Batu Hijau Model for Throughput Forecast, Mining and Milling Optimisation and Expansion Studies

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EXECUTIVE SUMMARY

PTNNT Batu Hijau and Metso Minerals Process Technology (Asia-Pacific) (MMPT-AP) have developed a comprehensive model for forecasting and optimising throughput at the Batu Hijau operation. The model is based on mechanistic models of blast fragmentation, crushing, milling, and classification. The inputs to the model are the proportions and main characteristics of the defined ore domains and their proportions (e.g. Rock Quality Designation (RQD), Point Load Index (PLI), Bond Work Index, lithology, design and operating conditions). The final model is able to predict monthly throughputs within an accuracy of 5% and is also being used for optimisation of the entire mining and milling processes and for expansion studies.

MMPT-AP has developed a stand-alone program to encapsulate the final throughput model with a user friendly interface. This is used to input ore delivery information with blend composition and key model parameters and to output the model predictions (throughput, circuit performance and product size distributions from the ROM to the final grinding product). The intent is to give users in the mine and plant a simple interface to run simulations and allow geology, mining, processing and management the ability to predict unblended throughputs for each of the defined ore domains as well as final blend throughput.

INTRODUCTION

The Batu Hijau ore body is a copper and gold porphyry deposit located in southwest Sumbawa, in the province of Nusa Tenggara Barat, Indonesia. The process plant was designed to treat 120,000 TPD of ore through two SABC mill grinding circuits to produce a copper-gold concentrate.

Concentrator operations started up in September 1999 and have been subject to continuous improvements to increase mine and mill production rates. Major improvements in mill availability, flow sheet changes to the SABC pebble crushing circuit in 2002 and 2003 plus miscellaneous de-bottlenecking projects increased mill production rates by >10% since 2001. Improvements in Mine blasting practices increased fragmentation of harder ores and improved mill throughput by 2-7% since late 2003. Average flotation feed grind size increased from 200 to 240 microns as a result of the throughput increases, with only minor penalty to flotation recovery.

Mill throughput rates are highly variable with daily throughput rates ranging from 4,500 to 7,300 TPH. The effect of mill feed size and hardness on throughput rate is apparent with feed size F80 ranging from 40 to 95mm.
Several years of record low commodity prices immediately after start up at Batu Hijau placed pressure on the mine to produce grade and the mill to maximise throughput, for the operation to remain economically viable. Hence, corporate management required an accurate (±5% annual tonnes) mill throughput model, for strategic planning to ensure life of mine economics.

It was also recognised that optimisation of ore delivery on a revenue per mill run hour basis, could offer economic benefits by maximising metal production and provide a basis for ore blending. Revenue per mill run hour could be determined by including mill throughput rate in the traditional mine revenue per tonne model (grade x recovery – smelter charges).

ORE CHARACTERISATION and MILL THROUGHPUT MODELLING

SAG Mill throughput rates are dependant on ore hardness or breakage rates in the mill and mill feed size distribution. If both breakage rates and mill feed size can be measured or modelled for an ore, a JKSimMet model can accurately predict SAG mill performance. Breakage rates are dependant on rock strength while mill feed size is dependent on in-situ rock structure, rock strength, blast intensity and primary crushing.

The first step in producing an accurate mill throughput model is to develop an understanding of geological parameters that define rock strength and rock structure. In a collaborative effort through 2004, the Batu Hijau Mine-to-Mill Team and Metso Minerals Process Technology – Asia Pacific (MMPT-AP) conducted a comprehensive review of ore hardness and fragmentation in the Batu Hijau ore body to define mill throughput domains. Metso provided a modelling process for each domain that utilised blast fragmentation and primary crusher models to predict SAG mill feed size and produce a more accurate mill throughput model.

HISTORICAL ORE CHARACTERISATION

This section summarises the post start-up ore domain definitions used at Batu Hijau. Ore Domains used for design of the Batu Hijau grinding circuit is not discussed.

