INCORPORATION OF A FULL PROCESS PLANT MODEL AS AN ACTIVE CONSTRAINT FOR MINE PLANNING AND PRODUCTION SCHEDULING

R.A. Bearman[1], P. Cesare[2], S. Munro[3], D.Wandel[2]

1. Bear Rock Solutions Pty. Ltd. PO Box 150, Melville WA 6956
2. Strategic Mines Pty. Ltd., PO Box 2074, Churchlands WA 6018
3. Met Dynamics Pty. Ltd. PO Box 204, Woodvale WA 6026

ABSTRACT

Consideration of the processing plant operational envelope is a key factor in production scheduling, and therefore mine planning, for any mining operation. In many cases hard-wired or regression-based tonnage-grade-recovery relationships are used as mine planning constraints and as a means of valuing the system output. In extensions of this type of approach, various regressions can be used to describe throughput limits based on a number of global metallurgical parameters.

The ultimate position for the optimisation of a mine plan and production schedule is to have a full process plant model running as an integrated part of the mine planning exercise. A plant model suitable for this needs to have all the required sensitivities to input parameters such as fragmentation, grade, mineralogy, strength and hardness. The model then needs to convert these to performance measures for the plant, which include recovery, throughput, product size distributions, energy consumption, water use and operating cost.

In this paper an approach is outlined that takes this view and then goes beyond it to provide a full, time based bottleneck identification and valuation tool.

Using such an approach it becomes possible to run mine plans and production schedules in windows of days, weeks, months and over Life-of-Mine with a time enabled process model acting as the active constraint. In this way virtual bottlenecks can be identified for various mine plans and schedules well ahead of time. The value of de-bottlenecking can be defined, not just at a plant scale, but in terms of the overall mining operation and the data can be used as the basis for capital investment decisions.

Keywords

Mine planning; production scheduling; process plant; constraints.

INTRODUCTION

The ability to plan and schedule a mine to obtain the optimum value from an orebody obviously relies on a strong understanding of the geology and the mining strategies deployed. The inclusion of process plant performance is also critical, but in many cases the processing constraints applied are high-level and comprise a series of hard-wired or regression-based metallurgical relationships.

The premise of this paper is to use a higher resolution view of the process plant performance applied via detailed models, which will act as an active constraint in the mine planning and scheduling process.

Process plant models are well established and widely applied for all types of studies and in the optimisation of performance. As a general rule a majority of process models are termed "steady-state" as they reflect a point in time where the throughputs and size distributions within the circuit are fully balanced. Flowsheet simulations using a steady-state simulation platform are ideal for generating a mass balance around the circuit and for sizing process equipment. In this regard they are the work-horse of the circuit design business in mining.

In addition to the usual steady-state simulation packages there are also extensions that can run with a continuous time-base and these are regarded as dynamic models. The more sophisticated of these platforms carry detailed mathematical models of process equipment and simulate the disruptions caused during everyday operation, rather than needing to rely on a given point in time where the circuit is stable. Truly dynamic process simulations can in fact model process control strategies and transient interruptions to plant.

One platform capable of both steady-state and dynamic simulation is the SysCAD package. SysCAD flowsheet models can be fed with time-stamped feed data at appropriate intervals, which can be seconds, hours, weeks, months or years. The shorter intervals make use of SysCAD's dynamic simulation mode, where logistics, buffer and transport stages such as conveyors and bins impact plant operation. The longer intervals satisfy the assumption of circuit balance, and a series of steady-state simulations are undertaken at each time-step.

Given such functionality SysCAD and associated model sets have been used to simulate a wide range of process-related issues. Although it would generally be considered that the "home" for such a modelling approach would be process plant optimisation, the use of this and other packages has moved more towards the wider system. The consideration of the mine-to-mill system started this trend in the 1990's and this interest has continued.

The SysCAD deployment reported in this paper represents one platform, but another system nearing full release is the Integrated Extraction Simulator (IES) developed as part of the CRC ORE initiative (CRC ORE, 2013). All such platforms offer different features and approaches and for the end-user the main consideration is to choose a platform that provides the most effective solution.

In 2012, Bear Rock Solutions (BRS) and Met Dynamics undertook a full cave–concentrate modelling project, initiated by the mining department of the client. The focus of this was to forecast potential mismatches of the mine production and concentrator capacity into the future, dependent on the characteristics of the mined feed. The project then sought opportunities to raise throughputs and examine the economic and performance trade-offs.

