MODELLING AND SIMULATING THE CARAJAS GRINDING CIRCUIT[1]

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Abstract
The aim of this work was to model the Carajás grinding circuit which consists of two parallel ball mills designed for producing pellet feed. The results of the modeling exercises were used for assessing circuit performance as well as for simulating for the treatment of various ore types at Carajas mines. The method consisted of surveying the exiting industrial grinding circuit, as well as conducting characterization tests on selected samples. Data obtained from surveys were mass balanced and used for calibrating the corresponding mathematical models. These models were recalibrated to represent the integrated circuit, which was used to predict the performance of different ore types that occur in the Carajas mines. As result an analysis of different ore types was carried out by comparing simulated products and indicating significant differences among selected ore types.
Key words: Simulation; Ball mill; Characterization; Iron ore.

MODELAGEM E SIMULAÇÃO DO CIRCUITO DE MOAGEM DE CARAJÁS

Resumo
O objetivo do presente trabalho foi modelar o circuito de moagem de Carajás, o qual consiste de duas linhas de moagem paralelas, projetadas para produção de *pellet feed*. Os resultados dos exercícios de modelagem foram utilizados para avaliar o desempenho do circuito, bem como para simular o circuito com os vários tipos de minério de Carajás, que não são alimentados à usina de moagem. O método baseou-se na amostragem do circuito industrial e na caracterização tecnológica de amostras selecionadas. Os dados obtidos através das amostragens foram submetidos ao balanço de massas e empregados na calibração dos modelos correspondentes. Estes modelos foram submetidos a uma rotina de calibração de forma a representar o circuito integrado, e estão utilizados para prever o desempenho dos diferentes tipos de minério das minas de Carajás. Como resultado, uma análise destes tipos de minério foi conduzida com base na comparação dos produtos simulados, indicando as diferenças significativas entre o desempenho dos tipos de minério selecionados.
Palavras-chave: Simulação; Moinho de bolas; Caracterização tecnológica; Minério de ferro.

[1] *Technical contribution to the 2nd International Symposium on Iron Ore, September 22 – 26, 2008, São Luís City – Maranhão State – Brazil*
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1 INTRODUCTION

Originally designed for sinter feed grinding, the Carajas grinding circuit is composed of two ball mills in separated lines in a closed configuration with cyclones. Both cyclone overflows go to a sump, from where slurry is pumped to feed the desliming circuit, where the product size distribution is adjusted to obtain an adequate pellet feed. There is a significant amount of high grade material, suitable for incorporation in the product that is discarded as waste in the desliming process. In addition to the high iron grade material losses, the circuit is required to treat sinter feed and ROM ores from selected mine faces that are suited to pellet feed production. This scenario requires that the characteristics of different ore types need to be better understood in relation to grinding circuit performance prediction. Ultimately the aim is to be to adjust the circuit operation to suit a variety of ore blends, so that the mass recovery and the circuit productivity increase.

This paper presents the Carajas grinding circuit mathematical modeling study for production of pellet feed. The results also include a performance analysis of the existing circuit and circuit simulation for three Carajas ore types never fed to the mill.

1.1 Mathematical Modeling

In simplistic terms, it is possible to say that a mathematical model of a system is an approach to represent a physical reality using a set of self consistent equations. Usually, model equations predict output characteristics in terms of input variables. The application of models are direct and its efficacy is dependent on the characteristics to be predicted, the factors or variables that are assumed to affect the process and the assumptions and hypotheses used in expressing these variables in the mathematical structure (NAGESWARARAO et. al., 2004).

As models are based on simplifying assumptions and process measurements, errors in any measurement must be minimized. Any errors in the data used for developing the model parameters, will be carried forward into the model and consequently into the simulation results.

1.2 Ball Mill Model

The initial attempts to model ball mill operation were marked by empirical approaches to predict the power draw of such equipment. Researchers at the time were motivated by the possibility of reducing energy consumption through power prediction. Using the ore characteristics as the basis, energy-size relationships were developed by Rittinger in 1867, Kick in 1885, Bond in 1952 and Hukki in 1961 and also in 1975 (KELLY and SPOTISWOOD, 1982) to predict the power draw of comminution equipment, in particular crushers and ball/rod mills. Of these only Bond's is broadly referenced in current mill circuit design.

Energy-size models are useful to predict the energy consumption and select mill sizes. However, they don't consider particle transport or breakage characteristics of the ore. Researchers have addressed these deficiencies and developed two main classes of comminution models (NAPIER-MUNN, 1996):

- Fundamental models: consider each element with the process;
- Phenomenological models: consider the comminution equipment as a transform between feed and product size distribution.

