Developments on Optimisation of Grinding in Australia - A survey study

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Stockholm juni 2004
**Short Summary**

This survey report provides most of information on recent developments of models for modern mills, simulators and on-line control systems for comminution circuit optimisation in Australia.

Recent model development for modern mills mainly focus on the simulation in the high pressure roller mills (HPRM) and the horizontal and vertical stirred media mills. For the HPRM modelling, the normal and semi-empirical models for power draw, product size distribution and throughput have been validated. These models have been used for the scale-up purposes. In the simulation of the experimental results obtained in the stirred media mills (including tower mills), the population balance method with tracer technology has been used. The computational fluid dynamics (CFD) method and the discrete element method have been also utilised to predict the performance of the stirred mills.

The steady-state process simulation for comminution circuit optimisation can be simulated by a software named JKSimMet. This simulator combined with JKSimBlast/ has been applied to analyse and optimise the comminution chain from mine-to-mill in order to reduce energy consumption without decreasing the throughput and operating efficiency. The USIM PAC package also offers a design criteria for comminution process optimisation in Australian mineral processing industry.

On-line analysis and control systems for elemental analysis, moisture, particle size and geometry have been developed for effective control and optimisation of a processing flowsheet on streams (especially in comminution processes), in Australia. In addition, acoustic emission soft-sensors have been applied for control and optimisation of a mill performance.

*Keywords: Mill, Grinding, Comminution, Modelling, Simulation, On-line control, Optimisation*
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Introduction

Comminution and in particular, tumbling ball mills and AG/SAG mills and their circuits, have received the greatest attention in modelling and simulation for many years. In the last 5-10 years, there has been an increasing focus on some modern mills like stirred or agitated mills, high-pressure roller mills, centrifugal mill, etc as the industries have sought to develop finer and ultra-finer products for effective size reduction, mineral liberation and energy saving. However, there are quite few of effective models and simulators available for optimisation of grinding performance with these modern mills from the existing literature. Also, the optimisation of the grinding mills and the circuits requires an accurate estimation and control of feed material and product quality by means of on-line analysis instruments.

This survey report represents information on some recent developments of three aspects, i.e., models for modern mills, simulators for comminution circuit optimisation and on-line analysis and control in Australia, which have been collected during my recent trip. To collect the corresponding information, I had widely discussed these aspects with 28 scientists and engineers in the following 9 units around Australia:
1. Xstrata Technology (the former MIM Process Technologies),
2. Queensland Centre for Advanced Tech., CSIRO Minerals,
3. School of Engineering, The University of Queensland,
4. JKMRC, The University of Queensland,
5 Metso Minerals (Aus) Pty Ltd.,
6 Mount Isa Mines Ltd.,
7 Lucas Heights Science & Technology Centre, CSIRO Minerals,
8 Centre for computer simulation and modelling of particulate systems, The University of New South Wales and
9 Group of Computational Fluid Dynamics, CSIRO Minerals.
Models for modern mills in ultra-fine and fine grinding

Recent development and application on mills has been mainly focused on two types of equipment, i.e., the roller press under high compressive loads and agitated or stirred mill with small media. Consequently, modelling of the performance of these machines have been carried out for the optimisation purpose in Australia.

High Pressure Roller Mill

The modelling for the performance in high pressure roller mills have largely been restricted to describing product size distribution curves from the lab scale machines using the self-similarity principle (Kapur, 1972; Fuerstenau, 1991). However, recent work in Australia have been made on the performance models, which are able to describe the throughput and power draw in addition to the particle size distribution (Lim and Weller, 1997; Morrell, Tondo and Shi, 1997). Lim and Weller (1997) from CSIRO Minerals have developed an empirical model for the HPRM throughput. This model takes into account the effects of variation in grinding force ($F_{sp}$), rolls speed ($F_u$), maximum feed size ($F_T$), moisture content ($F_w$), rolls surface type ($F_r$) and scale-up factor ($F_s$):

$$Q = F_r F_s F_u F_T F_w (1 + s \cdot \log F_{sp})$$

(1)

where $s$ is a constant of measuring the sensitivity of the specific throughput to changes in specific grinding force. Also, Morrell, et al (1997) in the JKMRC have derived models for the prediction of power draw, product size distribution and throughput as well. A linear model with a correcting factor for the mass throughput, $Q$, (t/h), is:

$$Q = 3600 \cdot U \cdot L \cdot x_g \cdot \rho_g \cdot c$$

(2)

where $U$ is circumferential velocity of the rolls (m/s), $L$ is the length of the rollers (m), $x_g$ is a working gap (m), and $\rho_g$ is the flake density (t/m$^3$) and $c$ is the correction factor and can be expressed by:

$$c = 1.3365 - 12.759 \cdot U \frac{x_g}{D}$$

(3)