A key part of the project was to observe how the process plant model could provide an active constraint for the mine scheduling. Given the success of this project, the natural next step was to examine how this integration of mine planning and scheduling with an active process constraint could be more widely deployed.

Strategic Imperative

In the mine planning process, the incorporation of an active process plant constraint provides a much higher level of fidelity compared to traditional methods.

From a strategic stand-point, having the ability to produce Life–of-Mine (LoM), five year, annual and production level mine plans with a full knowledge of how the plant will perform under the varying feed conditions leads to a more robust and accurate overall plan. With such a future viewed modelled, it is also possible to examine how and where capital investment is required to ensure a full match between mine plan and metal/concentrate production.

The benefits being pursued in this approach include:

- Higher levels of confidence in the ability of the overall system to meet production plan targets and deliver maximum value;
- Greater understanding of the system capability in regard to changes in fragmentation, feed type and hardness;
- Quantification of the impact of fragmentation and ore characteristics on the total system;
- Identification of system bottlenecks ahead of time;
- Ability to develop detailed trade-offs between capital investment in modifications/changes in the mining phase, compared to the processing plant.

Traditional Planning Approaches

Mine production planning and scheduling is central to optimising the value of the resource. Much of the effort in the area has been focussed on software systems that seek to optimise the production plan with due regard to the operational features of a mine, whilst optimising for Net Present Value (NPV) and mine life. Operational Research and related approaches are well known and the major software providers in the area have undertaken extensive development to deliver an array of suitable techniques.

The objective functions describing the desired outcomes of the planning process, are as mentioned above, mainly related to NPV and mine life. In such approaches the amount of input from the processing end of the total system tends to be very limited. In most instances the metallurgical input is limited to grind versus recovery curves or regressions which are inflexible and do not have the ability to react to changing operational conditions.

Given that the objective should be to maximise value for the whole operation, within set constraints, there is an obvious disparity between the vast effort put into the mine production planning process and the scant input from the metallurgical side.

Geometallurgy

A major effort devoted to improving metallurgical input to mine planning has involved the use of geometallurgy. The emergence of geometallurgy has taken place over the last 15-20 years and has a strong connection to overall mine-to-mill types of initiatives, i.e. a desire to improve the total mining/processing system.

The crux of geometallurgy is to embed geologically-specific metallurgy data into block models. Once a block model is populated with geometallurgical data, mine planning and scheduling models can carry this data through to the delivery of plans and related output.

Such an approach has been highly influential and it has allowed mining companies to be far more definitive in the development of mine plans. Using this approach it has been possible to incorporate the variability inherent in the geology and hence the metallurgy into a plan that better optimises the effective utilisation – and hence value – of an orebody.

To enable effective population of the block model with geometallurgical properties, the focus has been on the use of indicative indices. Table 1 list a range of indices that can be used, depending on the approach taken. The original list can be found in Bye (2011), with additions made as part of this paper.

Table 1: List of typical geometallurgical tests/indices that can be incorporated into block models

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Bond Work Index (CWI, BMWI, RMWI);	Rock mass rating systems (RMR, Q, etc.);
JK Drop Weight Test (DWT) and breakage	Rock quality designation (RQD) ;
SMC test parameters;	Fracture frequency per metre (FF/m);
% fines;	EQUOtip (measure of relative hardness);
SAG Power Index (SPI);	Blastability indices;
Point load index (PLI);	Mineralogy;
Uniaxial Compressive Strength;	Multi-element assays;
Tensile strength	Lithology;
Crushing indices (JKCi);	Alteration.
Rock elastic moduli / sonic properties;	

Using these indices, relationships can be developed between the index and key process parameters, such as throughput, grind size and even recovery. A key element being that on a block-by-block basis it is possible to see how process performance changes with mine feed.

Keeney et. al. (2011) took the approach of using geometallurgical parameters and indices as the basis for throughput prediction at the Cadia East operation. Use of this geometallurgical approach allows processing indices to be carried by the mining process, but the translation into the prediction of plant performance still relies on the use of the indices in associated regressions.

Obviously this is a significant advance over hardwired grind/throughput/recovery curves, but even with complex regressions there is still a gap between mined feed and true process performance as such equations rely on using defined values for key parameters. Given that many of these parameters change with time, feed type, operational conditions and through the deployment of process control strategies, they still only represent a proxy for process throughput.

