Construction and Application of a New TPH Model for Caserones

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ABSTRACT

Caserones is a Chilean copper mine operated by SCM Lumina Copper Chile since 2014. The mining complex is located 162 km southeast of Copiapo, in the Atacama Region, near the Argentinean border and at about 4,600 m.a.s.l. In 2016 Caserones produced approximately 30 kt of copper in cathodes, and about 110 kt of copper and 3 kt of molybdenum in concentrates.

Originally, Caserones´ production planning was based on a SPI-Wi Throughput (TPH) model. Three years after the first model's inception, Caserones contacted Altair Mineria S.A. (ALTAIR) for assistance in building a throughput model (TPH model) based on JKSimMet. The original model was not sufficiently accurate to meet Caserones´ planning objectives.

This article is focused on presenting the new TPH model construction methodology, the operating and the block variables that participate in the model, the equations that describe throughput prediction, and the reconciliation between actual and predicted results.

In summary, a robust and accurate industrial instantaneous throughput model has been satisfactorily developed for the grinding circuit of Caserones. The model has a weekly mean absolute error of 3.5%, calculated from the back–analysis of actual production data from December 2016 to February 2017. Adequate sampling selection and collecting procedures, appropriate laboratory testing and accurate base case simulation contributed to the model´s robustness.

INTRODUCTION

Caserones is a Chilean copper mine operated by SCM Lumina Copper Chile since 2014. The deposit is an Andean-type copper deposit located at the southern end of the Maricunga District, 162 km southeast of Copiapo, in the Atacama Region near the Argentinean border at 4,600 m.a.s.l. Caserones has reserves of 1,047 Mt of copper sulphides, with an average grade of 0.34% copper and 120 ppm of molybdenum; and 300 Mt of leachable material with an average grade of 0.30% total copper. In 2016, Caserones produced approximately 30 kt of copper in cathodes, and around 110 kt of copper and 3 kton of molybdenum in concentrates.

Figure 1 Caserones mining complex location

The ore is extracted from an Open Pit mining operation. The primary sulphides are fed to the concentrator grinding circuit, comprising a gyratory crusher and a SABC–AB circuit. The ground ore is treated in a conventional flotation circuit that recovers copper and molybdenum. The oxides, and a mixture of oxides and secondary sulphides (hard to separate from the oxides are sent to a Leaching–Solvent Extraction–Electro-Winning plant to produce copper cathodes.

In November 2016, Caserones contacted Altair Mineria S.A. (ALTAIR) for assistance in building a throughput (TPH) model with the information obtained from a laboratory testing program over some representative samples that were collected from an extensive metallurgical (8,000 m) drilling campaign. Laboratory testing comprised JK Drop Weight (DWI) and Bond Ball Work Index testing (BWI).

The construction of this model involved the simulation of several scenarios in JKSimMet in order to develop a set of equations that predict the specific power consumption and the instantaneous throughput as a function of two kinds of inputs, namely: a) estimated grinding parameters that can be included in a block model, such as densities, *DWI* and *BWI*; and b) user–entered operational variables or set–points, such as: ROM's feed size (F_{80}), feasible power draw in main grinding equipment, and grinding circuit target particle size (P_{80}).

METHODOLOGY

Altair´s methodology for building geometallurgical models is based on previous work published by Alruiz (Alruiz et al, 2009) and ALTAIR experiences with other clients, for instance: Minera San Geronimo in Chile, Codelco Andina in Chile, and Yamana Gold in Brazil.

The methodology applied in Caserones consists of the following stages: a) sampling procedure review; b) assembly of a grinding laboratory parameters´ database; c) analysis of grinding circuit operational information; d) definition and simulation of a "Base Case"; e) JKSimMet steady-state simulations´ database, using the laboratory hardness parameters of each variability sample; f) development of industrial–scale model equations for the Specific Power Consumption function of the whole grinding circuit (*W*) and *TPH* using stepwise regression; and g) model validation (back analysis) against production results.

Review of representative sample and laboratory testing

A geometallurgical drillcore sampling program using geological criteria (lithology, alteration, mineralogy and copper grades) and spatial location criteria was defined. Later, 230 variability samples of 20 kg from the 2017–2021 mine plan period were selected from available drill–cores and selected /submitted for laboratory testing. Figure 2 shows the spatial distribution of these samples. They have been colored in accordance with their chronological position in the mine plan.