Initial ore characterisation for mill throughput prediction was based on lithology and RQD. An RQD cut-off of 50% was used to differentiate hard from soft ore. Process operating experience in 2003 indicated that lowering the RQD cut-off to 40% provided better definition by equalising the tonnage of ore in the plus and minus RQD fractions of each major lithology.

<table>
<thead>
<tr>
<th>Ore definition 2000-2003</th>
<th>Ore Definition 2003-Q2 2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faulted</td>
<td>Volcanic RQD&lt;40%</td>
</tr>
<tr>
<td>Volcanic RQD&lt;50%</td>
<td>Volcanic RQD&gt;40%</td>
</tr>
<tr>
<td>Volcanic RQD&gt;50%</td>
<td>Diorite RQD&lt;40%</td>
</tr>
<tr>
<td>Diorite RQD&lt;50%</td>
<td>Diorite RQD&gt;40%</td>
</tr>
<tr>
<td>Diorite RQD&gt;50%</td>
<td>Intermediate Tonalite RQD&lt;40%</td>
</tr>
<tr>
<td>Intermediate Tonalite RQD&lt;50%</td>
<td>Intermediate Tonalite RQD&gt;40%</td>
</tr>
<tr>
<td>Intermediate Tonalite RQD&gt;50%</td>
<td>Young Tonalite RQD&lt;40%</td>
</tr>
<tr>
<td>Young Tonalite</td>
<td>Young Tonalite RQD&gt;40%</td>
</tr>
<tr>
<td>Undifferentiated (Stockpile rehandle)</td>
<td>Undifferentiated (Stockpile rehandle)</td>
</tr>
</tbody>
</table>
NEW TECHNIQUE FOR ORE DOMAIN DEFINITION

Recognition that both SAG mill feed size and ore hardness/breakage rates dictate SAG mill throughput rates allows geological indicators for both to be used to define ore domains for mill throughput prediction.

The geological model developed by exploration geologists at Batu Hijau is extensive and is testament to their efforts in core logging and rock characterisation. Table 2 shows the number of measurements utilised in the geological model. Definition of ore hardness domains depends on correlations between the relatively few metallurgical comminution tests and the statistically representative measurements like grade, RQD and PLI.

Table 2. Geological Database Summary

<table>
<thead>
<tr>
<th>Units</th>
<th>Number of Samples</th>
<th>Avg Value 2004-LOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu Grade</td>
<td>% Cu</td>
<td>&gt;50,000</td>
</tr>
<tr>
<td>RQD</td>
<td>%</td>
<td>&gt;70,000</td>
</tr>
<tr>
<td>RMR</td>
<td>%</td>
<td>&gt;70,000</td>
</tr>
<tr>
<td>PLI</td>
<td>N/mm²</td>
<td>&gt;12,000</td>
</tr>
<tr>
<td>Wi CR</td>
<td>kWh/t</td>
<td>265</td>
</tr>
<tr>
<td>Wi RM</td>
<td>kWh/t</td>
<td>287</td>
</tr>
<tr>
<td>Wi BM</td>
<td>kWh/t</td>
<td>287</td>
</tr>
<tr>
<td>Ai</td>
<td></td>
<td>287</td>
</tr>
<tr>
<td>Axb</td>
<td></td>
<td>39</td>
</tr>
</tbody>
</table>

In-situ rock structure, as indicated by block size, in combination with blast powder factor will dictate ROM fragmentation size and hence SAG mill feed size distribution. Ore hardness and hence breakage in the SAG mill can be correlated to rock strength measurements, such as UCS and point load index.

Sag Mill Feed Size

Process plant operating data (4 day averages) from Nov 2003 to April 2004 confirm the following relationships

- SAG mill feed rate decreases as feed size F80 from Split-OnLine measurements increases
- SAG mill feed size increases as RQD\(^1\) increases

Thus SAG mill feed size and throughput rate is related to RQD, but size can be modified with blast designs to influence mill throughput.