In this paper the authors propose an approach to fill the gap between the use of a process performance proxy and how plants actually perform. The improved representation is then incorporated into mine planning and scheduling to give a higher resolution plan and one that can extract extra value from the orebody.

The approach proposed is to have a full, time dependent process plant model running as part of the mine planning process so that the plant model provides an active constraint. Due to the detail of the model and the fact that it can run as a time based simulation, factors such as the following can respond to changing input conditions (mining/geological/metallurgical) and cause the active constraint to vary:

- Process equipment;
- Process control;
- Logistics elements (i.e. stockpiles, bins); and
- Dry and slurry flows and transport.

The active process constraint, as summarised above, lies at the heart of the approach and it is this in combination with flexible approaches to mine planning that will be examined in the paper.

PROCESS MODEL DEVELOPMENT

A key requirement for this approach is a process plant model that is capable of accurately representing operating constraints over a wide range of mining conditions. To this end, a strong 'predictive' capability is required to capture the range of complex, non-linear interactions between the mine-plant interface and within the plant itself. Plant models with this level of functionality are typically constructed by arranging a series of unit operation models, derived from fundamental metallurgical phenomena, into flowsheet system configurations.

In addition, the specific requirements of this approach dictate that the model employed differs even from those traditionally used for general plant simulation and optimisation.

To effectively use this active process constraint approach, the model needs to be capable of the following:

- Capturing system performance all the way from the mine to the concentrate;
- Allowing multiple feed sources;
- Handling streams containing more than one material type, with combinations of material properties, including breakage characteristics;
- Simulating various time-steps and total durations;
- Embedding typical plant responses to changes in feed properties, external disturbances etc.;
- Identifying plant bottlenecks and maximum throughput limits;
- Predicting throughput, product size distribution and energy intensity at all points in the plant, in relation to changes in input fragmentation, ore composition, hardness etc.; and
- Encapsulating all models seamlessly in one software platform.

A range of platforms satisfying the above requirements were considered for the process plant model. BRS in association with Met Dynamics, have wide experience with the SysCAD platform and a comparison of the required features and the capabilities of SysCAD showed that all the above features can be delivered effectively.

The system models developed and the underlying platform used, offer a range of unique capabilities currently not available from any other commercial simulation packages.

The major elements of the process simulation solution are:

- Single simulation platform (SysCAD) covering the mine plan to concentrate system, and potentially beyond to downstream extractive or refining processes;
- Multicomponent simulation of SAG and ball mills, crushers, classification, i.e. impact of ore blends on throughput, product size and power draw;
- Integrated process control and operating philosophy responses to changing conditions, i.e. the model automatically adjusts behaviour as per the real plant;
- Consideration of mechanical equipment availability, where mismatches frequently arise between individual plant sub-areas and the mine-plant interface as a whole;
- A constraint analysis methodology which automatically maximises feed until the first bottleneck is reached and the hierarchy of constraints is reported; and
- Scalability of computational effort across multiple, parallel instances - this allows a large number of simulations to be performed simultaneously, and is particularly

useful for analysing the large datasets typically arising from uncertainty in geometallurgical and scheduling applications.

Met Dynamics maintains a suite of customised comminution, classification and concentration unit models which supplement SysCAD's native mass and energy balancing capabilities.

As a guiding principle, unit operation models are selected that allow real operating parameters to be specified, e.g. HPGR pressure, screen panel apertures and open area etc. This is in preference to empirical 'fitting' parameters with limited physical meaning, and allows practical equipment configuration alternatives to be tested easily and sensibly.

Depending on the application, the range of unit operation models deployed can be extensive and in certain cases additional functionality may be required, with one example being 'multicomponent' modelling.

Multicomponent modelling allows each unit operation to process a blend of ore types of differing hardness, density, grade and fragmentation, as is typically received from mining operations. Multicomponent processing has been feature of BRS-Met Dynamics models for over five years.

Given that energy consumption and intensity is a key part of total system optimisation, all the models selected and deployed have the proven ability to realistically reflect the power and energy consumed.

Process Control and Operating Philosophy

The manner in which a processing plant is operated is often an overlooked feature of process modelling, yet the decisions made by both process control systems and human operators are critical to maximising the performance of complex plant flowsheets.

A key feature of a real operating plant is the ability of a process control system, or human operator, to alter plant operation in response to changes in feed or other process disturbances.

