APPLIED GEO-METALLURGICAL CHARACTERISATION FOR LIFE OF MINE THROUGHPUT PREDICTION AT BATU HIJAU

*F. Wirfiyata[1] and K. McCaffery[2]

[1]PT Newmont Nusa Tenggara
Jl Sriwijaya 258
Mataram, Lombok, NTB, Indonesia
*(*Corresponding author: fatih.wirfiyata@nnt.co.id)*

[2]Newmont Mining Corporation
6363 South Fiddlers Green Circle, Suite 600
Greenwood Village, Colorado, USA 80111

APPLIED GEO-METALLURGICAL CHARACTERISATION FOR LIFE OF MINE THROUGHPUT PREDICTION AT BATU HIJAU

ABSTRACT

Accurately modeling and predicting long term mill throughput is one of the challenges facing metallurgists, geologists and mine engineers in their quest to consistently deliver accurate life of mine business plans.

Batu Hijau has systematically improved long and short term mill throughput predictions since feasibility and commissioning in 1999. This has been achieved through a combination of ongoing improvement to the geology ore hardness and grade characterisation model, drill and blast optimisation and, by application of these data to model mill throughput.

Batu Hijau has demonstrated the ability to consistently estimate long term mill throughput within ±2% accuracy. Aside from reliably predicting expected production rates with the existing plant configuration, this predictive ability provides a solid foundation for identifying operating and design criteria for short term grinding circuit optimisation and future expansions.

This paper discusses ongoing throughput prediction model development at Batu Hijau based on geo-metallurgical characterisation. Also discussed are tools used for day to day production performance management. This includes on line "Mine to Mill" variable monitoring to improve operations parameter decision making and performance assessment.

KEYWORDS

Geo-metallurgy, Mine to Mill, throughput optimisation

INTRODUCTION

The Batu Hijau copper-gold porphyry deposit is located in south western Sumbawa and was discovered in 1990 by Newmont Mining Corporation. Project construction commenced in 1996 and the plant commissioned in 1999.

Throughput of the Batu Hijau crushing and grinding circuits is highly variable, ranging from 3,500 to 7,500 tph and is dictated by ore characteristics that are dependent on the mining phase sequence and blast fragmentation. SAG feed 80% passing (F_{80}) size is a product of blasting and primary crushing and varies from 40 to 90 mm. Two parallel SABC grinding circuits are followed by a typical bulk sulphide flotation flowsheet to produce a copper-gold-silver concentrate for sale.

The Mine to Mill strategy at Batu Hijau has been to continually improve orebody geo-metallurgical characterisation and, via practical use of these data, to improve the ability to forecast mill throughput and other production performance parameters. Common understanding of the factors that drive throughput has been embedded into daily Management Operating and Business Planning (BP) systems.

The orebody is well characterised through continuously refining the geological block model via in-fill drilling. The focus has not only been on improving geo-statistical data density and quality for geological and geotechnical characterisation data such as:

- Rock Quality Designation (RQD),
- Rock Mass Rating (RMR)
- Point Load Index (PLi)
- lithology, alteration, contained value and penalty metal grade

but also metallurgical parameters:

- recovery
- concentrate grade

and hardness parameters including:

- Bond Ball Mill Work Index (WiBM)
- JK Drop Weight (modified and full test) parameters

This paper focuses on throughput estimation and is a continuation of works discussed in McCaffery et al (2006).

Several approaches have been used to develop the current throughput estimation model. This work has been supported using expertise of external expert modeling consultants such as Metso Process Technology & Innovation (PTI) and SMCC Pty Ltd (SMCC). The two main approaches involve models based on ore geological and metallurgical characteristics, comminution characteristics, blast design and mill power. Performance of these models has been monitored by site personnel for accuracy against actual performance and the preferred model modified slightly and used for Life of Mine (LOM) business planning and, as a baseline for future plant optimisation.

Several tools have been developed to aid Mine to Mill monitoring by integrating the Mine Operating Reporting System (MORS) and the OSIsoft® PI system™ plant data historian. This integrated system allows mine and mill personnel to track (in near real time), ore source, equipment location, ore characterisation data, tonnes flow and process parameters such as ore size distribution, copper grade, recovery and other operating parameters used to control the milling and downstream flotation processes.

Key to success of this programme has been successfully capturing and utilising Mine to Mill tools to improve the knowledge of all stakeholders, continuous education and regular evaluation/audit to identify opportunity for continuous improvement.

GEOLOGY AND ORE CHARACTERISATION

The Batu Hijau deposit is an arc island copper-gold porphyry system. The deposit can in general be described as a central intrusive young and intermediate tonalite core surrounded by a quartz diorite intrusive and volcanic lithic breccia material. Young tonalite, intermediate tonalite, volcanic and diorite form the main lithological classifications for the orebody.

These lithologies, their distributions and association with mineralisation have served as the foundation for ongoing metallurgical studies. Copper and gold mineralisation is directly related to quartz veining density and wall rock alteration. Mineralisation is highest in the centre of the deposit, increases with depth for both copper and gold and dissipates radially through diorite and volcanic lithologies with decreasing quartz vein density. Further detail of the deposit's geology is discussed by Clode et al (1999) and Garwin (2002).

Geotechnical measurements such as RQD, RMR and PLi as well as other rock hardness or related parameters are included in the exploration geological model. These include Bond Crusher Work, Ball Work, Rod Work and Abrasion indices (WiCR, WiBM, WiRM and Ai), JKMRC impact breakage resistance (Axb) and the JKMRC abrasion resistance (t_a) as determined from Drop Weight testing.

Accuracy of the hardness model over Life of Mine (LOM) is key for development of reliable throughput estimations for use in mine plan generation. Ongoing work has focused on understanding hardness parameters and how they affect mill throughput.

2006 and 2007 reviews of throughput model predictions versus actual mill performance and mapping this against the associated geological and metallurgical throughput drivers triggered an intensive in-fill drilling program to improve geology model ore hardness measurement accuracy and interpretation. This work indicated that copper grade and WiBM played a larger role in influencing throughput than had been previously thought.

Given that prior in-fill sample density was low in the periphery and deeper areas of the deposit, geology hardness modeling was concentrated in these areas using WiBM and Drop Weight parameters. Figure 1 demonstrates the improvement in deposit coverage for WiBM. This work was completed in 2008. The current database is considered *adequate* to understand hardness characterisation within the Batu Hijau deposit and to build reliable business plan throughput estimations. The change in critical parameters such as WiBM is shown in Table 1.

Table 1- Comparison of Geology Model Hardness Parameters 2004 and 2008 In-fill Drilling

		2008 In-Fill			**2004**		
		High Grade Ore	**Medium Grade Ore**	**Low Grade Ore**	**High Grade Ore**	**Medium Grade Ore**	**Low Grade Ore**
Grade	**Cu**	0.57	0.33	0.28	0.58	0.37	0.28
Geotech	**RQD**	47	45	45	45	44	41
	PLI	5.1	3.9	3.9	4.9	4.6	3.6
	RMR	56	53	54	55	55	54
Comminution	**WiCR**	8.2	6.7	6.2	8.2	6.5	6.2
	WiRM	13.8	14.4	15.0	13.8	15.9	15.0
	WiBM	11.6	**13.9**	**15.1**	11.4	11.8	12.1
	Ai	0.26	0.2	0.17	0.25	0.12	0.17

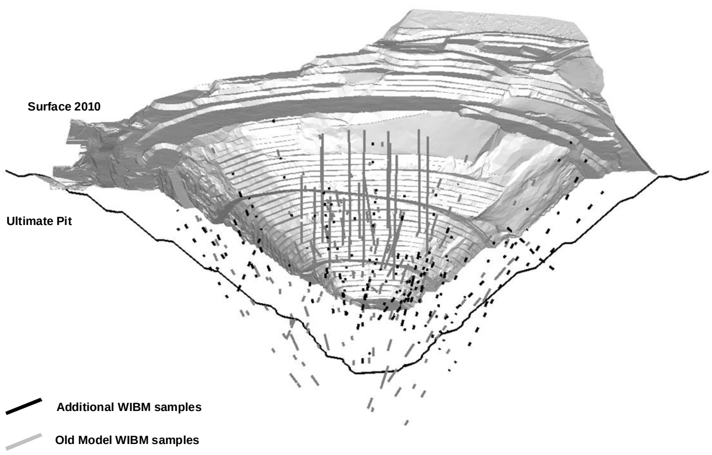

Figure 1- 2008 WiBM Sample Locations

THROUGHPUT MODELING

2004 to 2007 Throughput Model

SAG throughput is influenced by both mill feed size and ore hardness/breakage rates. Work from 2004 to 2006 was assisted by Metso PTI and concentrated on optimising blasting to increase fines generation in the feed and developing throughput models that utilised high density geotechnical parameters such as PLi and RQD to propagate low density JK Drop Weight test results throughout the orebody. This work is discussed in detail in Burger et al (2006) and McCaffery et al (2006).

