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Review and Upgrade of the Throughput Forecast Model of Minera Los Pelambres

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ABSTRACT

Minera Los Pelambres (MLP) is an open pit mine and processing operation located 200 km north of Santiago in Chile. The processing plant treats 175000 tonnes per day producing both copper and molybdenum concentrates. The comminution circuit consists of two primary crushers followed by three Semi-Autogenous Grinding (SAG) mill - ball mill - pebble crusher (SABC) grinding circuits. A fourth line will be installed in the future.

The MLP drill core database is very comprehensive and detailed for geometallurgical mapping purposes. MLP has developed an empirical throughput forecast model using this database, and the model parameters are ore hardness (JKMRC breakage Axb parameter calculated from SMC test results), SAG mill feed 80 % passing size in mm (F80), and the proportion of hard ore in the blend. The model has been refined over an extended period of time, resulting in mean relative errors of only 3.5 % and 3.2 % on a monthly and annual basis, respectively. Nevertheless, MLP wished to improve the accuracy of the model, particularly over the longer term, thereby further enhancing production forecast and planning for the Life-of-Mine (LOM).

In late 2021, Hatch was engaged to review MLP's modelling, ore domain definition, ore characterization (rock strength and structure), and blast fragmentation measurements. Current plant operation was also reviewed, the comminution circuit was analyzed, and a new power-based throughput forecast model was developed. To provide a better description of the SAG mill feed size distribution (coarse and fine material in the feed), both F80 and content of fines (% passing 10 mm) were included in the model. The new model resulted in a mean relative error of 3.0 % and 1.4 % on monthly and annual basis, respectively, and is more responsive to variations in ore and operating conditions than the previous model. Other opportunities were also identified that would allow further improvements in the accuracy of the model as well as circuit optimization.

INTRODUCTION

Comminution circuit models can be used to estimate throughput considering changes in ore characteristics, mine planning, blending strategies, and operating conditions. Accurate models can assist to improve process stability and maximize profit over the LOM. MLP has developed, and refined over the years, a very good empirical throughput model, leveraging the comprehensive geometallurgical mapping of the orebody. It considers the main variables influencing grinding circuit throughput: ore hardness and feed size. A detailed review of the current model was conducted by Hatch and a few opportunities to improve its accuracy were identified.

A new power-based throughput forecast model was developed for the MLP comminution circuit. This modelling methodology is presented in detail by Farmer *et al*., 2021, and Brennan *et al*., 2022. Basically, it estimates the specific comminution energy for each geometallurgical domain. The circuit specific energy is calculated by a weighted average of the specific energy using the proportion of each domain in the feed over a certain period of time (day, week, month, and year). The circuit throughput is then calculated for a given mill power draw. The last three years of production data (in the mine and plant) were analyzed and used for model calibration and a separate, more recent period, was used to validate model estimates and its accuracy.

METHODOLOGY

Geometallurgical Domain Definition and Drill Core Testing Database

The MLP drill core testing database is very large and is a world class example of detailed geometallurgical mapping of ore hardness for block modelling. There are 2264 SMC Test® results in the database which provides a very high resolution of the breakage properties/hardness within the ore body. The geometallurgical domains (called M units) were defined and populated into the block model along with the SMC test results. Previously published simulations (Caceres et al., 2015) demonstrated that the accuracy of the Axb hardness parameter values populated in the block model are very good.

Previous Power-Based Throughput Models developed by MLP

MLP developed and tested different power-based throughput forecast models previously. One described by Misle et al. (2013) was quite accurate at the time; however, it was complex and onerous in terms of data input requirements. Another subsequent model used the Morrell method for total comminution specific energy (Morrell, 2009) but introduced additional parameters related to the ball mill circuit which had limited benefit in improving accuracy due to the circuit being SAG mill limited.

Existing Empirical Throughput Forecast Model

The MLP throughput forecast model in use at the time of the review was an empirical relationship that assumes the circuit is SAG mill limited and the throughput is a function of ore hardness (Axb parameter), F80, and proportion of hard ore in the blend.