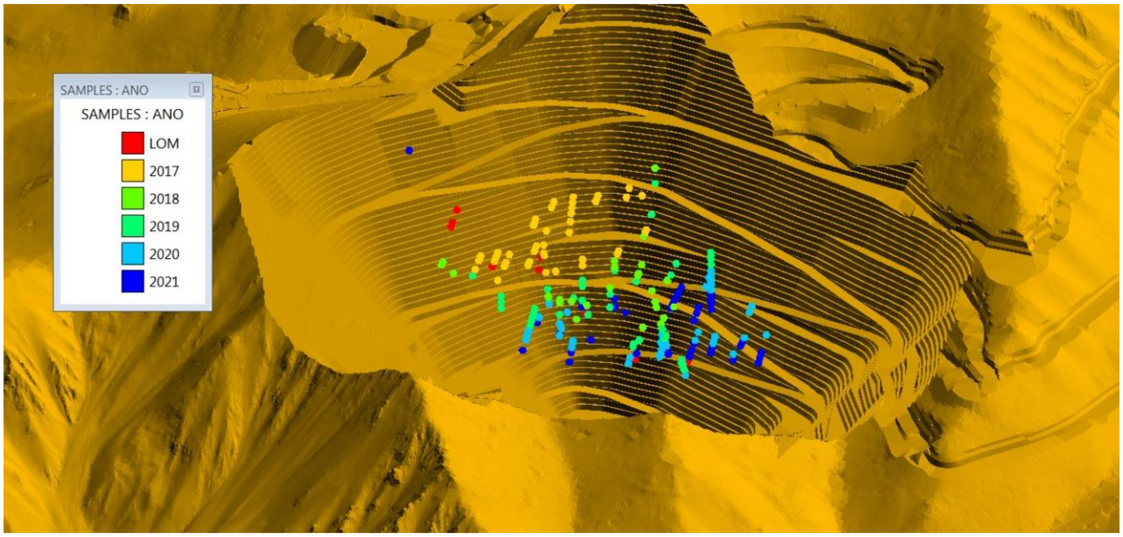


Figure 2 Geometallurgical sample distribution within the orebody and the quinquennial mine plan

The most important parameters in ore hardness characterization are those obtained from the SMC/JK Drop Weight and Bond Ball Mill Work Index tests. Information for each of these tests is used in the prediction of the specific power consumption for each stage of size´s reduction. For instance, the SMC *Mic* parameter (Morrell, 2009) is correlated with power calculations in crushing stages, Drop Weight Index (*DWI)* parameter is used for SAG mill power calculations, and Bond Ball Work Index (*BWI)* for Ball Milling power calculations. Table 1 shows the basic statistics for each of these parameters across the geometallurgy core intervals.

Table 1 Summary of comminution tests performed over variability samples

Value	**Mic, kWh/t**	**DWI, kWh/m^3**	**A x b, %**	**BWI, kWh/t**
Minimum	6.3	2.74	30.11	8.95
Maximum	19.5	8.71	91.61	17.95
Average	11.4	5.14	53.03	13.9
Standard deviation	2.4	1.09	11.58	1.44

Figure 3 is a XY-scatter plot that shows the sample distribution over four quadrants of high and low BWI and DWI hardness. It is observed that the DWI/BWI ratio (SAG/Ball hardness ratio) calculated for all variability samples show a relative uniform distribution across the four quadrants, i.e. the number of samples in each quadrant is approximately the same.

