels of scheduling, it is felt that for a large mining complex such as at Mount Isa that at the level of detail currently used that the number of possible paths that the scheduling tree would have to pursue over a significant time interval would be prohibitive large.

Runge's XPAC scheduling system has recently been adopted for production scheduling at Mount Isa, particularly for the copper stream where the sequencing and scheduling constraints for stopes is far more complex than for the lead/zinc stream. In the lead mines, the mining sequence within a stoping block is tightly and simply constrained: development and production is in the sequence footwall to hangingwall orebodies, bottom lift to top lift and along strike following diamond drilling. Thus, for the lead/zinc stream, the primary question is not the sequence of stoping within stoping blocks, but the scheduling of production from blocks. A rules-based system like XPAC is more flexible in defining complex logical constraints on the mining sequence than a MIP, which can incorporate the same logical constraints but must do so within the limits of systems of linear inequalities incorporating binary variables. Where the application of a rule-based system and an MIP differ dramatically is in what is being optimized. At Mount Isa, XPAC is provided with the production target. It does not optimize or in any way determine what these production targets should be. Nor does XPAC find a solution which is necessarily optimal with regard to life-of-mine scheduling. Rather, a sequence of periods are solved, with each period's solution being based on the solution for the previous period.

The MIP approach to scheduling

A MIP is a strategic mine planning tool that in this application optimizes dynamically across all production periods simultaneously such that the solution for any period is optimal with respect to all other periods. In this application, the MIP is used for strategic planning in that it optimizes production from each stoping block across the life of the lead/zinc complex. Thus, an optimal production target is solved for each block for each planning period. Note that there need be no constraint regarding the life of an individual mine, nor need there be a minimum level of bullion production. With these constraints removed, the MIP will also determine the optimal annual system capacity and closing date for each mine. Likewise, capacity expansion decisions such as mill expansions or decline construction can also be included in the MIP with discounted fixed costs associated with the dates of construction. The Present Value maximizing objective function can then determine an optimal capacity within the scope of the entire project as well as the life of the project for the given reserve and revenue assumptions. It is this strategic level of application which most clearly discriminates an MIP from other commercial mine scheduling systems.

MIP assumptions

The assumptions used for MIP production scheduling are no different from the conventional approach described in the previous section, but deserve to be noted as many of these assumptions are required by the methodology and can only be resolved through the consideration of alternative scenarios (MIPs do not lend themselves to sensitivity analysis as do Linear Programs) or through R&D into more complex formulations and much more rapid solution algorithms:

- A single kriging-based resource model is used
- The mineable extent of each orebody is based on a single cutoff and a minimum stope dimension
- A proportion of the inferred reserves are included in the resource with the measured reserves using a conversion factor derived from prior experience
- Cutoffs are presumed prior to scheduling
- Mining costs are fixed by stoping method and do not vary by location
- Earliest start and latest end dates for production in each block are estimated in advance of optimization
- Development and capital cost associated with a block are discounted based on the start of stope production assuming fixed development rates
- NSR is calculated from individual stope metal recoveries which are based on extensive metallurgical testing
- Optimization is based on current metal prices.

Most of these assumptions could be resolved by running

alternative scenarios (such as using worst and best case metal prices based on forecasting) or by cyclic optimization (if the cutoff grade was to be optimized as well). Continued research is addressing more difficult assumptions such as the integration development and production schedules and the use of grade-tonnage curves instead of single estimates of block resource based on conversion factors, kriging and a single fixed cutoff grade.

MIP data and formulation

Input to the MIP Solver includes data, the MIP formulation and various settings for the MIP solution algorithm and associated heuristic procedures. Data is primarily composed of parameter values indexed over sets. The primary set index is the stoping block which is in turn indexed by the mine. The main parameter values are related to block resources (NSR, cash margin, mining rate, tonnage, contained metal and metallurgical recovery), development of blocks (metres, rates, tons ore and waste, earliest start and latest end dates), capacities (ramps, shafts, zinc filter plant, lead concentrator, smelter and lower and upper bounds on feed components).

The decisions solved by the MIP include a mix of continuous ($x >= 0$), semicontinuous ($x = 0$ or $L <= x <= U$, where L to U is the allowable production range in a stope) and binary (0 or 1) variables. The primary decision variable of interest is the production from a block in a given time period. This is restricted to be either zero or within a feasible operating range for the mining method used. Continuous variables are used to track total production moved through the production system (such as the tonnage up a ramp in a year) or the amount of concentrates purchased off site. The logical decisions are modelled as binary variables. These control the production activity of a block, mining and development precedence relationships between blocks and capital expansion decisions (such as what year, if any, to expand the concentrator or zinc filter plant).