The active constraint process simulation is therefore supplemented with a layer of control logic that modifies various plant parameters according to process control set points or reasonable operator responses.

Incorporation of control logic has the effect of modifying flows around the circuits as mining progresses through the orebody, frequently resulting in improved throughput compared to the uncontrolled case, as is the intention in practice.

This level of automated functionality is typically not available in other software packages, yet is an important factor determining the performance of a mineral processing operation under varying conditions.

IMPLICATIONS FOR MINE OPERATIONS AND PROCESSES

To gain the most from the use of the active process model approach, reserve schedules need to be presented in an appropriate format and contain a range of suitable information. Fundamentally reserve models are a sub-region (dependant on wall geotechnical parameters and pit shell economics) of the resource model, with the addition of ore loss and/or dilution effects due to the mining methodology deriving what is termed the selective mining unit (SMU) block size. Hence, the information made available within the resource model is key.

Current practices

It is usual for geologically important boundaries and features to be interpreted into 3D polygons in geological models, using drill hole assays and logging, geo-physics and mapping information. These polygons will be then be sub-blocked and a suite of elements is then interpolated into the blocks - most often using the kriging method - to create a resource model. One of the few physical characteristics traditionally interpolated into the resource model's blocks is specific gravity, allowing each block volume to gain a corresponding tonnage estimate.

As indicated above, the resource model is the basis of the reserve model, which is usually limited by the volume representing the pit shell, in the case of open pit mining.

To produce an estimate of product volumes and qualities from the mining sequence, current methodologies incorporate 'global metallurgical regressions' developed specifically for each of the identified ore types and applied across appropriate blocks within the resource and reserve models. These regressions, being global in nature, provide an averaged relationship between the head grade/tonnes and processing performance, often derived from laboratory scale or pilot plant testing of a limited volume of pit or drill core samples.

What can often be overlooked or misunderstood is the level of variability that exists both across and within each particular ore type. This is then exacerbated by the practice of defining scheduling increments which agglomerate ore and waste blocks into a scheduling block, e.g. a pit bench, containing total ore and waste tonnes with averaged grades, and recoveries.

As an example Alumina grade variability within an iron ore deposit, presented as a histogram of tonnes within grade bins by the respective geological stratigraphic unit, is presented in Figure 1.

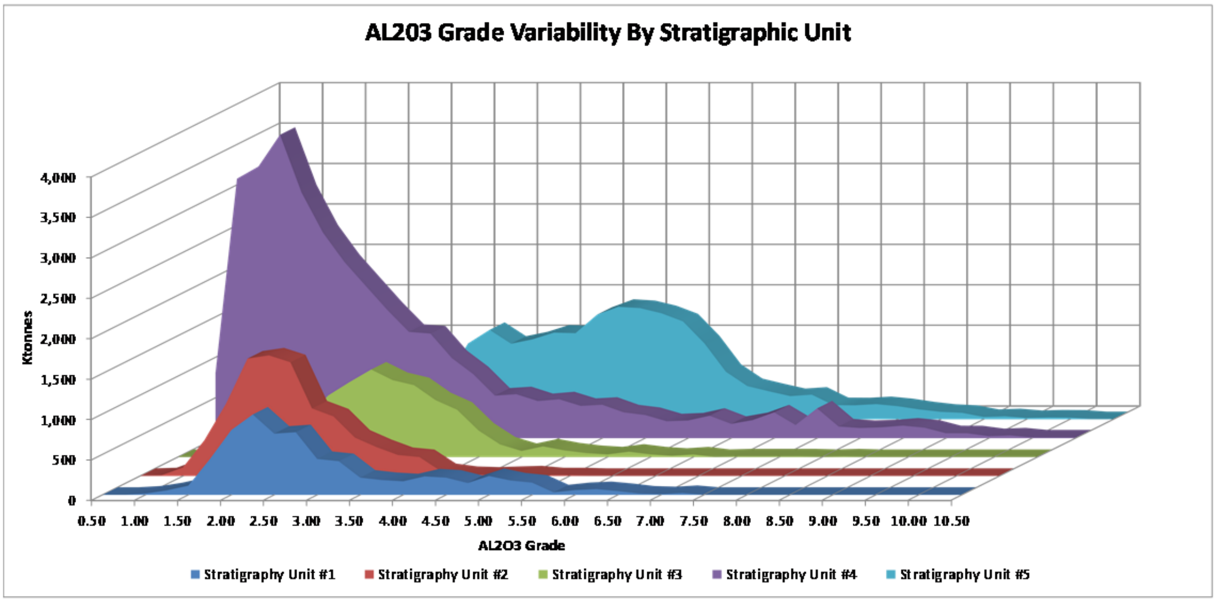

Figure 1: Variability at a mining scale for alumina in a typical iron ore

A further example by Kenney et. al. (2011) presented variability data for ore types found at the Cadia Valley Operations. Figure 2 shows the ranges of results obtained for key comminution parameters, namely the JK 'A' and 'b' parameters and the Bond Ball Mill Work Index.