The main results were:

- Generation of a drill and blast "Cookbook" to optimise blast fragmentation. This was established by grouping model blocks on the basis of ore hardness domains defined via PLi and RQD ranges. This Cookbook is still actively used and has had only minor modification to reduce powder factor where high levels adversely impact final wall stability.

- A sixteen domain throughput model based on lithology and ore hardness domains. The approach was to pass each of the characterised ore domains through consecutive blasting fragmentation, primary crushing and grinding circuit models. Variability was considered for powder factor, RQD, PLi and Bond Work Indices.

The Metso PTI throughput model was found to be a good predictor of throughput in 2004. A gap developed between actual and predicted throughput in 2005 and was found to be related to copper grade, where the model tended to under predict at high grades and over predict at lower grades. In 2006, the models were recalibrated by adding a grade correction term to account for the observed grade effects.

Characteristics of ore that is to be fed to the mill were extracted from the geological block model via mine plan cut shapes. These were loaded into the Metso Mill Throughput Model executable program for the given period to generate a throughput estimate. This "black box" executable model consisted essentially of a multidimensional look up table that utilised the above listed ore characteristics and a designated throughput. The resulting look up table throughput was then adjusted via a linear function according to the grade of the plan cut shape.

In 2007, the equations describing the 3D surface (PLi vs. RQD vs. TPH) for each ore domain were identified by Mill Metallurgy and coded by Geology and Mine Engineering into the block model together with the grade adjustment on a 25 m x 25 m mining block basis. This removed the need to operate the black box model external to the block model. It did not however account for material that had been stockpiled since it was not possible to re-differentiate this by lithology and therefore domain although, weighted averages of grade, WiBM, RQD and other variables were available in the stockpile geology model. A fixed throughput was assumed for this material. This was considered to be an issue later in mine life when large volumes of stockpile material would be delivered to the mill as varying proportions of mill feed.

No major effort was made to fully understand and explain the geological mechanisms that control the observed copper grade influence on mill throughput. A similar grade-throughput effect has been observed for other copper porphyry orebodies such as Ernest Henry, Bougainville Copper and Ok Tedi and so it was accepted by Batu Hijau personnel that this effect is not uncommon. Ongoing studies therefore concentrated on improving confidence in the grade-throughput relationship across all expected grades to be delivered to the mill over LOM. It was proposed however that the grade-throughput relationship was related to the underlying controls of copper and gold mineralisation in the orebody.

Concerns identified with the 2006 grade adjusted model were that grade corrections were linear and only valid down to about 0.4% copper head grade. Significant periods of delivery of ore within this grade bracket were experienced in 2005 through to June 2008 and the appropriateness of the applied grade adjustment was confirmed up to December 2007. After this point, a substantial difference was observed between predicted and actual throughput as demonstrated in Figure 2.

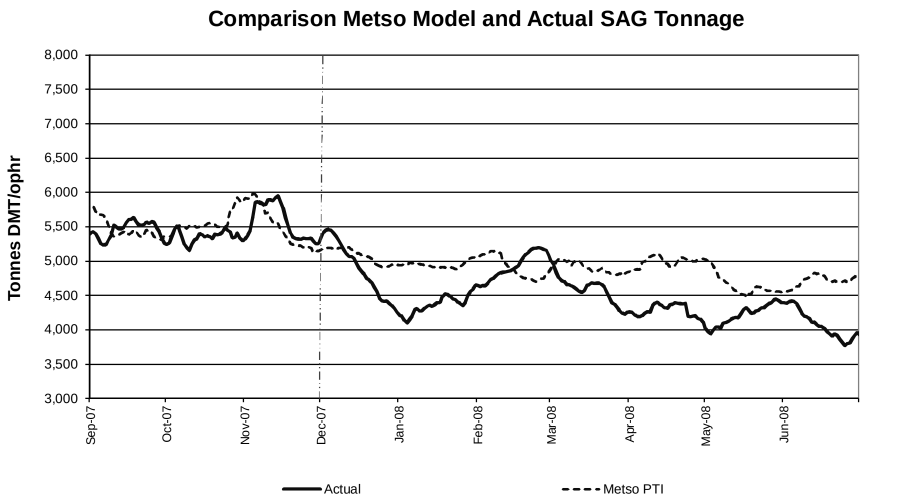

Figure 2- Metso PTI Continuous Model – Includes Grade Adjustment

Further orebody characterisation was considered to be needed in years from 2009 to end of mine life, where head grade in the 0.24% to 0.4% copper range was expected, in order to improve confidence in long term predictions.

2006 to 2007 Throughput Model

SMCC Pty Ltd was retained in late 2006 to conduct an independent review of the throughput prediction methodology. The purpose of the study was to evaluate basic validity of the modeling approach.

PLi was found to provide a reasonable indication of ore hardness from a SAG mill perspective when feed grade of ore was more than 0.6% copper. Where grade was lower than this, PLi did not correlate well with plant performance. It was believed that this effect is related to changes in hardness of finer particles in mill feed (1 to 30 mm range) relative to the larger and less mineralised particles. The Point Load test is not equipped to measure hardness of particles of this size. Further it was found that unlike PLi, JK Drop Weight Index (DWi) and WiBM exhibited inverse relationships with head grade.

The Point Load test typically breaks 50 – 65 mm rocks to 25 – 35 mm and accounts for only 10 – 15% of the SAG mill energy range. The DWi represents energy required to break particles in the 16 to 63 mm (30 mm average) size range to 1 mm and hence covers 80% of the SAG mill energy spectrum. This makes it a more representative parameter to indicate SAG mill ore hardness.

The Metso PTI modeling approach utilises PLi to propagate DWi throughout the orebody model. SMCC concluded that the grade correction applied to the Metso model served to correct the PLi values to give an improved indication of hardness over the full SAG feed size range.

Tying this back to the proposed theory that hardness is related to the quartz fracture vein density that drives mineralisation, it was suggested that for the inner areas of the orebody, all particle sizes have a higher level of homogeneity of mineralisation. The consequence of this is that hardness of larger particles is similar to hardness of smaller particles. As quartz fracture vein density and mineralisation decreases radially, mineralisation with broken rock particle size tends to become less homogeneous and hardness of larger particles is less representative of smaller particle hardness.

SMCC also developed an alternative approach for throughput prediction (both lines) that used a simple correlation between DWi and copper head grade as a hardness proxy as shown in Figure 3. The SMCC model can be mathematically expressed as follows:

$$TPH = K.\ kW / (RQD^a .\ fn(DWi,Cu)) \quad (1)$$

Where:

K = calibration constant
kW = combined power draw of SAG mills
RQD = average RQD of feed expressed as a percentage
a = constant
fn(DWi, Cu) = function relating DWi to Cu grade of the feed.

