Preprint 13-120

MODELING AND SIMULATION OF MINERAL PROCESSING CIRCUITS USING JKSIMMET AND JKSIMFLOAT

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ABSTRACT

In recent years there have been significant advances in computing power and programming technology, enabling more complicated processes to be modelled in greater detail. This has led to increased understanding of these complex processes, including mineral processing circuits.

JKSimMet was developed over the past 35 years, incorporating outcomes from various research projects conducted at the Julius Kruttschnitt Mineral Research Centre (JKMRC), part of the Sustainable Minerals Institute at The University of Queensland. It is a steady-state software program that allows the user to mass balance, model fit and simulate crushing, grinding and classification circuits.

JKSimFloat has been developed over the past 20 years, incorporating outcomes from the JKMRC and other institutions around the world through the AMIRA International P9 project – The Optimisation and Simulation of Mineral Processing Circuits. It is also a steady-state software program, similar to JKSimMet, but is focused on analysing flotation circuits.

Both programs have been used in a wide variety of optimisation and design projects over many years. This paper provides an overview of both JKSimMet and JKSimFloat and examples of how both programs have been used to better understand, develop and optimise mineral processing circuits around the world.

INTRODUCTION

The JK approach to simulating circuits has always been to decouple machine characteristics from ore characteristics and has spawned many very successful computer simulation software packages; most notably JKSimMet (McKee & Napier-Munn 1990) and JKSimFloat (Schwarz and Alexander 2006b; Schwarz and Alexander 2007). Machine characteristics are easily measureable and readily available in the database of parameters on record with JKTech (Schwarz and Alexander 2006a). Ore characteristics need to be determined for individual ore bodies and breakage tests have been available some time, from the batch wise original Bond Work Index tests to the new multi-particle test (Shi et al 2008). Tests for particle floatability have also recently been developed with the JK Floatability Index enabling prediction of plant performance based on laboratory flotation results (Collins et al, 2009).

Background to JKSimMet development

The germination of many of the comminution and classification models found in JKSimMet today began with the first incarnation of the AMIRA P9 project in 1962, followed by the 1970 founding and evolution of the Julius Kruttschnitt Mineral Research Centre (JKMRC).

Ball mill, crusher and rod mill models appeared in the 1970's based on work by Whiten (Whiten 1972) and Lynch (Lynch 1977) followed in the 1980's with hydrocyclone models based on the work of Lynch and Rao (Lynch and Rao 1975) and Nageswararao (Nageswararao 1978).Autogenous mill models were based on the work of Leung (1987) and particle breakage modelling and measurement techniques were developed by Narayanan and Whiten (Narayanan and Whiten 1983 and Narayanan 1985). Further comminution studies, led by Morrell (Morrell and Morrison 1989, Morrell 1992, Morrell 1993,Morrell 1996) led to development of the variable rates Autogenous mill model and the power prediction methods found in JKSimMet. A model for high pressure grinding rolls (HPGR) based on work by Daniel and Morrell (Daniel 2002; Daniel and Morrell 2004) was introduced in the early 2000's. From the 1970's through today, sophisticated numerical techniques have been adapted and further refined for use in JKSimMet to perform functions of simulation convergence, model fitting (calibration) and mass balancing. (data reconciliation).

By the early 1980's models developed by the JKMRC had been collected and integrated into a single simulator framework that was the forerunner of JKSimMet. The first commercial version of JKSimMet was introduced in 1986, coinciding with the founding of JKTech, commercial arm of the JKMRC.

One of the mineral industry's first simulators to have a graphical user interface, the current version of JKSimMet shares its 3rd-generation interface with JKSimFloat, as well as its 2nd-generationmulti-dimensional mass balancing routine.

Background to JKSimFloat development

JKSimFloat incorporates the modelling methodology developed as part of the AMIRA International P9 project, titled 'The Optimisation of Mineral Processes by Modelling and Simulation' and sponsored by many of the worlds' leading mineral processing companies and suppliers to the industry. This is a collaborative research project involving the Julius Kruttschnitt Mineral Research Centre (JKMRC) in Australia (from 1952), the University of Cape Town (UCT) in South Africa (from 1997),the McGill University of Canada (from 2001), and other universities in more recent years. This methodology uses data obtained from the flotation plant and incorporates various semi-empirical sub-process models to represent the data for simulations.