The phenomenological approach is focused on this work. The most widely used model is the Population Balance Model (EPSTEIN, 1947) and the Perfect Mixing Model (WHITEN, 1976). The objective of those models is to predict product size distribution as a function of mill feed size distribution and breakage characteristics.
Both models are based on the mass balance of a continuous mill in steady state, i.e., the material fed to the mill, breakage occurs and it is transported out, without material loss or accumulation for any particular size fraction. In addition, the rate of breakage that occurs inside the mill chamber is constant for each size fraction.
The breakage rate is described by the product $r_i \times s_i$, where r_i is the breakage rate of size fraction i and s_i the mass of each fraction i in the mill load.
Consequently the balance equation can be written:

$$\mathbf{f_i} + \sum_{j=1}^{i-1} \mathbf{a_{ij} r_j s_j} = \mathbf{p_i} + \mathbf{r_i s_i} \qquad (1)$$

Where
f_i = mass flow rate of size fraction i in the mill feed
p_i = mass flow rate of size fraction i in the mill product
b_{ij} = fraction of broken particles from size fraction j into size fraction i (appearance function)
d_i = discharge function of size fraction i
These assumptions about the breakage are essentially the same for both models, but the nature of mixing is not. In the Whiten's model the mixing is considered perfect, so the mill contents are related to the product with a discharge rate for each size fraction by the relation $\mathbf{p_i} = \mathbf{d_i} \times \mathbf{s_i}$. Substituting the mass of each fraction, the balance equation around each size fraction is:

$$\mathbf{f_i} + \sum_{j=1}^{i-1} \frac{\mathbf{a_{ij} r_j p_j}}{\mathbf{d_i}} = \mathbf{p_i} + \frac{\mathbf{r_i s_i}}{\mathbf{d_i}} \qquad (2)$$

The size distributions and flow rates can be measured in operating mills by sampling and mass flow measurement instruments, respectively. Breakage rates, appearance function and discharge function can be estimated from laboratory tests or be back calculated. The perfect mixing model structure combines simplicity of direct calculations with the convenience of separate individual parameters.
In the perfect mixing model, the breakage rate is the most important parameter. It is a parameter associated with the size fractions and is defined as the fraction of material broken per unit time or the frequency of breakage events. The breakage rate is inherently dependent on what is considered to be a breakage event. Each particle within a mill experiences breakage interactions with other particles with a distribution of intensities. Therefore the breakage rate distributions are highly dependent upon the characteristics of the material and the breakage enviroment. It has been shown by Leung (*apud* DELBONI Jr, 1999) that the breakage rate distributions are considerably affected by different appearance functions (see below).
The breakage rate is a parameter that can be modeled following two different approaches. The first was adopted by Austin and co-workers (1984) and has a basic assumption that the breakage is essentially a first-order process. The experimental procedure is based on grinding mono-sized samples separately in laboratory mills. The mathematical treatment of the staged grinding data results in the breakage rate distribution. The second, employed by the JKMRC, is based on back calculation from experimental data or, in situations where it is not possible, estimated from similar equipment and operating conditions. Breakage rate and discharge function have been combined into a single parameter represented as the quotient r/d. So, as long as the feed (f_i), the product (p_i) and the appearance functions (a_{ij}) are known, the breakage rate can be back calculated through equation 4.

Appearance functions represent size distributions that result from breakage events. Specific tests, such as the drop weight test, were developed from which the relationship between applied energy and resultant breakage can be experimentally determined.
The discharge rate is defined as the rate at which the load flows out of the mill. According to the perfect mixing model it has the units of inverse time and is the quotient between the mill discharge flow rate and the load contents of each size fraction, as showed in the equation 2.

1.3 Classification Model

The hydrocyclone is the standard classifier used in closed grinding circuits in mineral processing plants. The first efforts to research control, modelling and optimization of industrial cyclone classifiers began at the University of Queensland in the 1960´s.
A number of methods for hydrocyclone modelling have been developed since then and are commonly based on the application of the efficiency curve. The mathematical equations most used to describe the reduced efficiency curve are based on three parameters: mean size ($\boldsymbol{d_i}$), the corrected cut size ($\boldsymbol{d_{50c}}$) and a separation coefficient.
Several models to describe the performance of industrial hydrocyclones were developed, but only two models are broadly used for industrial scale simulation studies of comminution and classification circuits. These are known as the Plitt and the Nageswararao models. The Nageswararao model is a generalized model for hydrocyclones, developed at JKMRC by different researchers, quoting Rao, Lynch, Marlow, Nageswararao and Castro (NAGESWARARAO et. al., 2004). Alternatively, in 1976 Plitt developed an empirical model based on laboratory data.