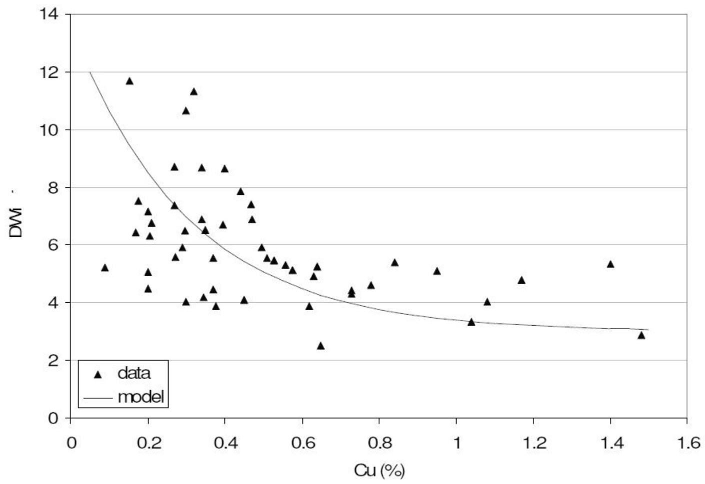

Figure 3: SMCC Initial DWi/Cu Model

The functions determined by SMCC were:

$$DWi = 9 \times (1.33 - (1 - e^{3.26(0.05\text{-}Cu\%)})) \quad (2)$$

$$TPH = 0.916 \times 22950 \times RQD^{-0.131} \times DWi^{-0.6} \quad (3)$$

The predicted throughputs for the SMCC and the Metso PTI models are compared against actual over the same period in Figure 4.

The models gave similar expected throughput indication (±2 to 3%). It was considered by site personnel based on this finding that the SMCC model could be used as a check or validation tool for the Metso PTI model. Both models still did not always provide accurate predictions for all dips and peaks in throughput and required validation over the full range of expected future ore delivery grades.

Perceived advantages of the SMCC model were that:

- It was simple and independent of ore lithology and therefore domain.
- It could easily be coded directly into the geology block model.
- Due to restricted ability of Mine Geology to report back mined ore characteristics by domain for stockpile material, the SMCC model could be used on a daily basis as a back calculator check on model performance where significant quantity of this material is fed to the mill.

Annual throughputs for LOM were predicted using both models with the prediction that throughput could be expected to decline with time, concurrent with a progressive reduction in head grade.

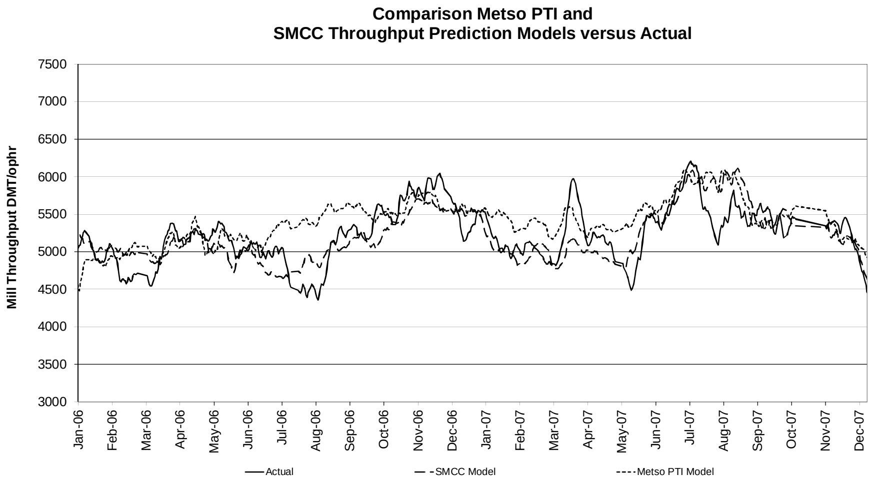

Figure 4: Comparison Actual Mill Throughput with Model Predictions

To determine which part of the plant could be expected to be the throughput limiting circuit in later years, SMCC also developed a correlation between WiBM and Cu grade. The simple model developed is shown on Figure 5.

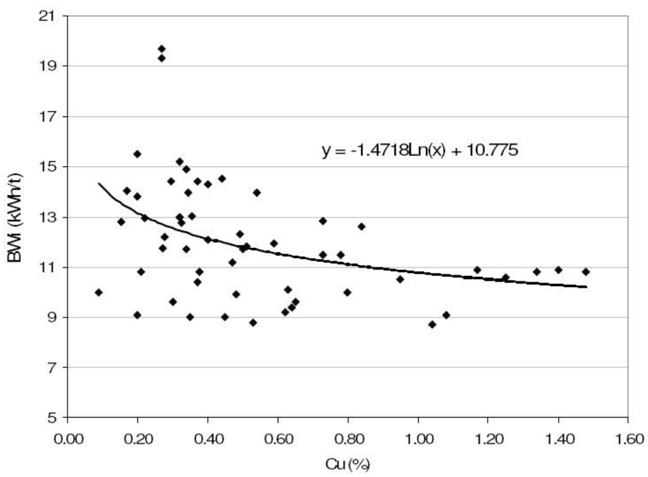

Figure 5- SMCC WiBM and Copper Grade Correlation

Although WiBM values were expected to increase over time, in the range from 11.5 kWh/t to about 13 kWh/t, the relative increase was not as much as the DWi. SMCC predicted that on this basis, the SAG mill would remain the rate-limiting circuit.

The significant scatter in results for both DWi and WiBM against copper grade required that further ore characterisation be completed. A larger data set would assist to improve confidence in model fit parameters and future throughput predictions. The minimum requirement was for increased numbers of DWi and WiBM tests. These recommendations were in line with previous modeling and uncertainty related to lower grade ore delivery.

2008 Throughput Model

The situation changed again in 2008 as shown in Figure 6. Both models grossly over predicted throughput to the tune of >9% when compared to actual and neither model adequately accounted for <u>all</u> parameters and/or variations that drive mill throughput.

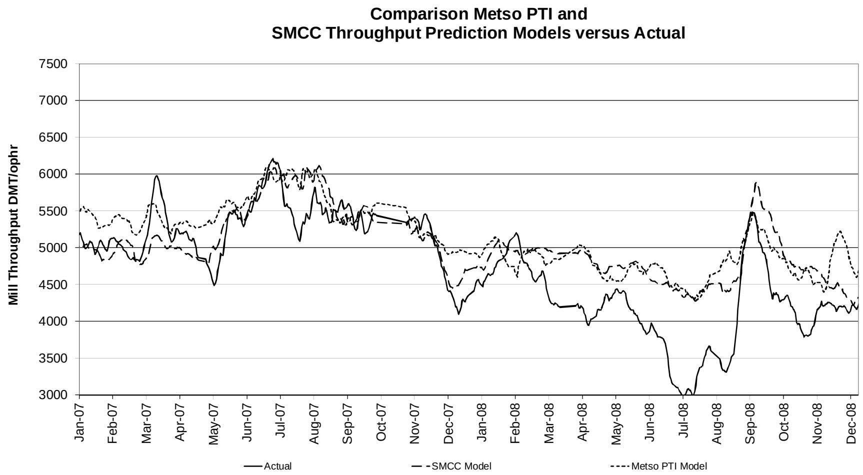

Figure 6 - Model Performance in 2007 and 2008

<u>In-fill Hardness Testing 2006 to 2008</u>

Ore characterisation continued from 2006 to 2008 via progressive annual in-fill drilling programmes and concentrated on building up data density in low grade and peripheral ore zones as shown in Figure 1. A further 63 Drop Weight Index tests and 540 WiBM index tests were completed.

The complete database of DWi is shown in Figure 7. The SMCC grade with DWi correlation is overlaid on this plot and indicates that the model was consistent with latest measured values although there was still significant scatter. This was mainly noted for Tonalite ores. It was not considered that any change was warranted in the model.

The grade with DWi effect was especially evident for Volcanic and to a lesser extent for Diorite ores. Tonalite ores also did not display as significant a relationship. Volcanic and Diorite lithologies however comprise the bulk of future low grade ore with Volcanic ores making up approximately 60% of ore delivery. The Metso PTI predictions are consistent with this result where, in general, Volcanic ore domains receive a more severe reduction in throughput due to grade than Tonalites.