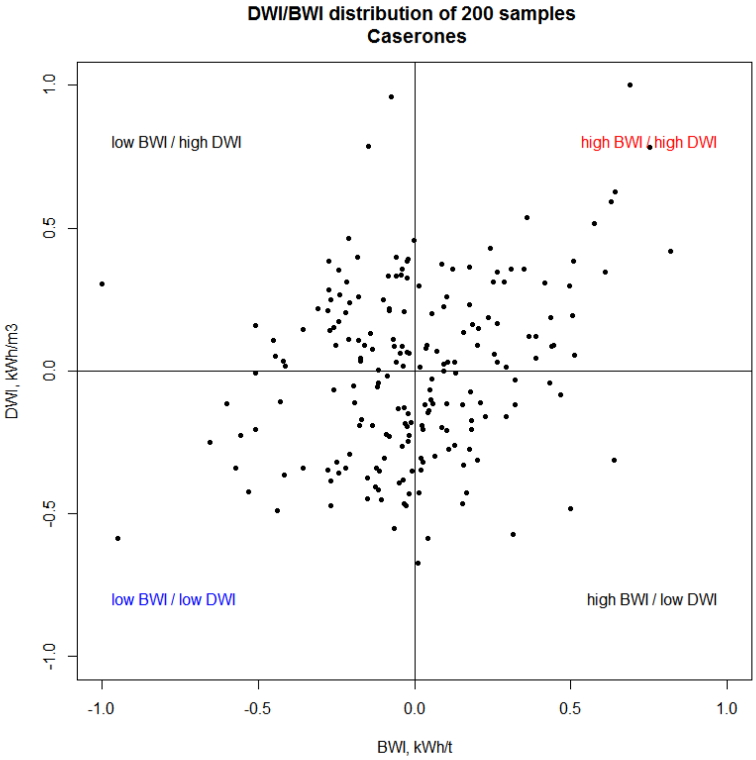
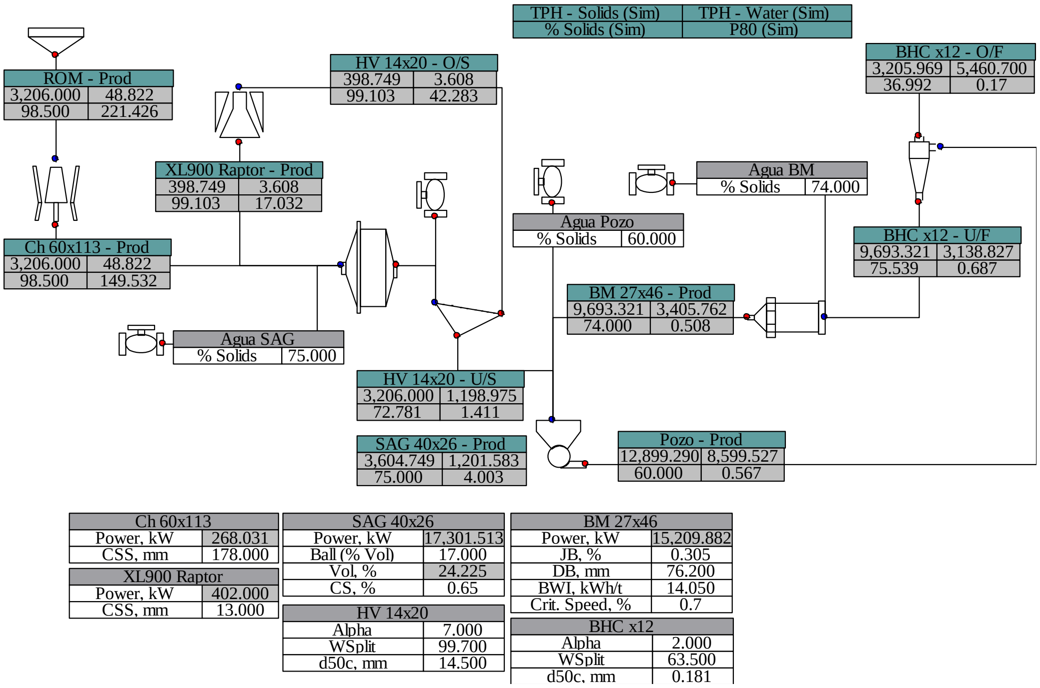


Figure 3 Caserones DWI/BWI sample distribution in the five–year period.

Steady–state simulations in JKSimMet

The first step in the construction of the model is to develop of a Base Case simulation. This simulation represents average real operating conditions, which include favorable and unfavorable conditions caused both by the ore and by the equipment. Caserones' operational results and historical ore characteristics data from August 2016 until November 2016 were collected in order to build this simulation. Also, the circuit flowsheet, the equipment characteristics and ROM particle size distribution required to build this simulation were obtained from the Caserones Feasibility Study and Mine Planning Team. The Caserones Base Case simulation in JKSimMet (JKTech, 2012) is presented in Figure 4.