JKSIMMET

Basis of models

The JKSimMet comminution models divide comminution performance into that resulting from machine parameters, such as breakage rates (also known as selection functions) from ore parameters, such as appearance functions (which derive from measurement of an ore's resistance to breakage). The JKSimMet mill models belong to a generic family of models known as "population balance models", and they all share a common underlying model which involves solving a steady-state balance around each individual particle size found in the mill feed, load and product streams, as shown in the following equation:

$$f_i - r_i \, . s_i + \sum_{j=1}^{i} a_{ij} \, r_j \, s_j - d_i \, s_i = 0$$

where:

- f_i - fraction of size i in mill feed
- r_i - rate of breakage from size i to smaller sizes in load
- s_i - fraction of size i contained in mill load
- a_{ij} - appearance function vector element which specifies quantity of each larger broken particle j appearing in size i
- d_i - rate of discharge of size i from mill due to transport

The rates in the population balance equation represent the machine parameters and the appearance function is an ore parameter.

At the heart of the hydrocyclone and other classifier models such as screens and trommels, is the well-known concept of the efficiency curve, which defines the classification performance. The JKSimMet cyclone model builds on this concept by adding correlation equations which relate the normalized classification performance, as well as the capacity of the cyclone to certain equipment dimensions such as cyclone diameter, vortex finder, apex and cone angle. Key model parameters in the equations can be determined by the calibration process known as model-fitting, allowing the user to then scale the fitted hydrocyclone (or parts of the fitted hydrocyclone) up or down from the actual cyclone which was measured.

When the comminution and classification model parameters have been calibrated to actual plant performance, the models can then be used to predict the performance of the plant when changes are made to the equipment dimensions or certain operating conditions. Predictions can also be made to determine the effect of changing ore parameters, allowing the user to see how the plant performance will vary with changes in the feed.

Case study 1: Model and optimize SAG-only circuit

An existing large tonnage copper operation was operating with a single 38 ft, 19.4 MW SAG mill followed by two 25 ft 11.1 MW ball mills. The SAG mill was operating in a SAG-only configuration, closed by a vibrating screen. A base-case model of the existing circuit was constructed and model-fitted (calibrated) against plant survey data using JKSimMet. The resulting model accurately depicted the grinding circuit conditions at the time of the survey, as shown in the following flowsheets:

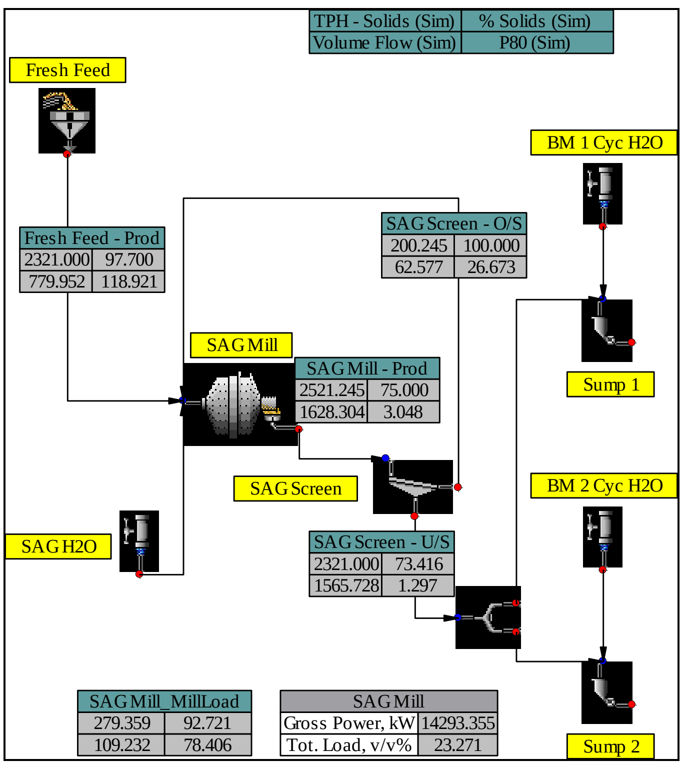

Figure 1. Case Study 1 – Existing SAG circuit flowsheet – original circuit as modelled with JKSimMet.