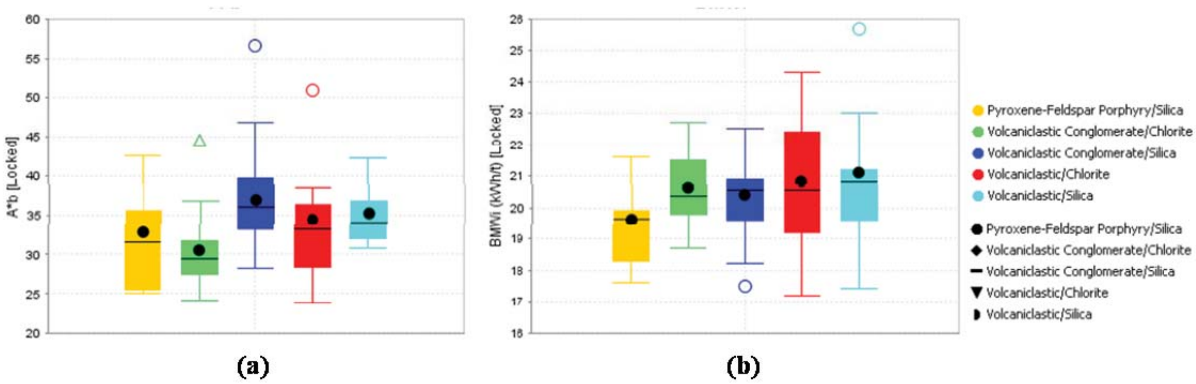

Figure 2: (a.) Variation in JK 'A' and 'b' parameters and (b.) Bond Ball Mill Work Index, (Kenney et. al. 2011)

A key issue faced in developing the mine plan is how to preserve the inherent variability of the resource and reserve mining models in scheduling increments that will still permit responsiveness when running the mining schedule, whilst providing sufficient granularity for the process model to define performance with some degree of certainty.

An SMU block by block schedule ideally preserves the orebody variability but can be very unwieldy in file output size depending on the time horizon of the mine plan and without considering the added complexity of pre-plant ore stockpiling and reclaiming.

Overcoming these issues is not straightforward, and as computing processing power continues to become cheaper, mine scheduling software can respond by respectively increasing the base granularity of the scheduling unit and still provide usability.

A New Paradigm in Mine Geology

The accuracy of LoM plans with the use of global regressions is acceptable for the scale in which they are used (i.e. strategic direction). However over shorter periods (e.g. rolling 3 month mine plans), global averages probably do not represent the actual physical properties for the smaller volume of ore to be mined in that time period. By applying global regressions to those blocks, the result will be actual product outputs that differ from those predicted in the mine plan (based on the use of global regressions).

The prospective combination of the process model and block scale grade and physical characterisation of the reserve model, allows a higher resolution of the variability in product volumes and qualities that are inherent within the deposit. This inherent variability is inevitably hidden by the use of a deposit-wide ‘global’ metallurgical regression for each ore type and then further hidden with the generation of scheduling blocks.

However to achieve this improved resolution in predicting ore and product variability, the suite of geometallurgical information interpolated into the model’s blocks to create a resource model will need to increase.

INTEGRATED APPLICATION OF THE ACTIVE PROCESS CONSTRAINT APPROACH IN PLANNING AND SCHEDULING

Using inputs from the block model, mine planning and scheduling provides a data set to the active process model. Typically the data input will include:

- Block ID and spatial location;
- Tonnes mined;
- Production schedule;
- Assigned ore type, including grade and assay data for a range of elements; and
- Geotechnical and rock strength data, including mill related data or indices.