where $D$ is the diameter of the roll. In order to verify that these models developed from the lab-scale mills can be used for prediction of the full scale machines, the JKMRC has recently carried out a work regarding the HPRM model verification and scale up (Shi, 2003). Figure 1 shows the procedure for this work. The four rock materials selected to test were from Rio Tinto, De Beers and BHP Billiton. The surfaces of the roll used were smooth and studded. Figures 2-5 shows the results for the product size distributions and power draw obtained from the experiments in the lab-scale machine and predicted full scale. Also, the prediction of the throughput of full-scale HPRM using the lab-scale data is shown in Figure 6. From this work, it was concluded that the models are able to provide a high degree of accuracy in the prediction of the product size distributions; the throughput predictions are also good for the smoothed rolls in term of tph actually passing between the rolls, but with the studded rolls the throughput prediction appears to be dependent on the relative height of the studs. These
models were supposed to put into the simulator JKSimMet for the simulation purpose after this work.

**Agitated or Stirred Media Mill**

Stirred media mills (including tower mill) for ultra-fine and fine grinding only really differ from one another in terms of the design if stirrer that they incorporate. Otherwise their operation is identical. They typically comprise a stationary cylindrical vessel, which can be mounted either vertically or horizontally. Figure 7 shows the typical versions of these units. Currently, stirred mills find industrial application in fine (15-40 µm) and very fine (< 15 µm) grinding in Australia (Napier-Munn, et al., 1999; Johnson, et al., 1998). There is a good evidence that conventional ball mills are capable of grinding finer than is traditionally accepted, for instance by the application of very fine media, but tumbling mills are ultimately limited in terms of the energy that they can transmit to the media. In order to increase the energy efficiency and optimise the performance of stirred mills, some recent work on the corresponding modelling have been undertaken in Australia. Some organisations and companies like the CSIRO Minerals, JKMRC in the University of Queensland, Xstrata Technology, Metso Minerals (Aus) Pty Ltd., and Mount Isa Mines Ltd. as well mainly involve the model developments on stirred mills.

The JKMRC has put efforts to model the size reduction and power draw of tower mills (Morrell, 1993 and Duffy, 1994) and to scale up tower mill using modelling and simulation (Jankovic, 1999). Morrell, et al (1993) used the population balance model to predict the size reduction in tower mills. The model used is stated as

\[
P_i = f_i - \left( \frac{r_i}{d_i} \right) p_i + \sum_{j=1}^{i} d_{ij} \left( \frac{r_j}{d_j} \right) p_j
\]

(4)

where \( f_i \) is mass flow of size i in the feed, \( p_i \) is mass flow of size i in the product, \( d_i \) is discharge rate of size i, \( r_i \) is breakage rate of size i and \( a_{ij} \) is appearance function (the fraction of size j material broken into size i). To allow for residence time changes brought about by changing the volumetric flowrate of material to the mill, or changes in hold-up of solids caused by changes in mill volume, ball charge or slurry density, the following relation is applied:

\[
\left( \frac{r_i}{d_i} \right) = \frac{u}{v} \left( \frac{r_i}{d_i^*} \right)
\]

(5)

where \( u \) is volume of the mill occupied by slurry and \( v \) is volumetric feedrate. The volume of the mill filled by slurry can be estimated from the volume of the cylindrical section of the mill between the inlet and outlet, less the stirrer and ball volume. The value of the factor \( (r/d^*) \) varies with particle size and typically will be distributed as shown in Figure 8. The particle size at which the maximum rate occurs \( (x_m) \) is a function of the ball size and will increase as the ball size increases.

It was assumed that charge density and stirrer speed should be linearly related to the net power in tower mill (Duffy, 1994). The net power \( (W_{net}) \) equation can be expressed by
\[ W_{net} = kH_bN_s\rho_cD_b^{0.111}D_s\gamma T^b \text{ (kW)} \]  

where \( k \) is calibration constant, \( H_b \) is height of ball charge (m), \( N_s \) is helical screw stirrer speed (rpm), \( \rho_c \) is charge density (tonnes/m\(^3\)), \( D_s \) is helical screw diameter (m), \( T \) is number of turns of the helical screw per start, \( D_b \) is mean ball size and \( a \) and \( b \) are constants to be fitted to data. The fitted no load and net powers were combined and plotted against observed gross power (Figure 9). Clearly, the fit is good, which suggests that the proposed stirrer diameter relation is valid.