The circuit was surveyed during a period when the mill was being fed by a typical, recurring "hard" ore type. During this period, primary crusher product was typically coarse, with 80% passing size (f80) = 119 mm. [*Ore hardness parameters A, b and ta, are measured by the JKTech drop weight test. This particular ore, while nearly twice as "hard" compared to other ore types in the deposit, was found to be "soft" when compared against several thousand measured ore types in the JKTech DWT data base*.] Circuit throughput was 2,321 dmtph. The SAG mill and the ball mills were all drawing significantly less power than installed motor capacity. This suggests all three mills had sufficient power capacity for additional throughput.

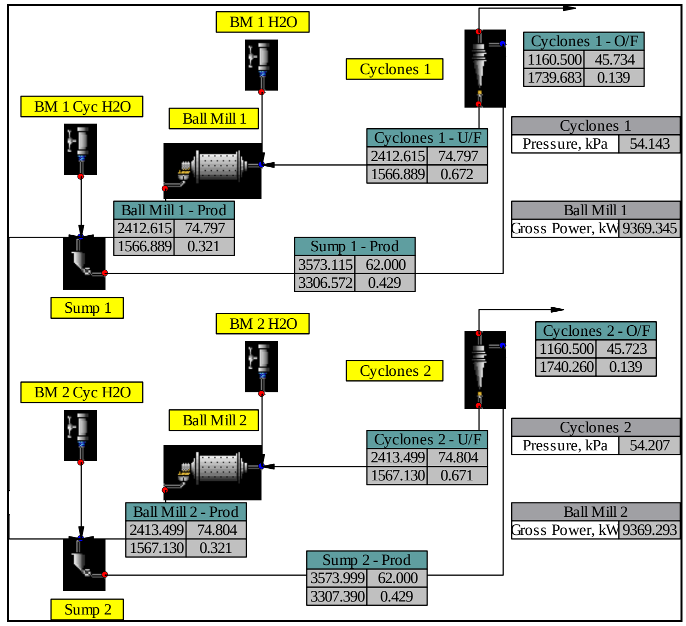

Figure 2. Case Study 1 – Ball mill circuit flowsheet – original circuit as modelled with JKSimMet.

The mill operators were interested in determining whether adding a pebble crusher to the SAG mill circuit would increase throughput and mill utilization. At the same time, however, the goal was to maintain final grind (cyclone overflow 80% passing size or p80) as closes as possible to the baseline operation with p80 at 139 microns.

JKSimMet demonstrated that significant extra throughput would result from installing a pebble crusher with closed side setting of 13 mm. At the same time, SAG discharge grates were increased from 38 mm to 63.5 mm to remove additional critical-sized material from the SAG load; while returning material with p80 of 14.5 mm back to the SAG mill. As seen in the following flowsheet, the effect of these changes was to increase SAG mill throughput by 16% to 2,692.5 dmtph.

However, the additional throughput and coarser transfer size (t80 = 3.66 mm vs 1.3 mm before adding the crusher), caused the ball mill circuit to produce a coarser product (p80 = 154 microns vs 139 microns before adding crusher). It was noticed that the ball mills were drawing well below installed power capacity at 9.36 MW or about 84% of installed capacity, with ball charge at only 27%. Additionally, the ball top size was 76.2 mm, which is too small for the mill, ore SG, work index and transfer size, according to the Bond ball calculation equation:

$$B = \left[\left(\sqrt{\frac{F}{K}} \sqrt[3]{\frac{S_g W_i}{(\%C_s \sqrt{3.281 D}}} \right) \right] \times 25.4$$

where:

B – Ball diameter (mm)
F – F80 (microns)
W_i – Ball mill work index (kWh/mt)
Sg – Ore specific gravity
%CS – Percent critical speed
D – Diameter inside shell (m)
K – Constant = 350 for wet overflow mills