The original version of this throughput forecast model was presented by Muñoz et al. (2017). It has since been further refined and updated by MLP. The principles of the empirical equations were explained in this paper along with the various adjustments that are accounted for in the model, such as: the effect of recirculating pebbles to the SAG or ball mill, the effect of stockpile level on F80, and the effect of SAG speed ramp up after mill reline. The main underlying model equation is as follows:

$$TPH = Ar + Br.(A \times b) + Cr.\left(\frac{1}{F80}\right) \quad (1)$$

Where Ar, Br, and Cr are fitted parameters and the model also requires the SAG mill F80. Predicting the SAG mill F80 for the ore characteristics and blend properties to be processed in the future is one of the main challenges for throughput forecast modelling.

The MLP SAG F80 model is updated every year. It uses a weighted average calculated from the proportion of each M unit and the F80 of each M unit. The F80 of each M unit is determined by regression using the WipFrag online fragmentation analysis camera data for the previous year. The WipFrag accuracy and reliability has been assessed by MLP and the WipFrag F80 can be used with confidence, as explained by Muñoz et al. (2017). Whilst the F80 values for each M unit are re-fitted every year, these values reflect the past ore characteristics, not those of future ores.

The SAG F80 modelling is one of the main limitations of the MLP empirical throughput forecast model and one of the main causes of discrepancy with actual throughput values. SAG feed size has a very significant impact on throughput. The very high quality and density of ore characterization data at MLP provided scope to improve the SAG F80 model and subsequently the ability of the throughput forecast model to predict changes due to future ore characteristics. This would also eliminate the need to refit (calibrate) the F80 of each M unit each year. Additionally, using only the F80 as a measure of SAG feed size does not consider the impact of the amount of fine material (% - 10 mm) in the feed, which also strongly influences SAG mill throughput (Kanchibotla, Valery & Morrell, 1999, Valery *et al*, 1999, Valery, Duffy & Jankovic, 2019). Both these limitations are addressed in the new throughput forecast model discussed in the following section.

New Throughput Forecast Model

To overcome the limitations of the empirical model, a power-based model was developed which uses Drop Weight index (DWi) for ore hardness and includes both F80 and % -10 mm to account for both the coarse material and fines in the SAG feed. The MLP circuit is SAG mill limited; therefore, a model based on SAG mill specific energy only, rather than total specific energy, is more accurate in this case.

To ensure model accuracy, high quality input data is required. DWi is an appropriate measure of hardness for SAG milling, can be averaged (unlike Axb which is non-additive), and is estimated from the comprehensive SMC Test® work already conducted at MLP. Accurate models to predict feed size parameters (F80 and % -10 mm) considering future ore characteristics are also required to ensure reliability of the throughput forecast model over time.

Therefore, a new mechanistic model was developed for the SAG F80 based on ore properties and the crusher gap:

$$F80 = OSS^K + \sum_j \left(kj * DWi_j + fj * RQD\right) * \%blend_j \qquad (2)$$

DWi and Rock Quality Designation (RQD) ore properties were determined to be significant contributors to the F80 of the SAG feed and are incorporated in the new SAG F80 model. K, kj, fj are constants that are specific to MLP (fitted to the F80 data). This mechanistic model should improve accuracy of the F80 prediction compared to the previous model (which was based on past regressions) and eliminate the need to regularly refit the SAG F80 model.

The percentage of fines (-10 mm) in the SAG feed also has a strong influence on SAG mill throughput (Valery *et al*, 2001). However, this is generally not accounted for in throughput forecast models due to challenges in predicting the amount of fines in the SAG feed. The fines are mostly influenced by drill and blast operations (predominantly blast intensity or powder factor) and ore hardness (Kanchibotla, Valery & Morrell, 1999, Valery *et al*, 2001, Valery, Duffy & Jankovic, 2019). Therefore, blast modelling and simulations were conducted to establish relationships to predict the percent of - 10 mm in the Run-of-Mine (ROM).