Ch 60x113	
Power, kW	268.031
CSS, mm	178.000

XL900 Raptor	
Power, kW	402.000
CSS, mm	13.000

SAG 40x26	
Power, kW	17,301.513
Ball (% Vol)	17.000
Vol, %	24.225
CS, %	0.65

HV 14x20	
Alpha	7.000
WSplit	99.700
d50c, mm	14.500

BM 27x46	
Power, kW	15,209.882
JB, %	0.305
DB, mm	76.200
BWI, kWh/t	14.050
Crit. Speed, %	0.7

BHC x12	
Alpha	2.000
WSplit	63.500
d50c, mm	0.181

Figure 4 Caserones Base Case simulation in JKSimMet Software

The Base Case simulation was used, as a starting point, to perform 1,200 simulations using the grinding parameters from the 230 variability samples for a range of operational scenarios, which consider different ROM feed particle size distributions and two different operational throughput set–points. In these simulations, the grinding product P_{80} was a consequence of the previously defined conditions. Figure 5 shows the relationship between specific energy consumption and P_{80} to flotation. Each point represents a simulation in JKSimMet and the blue color point is the Base Case. Note that for a given P_{80}, different values of *W* appear. This "broad band" phenomenon can be explained when other important variables, such as ore hardness (*DWI* or *BWI*) and particle size distribution in the feed (F_{80}) are included in the analysis.

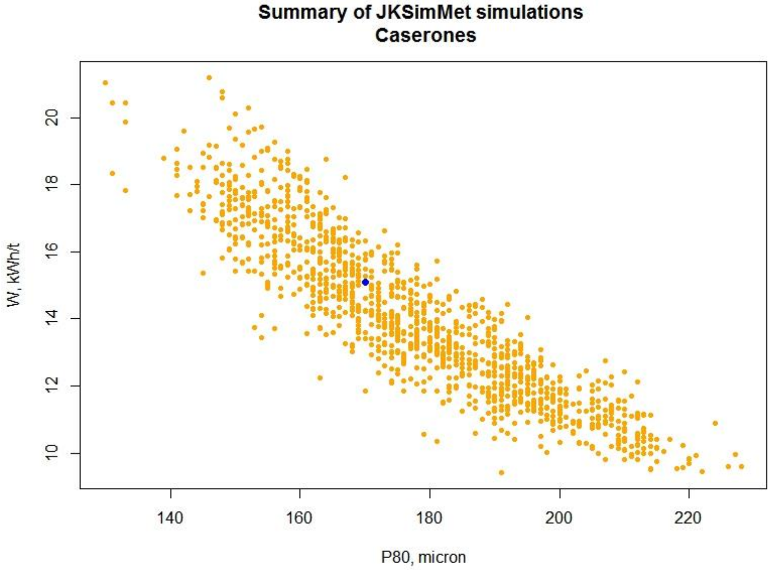


Figure 5 Summary of steady–state simulations for each variability sample in JKSimMet

Equation development for the TPH model

To find the model structure, the algorithm known as stepwise regression was used. This procedure searches over a large space of possible models where all the potential explanatory variables (ore and circuit configuration/equipment) are considered. The most suitable group of candidate variables are normally those that fit with well-known empirical grinding relations, and those variables that were used by Altair in previous works for other clients.

Throughput Model

The throughput model is based on the relation $P = W \times TPH$ relationship; where P is the available power draw and W is the specific energy consumption for a given circuit, ore and operational parameters. The Caserones grinding model comprises two complementary equations, one for specific energy and another for throughput.

In general, a model created by stepwise regression, F-statistic or multiple correlation coefficients is not reliable to evaluate the model predictability. A better methodology is to fit the model parameters with a subsample (80%) and use the remaining 20% of the dataset to assess the accuracy of the model (Mark and Goldberg, 2001). This routine is repeated approximately 500 times to randomly define the model fitting subsample space. Then, the average of the global mean absolute error (MAE) of each prediction, the difference between the simulation database and grinding model prediction, is considered the model error. Figure 6 shows XY–plot of experimental versus predicted values as a visualization of model predictability. In addition, histograms of the model fit and validation error for all trials are shown.