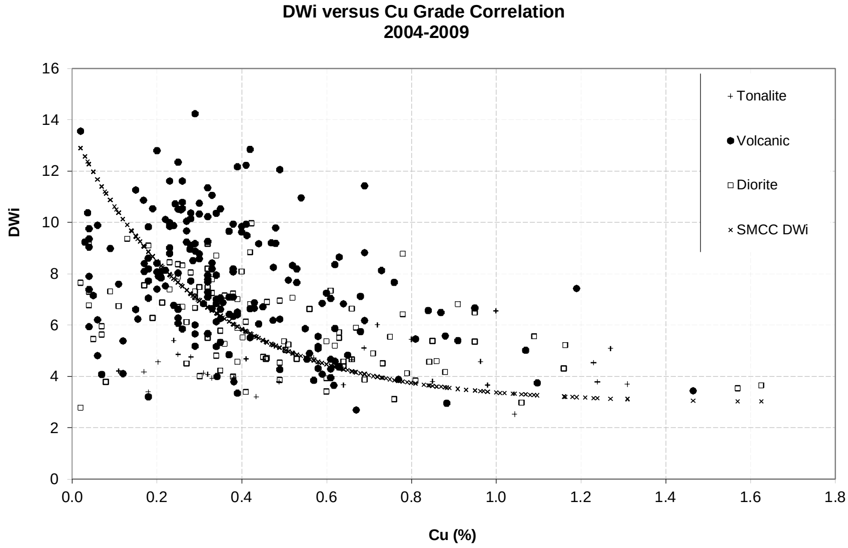

Figure 7 - Updated DWi and Copper Grade Relationship

Ball Mill Work Index Model

The complete metallurgical hardness database for WiBM measurement versus copper grade is shown in Figure 8. Overlaid on this plot is the original SMCC grade with WiBM correlation. A simple logarithmic fit has also been overlaid for the Volcanic ores. The updated data indicates that compared to Figure 3 (previous SMCC plot), the original SMCC correlation tends to understate WiBM at lower grade, especially for Volcanic ores.

Figure 8 shows an increased number of data points with WiBM > 15 kWh/t. This suggests that while on average, ore will continue to have a WiBM in the range of 13 kWh/t, it is very likely that low grade Volcanic ore will tend to be ball mill circuit limiting. The grade-WiBM relationship appears to be relatively independent of grade for Tonalite ores. As already noted for DWi, tonalites do not form a large percentage of future low grade ores.

Based on these findings, it was considered by site personnel that WiBM could strongly influence and potentially limit mill throughput, especially for Volcanic ore types where head grade is low.

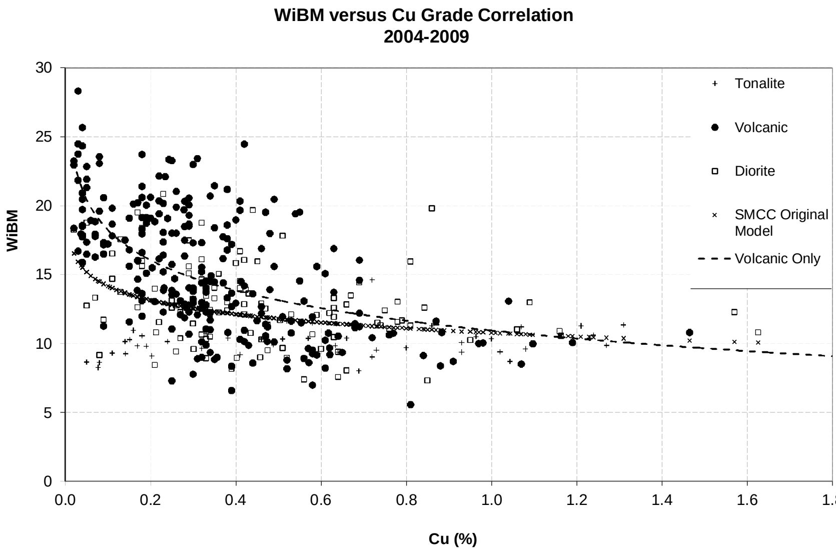

Figure 8 - Updated WiBM versus Copper Grade

Monitoring of mill throughput continued in 2008 in parallel with grinding specific energy, head grade, WiBM and RQD. Daily production data trends are plotted in Figures 9 through 11 and show that:

- While the inverse relationship between RQD and mill throughput applies, throughput varies more widely than could be wholly explained by variation in RQD%.
- There is a strong inverse relationship between WiBM and mill throughput. This is stronger than the RQD and throughput inverse relationship. WiBM is strongly inversely related to copper head grade.
- As head grade decreases below 0.5% copper, grinding specific energy (SAG + ball kWh/t) appears more strongly influenced by WiBM and suggests grinding will tend to be more ball mill circuit limited at lower head grades. The limiting changeover point coincides with a Ball Mill Work Index of about 12 to 13 kWh/t.