Jankovic (1999) continued to investigate the scale up of tower mill using modelling and simulation. The purpose was to study the validation of model from a lab scale mill (0.1 kW) to the full-scale mills (150-920 kW). The designed procedure for the scale up was 1) lab tower mill test, 2) grinding table test, 3) breakage rate fitting, 4) collision frequency, 5) breakage rate scale-up and 6) pilot and full scale mill simulation. The power scale-up and the breakage rate scale-up were found to follow the relations:

\[ \frac{P_{\text{industrial}}}{P_{\text{lab}}} \left( \frac{B_{\text{lab}}}{B_{\text{industrial}}} \right)^{1.64} = K \]  

\[ \left( \frac{r_i}{d_i} \right)_{\text{industrial}} = \left( \frac{r_i}{d_i} \right)_{\text{lab}} K \]  

Figure 10 shows the results of the breakage rate scale-up obtained from the predication by modelling and experiments. The simulated and experimental results for the tower mills at various locations in Australia are given in Table 1. It is seen that the simulated data match the experimental results properly except for the grinding a nickel concentrate at Mt Keith. Therefore, it can be concluded from this work that the models for tower mills or vertimill developed based on the lab- and pilot scale units need to be improved using industrial data. The scale-up methods can predict the performance of the full-scale units accurately, providing that the work at lab is carried out according to the strictly defined procedures. The developed models and methodologies can be used for the scale-up and optimisation of industrial size vertical stirred media mills. However, the samples used for the scale-up procedure in the lab and pilot test work must be similar size distribution to the industrial mill feed. The another limitation is to require the relatively fine materials for the lab- and pilot mills for the scale-up work.

<table>
<thead>
<tr>
<th>Location</th>
<th>Circuit P(_{80}), mm</th>
<th>Circulating load, %</th>
<th>Scale-up</th>
<th>Scale-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM tower mill</td>
<td>36</td>
<td>9</td>
<td>11</td>
<td>95</td>
</tr>
<tr>
<td>Cannington Pb</td>
<td>32</td>
<td>20</td>
<td>20.3</td>
<td>120</td>
</tr>
<tr>
<td>Cannington Zn</td>
<td>12</td>
<td>10.9</td>
<td>12</td>
<td>230</td>
</tr>
<tr>
<td>Cannington Ag</td>
<td>1.6</td>
<td>18</td>
<td>21.2</td>
<td>90</td>
</tr>
<tr>
<td>Granny Smith</td>
<td>14.8</td>
<td>32</td>
<td>38</td>
<td>120</td>
</tr>
<tr>
<td>Mt Keith</td>
<td>65</td>
<td>68</td>
<td>82</td>
<td>220</td>
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</table>
Tracer studies on a vertical Sala Agitated Mill (SAM) and a horizontal Netzsch Stirred Mill (LME4) was undertaken, and the size distribution results from solid tracer tests on quartz and calcite were used to determine the breakage characteristics of the pilot-scale mills by the CSIRO Minerals and MIM Process Technologies in Australia (Weller, et al., 2000). In their work, modelling of residence time distributions of the SAM and the LME4 with respects to various parameters such as mill rotation speed and flow rate was performed based on the population balance model. In addition, the breakage behaviours with the brittle industrial minerals (quartz and calcite) in the vertical SAM were predicted by means of the batch population balance model.

The results show that breakage in a grinding environment in the pilot scale stirred mill closely matched industrial scale mills, which was studied by impulse addition of tracer to the pilot scale mills operated at steady-state hold up conditions. It was indicated that the liquid tracer and fine solids transport through the Sala vertical mill, as determined by the corresponding residence time distributions, are the same provided that the hold-up is maintained constant. The residence time distribution of the mill is independent of whether the feed is introduced at the top or the bottom of the mill. Modelling of the residence time distribution of the Sala machine is not as strongly compartmentalised as in the case of the Netzsch mill. Also, the breakage results show that the batch population balance model can reasonably be used to determine the cumulative breakage function and breakage rate for material in the SAM operating at steady state hold-up (see Figures 11 and 12). However, the accuracy of the fitting procedure is dependent on the selection of size fraction data and whether the mode of breakage is regarded to be independent of time. There is a reasonable match of the best data fitting model results to experiments. On the basis of the results, the cumulative breakage functions and breakage rates of quartz and calcite tracer in the SAM are roughly power law functions of particle size above a lower size limit. There is an evidence of what may be a strong change in the grinding characteristics of quartz and calcite near the finest grinding sizes for the SAM. However, this may be a function of particle sizing experimental technique.

It was found that the population balance model used in the study is only strictly appropriate for a single mixer model of breakage of impulse injected tracer in a steady-state hold-up stirred mill. They suggested that a possible significant improvement in the model accuracy could be gained by formulating and solving an appropriate population balance equation that directly incorporates flow effects modelled by multiple mixers in series. This approach would directly utilise the optimal number of mixers and associated mean residence times gained from the analysis of residence time distribution. An even more sophisticated approach would be a coupled convection-diffusion and population balance model for charge transport along the axis of the stirred mill during the comminution process.