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\(^1\) RQD% or Rock Quality Designation is defined as the cumulative length of core pieces longer than 10 cm in a core run divided by the total length of the core run including all lost core sections and excluding mechanical breaks caused by the drilling process. RQD% is a measure of in situ block size
Ore Hardness

Mill throughput modelling using JKSimMet software requires ore breakage properties to be derived from the JKTech Drop Weight test procedure in combination with SAG mill feed and product size distribution.

The JK Drop weight test is expensive, time consuming and requires large samples, but it provides an accurate measurement of the breakage distribution function of the ore in a SAG mill. By early 2004, drop weight tests had been conducted on 39 samples of Batu Hijau ore taken from infill drill programs in 2002 and 2003. The results indicated significant variability in ore hardness with the A x b results ranging from 23 to 107. The bulk of results ranged from 35 to 65 indicating the average ore is amenable to SAG milling.

A mechanism was required to be able to model the SAG breakage function through the whole ore body (1.3 billion tonnes). A relationship between drop weight Axb and Point Load Index, as a measure of rock strength, has been identified for many different ore bodies (JKMRC/AMIRA). The Point load test is a cheap, quick test on a small sample of drill core. More than 12,000 tests have been performed on Batu Hijau drill core providing sufficient data density to define ore hardness domains. Low PLI and High Axb values indicate low resistance to breakage (ie High breakage rates) and hence higher mill throughput rates. The PLI and Axb measurements from the Batu Hijau drop weight tests demonstrate a similar relationship observed for other ores, but each lithology has a unique PLI vs Axb relationship. Note: Axb results were adjusted by dividing by ore density (~2.62 t/m$^3$ for Batu Hijau).
Using the Point Load Index to “map” ore body hardness is an efficient approach for throughput modelling and forecast. It provides a high sample density within the ore body at no extra cost to the mine as the test is done routinely for geo-mechanical classification. Use of other tests (JK drop weight, SMCC, SPI test) is limited to much lower sample density due to the significant cost involved to obtain drill core samples and conduct the tests. To map the ore body for 4 years of production at Escondida, only 978 SPI tests were carried out, which was insufficient to achieve the required mapping precision. Point load index was used to improve the interpolation procedure (Flores, 2005).

Point Load Index Database Corrections. Whilst reviewing Batu Hijau data in 2004, Metso MMPT identified significant errors in the PLI database in the Batu Hijau exploration block model. These errors were due to two factors.

- Poor data collection/measurement for one in-fill drill campaign from year 2002. This data was removed from the database in March 2004.
- Incorrect calculation of PLI. This issue was resolved in May 2004 using the standardised PLI (Is50) calculation from the raw data.

The formula for calculating size corrected Point Load Index (Is50) is:

\[
Is(50) = 1000 \left( \frac{D_e}{50} \right)^{0.45} \left( \frac{P}{D_e^2} \right) \quad (\text{MPa})
\]

Where:
P = Force applied at failure (N)
De = Equivalent core diameter (mm)
\[ D_e^2 = D^2 \quad \text{(diametral)} \]

\[ D_e^2 = 4A/\pi \quad \text{(for axial, block and irregular lump)} \]

Where A is the minimum cross sectional area of a plane, through the platen contact points.

**Ore Domain Definition**

Definition of mill throughput domains on the basis of ore hardness and mill feed size can be achieved using both RQD to infer size and PLI to infer ore hardness.

A review of RQD and PLI distributions at Batu Hijau indicated three ranges of RQD and PLI could be used to define a matrix of nine (9) mill throughput domains. The ranges were selected to evenly divide the ore body tonnes into each domain.

![Figure 3. Selected RQD and PLI ranges](image)

Each domain was categorised into soft, medium or hard on the basis of ore hardness or fragmentation size expected within the domain.