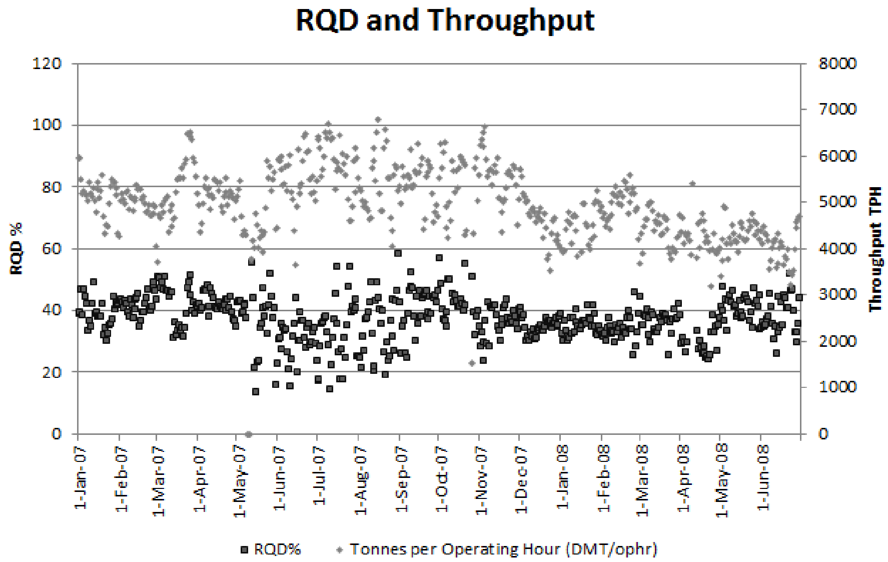

Figure 9 – Trend of Actual Mill Throughput with RQD %

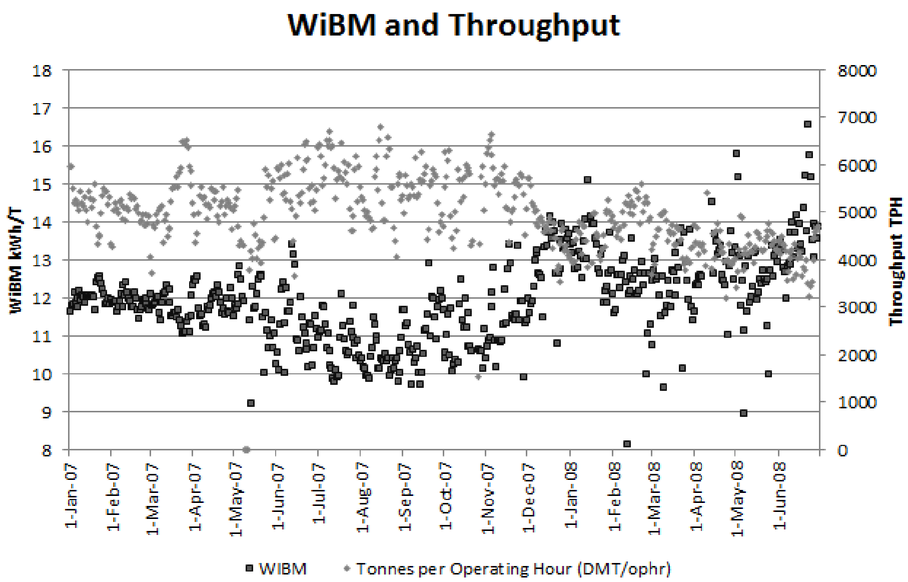

Figure 10 - Actual Mill Throughput with WiBM

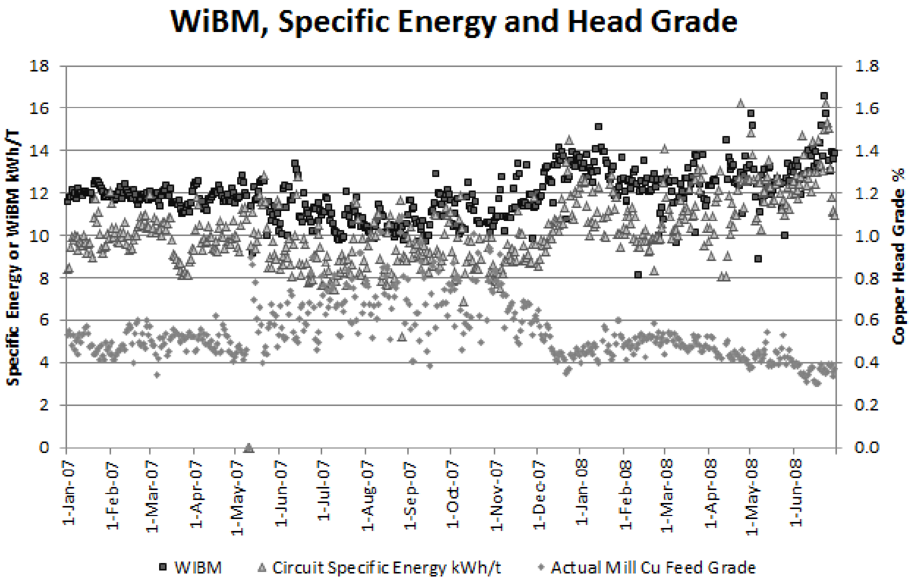

Figure 11 - Mill Head Grade with WiBM and Specific Energy

Combined, these observations suggested that the throughput model should be modified to include a Ball Mill Work Index term. This would only be required above a limiting Ball Mill Work Index value that was estimated to be 12.25 kWh/t. The SMCC model approach was most easily modified. The original base functions determined by SMCC were retained. A WiBM correction term was determined by site Metallurgy using a standard difference of squares minimisation technique.

Mathematically the new model (both mills) is expressed as:

$$TPH = K.\ kW / (RQD^{a}\ .\ fn(DWi,Cu\%).WiBM^{b}) \quad (4)$$

Where:

K = calibration constant
kW = combined power draw of SAG mills
RQD = average RQD of the feed expressed as a percentage
a = constant = -0.131 (original SMCC model)
WiBM = Ball Mill Work Index kWh/t
b = WiBM correction constant
fn(DWi, Cu) = function relating DWi to the Cu grade of the feed.

The new functions are:

$$DWi = 9 \times (1.33 - (1 - e^{3.26(0.05-Cu\%)})) \text{ (unchanged from SMCC model)} \quad (2)$$

When WiBM< 12.25 kWh/t:

$$TPH = 0.916 \times 22950 \times RQD^{-0.131} \times DWi^{-0.6}, \quad (3)$$

When WiBM>= 12.25 kWh/t:

$$TPH = 0.916 \times 22950 \times RQD^{-0.131} \times DWi^{-0.6} \times WiBM^{-0.0323} \quad (5)$$

The revised function was applied to actual daily ore delivery data back to January 2006 and compared against the Metso PTI model output over the same period as shown in Figure 12. Input data was filtered to remove all days where SAG mill or Ball mill utilisation was not > 90%. The average difference between actual and predicted was <0.4% for the WiBM corrected SMCC model and 5% for the Metso PTI model over the 3 year period.

A sizable difference still periodically existed between Actual and the new SMCC model prediction as is particularly evident from June to about September 2008. On field investigation, the difference was found to be a result of a physical circuit equipment bottleneck, causing under-performance of actual mill throughput rather than over prediction by the model. This is further discussed in the Circuit Optimisation section of this paper.

Monitoring of the new model with the Ball Mill Work Index correction continued and in late 2008 it was decided to apply this model as the throughput predictor for Business Planning forecast purposes for 2009 onwards. The choice to proceed down this route was mainly because of the ease of application of the model within the geological block model.

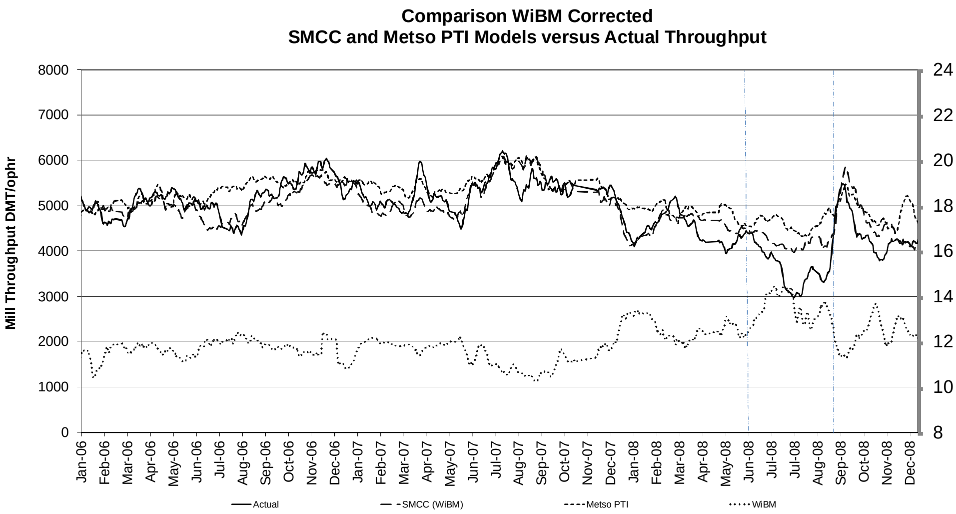

Figure 12: Comparison of Metso and WiBM Modified SMCC Throughput

BUSINESS PLANNING

The Business Planning review at Batu Hijau is updated on a quarterly basis based on changes in mine plan and includes both operating and capital strategies.

For operating strategy, the production forecast involves estimation of throughput, mill availability, recovery and expected product concentrate grade. This information is all highly dependent on ore geo-metallurgy and must be revised as a result of any changes in the mine plan. A flowchart describing the business planning process is shown in Figure 13.

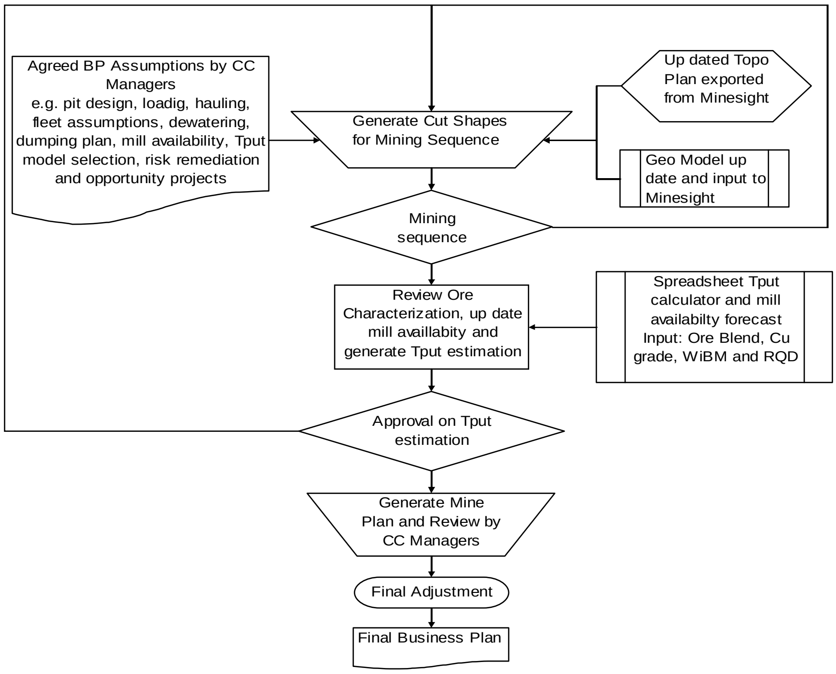

Figure 13– Flowchart Business Plan Process

As a first step, management agree on forecast input data including pit design, loading, hauling, support and rental fleet assumptions, pit dewatering levels, dumping plan, mill availability, throughput model selection, dry season, risk remediation and opportunity projects. This agreement is documented and used to update the previous mine plan and start the second step.