The group of Computational Fluid Dynamics, CSIRO Minerals has developed the model for a 4-litre Netzsch horizontal bead mill based on the computational fluid dynamics (CFD) (Lane, 1999). A number of CFD simulations have been carried out adopting several alternative approaches to simulating the flow in the horizontal mill. These methods involved: a) A model was set up to represent the entire mill interior as close as possible to the manufacturer’s specifications, including the rotor shaft with nine discs each with five holes. b) To study the flow in some detail, a small section of the mill was modelled, which neglecting end effects may be regarded as the basic repeating unit in the mill. c) The modelling of the entire length of the mill. A steady-state approach to the solution was attempted. The flow field prediction was obtained using explicit time stepping, stopping the calculation after 400 time steps of
0.04 seconds with 20 iterations per time step. d) The residence time distribution of ore particles in the mill will be calculated from the CFD modelling.

Figure 13 shows the velocity vectors in a radial-axial plane when modelling the full length of the mill. It was found that the material in the mill has a complex spiralling pattern, where as well as moving in an azimuthal motion in the direction of agitator rotation, there is a series of circulatory mixing cells in the radial-axial plane, where the shearing action of each disc causes the mixture to be centrifuged radially outwards towards the outer wall. The fluid then impinges on the outer wall and is drawn radially inwards again. The distribution of shear rates in a radial-axial plane is shown in Figure 14. Higher shear rates are generated due to the relative movement between discs and the outer wall. The highest shear rates corresponds to the highest local rates of energy dissipation, and it is found that most of the energy dissipation occurs in a small volume surrounding the outer part of the discs and at the outer wall. This means that most of the grinding would be expected to take place in these zones. Thus, it is predicted that grinding of all particles may depend on the circulation of particles in and out of these zones of high-energy dissipation. The results of CFD simulation of the residence time distribution are shown in Figure 15 along with the experimental tracer results. Qualitatively, these results give a similar curve with a very broad residence time distribution, which indicates axial dispersion of slurry particles. Both curves indicate early exiting, with the peak in the distribution occurring considerably earlier than the nominal mean residence time of 80 seconds, and the curves also show long tails. However, the peak in the CFD result occurs at a time only about half of that in the experimental result.

In their summary with the CFD modelling, the present study has shown that a range of information may be obtained by modelling horizontal stirred mills including flow pattern, velocities and shear rate with the mill. This model can also be used to compare power draw, mixing (residence time distributions) and disc wear rates, and hence is expected to be a valuable tool for improving grinding performance while minimising power consumption and wear.

The discrete element method are being applied to model the 2-D performance of the stirred mills in Xstrata Technology (Clark, 2003). The simulation of the wear and grinding behaviours of grinding media with various geometry. From the results, the balls or beads give a higher energy efficiency, compared to the irregular shape media.

Other mills

Besides the high pressure roller mill and stirred mills, the modelling for the performance of other mills in fine and ultrafine grinding are in the development in Australia. The mills include centrifuge mill and Hicom mill.

The CSIRO Minerals has used a discrete element method to simulate the charge motion in a centrifugal mill with various loadings. The charge in a 30-cm centrifugal mill, used for high intensity and ultra-fine grinding, has been investigated. The cylinder executes a centrifugal motion with diameter 12-cm. The supporting arm rotates at 1000 rpm while the mill cylinder counter-rotates at the same rate. It is filled with uniform 6-mm particles and there are four flat lifters. These parameters were chosen to match the experimental configuration used by Hoyer (1984). The particle distributions, both measured experimentally and predicted by the DEM simulations, are shown below for three different particle loadings. It can be observed that the numerically predicted charge profiles show very close agreement with the high-speed
photographs of Hoyer. The 75% and 50% loaded cases exhibit a steady stable charge profile that simply rotates with the mill whilst the granular material deformed smoothly. This is in accordance with the behaviour observed experimentally. Furthermore, the charge profiles matched the experiments very closely, with the 75% case being indistinguishable even to the point of predicting the same amount between the lifter and the charge as the charge separate the lifter at the top. Theoretically there is a complete change in the flow behaviour for loads less than 30%. This also observed experimentally. The simulation of the 25% loaded case exhibits the same unsteady flow as the experiments with the particles forming a characteristic distorted three pointed shape that flops around the inside of the mill with a tumbling motion spraying loose particles all around.

Power measurements were also made for the centrifugal mill with a fill level of 40% and a charge consisting of 4 kg of steel balls and 1 kg of quartz for a range of rotation rates. Matching DEM simulations were performed to determine the accuracy of the DEM predictions. The figure below shows the experimental, theoretical and DEM results for various rotation rates. The power predictions are all normalised by the mass of the charge to give specific power consumption, in order to enable direct comparison of these quantities. For most mill speeds multiple power measurements were made. They show a reasonable amount of variation. The spread in these results provides some idea of the amount of experimental error or variation that is intrinsic to these systems. The precise reasons for these variations are unknown.