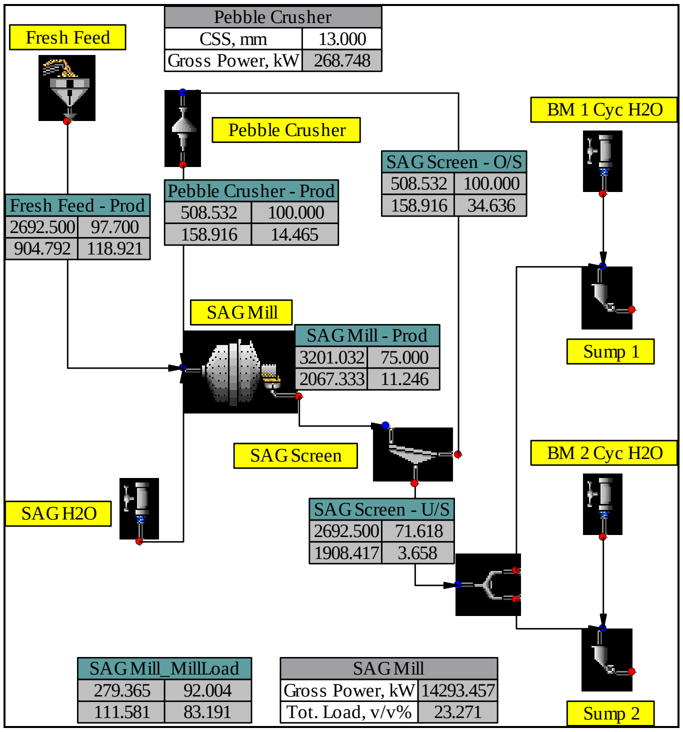

Figure 3. Case Study 1 – SAG mill circuit with pebble crusher added.

It was also noted that an additional cyclone needed to be opened in each mill circuit, increasing from 9 to 10 operating cyclones per ball mill, in order to keep cyclone / pump pressure below 60 kPa. The combination of smaller ball top size (63.5 mm), and increasing the ball mill charge from 27 to 31.5 % v/v, and slight adjustment of percent solids in cyclone feed (lower water addition) had the desired effect of reducing final product p80 back to 139 microns, while increasing ball mill power draw to about 10.88 MW or 98% of installed capacity. At the same time, circulating load as a percent remained at 207%, while pump volume flow in each ball mill circuit increased from 14560 gpm to 16,438 gpm, still within the maximum capacity of the cyclone feed pumps. The solids overflow density increased only slightly from 45.7% to 46.5%. The following figure shows the effect of these changes on the ball mill circuit:

The operating company determined from this exercise that the cost of installing the crusher was easily paid for by the increased throughput at identical recovery, since it was also determined that there was sufficient extra capacity in the float circuit which had been design to accept higher throughput of softer ores. The pebble crusher was subsequently installed and surveys and modelling since then has confirmed it is performing as predicted.

Case study 2: Determine optimum mill / motor sizes for an SABC grinding circuit in a pre-feasibility design study

An operating company wished to develop an ore body, from which a small number of drill core samples were available to establish the preliminary variability of hardness within the deposit. The samples were subjected to both JKTech drop weight testing to establish SAG mill performance and Bond ball mill work index to establish ball mill performance. From these tests, the 75thpercentile hardest ore among the samples with respect to SAG performance per drop weight test A, b and t_a parameters, was selected to provide the design basis values of these parameters, while the 75th percentile hardest sample with respect to ball mill performance, provided the design basis value of Bond ball mill work index. These values, while only slightly softer than the mean of the large JKTech drop-tested sample database, are still considered to be “soft” yet competent. Ball mill work index at around 15 was considered to be “moderately” hard.

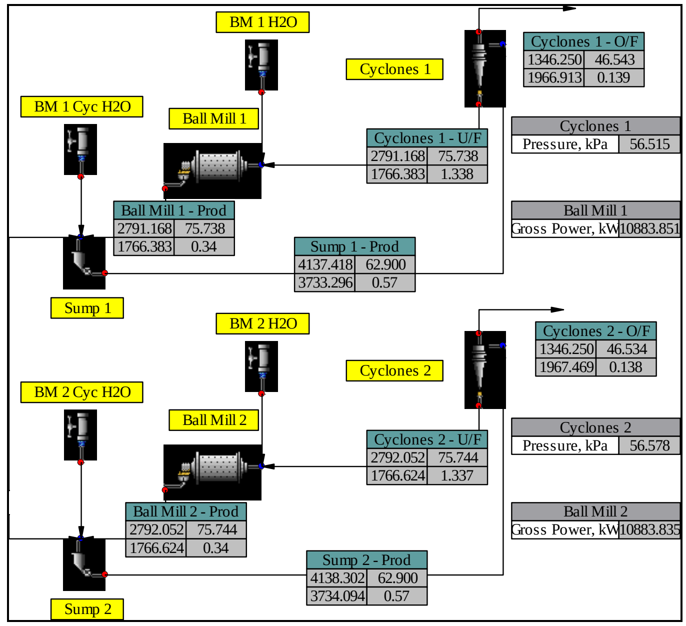

Figure 4. Case Study 1 – Ball mill circuit after pebble crusher added and ball mill optimized by adding smaller balls and increasing ball charge.