Mine Engineering generates cut shapes for the proposed mining sequence starting with a topography update and export of the plan and associated data from MineSight software. The updated information integrated into this software includes characteristics like ore hardness, modeled recoveries and other data including the concentrate grade model, as generated by Mine Geology. The mining sequence and related ore domain data files are reviewed by plan shape for execution viability and to identify any data anomalies. Where obstacles are identified and the proposed cut shapes found unreasonable, revisions are requested.

The completed deliverable from this step is used for throughput estimation by the Metallurgy section. Ore blend data, grades, stockpile feed information and ore hardness parameters are modeled and combined with the mill maintenance downtime plan to determine expected throughput for each period. Depending on processing "hard" constraints, for example, targets to ensure safe and environmentally compliant operation, circuit volumetric limitations or concentrate quality (grade and impurity) targets, requests for alternative ore blend delivery may be made. The process is iterated until all constraints are met for a maximum revenue production scenario.

After being reviewed by the site operational area cost centre (CC) managers, the production plan is approved and issued. Since following the above described approach, deliverability and annual compliance of actual production against the plan has improved markedly as shown in Table 2. Plan non-compliance now only results as a result of difficult to predict events such as geotechnical failures or extraordinary unplanned maintenance events.

Table 2- Comparison Actual Throughput Compliance with Budget

Year	Actual Mt	Budget Mt	Difference	Explanation
2004	49.2	51.5	-4.5%	Post plant modification. Major plant failure overland conveyor.
2005	45.5	50.0	-8.9%	Maintaining circuit
2006	42.6	49.8	-14.3%	Plant modification and Mine Plan changes (unplanned high wall failure)
2007	42.4	43.5	-2.4%	Maintaining circuit
2008	34.3	40.2	-14.7%	Model prediction issues resulting from high WiBM ore
2009	40.5	39.7	1.8%	SMCC WiBM model used
2010	43.4	43.6	-0.6%	SMCC WiBM model used

Mill Throughput Adjustments

Depending on operational issues or other factors, positive and negative mill throughput and recovery adjustments are applied to ensure the business plan target is achievable.

Negative adjustments account for anticipated circuit efficiency issues that might arise due to maintenance or other limitations. An example is loss of surge capacity in the coarse ore mill stockpile during periods where milling rate is expected to be higher than ore tonnage supplied to mill. This can occur during extended maintenance downtime on the upstream ore crushing and transfer systems. For events of this nature, size segregation occurs in the feed stockpile causing SAG feed size variability and subsequently causes lower average milling rate. Another example is ramp-down and ramp-up periods before and after major plant shutdowns and where the circuit is brought back on line progressively with one ball mill per line remaining offline for longer.

Positive adjustments account for planned plant equipment modification or operational strategy initiatives that will result in incremental throughput improvement. For example, a primary crusher Continuous Improvement project identified changes to crusher hydro-set gap operation that delivered more consistent feed top size to the mill. Based on a pilot trial, this initiative was proven to give a 1.5% throughput improvement that was incorporated into the plan as a constant incremental increase.

Recovery adjustments are also made depending on expected age of any long term stockpile material that may be delivered over a plan period.

Mill Availability

The mill availability estimate is developed based on the major plant shut down plan for equipment requiring full or partial shutdown such as for SAG mill and ball mill relines or tailing pipeline maintenance. In the longer term, it is hoped to use fundamental ore characteristics to complement wear measurements to improve downtime scheduling and to better predict deterioration in throughput performance resulting from progressive liner wear.

Minor down times are scheduled to accommodate operational strategy, e.g. ball charge and total charge inspections after new SAG liners are installed and SAG mill grate configuration changes to allow operational balancing of expected grinding operation restrictions and to maintain consistent open area.

An additional allowance of 5% of unscheduled downtime is also applied to each milling train based on downtime operating history. Other allowances are conditional and depend on major equipment critical issues e.g. Issues that result in probable intermittent operation or equipment availability risk that may result in down time required for remediation.

MINE to MILL MONITORING

Maintaining business planning accuracy and consistently optimising the process requires good tools to monitor production performance. Batu Hijau has developed the capability to perform Mine to Mill monitoring on line in near real time.

In the past, providing on line Mine to Mill monitoring was limited by site ability to integrate the different software platforms. Mine Operations rely on a Modular Dispatch system to monitor ore shipment by truck to the primary crusher facilities on an hourly basis while Mill Operations use the Distributed Control System (DCS) for on line production monitoring. The site requirement was to integrate both systems in a single on line monitoring system that could easily be accessed both users.

Historically, Mine to Mill monitoring was manually performed via MS Excel spreadsheets on a daily basis. A variety of Mine Engineering, Mine Geology and Mill Production reports were combined to allow analysis of performance. This required a significant amount of data transfer and time consuming human effort. Analysis of Mine to Mill results was limited to some technical people and was used for high level work only. The large datasets provided the foundation for all process modeling works that had been done over the years.

Mine Monitoring

The Mine Modular Dispatch system had been used since mining activities started at Batu Hijau in 1999 and retained all material movement data records. The system was upgraded to Jigsaw and Masterlink in 2009 when the existing hardware and software reached the end of its service life.

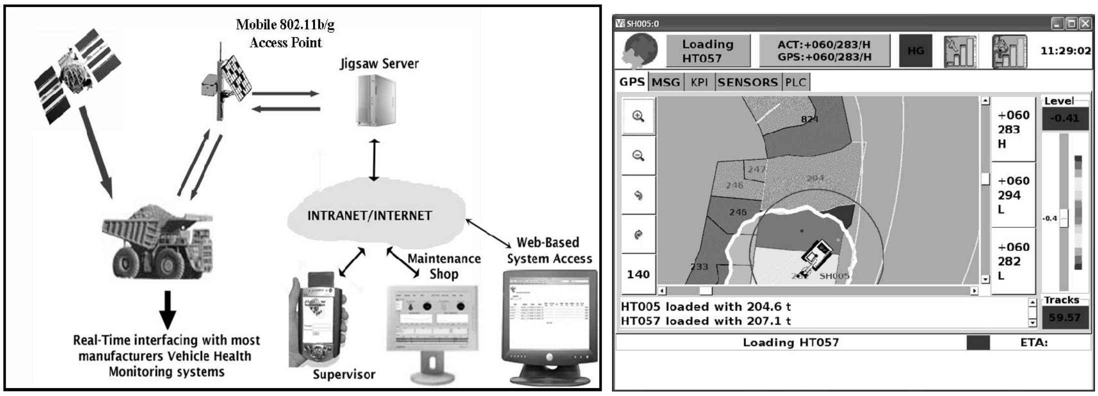

Figure 14– Typical Jigsaw and Masterlink Setup and Web Based Outputs.

The Jigsaw system was selected as a replacement for Modular based on cost but more importantly on ability of the system to utilise wireless networking for storage, retrieval, transmission and reporting of data to an in house developed Mine Operating Reporting System (MORS). MORS is a reporting system based on an SQL database that allows data to be converted into web based information and to download in MS Excel format.