The objective function maximizes the Net Present Value of the lead/zinc stream based on discounted cash margin from stope production (after considering both metallurgical and smelter recovery) less block development costs and any fixed costs associated with capital expansion of mine or mill capacity (as controlled by binary variables).

The following constraints limit production to feasible operating practice depending on the mining, milling or marketing scenario under consideration.

- The total ore tonnage coming from stope development and production is limited by the ore available in the block.
- The total units of lead, zinc and silver derived from a stope is limited to the units available in the reserves model for the block and the metallurgical recovery specific to the stope.
- The total tons of ore delivered to the concentrator must be within its upper and lower capacities for feed tonnage for each of the planning.
- The tons of lead/silver bullion produced must at least meet minimum demand and cannot exceed smelter capacity.
- The tonnage produced by a mine cannot exceed the capacity of its infrastructure and should at least be sufficient to recover costs for remaining open.
- The number of active blocks in a mine is limited by the mine's production infrastructure.
- For each mine, the total production from all stoping blocks in that mine is capacitated by certain primary access systems, most notably production declines and shafts. These limits can experience initial periods of steadily increasing capacity, especially in the case of declines and ramps, as they're driven to deeper levels providing access to more stopes.
- The tons weighted average grade of lead ore delivered to the concentrator must be within acceptable lead feed grade limits.
- At least one stoping block in a mine must be active through the planning horizon. When it is of interest to determine dates of mine opening and/or closure, this can be replaced by constraints that ensure that production from a mine is continuous over its active life.
- Precedence relationships between stoping blocks that control the sequence (but not the timing) in which related blocks can come into and exit production.
- Various scenario dependent constraints that enable increased capacity either in mining or processing or in the purchase of off-site concentrates.

MIP solution process

The resulting MIP is solved using a combination of algorithms, including pre-solution algorithms, Branch and Bound, Linear Programming (LP) relaxations and Cutting Planes and a variety of heuristics. Due to the presence of binary variables (to control allowable mining sequences and rates), the difficulty of solving an MIP is orders of magnitude greater than for a correspondingly large (in terms of the number of variables and constraints) LP which can be solved using algorithms such as the Simplex or Interior Point methods which iterate either around the edge of the feasible solution space or directly through it to an optimal solution. MIP Solvers use a combination of heuristics and algorithms to apply increasingly tight bounds to variables, trim off suboptimal portions of the solution space and search for progressively better feasible solutions. MIP solution time depends on the heuristics used, algorithm settings, the formulation of the model and, in particular, the number of binary variables. In this study, there have been between 30–40 stoping blocks and up to 13 years of production optimized both on a 600 mHz PIII laptop and on a dual processor 1700 mHz P4. Solution time for a typical scenario on the laptop are within a few minute to a 10% threshold of optimal and over an order of magnitude faster on the P4 demonstating that experimentation with alternative production scenarios using large-scale MIPs is an entirely viable option for strategic mine planning.

Comments on difference in schedule outcomes MIP to conventional

The conventional schedule was completed with a different start date and hence slightly different data set. However, the impact of the MIP can be observed in the comparison of Figures 9a and 9b. The real changes are obvious only to someone who works in the mine and has access to the details of the schedule. However, in general terms the following changes are apparent.

- Less GF was scheduled by the MIP and more Hilton.
- Hilton was mined harder by the MIP than the manual schedule. This improved the business performance.
- The Hilton production ramp up was much smoother under the MIP reflecting the model's ability to balance infrastructure constraints that had been difficult to deal with in the manual schedule.

- Higher production rates were scheduled from the lead mine under the MIP compared to the manual schedule. Once again this gave improved business performance.
- The MIP gave a smoother schedule for the mines. This highlighted errors in the manual schedule, where infrastructure constraints has been exceeded at times and these had been missed or been just too difficult to fix in a long-term schedule in the time available.
- The balance of lead smelter being filled at the same time as zinc filter plant capacity being met was only achieved through the use of MIP. Manual iteration had failed to achieve the same result trying to get the right mix of mining areas. In the manual schedule this was accepted as a problem that could not be fixed in the long-term schedule in the time available. This is not visible in the charts that only show tonnes mined.