The only other design criteria provided were:

- Throughput = 50,000 dmtpd @ 92% availability = 2,264 dmtph instantaneous
- Feed 80% passing size (f80) = 150 mm
- Final Product 80% passing size (p80) = 150 microns
- Circuit: 1 x SAG mill /pebble crusher/2 x ball mills in SABC configuration

For this design exercise, JKSimMet was used to build a general model of the proposed SABC flowsheet. Once the model was constructed, different typical and realistic SAG mill diameter / length dimension combinations(available from mill vendors) were tested in successive simulations to determine the minimum size mill which meets the design throughput target at accepted operating conditions which allow operational flexibility as ore gets harder or softer than the 75th percentile “design basis” sample:

- 12% SAG ball charge
- 78% critical speed (assume variable speed drive)
- 75% solids SAG feed/discharge
- 25% total volumetric load (rocks, balls and pulp)
- Slotted grate apertures with width 50 to 63.5 mm

In design studies where there is no plant to calibrate the model parameters, default values must be used. In this case, the default breakage rate function of the JKSimMet SAG model, which was developed form over 60 sets of actual plant data with a wide range of mill sizes, is used. With the default breakage rate function, a total load of 25% v/v, must be maintained. If the load is exceeded at a given set of design operating conditions, either the throughput or the mill size must be decreased until a 25% load is re-established. In this manner, the optimum mill size and its related power draw is established. Once the mill size and power draw to perform the actual work of the design criteria is known, it is assumed that the design basis ore would be drawing about 85% of installed motor capacity, allowing that installed capacity to be estimated.

The following figure shows the SAG circuit for this design project, which resulted in determining that a 36 x 19 ft SAG mill, with 12% ball charge and operating at 77.35 critical speed, would meet the design criteria and would draw 12.7 MW in doing so. If 12.7 MW is assumed to be 85% of installed motor capacity, this suggests a 15 MW motor.

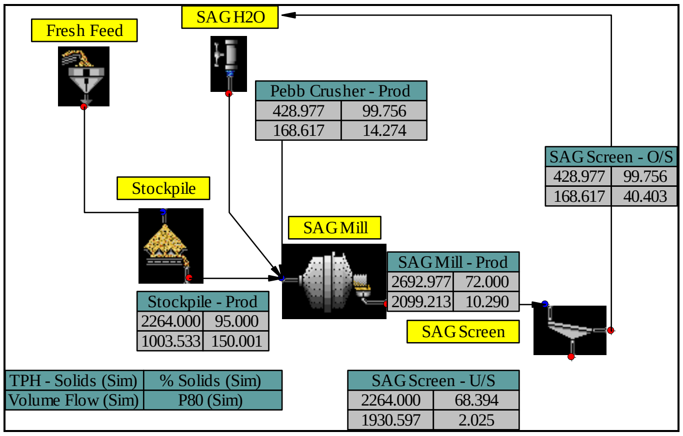

Figure 5. Case Study 2 – SABC circuit flowsheet – pre-feasibility design study to size SAG mill with JKSimMet.

Once the SAG mill size and power has been determined, a Bond calculation based on the design basis work index value is performed to determine the total power required to reduce the SAG screen undersize product t80 to final target cyclone overflow p80 of 150 microns. This total power is found to be 20.3 MW at the pinion, and if a conservative power loss of 5% across motor and drive is assumed, amounts to a gross power of 21.3 MW or 10.66 MW per ball mill, if 2 mills. Assuming this gross power draw represents 98% of total motor capacity, installed motor power would be 10.9 MW per mill. JKSimMet ball mill model with built in power calculation can be used to test different reasonable (per mill vendor data) combinations of diameter and length) needed to draw 10.66 to 10.9 MW. In this manner, two (2) x 24 x 36 ft ball mills with 10.9 MW motors are selected. The following figure shows the JKSimMet model of the ball mill circuit with a single circuit representing total flows of 2 x ball mill circuits. Cyclone parameters have been adjusted per best design practice to result in 250% circulating load with reasonable underflow density (75% solids and about 40% solids overflow density. JKSimMet predicts particle size distribution, volumetric flows, solids flows and pulp densities for each stream and can thus be used by engineers to estimate pumps and piping. The balance around the cyclones can be used by vendors to establish best cyclone configuration for this duty.