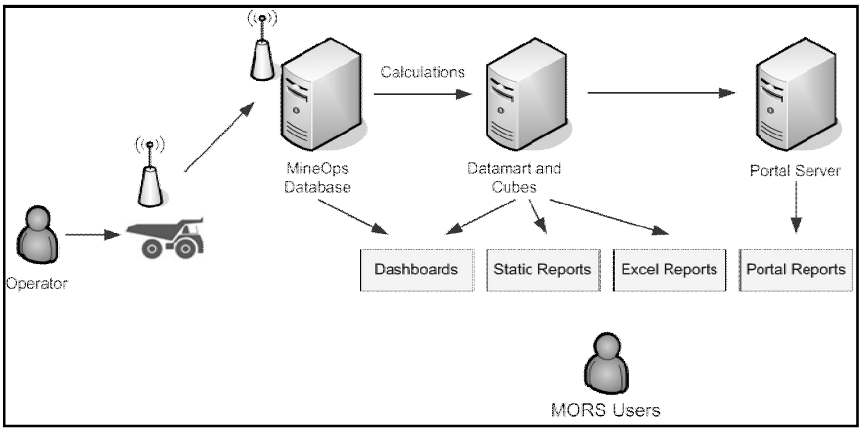

Figure 15– Mine Operations Reporting System Configuration

Mill Monitoring

OSIsoft® Process Information (PI™) was implemented at Batu Hijau in 2002 and is used widely by site Metallurgical Engineers, Process Maintenance and Process Operations for on line plant performance monitoring via desktop work stations. Shift and daily plant production reporting also uses this software. PI also provides information web based, MS Excel reporting capability.

Integrated Mine to Mill Monitoring

Batu Hijau Metallurgy developed an on line MS Excel spreadsheet to combine PI and MORS to present mine ore characteristics based on the source and blending data that impact plant performance on an hourly basis. Near real time information, including ore characterisation data of ore sources is provided from each mine polygon and is presented side by side with plant operating and production parameters. The basic on line spreadsheet format is shown in Figure 16.

The Mine to Mill hourly MS Excel spreadsheet is actively utilised to monitor mill production performance in relation to ore blend strategy for mill throughput, ore grades and recovery performance. Users are mainly Mine Engineers, Ore Control Geologists and Mine Operation Supervisors. The Process Division users are Control Room Operators, Metallurgical Engineers and Process Operation Supervisors.

A dedicated large screen monitor provides this information so Control Room Operators can see and acknowledge ore characteristics and expected throughput and recovery up to three hours before the plant receives and processes the ore. This lag time between trucks dumping ore to the primary crusher and receipt at the Mill allows operators and supervisors to prepare and adjust processing strategy hour by hour. Whenever an unexpected or unwanted situation occurs, for example, the ore contains too many fines driving a requirement to increase rocky ore; the process personnel will feed back this information to mine operations to revisit the ore blending strategy. Execution of requested ore blend changes depends, of course, on accessible ore sources and equipment availability.

Mill Metallurgy personnel use the data to monitor and adapt plant control settings, in particular grinding control targets, against ore delivery characteristics.

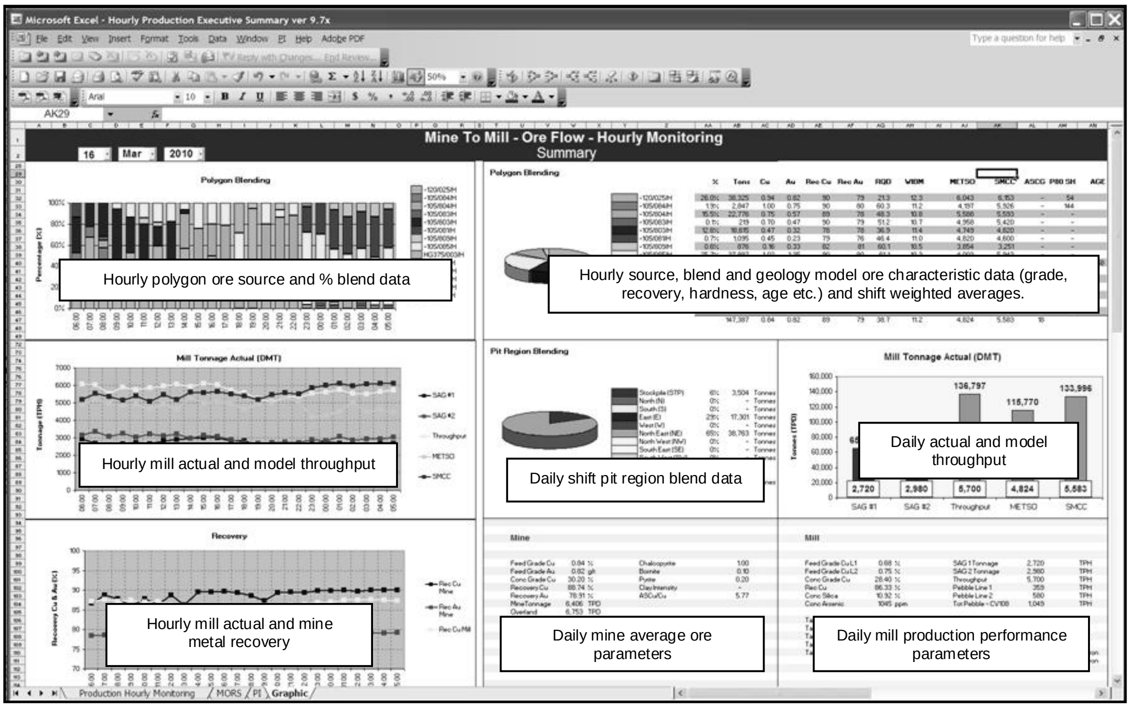

Figure 16– Mine to Mill Ore Flow Hourly Monitoring

CIRCUIT OPTIMISATION AND FUTURE MODIFICATIONS

Possessing detailed knowledge of future expected ore delivery and associated performance provides Batu Hijau operations with the ability to perform targeted short, medium and long term plant optimisation and modification.

Circuit Optimisation

A detailed understanding of ore characterisation, robust throughput models and on line monitoring of Mine to Mill performance has provided a confident base line of current grinding circuit capability and the ability to respond to future ore characteristics. This solid base case is used to identify grinding circuit bottlenecks that occur due to ore characteristic changes and hence can be used to provide a measured justification for any circuit changes proposed for improvement.

As an example, in mid-2008, the plant treated high WiBM (13-16 kWh/t) ore (see Figures 12 and 17). This resulted in very low plant throughput compared to the model prediction for ore with those characteristics. Field investigation showed that processing this harder material resulted in the requirement to operate the primary cyclone feed pumps below their design flow minimum.

Operators were unable to build up circulating load, even with addition of excess water to the circuit. Operating flows were at or near slurry settling velocity so that coarse solids settled and accumulated in the cyclone feed line. In certain circumstances, this material was purged to the cyclone feed distributor header and in the worst case, caused cyclone roping or near roping resulting in unclassified material reporting to cyclone overflow. The cyclone feed pumps and cyclone feed lines were found to be oversized for the required operating duty when processing this type of ore.