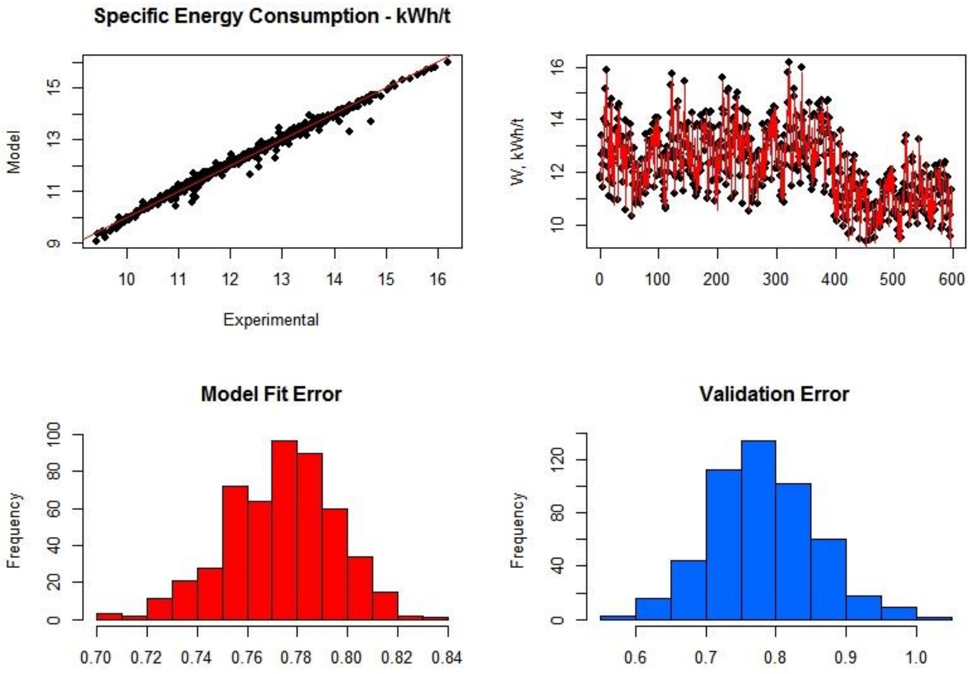


Figure 6 Summary of steady–state simulations for each variability sample in JKSimMet

For the specific energy consumption and throughput model, the mean absolute errors of all trials were 0.79% and 0.84%, respectively. The equations for both expressions are shown next.

$$W = 14.3\frac{DWI^{0.31} \times BWI^{0.12}}{SG^{0.96}}\left(\frac{F_{80}}{P_{80}}\right)^{0.28} \tag{1}$$

$$TPH = 155.9 + 1.6\frac{P_{SAG}}{W} + 0.6\frac{P_{BM}}{W} \tag{2}$$

The model input variables and parameters come from two sources: the block model and the circuit design or historical data. For Equations (1) and (2), specific gravity (*SG*), *DWI* and *BWI* values come from block model estimation and the rest of the parameters such as: F_{80}, P_{80} P_{SAG} and P_{BM} are obtained from data–logging and measurement tools. For instance, the grinding power draw P_{BM} and P_{SAG} are obtained from plant power measurement instruments, F_{80} from image analysis cameras installed over belts, and P_{80} from PSI or similar particle size measurement instrument.

However, the model presented in Equation 2 does not consider pumping and piping constrains. For this reason, a Circulating Load (*CL*) model was developed in order to adjust the model considering the maximum slurry transport capacity given by the design criteria. The *CL* model and the adjusted TPH_C model are as follows:

$$CL = 1.3 + 8 \times 10^{-9}\, TPH + 1.1 \times 10^{-2}\, BWI + 2.3 \times 10^{-8} P_{80}^{3.5} \tag{3}$$

$$TPH_C = \begin{cases} 155.9 + 1.6\dfrac{P_{SAG}}{W} + 0.6\dfrac{P_{BM}}{W}, & TPH(1+CL) < 24{,}608 \\ \dfrac{24{,}608}{1+CL}, & TPH(1+CL) \geq 24{,}608 \end{cases} \tag{4}$$

Model equations for planning purposes

Equations 1 through 4 can also be used for planning purposes. Nevertheless, they are valid for a given set of input values, because the expected SAG power draw and resulting grinding P_{80} depends on the comminution parameters. In order to avoid TPH results that are not physically feasible to obtain in the industrial operation, the following models for maximum achievable SAG power ($PSAG_{MAX}$) and maximum achievable grinding $P80$ (P_{80MAX}), were proposed.

$$PSAG_{MAX} = 13022 + 1619 \times SG + 8304 \times F_{80}^{-0.5} - 65 \times DWI \tag{5}$$

$$P_{80_{MAX}} = 0.4 + 36.1 \times SG + 817.8 \times F_{80}^{-0.5} - 9.5 \times DWI + 5.4 \times BWI \tag{6}$$

These equations, along with an $F80$ (SAG feed) between 100 mm and 170 mm, define the input domain for the throughput model equations.

RESULTS AND DISCUSSION

The TPH_C model was validated using historical data. This validation process or back analysis is the comparison between actual instantaneous throughput processed in the plant within a certain time-period, and the TPH values predicted by the model using the data contained in the block model (*SG, DWI, BWI*) and measured operation variables (F_{80}, P_{80}, P_{SAG}, P_{BM}) for the same period of analysis.