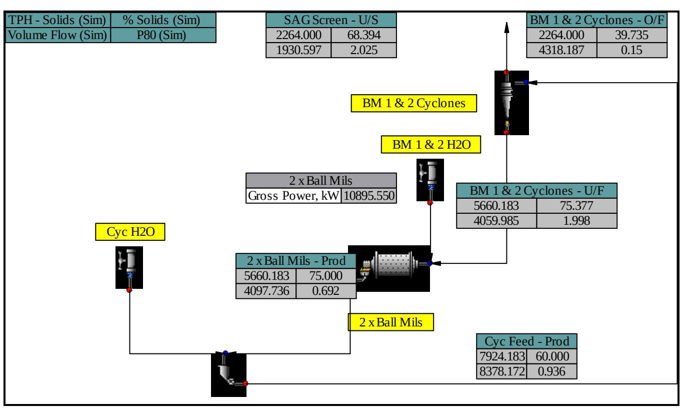

Figure 6. Case Study 2 – Ball mill circuit flowsheet – pre-feasibility design study to size SABC circuit ball mills with JKSimMet.

Using the results from this study to obtain mill estimates from vendors, the operating company has continued on to a feasibility study, which is currently underway. Additional drill samples will be taken to confirm the hardness variability and design basis and to bring the final mill sizings into better focus.

JKSIMFLOAT

Basis of models

As mentioned previously, the models used within JKSimFloat divide the flotation performance into that resulting from machine parameters, such as hydrodynamics and froth performance, and ore parameters, such as susceptibility to flotation. The underlying model for predicting the recovery of a particular group of particles from flotation cells (R_i) in JKSimFloat is shown below:

$$R_i = \frac{P_i \cdot S_b \cdot R_f \cdot \tau \cdot (1 - R_w) + ENT \cdot R_w}{(1 + P_i \cdot S_b \cdot R_f \cdot \tau)(1 - R_w) + ENT \cdot R_w} \quad (1)$$

where:

P_i – ore floatability for component *i,*
S_b – bubble surface area flux (min^{-1})
R_f – froth recovery
τ- residence time (min)
R_w – water recovery (-)
ENT – degree of entrainment (-)

The methodology used to obtain the above parameters has been described in details elsewhere (Harris et al, 1997; Alexander et al, 2000; Harris et al, 2002).

Case study 1: Kanowna Belle Gold Mine, Australia

Kanowna Belle Gold Mine is located near Kalgoorlie, in Western Australia with the following flowsheet:

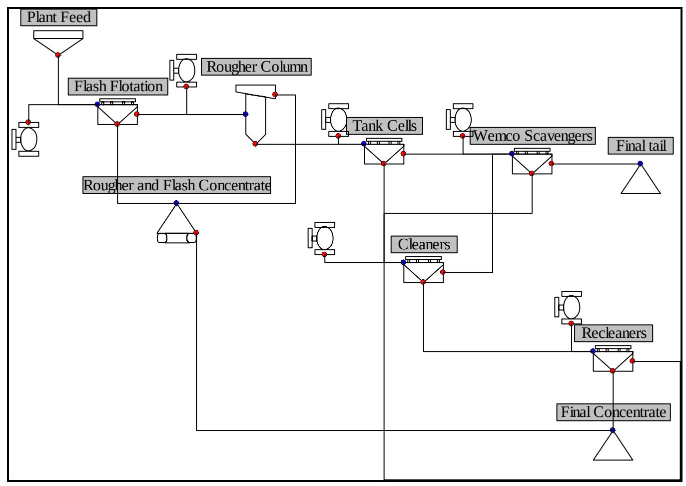

Figure 7. Kanowna Belle Gold Mine flotation circuit flowsheet.

A flotation circuit model was developed based on surveys, cell measurements including bubble size, superficial gas velocity, gas hold-up, froth recovery, entrainment, as well as laboratory batch flotation tests and set up in JKSimFloat for use as a simulator (Alexander et al, 2005).