For 300 rpm, the DEM prediction is extremely close to the single experimental result and is closer than the theoretical one. For the higher rotation rates (for which multiple experimental measurements were made) all the DEM predictions lie well within the experimental ranges. In general, they are near the middle of the ranges and for the 400-rpm case the DEM result is in the lower part of the range. One would expect the DEM predictions to be slightly lower than the true power consumption because mechanical energy losses in the motor and gears of the mill are not included in these predictions. The DEM power consumption is purely that consumed by the actual particle motions and their interactions with the mill chamber. It is also clear from this figure that the theoretical predictions of Hoyer (1985) represent an upper bound for the power, corresponding to the upper limit of the experimental range for each rotation rate. The DEM predictions are much closer to the mean experimental power for each rotation rate than are the theoretical values. This suggests that DEM is likely to give a good estimate of actual power draw and will predict this more accurately than does the theory.

This is one of the few applications for which we have been able to obtain high quality experimental data. The very close agreement between the simulations, the experiments and with the theory gives us a degree of confidence that the DEM approach of trying to model correctly the applications at the particle level is capturing sufficient reality to give good predictions. One important caveat is that the particles used in the experiments were very close to spherical and so the circular particles used to model them are a good approximation. Cases where the real particles are really non-circular are not always well matched by DEM simulations using circular particles. Flows such as in hoppers and in slowly rotating tumblers where the material is partially stationary and then must shear can be significantly affected by ignoring particle shape. More details regarding this application can be found in a paper by Cleary and Hoyer (2000).

Also, the CSIRO Minerals has been using the DEM to predict the three-dimensional performance of the Hicom mill (Morton, 2003). As known, the Hicom mill has become a
promising machine as an alternative for energy saving and effective size reduction in ultrafine grinding of industrial minerals like calcite and dolomite. The detailed information on the simulation of the comminution in the Hicom mill is limited due to the commercial reasons at this moment.

Simulators for optimisation of comminution process

A simulator for analysis, optimisation and design of comminution circuits so-called JKSimMet has been developed by the Julius Krutschnitt Mineral Research Centre (JKMRC), Australia (Morrison, et al., 2002). The JKSimMet is recognition of the need to integrate certain fundamental tasks in one piece of software. The tasks that have considerable synergy with one another include flow-sheet drawing, data analysis, model fitting, simulation and reporting. These tasks are integral to the iterative nature of the simulation process. This software or simulator is a user-friendly package for processing engineers. The current version 5 of JKSimMet incorporates all of the essential tasks. This is designed for use with Windows/MS. The graphical user interface of JKSimMet communicates with a Microsoft Access database that stores and organises the user’s data by projects and flowsheets within a project. This software contains an extensive library of unit models for use in all three major functions of data analysis, model fitting and simulation. The task of measuring the process must take place outside of the simulation software package. However, once the data describing the current state of the process have been collected and entered via the graphical flow sheet interface, they must be sorted and analysed for validity. The function of data analysis is to determine if a given set of data is “good” and “bad” is complex, and is best handled by the integrated software package. User friendly mass balancing forms the basis of a sister product called JKMBal as well as being almost certainly the most-used module of JKSimMet. Once the user has defined a flowsheet by drawing it and entering the individual flowstream data, JKSimMet permits the user to set up and run a mass balance to analyse the data. Proceeding stream by stream, the user indicates the quality of the data by entering standard deviation estimates, used by JKSimMet to set weights, which determine how much the software is allowed to adjust each data point in order to achieve a balance. In addition to total stream flows of solids and liquids, JKSimMet allows the user to specify the number and type of measurable components to be included for each flowstream. In model fitting, if mass balance analysis shows the data to be good, the next task in the iterative procedure of simulation us to establish parameters for the various models, which match the observed performance of the process embodied by the data. Model fitting is the step whereby the user “tunes” or adjusts the individual unit operations models until they are accurately predicting the actual measuring data. As with mass balancing, the user describes the quality of the data to JKSimMet via standard deviation estimates. The user also tells the software, which model parameters can be adjusted to match the measured data. In simulation, once accurate parameters and an accurate “base case” models of the existing process have been established by the model-fitting step, the user is ready to actually simulate the flowsheet. In this step, model parameters determined by the fitting step are held constant and various process options are tested by making changes to the model design variables in order to compare the outcomes against the existing process. Model design variables include, but are not limited to, items such as process solids feed rates, water addition rates, solids and pulp specific gravities, ore breakage characteristics, equipment dimension and flowsheet arrangement of unit operation. The user needs only to specify which unit models are required for the current flowsheet case, connect them with flowstreams and to specify the necessary design variables, which define the current or starting operating condition for each unit. Flowstreams are also models in this
software. Streams are modelled by specifying total flows of solids and liquids, as well as solid phase and characteristics (such as specific gravity). The JKSimMet has been regarded to be a steady-state process simulator for data analysis, plant optimisation and plant design for comminution and classification circuit.