Some results and conclusions

Figures 9–11 provide an example of MIP-based scheduling results of a lead/zinc production scenario (all these Figures have had the vertical axis adjusted to preserve confidentiality). In Figure 9, the combined production from all three mines is shown. Figure 10 shows the contribution to total profit by each mine over the life of current reserve levels and Figure 11 provides the final result of the scenario, the contribution to Marginal Value by each mine. It is interesting to note that the MIP provides both continuity of production during the mine's life with levels of production fluctuating below mine capacity as well as the date of mine closure. It must be remembered when examining an MIP solution that these annual values are optimal within the sense of Present Value maximization while adhering to all constraints on production: exactly the solution that had been sought with such difficulty and frustration using spreadsheets and cash margin curves in the conventional approach attempted earlier and still practiced by most underground metal mines. In contrast, once the data required for scheduling are available in spreadsheets, a production scenario can be run to near optimality within a few minutes making it possible to conduct a thorough sensitivity analysis and to examine a multitude of production scenarios associated with capital expansion, alternative resource levels and optimal capacities.

Ongoing research into the application of MIP at Mount Isa is mainly concerned with:

- Increased refinement of the block-based model to account for finer detail on grade fluctuation and development

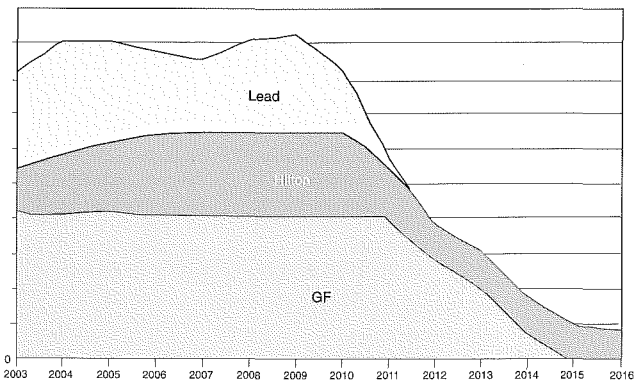

Figure 9a. Contribution to total tonnes by mine from MIP

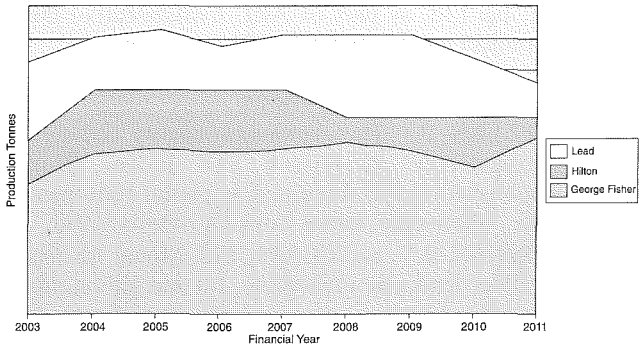

Figure 9b. Contribution to total tonnes by mine from manual scheduling methodology

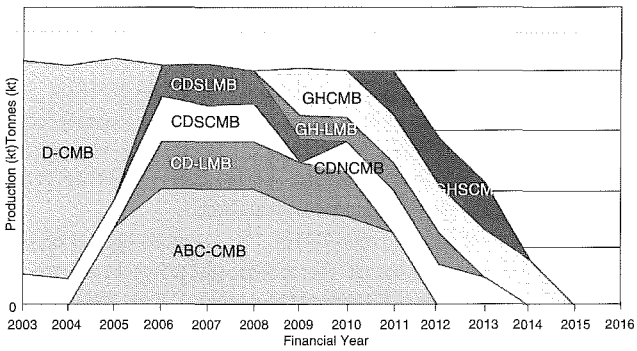

Figure 10. George Fisher production tonnes by stoping block

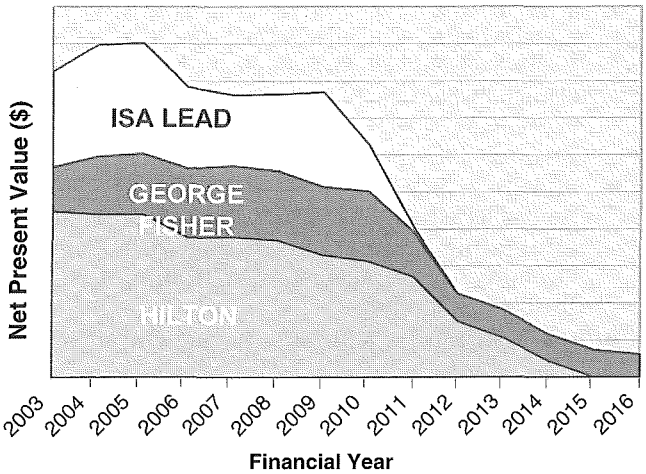

Figure 11. Contribution to marginal value by mine

- More detailed consideration of concentrator and smelter requirements
- Integration of critical path style optimization of development and production scheduling
- Expansion of the model to include copper production from the X41 and 3500 orebodies and the proposed reopening and expansion of the lead pit
- Further improvement of solution speed using advanced heuristic procedures as part of the MIP branch, bound and cut process.

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