The preference is to use the fragmentation model within the process simulation to generate a feed size distribution for the milling circuit, as generally size data assigned to blocks is again either an index or a high level descriptor. Such block based fragmentation data would typically be a size distribution marker such as an 80% passing size of the feed (F80), or in certain cases "% Fines", where "fines" often relates to some key size for processing. Examples of a fineness index would be the lump and fines sizes for iron ore, but such indices are also found in other sectors, where for instance a percentage passing 1.18mm is known to be good indicator of circuit throughput.

In some instances, there are useful block based parameters that can be used as part of a full blast fragmentation model, with these including, fracture frequency, RQD and blastability index.

The fragmentation, along with the mining parameters listed above, provides the input for the process model.

Depending on the target, i.e. short, medium or long term, the process model is set-up to run at time steps appropriate for the required duty. These time-steps can vary from a continuous time base, which is used if the effect of process control strategy is of concern to mine-process performance, all the way to gross time-steps for LoM simulations. In the case of LoM runs, it is typical to use quarterly, or six monthly time-steps, although it is simply a matter of computational intensity. If required LoM simulations could be reduced to a monthly, or even weekly basis, but such increments would be unusual and it would slow the calculation process considerably.

For the planning period covered in this paper the typical time-steps would be:

- Five year planning: monthly or quarterly;
- Annual budgeting: weekly or monthly; and
- Three month production: weekly, daily or hourly.

As the main aim of the approach detailed in this paper is to increase the resolution of planning and scheduling, by using an active constraint, the choice of time-step should be made in consideration of how, where and when it is likely that constraints will be encountered.

An approach that can be taken is to use a time-step that retains an acceptable run time for the model, but then reverts to a higher resolution view to examine and identify specific issues.

A typical example using the above suggestion is to run a five year plan simulation at monthly time-steps. An illustrative example of output from part of a five year plan analysis is shown in Figure 3.

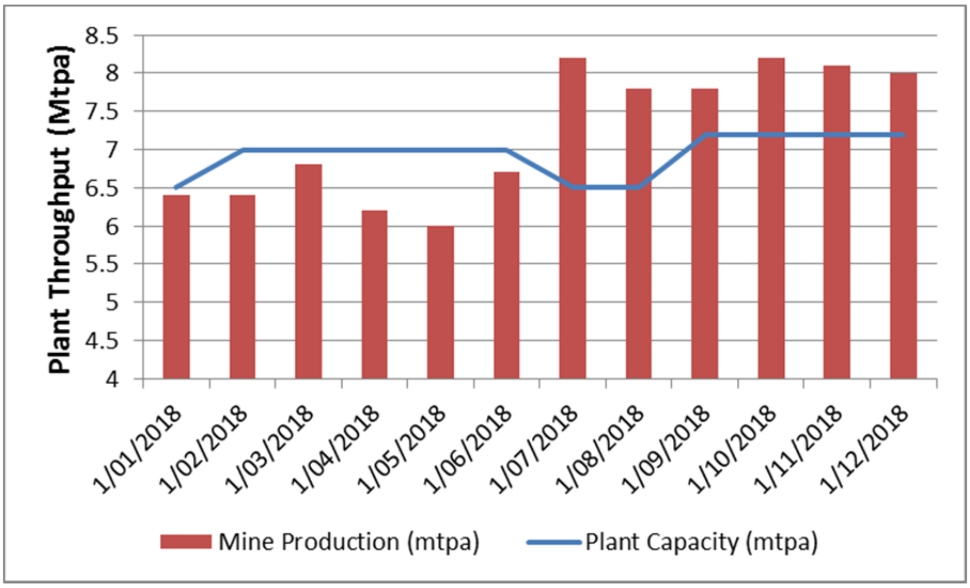

Figure 3: Potential capacity mismatch identified from modelling

Figure 3 shows that in the future there is a mismatch of mine production and process plant throughput capability. It is then possible to examine the issue at higher resolution to identify where the bottleneck occurs in the process circuit. Figure 4 shows the type of bottleneck analysis possible using the model.