Figure 16 shows the JKSimMet process optimisation methodology. This software lends itself well to a straightforward and rigorous methodology for process optimisation. The following figure outlines that methodology, which can be applied to almost all comminution and classification circuit optimisation exercises. The simplest application of simulation is to match the comminution particle size to the classifier product size. This usually achieves a 5 to 10% improvement in throughput at a similar particle size. The more complex the circuit, the larger the potential gains which can be achieved by balancing the stages to each classifier. The more interesting application of optimisation is to adapt an existing circuit to an ore body which grows harder at depth. For instance, the ore at the Kidston Mine started at a Work Index of less than 10 kWh/t and over a few years more than doubled. The staff at Kidston used JKSimMet to consider the effects of pre-crushing and two stages recycle crushing. Throughput as maintained keeping the operation viable for substantially more than planned mine life. For the detailed information, refer to Needham and Folland (1994). Also a similar problem at the ASARCO mine – a 50% increase in hardness was overcome by partial pre-crushing of SAG mill feed (McGhee, et al., 2001). The most profitable of all optimisation possibilities has been the matching of run of mine sizing to milling circuit characteristics. This approach uses JKSimBlast to estimate the product size distribution from blasting (Valery Jnr., et al., 2001). The two successful examples are referenced, i.e., one work at KCGM by Kanchibotla et al (1998) and the another for maximum iron ore lump product at Marandoo by Kojovic et al (1998). The first aimed to maximise throughput and the second to minimise to production of < 6-mm iron ore “fine” fractions.

Metso Minerals (Australia) Ltd. Co. has used the USIM PAC simulator for design/optimisation of mineral processing plant, which has been developed for 16 years by BRGM, France (Brochet, et al., 2002). The latest version available is the USIM PAC 3.0, which incorporates the modern developments. This is a user-friendly steady-state simulator that allows processing engineers and researchers to model plant operations with available experimental data and determine optimal plant configuration that meets production targets. The simulator can also assist plant designers with sizing unit operations required to achieve given circuit objectives. Figure 17 shows the methodology used to optimise an existing plant. In addition, they has also applied a crushing plant simulator named BRUNO (Kaja, 2002). This simulator has been utilised to facilitate the comminution equipment selection process. The program was a DOS based mass balance program that kept track of the tonnage rate of each size fraction in various circuit flows. The Bruno uses a graphical environment to define the circuit components and their relationships. The pallet contains feed material, plant feeders and grizzly feeders, primary gyratory crushers, jaw crushers, cone crushers, impact crushers, screens, silos and stockpiles. The Bruno plant simulator is a tool for calculation of the capacity and gradation of crushing and screening circuit. It can provide an opportunity to vary circuit components and optimise the performance of a circuit and the equipment selection, resulting in a more cost-effective crushing solution.
On-line control and analysis

In the effective control and optimisation of a processing flowsheet on streams (especially in comminution processes), on-line analysis and control systems for elemental analysis, moisture, particle size and geometry have been developed in Australia (Liu, 2003). These aspects involve
- acoustic emission soft-sensors (CSIRO Minerals);
- bulk elemental analysis (CSIRO Minerals);
- low frequency microwave moisture analysis (CSIRO Minerals);
- ultrasonic particle size analysis in wet and dry modes (CSIRO Minerals); and
- image processing technology (JKMRC).

The CSIRO Minerals has developed an acoustic emission (AE) soft-sensors for the control of the processing systems (see Figure 18). The AE is mechanical waves arising from the rapid release of strain energy within a stressed material. Sources may be defect related deformation processes, impacts, shear, abrasion and particle breakage. Energy radiates from a source as elastic waves, which can be detected at the material surface (typical 10-1000 kHz). The significant areas of work on surface vibration (AE) passive monitoring of process variables/machine condition are: a) grinding mill; b) hydrocyclones/DM cyclones and c) slurry pipeline. The multiple AE transducers are installed on the rotating AG/SAG mill surface or on stationary DM cyclone shell in order to log and analyse the data. This CSIRO technology has been in some field trials in mines around Australia, South Africa and Chile.

The CSIRO on-line bulk elemental analysers use advanced neutron-gamma technology to provide elemental composition measurements that are both rapid and accurate. They are unique in their use of robust BGO detectors as well as long-lived Am-Be sources, which significantly increases detection sensitivity to important or easily-measured elements such as C, H, O, Si, Fe, K, Au, Cl, Ca and Al. These systems are suitable or use in high-temperature and pressure environments, and the analysers are designed and tested to meet rigorous international radiation safety standards. The applications are a) blending control in cement (it is used to monitor and control the blend of raw material feed stocks in a cement manufacturing plant; b) coal quality in mines and power stations (it is used to measure ash, moisture, specific energy and fouling index in brown coal; c) optimisation of lead sinter plants (on-line analysis for sulphur, lead, zinc and iron in lead sinter feed), and monitoring of reduction rates in steel making.