**Table 3. Ore hardness Matrix**

<table>
<thead>
<tr>
<th>RQD (%)</th>
<th>PLI (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft</td>
<td>Medium</td>
</tr>
<tr>
<td>0-30</td>
<td>0-10</td>
</tr>
<tr>
<td>31-60</td>
<td>11-20</td>
</tr>
</tbody>
</table>

Volcanics = 49%
Diorite = 28%
Int. Tonalite = 21%
Young Tonalite = 1.4%
Batu Hijau Mine Engineers developed a Drill and Blast “Cookbook” based on the 9-Domain matrix, to define drill and blast parameters for use in ore shots. The design information was collated from historical performance data and blast trial results.

Table 4. Drill and Blast “Cookbook” for Mill Feed Ore

<table>
<thead>
<tr>
<th>PLI</th>
<th>Production Designs - Ore</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 x 8 - 7 m</td>
<td>6 x 7 - 6.5 m</td>
</tr>
<tr>
<td>70.30</td>
<td>70.30</td>
</tr>
<tr>
<td>0.34 kg/dmt</td>
<td>0.54 kg/dmt</td>
</tr>
<tr>
<td>40 m/hr</td>
<td>16.5 m/hr</td>
</tr>
</tbody>
</table>

- **Hole spacing**
- **Emulsion : ANFO**
- **Drill penetration rate**

**Ore Hardness with 16-Domains**

The 9-domain ore hardness matrix, based on RQD and PLI, was applied to each of the four major ore lithologies to produce 36 ore domains. Review of the ore delivery quantities in 36-Domains immediately identified 15 domains that contained less than 1% of the ore body tonnes hence could be eliminated. Spatial analysis of the remaining domains indicated spatial associations could be used to combine some smaller “halo” domains with a larger neighbouring domain. The resultant 16 domains each contain 5-10% of the ore body tonnes.
Table 5. 16-Ore Hardness Domains

<table>
<thead>
<tr>
<th>16-Domains</th>
<th>RQD 0-30</th>
<th>RQD 30-60</th>
<th>RQD &gt;60</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Volcanic</strong></td>
<td>PLI 0-3</td>
<td>V-FS</td>
<td>V-CS</td>
</tr>
<tr>
<td></td>
<td>PLI 3-6</td>
<td>V-FH</td>
<td>V-MM</td>
</tr>
<tr>
<td></td>
<td>PLI &gt;6</td>
<td>V-MH</td>
<td>V-CH</td>
</tr>
<tr>
<td><strong>Diorite</strong></td>
<td>PLI 0-3</td>
<td>D-FS</td>
<td>D-CS</td>
</tr>
<tr>
<td></td>
<td>PLI 3-6</td>
<td>D-FM</td>
<td>D-CM</td>
</tr>
<tr>
<td></td>
<td>PLI &gt;6</td>
<td></td>
<td>D-CH</td>
</tr>
<tr>
<td><strong>Intermediate</strong></td>
<td>PLI 0-3</td>
<td>IT-MM</td>
<td>IT-CH</td>
</tr>
<tr>
<td><strong>Tonalite</strong></td>
<td>PLI 3-6</td>
<td>IT-MM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PLI &gt;6</td>
<td>IT-MH</td>
<td></td>
</tr>
<tr>
<td><strong>Young Tonalite</strong></td>
<td>PLI 0-3</td>
<td></td>
<td>YT-CH</td>
</tr>
<tr>
<td></td>
<td>PLI 3-6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PLI &gt;6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Where:  
V = Volcanic  
D = Diorite  
IT = Intermediate Tonalite  
YT = Young Tonalite  
F = Fine fragmentation (ie low RQD)  
M = Medium Fragmentation or Hardness  
C = Coarse Fragmentation (ie very High RQD)  
S = Soft (low PLI)  
H = Hard (High PLI)

Plotting the 16 Domains in the geological model illustrated high variability for mill throughput within the deposit. Figure 4 shows a plan view of the 16 ore domains relative to the average high and low grade ore boundaries. The figure shows that most of the harder ores (high RQD and PLI) are located in the centre, south and west sections of the ore body. While significant faulting has produced a low RQD in most of the North and eastern sections of the ore body. Major faults strike NW to SE.
MILL THROUGHPUT MODELS
This section summarises the post start-up throughput modelling experience at Batu Hijau. Modelling conducted for design of the Batu Hijau grinding circuit is not discussed.