A mechanistic blast fragmentation model specific to the conditions for MLP was calibrated and validated. This model predicts the full ROM size distribution based on drill and blast design and ore characteristics. Simulations were conducted with varying powder factors (by changing blast design) and hardness (Unconfined Compressive Strength (UCS)), see example in Figure 1.

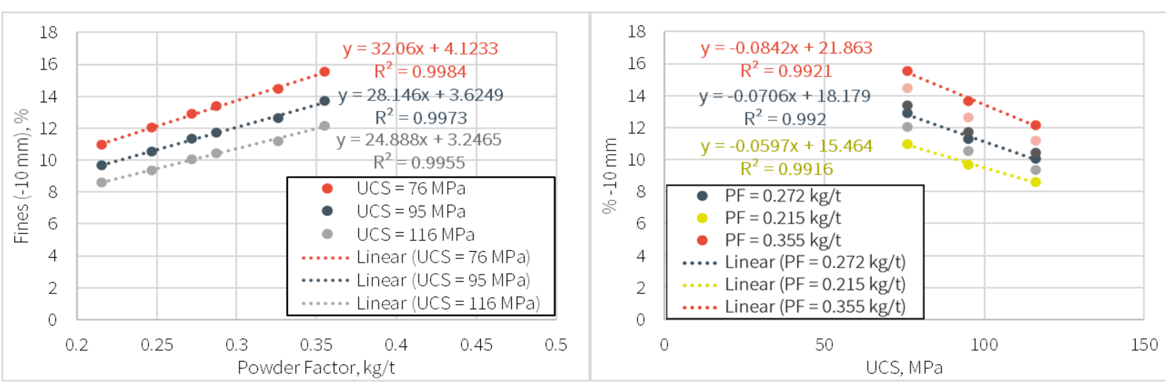

Figure 1 Example of establishing relationships between powder factor, hardness, and % -10 mm

These simulations were used to establish a relationship between powder factor, hardness, and the % -10 mm in the ROM for each M unit using the following equation structure:

$$\% - 10mm\ ROM = A * (PF) - B * (UCS) + C \quad (3)$$

Where A, B, and C are fitted parameters and vary for each M unit.

The additional fines produced during crushing are accounted for (based on calibration with previous JKSimMet modelling) to determine the % -10 mm in the SAG Feed:

$$\% - 10mm\ SAG\ feed = R * (\% - 10mm\ ROM) + F \quad (4)$$

Where R and F are constants that are specific to MLP (fitted to the modelling data).

This inclusion of fines content in the throughput forecast model increases the accuracy of the model and enables additional utility of the model as a planning tool. It has greater reliability in predicting changes that will result due to future changes in ore characteristics and the ability to determine the impact of changes in blasting practices.

To incorporate all the above, the new power-based throughput forecast model carries out a series of calculations:

1. **Estimate the weighted average hardness DWi** for the period based on feed blend proportions. The DWi of each M unit for each period is an output of the block model.
2. **Estimate the SAG F80 for each M unit**. The SAG F80 is estimated using the new mechanistic F80 model (Equation 2).
3. **Estimate the % -10 mm in the SAG feed:**
    a. Calculate the proportion of -10 mm in ROM for each M unit according to the correlation equations determined from drill and blast simulations (Equation 3).
    b. Calculate the proportion of -10 mm in the SAG feed for each M unit (Equation 4).
    c. Calculate the amount of -10 mm in the SAG feed based on proportions of M units (weighted average).
4. **Calculate the SAG mill Specific Energy (kWh/t)** based on the weighted average DWi, SAG F80, and % - 10 mm:

$$SAG\ Ecs = Q \times DWi^{\alpha} \times (SAG\ F80\ )^{\beta} \times \frac{1}{(\% - 10mm)^{\delta}} \quad (5)$$

   Where Q, α, β, and δ are constants that are specific to MLP (fitted to the plant data).