The low frequency microwave moisture analyser with low power emitted (< 1 microwatt/cm^2 at the antenna) was developed for continuous, on-conveyor applications ranging from conventional materials to highly attenuating material such as industrial minerals. This technology is based on a microwave transmission measurement system, where microwaves are transmitted through the material from above and received below the belt. The system measures the microwave phase shift and attenuation to determine the moisture content of the materials on the belt. It has been indicated that measurements are not affected by vertical segregation of the material on the belt, are independent of material particle size and belt speed and are effective with both fabric and steel cord belts. This analyser installs directly on the production conveyor belt. Installation requires little or no modification of the existing structures. The system comprises lightweight antennas (supported by C-frame or crossbeam) and a compact industrial instrument enclosure. Figure 19 shows the low frequency microwave moisture analyser operating on a conveyor of iron ore for BHP Billiton in Australia.
Effective comminution of material in slurries and in dry powder streams often rely on particle size. The CSIRO Minerals has applied the latest technologies to develop the instruments for measurement of particle sizes in slurry and in dense pneumatically conveyed powders (see Figure 20).

The ultrasonic particle size analyser so called UltraPS is suitable for the measurement of slurry particle sizes in a wide range of industrial applications like pigment, iron ore, industrial minerals and processing streams. It consists of a submersible probe and control electronics capable of producing full particle size distributions of particle cut point measurements within the size range from 0.1 to 1000 µm. Size information is derived from the measurements of ultrasonic velocity and attenuation over a range of frequencies. An inbuilt gamma ray density gauge provides correction for variation in the solids content of slurry. The density gauge uses an ultra-low activity radioisotope source exempt from licensing regulations. The UltraPS operates on high solids content slurries (up to 50 % by weight) and may be inserted directly into slurry stream or high flow-rate sample by-line without need for dilution. Representing a significant advance in particle sizing technology, the UltraPS is specifically designed to provide continuous, accurate in-stream measurement of slurry particle size in some applications. The system can be directly installed into a process stream. For highly aerated streams, the slurry can be fed continuously through a high flow-rate sample by-line to de-aerate the slurry prior to measurement. The UltraPS has been field tested in a variety of industrial plants, and is now installed and operating successfully in locations throughout Australia. In addition, the CSIRO is developing optical and ultrasonic techniques for the one-line measurement of particle size in high concentration dust streams. These measurements are particularly important for the control of dry milling processes (Spencer, 2003).

The JKMRC, in conjunction with the Split Engineering, USA, has used an improved version of Split-Online image processing system with the corresponding software to measure the continuous fragmentation size in the SAG mill process control strategies (Girdner, et al., 2001). This system can continuously capture digital image of particle or rock fragments from conveyor belts or other sources and processes these images to determine the particle or fragment size distribution. The data generated from the system can be incorporated into process control strategies to optimise the crushing and grinding circuits. Two types of improvement on the former version have been made. Numerous improvements have been made to the image processing and statistical algorithms that form the basis if the Split software. The most important improvement of this type is the incorporation of a texture algorithm to identify patches of fines. Previously these batches were mistakenly classified as large particles or rock fragments. Figure 21 shows a plot of texture values for a fine material. This data was analysed using 387 areas from 12 different images of both trucks and conveyors. Analysis of the data shows that a value of 0.95 separates the particles from the fines with minimal misidentification. The misidentification rate is approximately 11 % for this set of images, which is a marked decrease as compared to100 % misidentification of patches of fines as particles without the new criteria. Secondly, the Split-online software has been ported to the Windows platform. This improves the compatibility and maintainability of the software for mining operations around the world. Equally important, in the process of porting to Windows, major architectural changes have been made that increase the flexibility, modularity and expandability of the software.
Summary

Model developments on modern mills like stirred media mills (tower mills), high-pressure roller mills (HPRM), centrifugal mills and Hicom mill have received some attention in Australia. Methodology for the models involves empirical derivation method, population balance method (PBM), discrete element method (DEM) and computational fluid dynamics models (CFD). Their combination used for simulators and softwares, especially PBM with DEM, has become of particular interests to industrial applications. The models for power draw, product size distribution and throughput in the HPRM with various surface geometries (smooth and studded) have been applied for the simulation from lab- to full-scale machines. Efforts to model and simulate the size reduction and power draw of tower mill (vertical stirred mills) have been put for the scale-up purpose. The population balance model with tracer technology has been used to predict the performance (size reduction and residence time distribution) of the stirred mills. The present CFD modelling for the horizontal stirred mills can provide the information the flow pattern, velocities and shear rate with the mill. This model also predicts the power draw, residence time distribution and wear in the mill. The DEM has been used to simulate the 2-D performance of the wear and grinding beads with various geometries in the horizontal stirred mill. The simulation with DEM for centrifugal mills and Hicom mill has been also developed.