Simulations conducted included:

- Increasing water addition to the recleaners;
- Recycling the concentrate from the 2nd stage of cleaning;
- Further cleaning of the concentrate from the 1st stage of mechanical cells;
- Extra capacity in the recleaner bank.

From these simulations, it was identified that the hydrodynamics in the cleaner and recleaner cells were lower than typical and a further study indicated the use of high shear stators would improve the gas dispersion in these cells.

The implementation of the initial simulations conducted for changing operating conditions resulted in over 1.3% increased gold recovery in the flotation circuit and an improvement of US$1.3 million per year (Alexander et al, 2005). The implementation of the high shear stators improved the gold flotation recovery by 1.9% and had a project payback period of 3 months (Bilney et al, 2006).

Case study 2: Century Zinc Mine, Australia

The Century lead-zinc-silver deposit is located approximately 250km north-northwest of Mt Isa in north-western Queensland. A schematic of the area of the process flowsheet investigated using this methodology is given below:

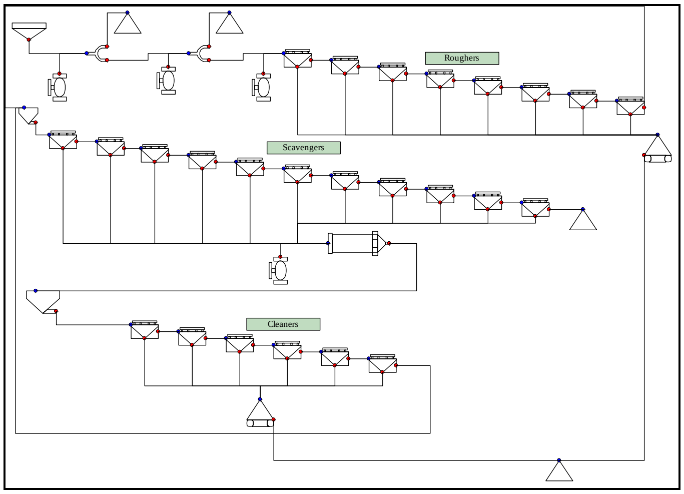

Figure 8. Century Zinc flotation circuit partial flowsheet.

Note that only a portion of the flotation circuit flowsheet is provided in Figure as only this portion was investigated using the JKSimFloat methodology.

A number of survey campaigns were conducted around the Century primary flotation circuit from 2002-2008 and models were developed from each campaign (Schwarz et al, 2008).

Simulations conducted included:

- Addition of a 200m^3 flotation cell at the head of the scavenger circuit (implemented in 2003);
- Additional regrind capacity;
- Increased air rates in scavenger and 1st cleaner cells;
- Increased feed rates;
- Extra capacity in the rougher circuit.

The combination of the model development and simulations enabled Century personnel to significantly increase the throughput possible in the flotation circuit while maintaining the primary zinc circuit performance (Schwarz, 2009).

GRINDING AND FLOTATION INTEGRATION

A powerful application of JKSimMet and JKSimFloat is by using these programs together to predict the impact of changing throughput and/or grind size on the flotation circuit recovery.

Case study 3: Minera Escondida Limitada, Chile

Escondida is one of the largest copper producers in the world and is located in the Atacama Desert in northern Chile, 170km southeast of Antofagasta. An integrated grinding and flotation study was conducted at Escondida using both JKSimMet and JKSimFloat, based on the Laguna Seca concentrator (Coleman et al, 2007). A schematic of the flowsheets used is provided in Figures 9 and 10.

Models were developed of both the grinding and flotation circuits for use in JKSimMet and JKSimFloat. A number of simulations were conducted, which included:

- Change in flotation feed size distribution;
- Increase in grinding circuit capacity to increase throughput;
- Estimation of impact of installing a flash flotation circuit;
- Flotation circuit configuration changes;
- Increased flotation circuit capacity.

Escondida personnel performed laboratory and plant-scale trials for several of the simulation scenarios and showed similar trends to the integrated simulator results. This allowed decisions to be made regarding plant improvements based on a validated throughput-grind size-flotation recovery relationship.