5. **Calculate the average throughput** of the three production lines based on the predicted SAG Specific Energy and available power:

$$\frac{t}{h} = \frac{SAG\ Power\ (kW)}{Specific\ Energy\ (kWh/t)} \quad (6)$$

6. **Calculate the yearly capacity** from Usability (Availability x Utilization) rate U:

$$Feed\ to\ Mills\ (Mtpa) = \frac{t}{h} \times 8760\ \times U \qquad (7)$$

RESULTS AND DISCUSSION

The accuracy of the previous empirical MLP throughput forecast model was already very good, in part due to the excellent ore characterization data and classification. The new power-based model achieves a similar accuracy on a daily basis but is improved on weekly and monthly bases (see Figure 2 and Table 1). In particular, the accuracy over the longer term is greatly improved (1.4 % error on yearly basis). This is one of the highest accuracies in throughput forecast modelling compared to many operations globally and is a great benefit for long term strategic and LOM planning and optimization.

Some of the improvement in model accuracy, particularly over the long term, is contributed to by the mechanistic model for SAG F80 which factors in the feed ore characteristics and therefore is more responsive to ore changes. This also eliminates the need to frequently recalibrate the F80 model. The inclusion of fines content (% -10 mm) in the SAG feed also contributes to the improved model accuracy. This considers the impact of both ore characteristics and drill and blast conditions on the proportion of fines in the feed which has a significant impact on SAG mill throughput.

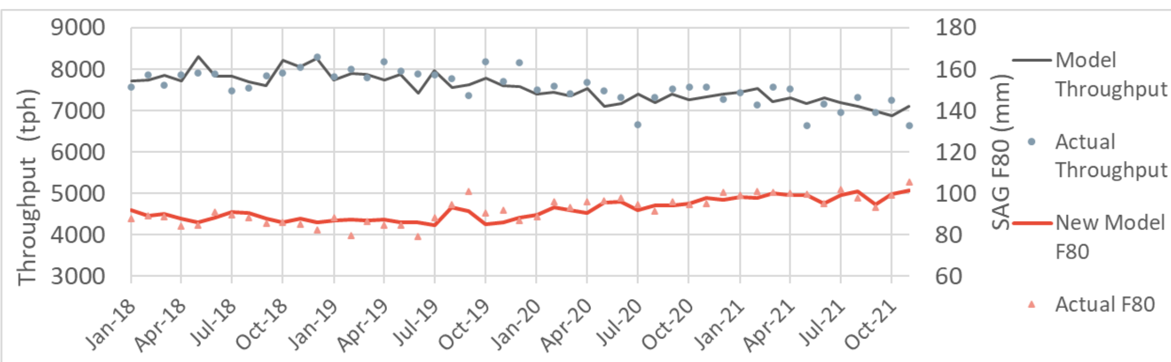

Figure 2 SAG F80 model and Throughput Model Validation – Monthly Basis

Table 1 Comparison of previous and updated TPH Model Accuracies

Model	Daily	Weekly	Monthly
Previous empirical MLP throughput model	6.0%	5.0%	3.5%
Updated Power-Based model with mechanistic F80 Model	6.2%	4.5%	3.0%

During the development of the new throughput forecast model, opportunities for further improvement were also identified. In particular, the ore hardness is highly variable and the compact in-situ rock structure (high RQD) in most of the ores is likely affecting fragmentation. Therefore, there is scope to further improve ROM fragmentation by optimizing the blast designs according to the properties of the rock mass (structure and strength). This may help to alleviate SAG mill constraints and make greater use of the available power in all ball mills which are not currently fully utilized.

CONCLUSION

The ore characterization and geometallurgical domain definition at MLP is very comprehensive which is of vital importance for accurate throughput forecast modelling. Consequently, the existing empirical model had good accuracy in the short term. However, due to the regression approach used for predicting SAG feed size, the model was not responsive to future changes in ore characteristics. Therefore, leveraging the high-quality ore characterization data, Hatch developed a new power-based throughput forecast model that used a mechanistic model to determine SAG F80 and also incorporates the proportion of fines (-10 mm) in the SAG feed (which also strongly influence SAG throughput). This new model has greater accuracy over the medium and long-term, thus enhancing the production forecast and planning for the Life-of-Mine (LOM).

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