Historical data from December 5th, 2016 to February 12th, 2017 was grouped by week (a 10-week period) and then inputted in the model to obtain modeled throughput values. Figure 7 presents the result of the throughput back analysis exercise by week. The model error was calculated using two statistics: the root mean squared error (*RMSE*) which gives a deviation of ±156 t/h and the mean absolute error (*MAE*) which gives an error of 3.5%.

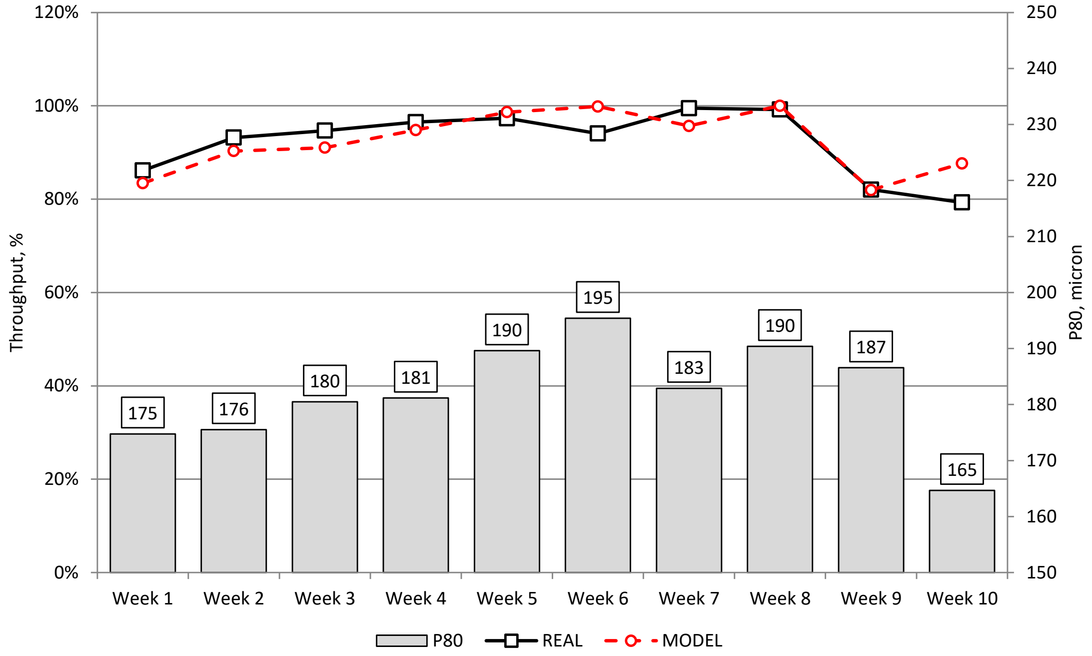


Figure 7 Model back analysis with data from November 2016 to February 2017

The variation of ore hardness (F_{80}, DWI, BWI) for this period was not as important as the variation of P_{80} grinding product; this aspect is observed in the trend of increasing throughput as P_{80} increases.

CONCLUSION

A robust and accurate industrial instantaneous throughput model has been satisfactorily developed for the grinding circuit of Caserones. The model has a weekly *RMSE* of ±156 t/h and a *MAE* of 3.5%, calculated from the back–analysis of actual production data from December 2016 to February 2017. Good sampling selection and collecting procedures, appropriate laboratory testing and accurate base case simulation contributed to the model robustness.

ACKNOWLEDGEMENTS

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ABBREVIATIONS

BWI	Bond Ball Work Index, kWh/t
CL	Ball mill circuit's circulating load
DWI	Drop Weight Index, kWh/m^3
F_{80}	80% passing of the primary crusher product or SAG Mill feed, mm.

MAE	Mean absolute error, %
Mic	Crusher index parameter obtained from SMC Test
P_{80}	80% passing of total grinding product, µm.
P_{80MAX}	Maximum 80% passing of total grinding product for a given *DWI* and *BWI*, µm.
PBM	Average Ball Mill power, kW.
PSAG	Average SAG Mill power, kW.
$PSAG_{MAX}$	Maximum SAG Mill power for a given *DWI* value, kW.
RMSE	Root mean squared error
SG	Specific gravity
TPH	Throughput, t/h
TPH_C	Corrected throughput by pump and piping constrains, t/h
W	Specific energy consumption of the grinding circuit, kWh/t

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