Historical Models
Several Mill throughput models were developed from 2001 to 2004 using the following techniques:

Simple Regression Modelling - 2002

Basic multiple linear regression models were generated by fitting several months of historical mill throughput data to daily proportions of each ore domain. Initial models were based on simple lithology separation and later subdivided as RQD was used to further delineate lithology.

The models generated provided reasonable throughput indicators however did not account for throughput variations resulting from differences in mill feed size distribution.

Bond Work Index Modelling – 2002

Bond Work Index based modelling was used to determine Mill Power as a function of work index. I.e. Mill Power = Fn (WiC^2) + fn(Wirm) + fn(Wibm). This model places most emphasis on ball mill power and assumes fixed feed size to the SAG mill for all ore types.

\[ \text{Mill Power} = \text{Fn} (\text{WiC}^2) + \text{fn}(\text{Wirm}) + \text{fn}(\text{Wibm}) \]

\[ \text{WiC} = \text{Bond Crusher Work Index}, \text{Wibm} = \text{Bond Ball Mill Index and Wirm} = \text{Bond Rod Mill Index} \]
Throughput predictions produced were significantly different to actual plant performance. This was particularly true for tonalite ores which have lowest actual mill throughput rates but lowest Bond rod and ball mill work indices. The tonalite ores are generally much coarser than the other lithologies as demonstrated by their inherently higher RQD.

This modelling method was similar to models used to design the Batu Hijau grinding circuit.

Figure 5 shows that the Bond work index modelling approach is not valid for modelling SAG mill throughput rates as it does not describe SAG mill breakage rates or account for variations in feed size to the mill.

![Figure 5. Mill Throughput Predictions](image)

**BOCCOST Empirical Modelling – Early 2003**

BOCCOST or Blasting Optimisation Crushing Conveying Optimising SAG Throughput is a database that captures approximately 200 variables from blasting, mining and milling operations and assigns them to a common point in space in the geological model in real time. The intention was that the relationships between these variables be determined with a view to optimise the overall blasting, blending and crushing process to maximise mill throughput.

Interpretative analysis of about fifteen variables from the BOCCOST database was used to model
(i) the relationship between size of material delivered to the primary crusher and pit geology and blasting practices
(ii) the relationship between SAG mill feed rate, pit geology and blasting practices.

Again, essentially basic multiple linear regression analysis was used over three defined ore body zones. The zones were differentiated broadly based on major differences in faulting and lithology that
corresponded with perceived mill throughput zones. Initial data screening was used to isolate the variables that had most impact on mill throughput and blasted rock size.

Model output was used as a tool to assist short and medium term mine planning. Prediction of blasted rock size from BOCCOST was viewed to be more accurate than the throughput predictions.

JKSimMet Modelling – early 2003

JKSimMet modelling based on mill surveys and 9 drop weight results across RQD and lithology defined ore domains, used the JKSimMet estimation of mill feed size P80. This model produced similar results to the simple linear regression model.

JKSimMet Modelling – late 2003

JKSimMet Modelling using mill feed size estimation from the BOCCOST empirical blast fragmentation model.

JKSimMet modelling from early 2003 was used to generate throughput versus mill feed F80 relationships for “hard”, “medium” and “soft” hardness ores of the form, Throughput = M x SAG p80^b. The constants M and b were determined based on functions of RQD for each ore hardness.

SAG feed F80 was estimated from a simple log fit of historical measured SAG F80 and BOCCOST blasted rock P80. This relationship is very robust as demonstrated in Figure 6 below.