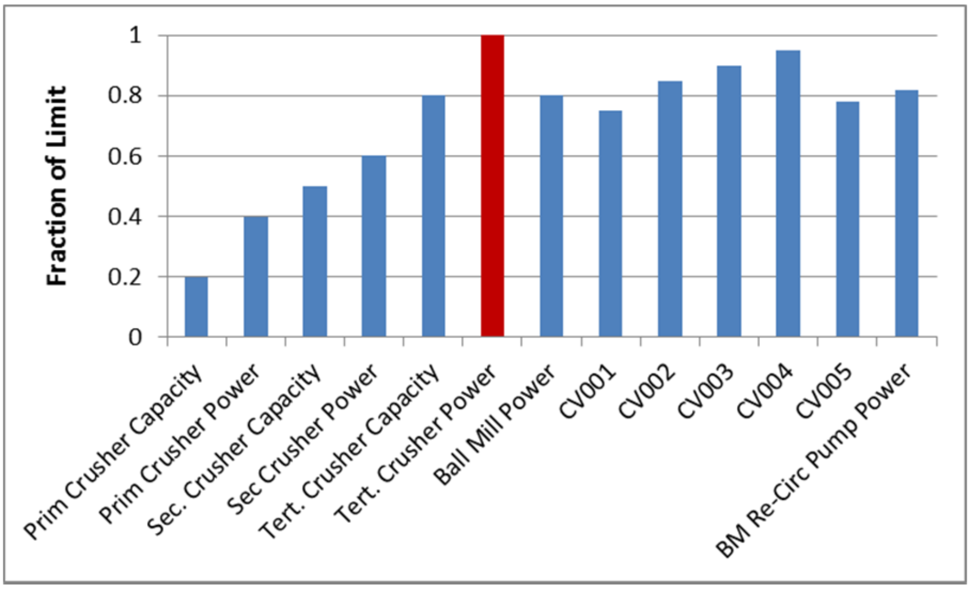

Figure 4: Bottleneck identification

With such mismatches identified, the simulations can be interrogated to determine the exact nature of the constraint in the process plant. For the period noted in Figure 3, the process requirements versus the limits for each stage can be seen in Figure 4. From this analysis the tertiary crusher power is shown to be the limiting factor.

If the power constraint for tertiary crushing is relieved, it can be seen in Figure 5 that the bottleneck moves to one of the conveyors.

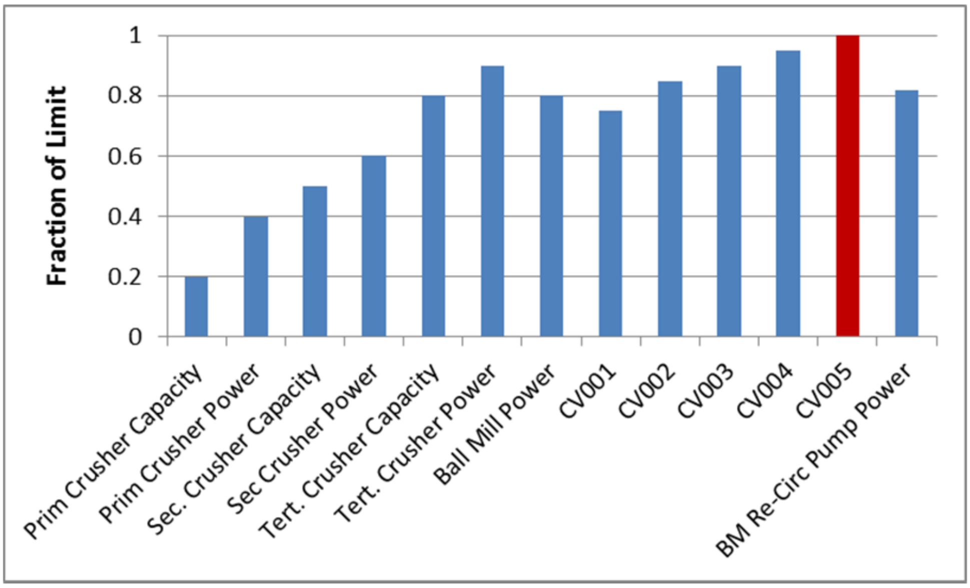

Figure 5: Illustration of the change in bottleneck, following relief of the crusher power limit

In the case illustrated in Figure 4 and Figure 5 the bottleneck moved to the next truly variable bottleneck i.e. CV005. Given the non-linear nature of flows within process plants, due to re-circulating loads and rate sensitive performance of equipment, bottlenecks may move in unexpected ways. This is another reason for having a model that is able to fully capture the true nature of the plant behaviour.

In terms of mine operations, the power in this approach is the ability to have a production plan, based not just on tonnes and regressions, but on a process model that identifies the active constraint in play for a given stage in the mine life, a given fragmentation and a defined rate.