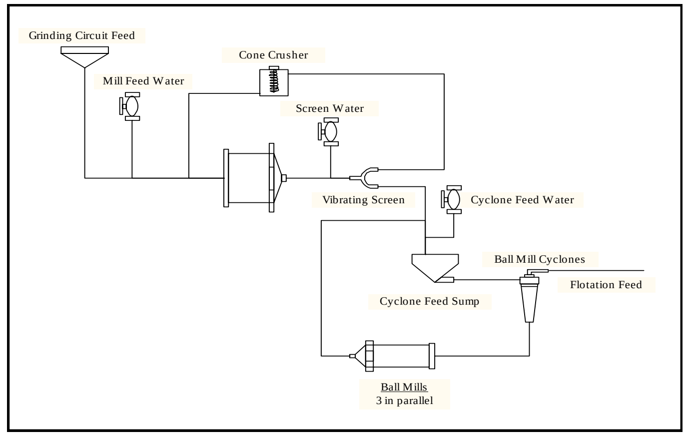

Figure 9. Laguna Seca grinding circuit flowsheet.

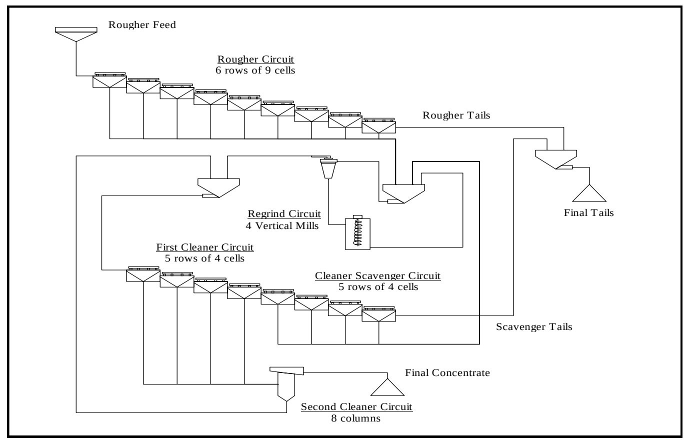

Figure 10. Laguna Seca flotation circuit flowsheet.

Case study 4: Anglo Platinum, South Africa

Since case study 3, a number of integrated studies have been conducted, with the methodology being expanded to include blast fragmentation models. A major study was undertaken with Anglo Platinum at one of their operating sites in South Africa and combined the simulation resources of JKSimBlast, JKSimMet and JKSimFloat (Ziemski et al, 2010).

A geology-mine-plant integration tool was developed to optimise performance as well as energy, water and greenhouse gas emissions. A schematic of the software architecture is shown below:

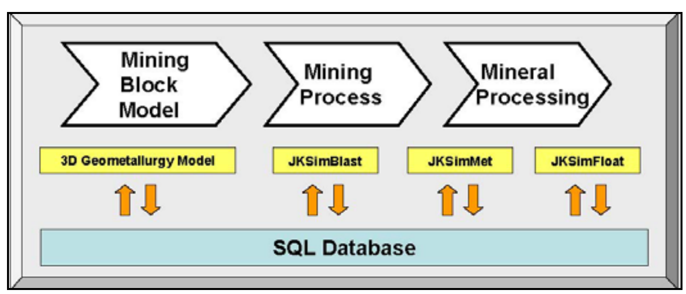

Figure 11. An overview of the geology-mine-plant integration software architecture.

Using this tool, a number of optimisation scenarios were conducted including changes in ore hardness, ROM size distribution and operating conditions. As well as the plant performance results, the energy consumption and CO_2 production was tracked to provide valuable sustainability information to site personnel.

As well as the plant optimisation simulations, a number of pit optimisation simulations were conducted to determine the impact of different ore types on the throughput and recovery in the plant. This information was then fed back to the block model to redefine the zones of economic and uneconomic ores within the deposit.

CONCLUDING REMARKS

In summary, software programs such as JKSimMet and JKSimFloat allow operators, metallurgists, researchers and consultants a greater ability to analyse, understand and optimise mineral processing circuits. The JK methodology of separating the ore and machine parameters has been proven many times over in gaining this better understanding of the processes occurring in comminution and flotation circuits. Continued research and implementation of this methodology will provide the industry with very powerful tools to improve mineral processing circuit performance.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the many JKMRC and JKTech staff and students associated with the development of the products discussed in this paper, together with the industry companies who funded much of the development, often through AMIRA.

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