![Comparison Actual and Predicted SAG Feed p80mm](image)

**Figure 6. Actual SAG F80 and BOCCOST model P80 comparison.**

Throughput prediction from this method was an improvement over previous modelling attempts in that it allowed for variable mill feed size distribution however still lacked adequate accuracy for incorporation into the ore block model revenue calculation.
INTEGRATED MILL THROUGHPUT MODELLING

In early 2004 Batu Hijau contracted Metso Minerals Process Technology (MMPT-AP) to assist with ore characterization and produce domain specific mill throughput models for use in long term production forecasting and evaluation of mill expansion options. Revised models were required due to pebble circuit flowsheet changes in August 2003 that produced a step change improvement in mill performance, such that previous throughput models were no longer valid.

Metso MMPT-AP conducted modelling of the full comminution process using blasting, crushing and grinding models to calculate SAG mill feed size, throughput rate and flotation feed grind size. The simplified model is presented in Figure 7. This model consists of the following combined mechanistic models:

- Blast fragmentation model
- Primary crusher model
- Milling circuit model (SAG mill, ball mill and cyclone models, pebble crusher in closed circuit)

The results of the simulations combining the blast fragmentation model, the primary crusher model and the complete SAG/Ball/Pebble/Screen models were divided into coarse/hard, mean and fine/soft for each lithology. The inputs to these models were:

- The rock mass data consisting of rock quality designation (RQD) which was used to estimate the volumetric joint distribution and then converted into a mean in-situ block size
- Unconfined compressive strength (UCS) inferred from PLI data
- Drop weight test data and their correlations to PLI.

The blast fragmentation model assumed a blast design with bench heights of 15 m, using blast hole diameters of 311mm and a burden and spacing of 7 and 6 metres respectively. The polygon and shovel P80’s were used to validate the model predictions.

The envelopes of ROM size distributions (soft/fine, mean, hard/coarse) were obtained using Monte Carlo sampling followed by model simulation. Monte Carlo sampling refers to the traditional technique for using random or pseudo-random numbers to sample from a probability distribution. These techniques are applied to a wide variety of complex problems involving random behavior. Each Monte Carlo iteration involves obtaining an estimate of each of the input variables to the model based on their mean value and standard deviation.

The ROM size distribution is calculated using the model and these randomly created input variable parameter estimates. This process is repeated 1000 times to obtain an envelope of possible ROM size distributions based on the variation in the input data. The ‘coarse’, ‘mean’ and ‘fine’ ROM size distributions are the upper, mean and lower size distributions based on the 5 and 95% confidence intervals.

The ROM fragmentation is used as input to the primary crusher model to predict the feed size for SAG mills. Simulations were conducted with a crusher closed side setting of 125 mm.
The primary crusher product size distributions were used as feed to the SAG mill model and simulations of the entire grinding circuit were conducted. The resulting simulated throughputs for each ore type were “blended” according to the reported ore blending information and compared to the actual average daily throughput.

<table>
<thead>
<tr>
<th>Blast Design</th>
<th>Primary Crusher Model (JKSimMet/MMPT AP)</th>
<th>SAG Feed Size Distribution</th>
<th>Grinding Circuit Model (JKSimMet/MMPT AP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMPT AP Blast</td>
<td></td>
<td></td>
<td>TPH          P80 grind size</td>
</tr>
<tr>
<td>Fragmentation Model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM Ore size</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distribution</td>
<td></td>
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<td></td>
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<tr>
<td>Lithology zones</td>
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<td>Rock Strength</td>
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<td>- PLI</td>
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<td>- DWi, A x b, ta</td>
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<tr>
<td>- Wicr, Wibm, Wirm, Ai</td>
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<tr>
<td>Rock Structure</td>
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<tr>
<td>- RQD, Mapping</td>
<td></td>
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</tbody>
</table>

**Figure 7. Schematic of the Modelling Approach**

**Preliminary Models for Ore Characterisation**

Metso modelling was conducted on three different sets of ore domains to determine the level of detail required to produce a representative and accurate mill throughput model. The models were validated and compared to daily production information:

- 8-ore domains used historically based on 4 Lithologies and 2 ranges of RQD (<40%)
- 9-ore hardness domains (matrix) based on 3 ranges of RQD and PLI but not lithology
- 24-domains based on 4 Lithologies, 2 ranges of RQD (<40%) and 3 ranges of PLI (<3, 3-6, >6)

Model prediction compared to actual production is shown in Figure 8. The 24 domain model produced the best fit indicating that a combination of lithology, RQD and PLI was required to accurately model mill throughput rates. The 9-domain model results show poor sensitivity to high and low throughput rates. Overall the results indicated the need to retain Lithology as a parameter in ore domain definition.

The results of this work led to the application of three RQD and three PLI ranges to each of the four lithologies to produce 36 domains. Spatial and quantitative ore characterisation reduced the 36 domains to 16 domains as shown in Table 5.
Predicting Mill Throughput for varied Blast Designs

The Metso modelling approach was applied to the 16 ore domains shown in Table 5, using two different drill and blast regimes

- Historical powder factor, little variation between ore types (0.25-0.35kg/t)
- Drill & Blast “Cookbook”, high powder factors in harder ores (up to 0.54kg/t)

Blast fragmentation simulations indicate a large variation in ROM fragmentation for each lithology as a consequence of different rock strength (PLI), rock quality designation (RQD) and blast design. Figure 9 shows the simulated ROM for Volcanic lithology.
Intense blast designs were implemented in mine operations in year 2004. The resultant improvement in ROM fragmentation size in harder ores is shown in Figure 10. The points plotted are annual averages for each of the 16-ore domains.

The reduction in variability of primary crusher feed size improved crusher operation and increased average power draw for harder ores as the crusher can be operated consistently at the target closed side setting of 120mm.

Figure 9. ROM Volcanic (hb-blast designs from the cookbook, c – old blast design)

Figure 10. Actual ROM Fragmentation improvement from intense blast designs
The primary crusher product (SAG mill feed) was obtained by “passing” the ROM ore through the primary crusher model. This approach produced a SAG mill feed size distribution for each of the 16 ore domains (and two blast designs).

Domain specific ore breakage parameters for input to a SAG mill model were obtained using the JKTech drop weight test Axb result versus point load index (Is50) relationships from Figure 2. This approach allowed evaluation of the variability of breakage rates and indicated a “possible throughput range” for each domain and blast design (powder factor) simulated.

Finally, the “average throughput” for each domain and blasting powder factor was determined based on “best fit” to actual daily throughput. The “average throughput” results presented in Figure 11 show that 10-15% mill throughput rate increase could be expected in the harder ore types with more intense blasting.

![Figure 11. Effect of Blast Powder Factor on Mill Throughput](image)

**Model Validation**
The 16-Domain Model mill throughput rates were applied to the daily ore delivery blends for year 2004 and compare well on a monthly/annual basis as shown in Figure 12.
Figure 12. Actual Mill Throughput 16-Domains Model predictions for 2004

Model prediction errors were estimated using a sum of squared error method, weighted for total tonnes milled in each time interval. The results are shown in the table and graph below indicating that estimation of mill throughput for weekly ore delivery could be utilised to optimise short term mine plans. The daily mill throughput prediction is inherently inaccurate as the daily mine ore delivery will not match average RQD, PLI and powder factor used to predict the average throughput rate for each domain. Additional external effects such as the particle size segregation on mill feed stockpiles and the non-linear effect of ore blending on mill throughput can not be accounted for in the model, hence further increasing the error of estimate for shorter time periods.