The implication of this is that for a given situation, the option value, i.e. the degree of difficulty and cost of relieving a bottleneck, can be balanced against the added production value and a trade-off can be made.

Importantly, this new level of production resolution will allow the development of a powerful option analysis tool for mine engineers. With block specific grade, physical characteristics and a process plant model that replicates the flowsheet (including control philosophies), a mine scheduling engineer would have enough information to produce schedules to meet specific criteria, e.g. least operating cost, least product variability, maximum throughput, maximum yield, etc.

As discussed earlier, the application of this increased level of orebody knowledge and resolution will be different according to the time horizon of the mine plan.

Five Year Mine Planning

The five year mine plan can be regarded as the first and most critical step in 'operationalising' the LoM strategic plan. Working within the direction set by the LoM, the five year plan is crucial in forecasting ore production quantities, qualities, operating expenditure and capital expenditure that maximise orebody value.

The increased granularity of orebody knowledge provides the ability to produce a mine plan containing detailed ore parameters and physical attributes over time, as an input to the active process plant model.

The model can then identify and quantify specific ore processing implications, which provide the opportunity for value adding trade-offs between the mine and mill. These trade-offs and help identify when key projects, either mine or mill related, are required.

Annual Budgeting

Working within the respective years framework provided by the five year mine plan, annual budgeting is pivotal in defining upcoming ore quantities, qualities and the resulting business revenue, costs and margin.

An increased level of orebody granularity and resultant process plant performance provides a greater insight into month by month production variability, leading to a greater understanding of product inventory levels. When aligned with forecast concentrate sales, this can provide the ability to optimise the timing of planned maintenance outages to minimise the effects on downstream customers.

This improved understanding of monthly product inventory levels can also help increase the confidence level of forecast business cash flows.

3 Month Production Planning

Within the 3 month production planning horizon the parameters of orebody availability and process plant configuration can be reasonably considered as fixed. Integrating the active process model within this horizon leads to increased confidence of the site's concentrate production capability. The methodology and toolkit enables mine schedulers to fine-tune, or modify, ore blending plans to maximise mill production during modular maintenance periods by advance stockpiling of specific ore types. The mine schedulers also gain the ability to minimise loss across the operation by scenario scheduling in cases of production constraints imposed by unexpected breakdowns.

Furthermore, mine schedules for specific flowsheets and control philosophies would allow improved confidence in evaluations of potential modifications to the mine method and/or flowsheet.

Grade Control

At the finest end of the resolution scale in mine planning and scheduling is the sub-SMU activity of grade control. In essence grade control is the closest point to the traditional use of process simulation, as grade control represents the last step in the build of plant feed stockpiles.

Information from blast hole samples, material type logging, blast block analysis and grade control schedules all provide the same basic geometallurgy inputs as previously discussed. Therefore in terms of the ability to build stockpiles and to forecast the expected process performance, the process model can again be used to test grade control strategies and approaches.

CONCLUSIONS

The use of an active and detailed mine-to-concentrate model as part of the mine planning and production scheduling process is not standard practice. The fact that the process model uses a single, integrated model platform and runs with a time-base is practically unique, and it brings a level of system understanding to the work that has not been routinely available. In particular, the use of a time-based process model allows investigation of short, medium and long term mine planning scenarios and hence the early recognition of mine–process mismatches becomes possible.

Through the adoption of such approaches, it is possible to examine a wide range of options around how mine and process capability can be most effectively matched within various planning timeframes. Given the ability to test various scenarios over the entire plan period, the mine operator has the ability to flex plans to meet required objectives, or examine system modifications and the relative merits of capital expenditure versus value delivered.

The ability to undertake a full mine plan versus throughput versus recovery trade-off analysis, provides an enhanced basis for economic evaluation and timely decision making.

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REFERENCES

Bye A.R. (2011), Case Studies Demonstrating Value from Geometallurgy Initiatives, Proc. 1st AusIMM International Geometallurgy Conference / Brisbane, Qld, 5 - 7 September 2011, pp9-30.

CRC ORE (2013), www.crcore.org.au/integrated-extraction-simulator.html, accessed on 25th August 2014.

Keeney L., Walters S.G. and Kojovic T., (2011) Geometallurgical Mapping and Modelling of Comminution Performance at the Cadia East Porphyry Deposit, Proc. 1st AusIMM International Geometallurgy Conference / Brisbane, Qld, 5 - 7 September 2011, pp73-83.