The JKSimMet simulator developed in JKMRC can be used as an engineering tool in steady-state process simulation for comminution circuit optimisation. This software package is run on PC under Window environments and user-friendly. This simulator combined with JKSimBlast has been applied to analyse and optimise the comminution chain from mine-to-mill in order to reduce energy consumption without decreasing the throughput and operating efficiency. In addition, some simulators like USIM PAC 3.0 offer a wide spectrum of design criteria such as comminution process optimisation in Australian mineral processing industry.

On-line analysis and control systems for elemental analysis, moisture, particle size and geometry have been developed for effective control and optimisation of a processing flowsheet on streams (especially in comminution processes), in Australia. In addition, acoustic emission soft-sensors have been applied for control and optimisation of a mill performance.

Acknowledgements

The author wishes to thank the MinBaS development program and the Swedish Mineral Processing Research Association (MinFo) for supporting this work. Thanks go to the Xstrata Technology (the former MIM Process Technologies), the School of Engineering and the JKMRC of the University of Queensland, the Centre for computer simulation and modelling of particulate systems of the University of New South Wales. Metso Minerals (Aus) Pty Ltd., Mount Isa Mines Ltd., and Queensland Centre for Advanced Technology, Lucas Heights Science & Technology Centre and Group of Computational Fluid Dynamics of the CSIRO Minerals. The author is also grateful to all scientists and engineers in the above units, who he met, for fruitful discussion and sincere helps on this survey work.
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Caption of figures

Figure 1  HPRM model verification and scale-up procedure.

Figure 2  Product size distributions and power draw obtained from the lab-scale experiments and predicted full scale of HPRM with smooth rolls in the case of Rio Tinto ore.

Figure 3  Product size distributions and power draw obtained from the lab-scale experiments and predicted full scale of HPRM with smooth rolls in the case of De Beers ore.

Figure 4  Product size distributions and power draw obtained from the lab-scale experiments and predicted full scale of HPRM with studded rolls in the case of De Beers ore.

Figure 5  Product size distributions and power draw obtained from the lab-scale experiments and predicted full scale of HPRM with studded rolls in the case of BHP Billiton ore.

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Figure 17  USIM PAC process optimisation methodology.
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Figure 19  Low frequency microwave moisture analyser operating on a conveyor of iron ore for BHP Billiton in Australia.

Figure 20  On-line ultrasonic particle size analyser.

Figure 21  Plot of texture value showing separation of fines and particles.
HPGR Model verification and scale-up procedure

1. Ore sample (industrial unit)
   - Ore Characterisation
     - Appearance function & specific comminution energy

2. Laboratory Scale Tests
   - Measure power & throughput & calculate $E_{cs}$

3. HPGR Model
   - Model fit a size distribution to the experimentally measured size distribution and determine $t_{10(hpgr)}$ and $Kp$

4. Industrial plant data
   - Compare the data with given industrial scale data

5. Scale-up
   - Use the model to simulate and predict full scale product size distribution throughput and power draw

Fig 1
Experimental Lab-scale

Predicted Full-scale

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Roll Surface</th>
<th>Roll Size (m)</th>
<th>kWh/t (full-scale)</th>
<th>kWh/t (lab-scale)</th>
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<tbody>
<tr>
<td><strong>Rio Tinto (historical)</strong></td>
<td>Smooth</td>
<td>2.2</td>
<td>1.8-2.5</td>
<td>1.8-2.5</td>
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<tr>
<td><strong>De Beers</strong></td>
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<td>2.8</td>
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<tr>
<td><strong>BHP Billiton</strong></td>
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<td>1.7</td>
<td>1.0-1.2</td>
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Fig. 2
**Experimental Lab-scale**

![Graph: Lab Scale FSD and PSD](image)

**Predicted Full-scale**

![Graph: Full Scale FSD and PSD](image)

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Fig. 3
Experimental Lab-scale Predicted Full-Scale

Fig 4

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## Experimental Lab-scale vs Predicted Full-Scale

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</table>

*Fig 5*
Throughput

![Graph showing throughput for Lab-Scale and Full-scale systems.](image)

Lab-Scale

Full-scale

Fig. 6
Fig. 7

Horizontal stirred mill
(after Stehr et al 1983)

Vertical stirred mill -
Sala SAM mill
(after Wild et al 1993)
Fig. 8
Breakage rate scale-up results

![Graph showing breakage rate scale-up results](image)
Fig. 11
Fig. 13
CSIRO Minerals' Ultrasonic Particle Size Analyser (UltraPS)

Fig. 20
Fig. 21