Table 6. 16-Domains Model predictions for 2004

<table>
<thead>
<tr>
<th></th>
<th>Average TPH</th>
<th>Average Error TPH</th>
<th>Average Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Production</td>
<td>6,062</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual Model Prediction</td>
<td>6,070</td>
<td>9</td>
<td>0%</td>
</tr>
<tr>
<td>Monthly</td>
<td>258</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weekly</td>
<td>401</td>
<td></td>
<td>7%</td>
</tr>
<tr>
<td>Daily</td>
<td>578</td>
<td></td>
<td>10%</td>
</tr>
</tbody>
</table>
CONTINUOUS THROUGHPUT MODEL

The 16-Domain mill throughput model is useful for monthly and annual throughput forecasting as the average properties of the ore delivered over these longer time periods is generally close to the average RQD and PLI within each domain. The model output of an average throughput rate per domain does not account for throughput variability within the domains hence significant step changes in throughput prediction occur at the domain boundaries.

To be able to improve the accuracy of the mill throughput predictions on a shorter time scale a continuous model was required that could accept any combination of RQD, PLI and blast powder factor per domain to reflect ore blocks delivered on a daily basis.

Metso conducted more than 40 complete model runs to generate multiple fragmentation and mill throughput predictions per domain and converted the results into a user friendly software package as shown in Figure 14. The user can input any combination of RQD, PLI and blast powder factor per domain to reflect specific ore parcels. Figure 15 illustrates the difference in the prediction resolution between the 16-Domain model using a single throughput value per domain and the continuous model. Batu Hijau engineers have found the continuous model to be informative, but not entirely practical for monitoring of long time periods (monthly/annual) as the model is coded into the software developed by Metso and hence can not be integrated into a spreadsheet calculation.

![Figure 14. Continuous Model user interface](image-url)
FUTURE MODEL REFINEMENTS

The path forward for refinement of ore domain characterisation and mill throughput modelling includes additional comminution test work on drill core, updates to the geological model from infill drilling and revisions to the mill throughput models based on the revised geology.

- Development of a continuous function equation for each ore domain that can be used in a spreadsheet rather than using the Continuous model program. Some work has started in this area to allow throughput prediction based on variation in RQD within each ore domain.
- Refining the model for periods where peaks and dips are not picked up. Over 80 additional modified Drop weight tests on 2004 and 2005 infill drill samples will be conducted in 2005 to boost model integrity.
- Ball mill and pebble crusher limiting ore – requires additional ball mill work index test work to produce a spatially representative ball mill work index model. Some lower grade ores appear to have significantly higher ball mill work index based on plant performance and testing of grabs samples. The Geological model is not complete in low grade ores.
- Development of a blend model to describe the non-linear impact of blending on the throughput rate estimates from each ore source.
- Determine the impact of mill throughput on flotation feed size distribution and consequently on flotation recovery. Increasing grind size with throughput has variable impact for Batu Hijau ore and significant losses can be incurred in some of the softer ore types. This will enable an improved revenue cut-off relationship to be determined to truly optimise blending and ore delivery strategy for maximising revenue.

CONCLUSIONS

An ore characterisation and mine to mill throughput modelling approach has been successfully applied at Batu Hijau. This has produced significantly better mill throughput rate predictions than previous modelling has allowed. The ore domain definition and modelling approach relies on definition of ore domains based on ore Lithology, rock structure (RQD) and rock strength (PLI) and takes the in-situ ore through blasting, crushing and milling models to produce an accurate prediction of mill throughput for medium to long term production forecasting. Short term predictions are influenced by external factors such as particle size segregation and residence time on process surge piles and the non-linear impact of blending.
Improved ore definition and understanding if the Batu Hijau resource has allowed:

- Enormous improvement in communications between the Mine and the Mill at Batu Hijau. Mine Engineering, Operations and Geology personnel understand the variables that drive mill throughput. The Mine and Mill work with a common purpose.
- Development of a blasting “cook book” for generation of an optimum product size for feed to the mill.
- Accurate prediction of blast fragmentation size which is the key to accurate prediction of SAG mill feed size (F80)
- Generation of a throughput model that has superior accuracy for annual and monthly throughput budgeting purpose

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REFERENCES