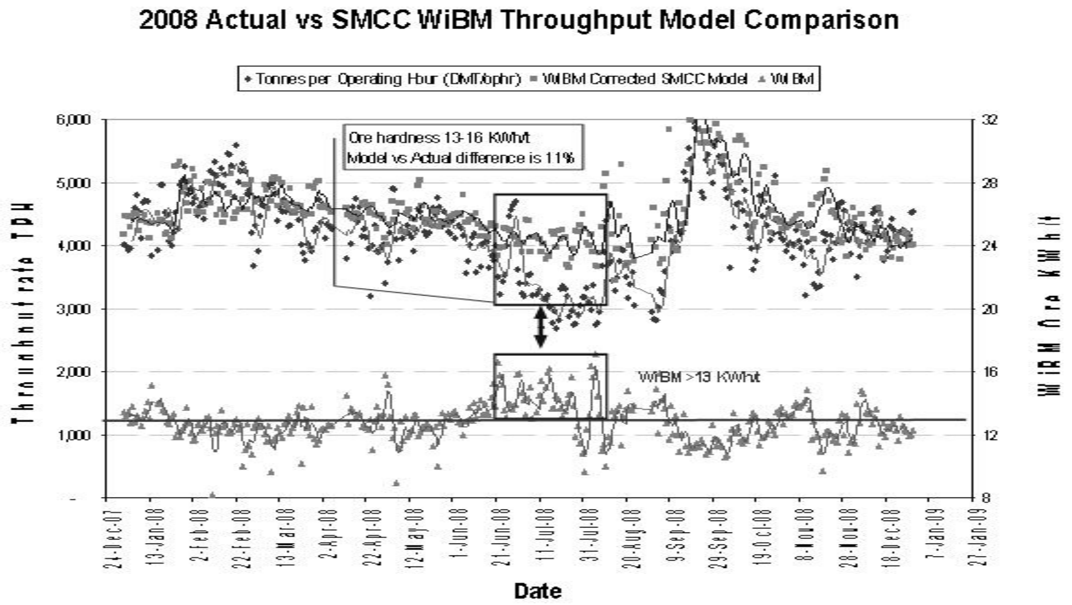

Figure 17– Circuit Monitoring Bottleneck Example

This condition was made worse by the fact that the cyclone vortex finder diameter was also too large for the low throughput range. The installed cyclone size was 33" (838 mm) with only 3-4 cyclones open against 11 cyclones available per nest. Large flow spikes occurred when a cyclone was opened or closed causing instantaneous circuit instability and consequently further throughput and recovery loss. Downstream wear on cyclone feed pump internals, transfer launders, flotation cells and the tailings line also increased. In the case of the latter, wear life was reduced by the short period of operation under these conditions from over two years to less than one year.

Short term action was taken to reduce cyclone vortex finder diameter, reduce SAG grate open area and increase ball size in the ball mills to help mitigate the WiBM driven circuit limitation effects. Analysis of future ore delivery characteristics indicated that this situation would happen again for significant periods. Based on this knowledge, operations management decided to reconfigure the equipment by re-sizing the cyclone feed pipe and testing different feed pump changes to suit the future expected operating ranges. Downsizing the cyclone dimensions from 33" to 26" (660 mm) with more cyclones per nest (from 11 to 15) was also initiated to accommodate the expected wider range in operating throughput and, to improve circuit control at low throughput.

This project was justified by mitigation of throughput reduction risk in the order of ~5% during future high WiBM ore delivery periods. Implementation of these changes will be completed in 2011 and is expected to enable actual throughput to approach the model predicted throughput when processing these types of ore.

High confidence in future ore characteristics and the associated throughput model estimation also allows operations to better manage SAG mill grate configuration and grinding circuit spare parts stocks such as maintaining inventories of different aperture trommel screen panels, cyclone vortex finders and spigots. Allowance for purchase of the required parts can be included in the operating cost budget and installation scheduled in the appropriate year for expected ore type changes.

Plant Circuit Modification

Batu Hijau conducted a Mine to Mill survey in 2009 in co-operation with Metso PTI. The objective was to confirm Mine to Mill throughput bottlenecks that could be anticipated for the current milling circuit configuration when treating low throughput ore with characteristics similar to future ores. The expected deliverable was to define a path forward for grinding circuit improvement that could be achieved either incrementally via minor modification to the current configuration, or to identify preferred future major mill expansion options.

Prior to the survey, a selected polygon was locked from mine activity and held for processing. The selection criteria was to identify ore with WiBM >13.6 kWh/t, Volcanic lithology and low head grade. Metso PTI's SmartTag™ system was used to cross reference the origin ore coordinates and allowed site personnel to measure actual blasting parameters, calculate process residence times in stockpiles and to know exactly when the selected material was passing through the mill. The SmartTag data showed that ore transit time from the primary crusher to the SAG mill during the survey was about 4.5 hours.

The survey results indicated that the point where the grinding circuit changed from being SAG mill limited to ball mill circuit limited occurred at around 2,250 tph per line and a feed 80% passing size of 65 mm. These data were necessary to consider changes that could incrementally increase throughput in the existing circuit so the plant could be always operated for a SAG mill limited constraint.

A series of JKSimMet simulations and modeling exercises were conducted to evaluate potential plant flowsheet configurations. Several options were considered including application of High Pressure Grinding Rolls (HPGR) technology to alleviate bottlenecks that correlated with high WiBM ore types. The expected throughput gain was calculated directly from the applied WiBM deduction based on the SMCC throughput prediction model and via comparison with the JKSimMet results against the fitted model base case.

The original start-up business plan for Batu Hijau was to expand the mill in about 2005 to include a 3rd SAG grinding line. This option was also re-explored for the updated future orebody knowledge.

The resulting options were evaluated based on incremental throughput gain, capital and financial modelling to identify the options for further definition. Based on this evaluation, it was determined to pursue a 3rd SAG grinding line option with increased ball milling capacity as the preferred approach. Capital and operating cost for the feasibility studies could be developed easily since change in performance and hence equipment sizing could be established with greater confidence.

For a well-informed flowsheet option selection, a robust throughput estimation model and understanding of future ore characteristics is critical. The business decision to support medium or major capital projects relies on a level of confidence in the methods used to estimate production increments on which the overall project economics are based, and to reduce overall project risk.

The throughput estimation model must be re-evaluated whenever modification is made to the circuit by equipment addition/resize/replacement or when a plant stream route is changed. A plant survey to measure the new conditions after changes are implemented should also be conducted to confirm the achieved result for the implemented option or to test for room for further improvements.

CONCLUSIONS

Making sound business decisions relies on dependable tools to estimate realistic production targets. A general rule is that there can never be too little geo-metallurgical characterisation data for an orebody. These data should cover as full a cross section of future expected ores as possible and be available as early as possible to minimise surprises. What appears to be an exception in terms of ore characteristics in earlier operating years could well become the rule in later operating years. Batu Hijau throughput modelling ability and accuracy has been continuously improved by increasing orebody geo-metallurgical knowledge. There have been surprises, however the ongoing impact of these have been reduced by the recognition that orebody knowledge was not adequate and using this knowledge to push for further in-fill drill work.

Mine to Mill monitoring tools assist Batu Hijau improve production strategy by making data visible. A good understanding has been developed between Mine and Mill operations personnel of the factors that drive mill performance. This promotes intensive discussion and feedback by identifying operational issues at both ends of the production value chain. Making Mine to Mill production parameters available on line is one such tool to deliver comprehensive data to support daily operation planning and strategy.

ACKNOWLEDGEMENTS

Gratefully acknowledged is the cooperation and contribution of the Process Operations, Process Maintenance, Process Metallurgy, Mine Engineering, Mine Geology and Project Development teams at PT Newmont Nusa Tenggara (PTNNT). The authors also express gratitude to PTNNT management for allowing Batu Hijau best practices to be shared with the public. Special thanks are extended to Metso PTI and Steve Morrell for their guidance and assistance.

The authors thank colleagues, past and present, that have helped to make the concept of Mine to Mill at Batu Hijau a reality and for continually seeking new standards of excellence.

REFERENCES

McCaffery, K., Mahon, J., Arif, J., & Burger, B. (2006). *Batu Hijau – Controlled Mine Blasting and Blending to Optimise Process Production at Batu Hijau*. Vancouver B.C:SAG 2006, II-372

Burger, B., McCaffery, K., McGaffin, I., Jankovic, A., Valery, W., & La Rosa, (2006). *Batu Hijau Model for Throughput Forecast, Mining and Milling Optimisation, and Expansion Studies.* Colorado: SME, pp. 461

Garwin, S. *"The Geologic Setting of Intrusion-Related Hydrothermal Systems near the Batu Hijau Porphyry Copper-Gold Deposit, Sumbawa, Indonesia"* Society of Economic Geologists, Special Publication 9, 2002. pp 333-366.

McLaren, D., Mitchell, J., Seidel, J., Lansdown, G., 2001, *"The Design, Startup and Operation of the Batu Hijau Concentrator"*, International Autogenous and Semiautogenous Grinding Technology**,** Barrett, D.J, Allan, M.J., Mular, A.L., Eds., Volume IV, pp. 316–335.

Clode, C., Proffett, J., Mitchell, P., Munajat, I., *"Relationships of Intrusion, Wall-Rock Alteration and Mineralisation in the Batu Hijau Copper – Gold Porphyry Deposit".* Proceedings PACRIM Congress 1999 (PACRIM '99), Bali Indonesia October 1999. pp. 485-498.