1.2.1 Nageswararao model

The Nageswararao model was the first of the models developed that incorporate an important concept which decoupled the machine and material characteristics. The model is used to determine specific constants from a test or survey. These parameters can then be used to model the performance of geometrically similar cyclones treating similar feed types.
According Nageswararao et. al. (2004), the model takes into account the centrifugal force field generated in the cyclone, as well as the effect of the differential movement of solid particles and the effect of changes in feed solids concentration on the cut size. To describe cyclone performance with the model, four relevant factors are considered:

- Euler number, which is defined as $\boldsymbol{Q/\left(D_c^2\sqrt{\frac{P}{\rho_v}}\right)}$;
- Cut size$\boldsymbol{d_{50_C}/D_C}$,;
- Water recovery to underflow, $\boldsymbol{R_f}$;
- Feed slurry volumetric recovery to underflow, $\boldsymbol{R_v}$.

These factors are represented by the equations bellow:

$$\frac{Q}{\left(D_c^2\sqrt{P/\rho_v}\right)} = K_{Q_0} D_C^{-0.1}\left(\frac{D_o}{D_c}\right)^{0.68}\left(\frac{D_i}{D_c}\right)^{0.45}\left(\frac{L_c}{D_c}\right)^{0.2}\theta^{-0.1} \qquad (3)$$

$$\frac{d_{50c}}{D_c} = K_{D_0} D_C^{-0.65}\left(\frac{D_o}{D_c}\right)^{0.52}\left(\frac{D_u}{D_c}\right)^{-0.5}\left(\frac{D_i}{D_c}\right)^{0.2}\left(\frac{L_c}{D_c}\right)^{0.2}\theta^{0.15}\left(\frac{P}{\rho_p g D_c}\right)^{-0.22}\lambda^{0.93} \qquad (4)$$

$$\mathbf{R_f} = \mathbf{K_{W_0}} \left(\frac{D_o}{D_c}\right)^{-1.19} \left(\frac{D_u}{D_c}\right)^{2.4} \left(\frac{D_i}{D_c}\right)^{0.5} \left(\frac{L_c}{D_c}\right)^{0.22} \theta^{-0.24} \left(\frac{P}{\rho_p g D_c}\right)^{-0.53} \lambda^{0.27} \tag{5}$$

$$\mathbf{R_v} = \mathbf{K_{V_0}} \left(\frac{D_o}{D_c}\right)^{-0.94} \left(\frac{D_u}{D_c}\right)^{1.83} \left(\frac{D_i}{D_c}\right)^{0.25} \left(\frac{L_c}{D_c}\right)^{0.22} \theta^{-0.24} \left(\frac{P}{\rho_p g D_c}\right)^{-0.31} \tag{6}$$

The following equation was used by the author to describe the reduced efficiency curve:

$$E_{0_{ai}} = C\left[\frac{e^{\alpha}-1}{e^{\alpha d_i/d_{50c}}+e^{\alpha}-2}\right] \tag{7}$$

Where

$E_{0_{ai}}$ = Actual recovery to overflow for particle size class *i*

C = Cyclone water split to overflow

d_i = Representative size of the particle size class *i* (in micron)

α = Cyclone efficiency curve shape parameter

2 METHODOLOGIES

The methodology of the work was based on mathematical modelling of the Carajas grinding circuit, test work for comminution characterization of the processed ore samples as well as characterization of samples of other ore types proceeding from different Carajás mine faces.

The proposed methodology had, therefore, a first phase consisting of three complete surveys of the grinding circuit followed by mass balancing and mathematical model fitting using the JKSimMet software. In the second phase the characterization test work was carried out. The third phase consisted of simulating the circuit for different ore types that are not presently processed by the grinding plant.

Results of the simulations were used to assess likely circuit performance, by consideration of particle size distributions of the simulated products.

2.1 Surveys the Carajas Grinding Circuit

This section describes the Carajas grinding circuit, the sampling technique adopted during the surveys and the procedures for characterization of the samples.

2.1.1 Carajas grinding circuit

The Carajas grinding circuit (Figure 1) produces pellet feed (in this case, the desliming cyclone overflow), which has specifications with respect to size distribution and consequent specific surface area, as follows:

- % > 0.106 mm: < 1%,
- % > 0.045 mm: 33 – 35 %,
- % < 0.007 mm: 12 – 13 %,
- Specific surface area (Blaine): 1200 – 1300 $\mathbf{cm^2/g}$.

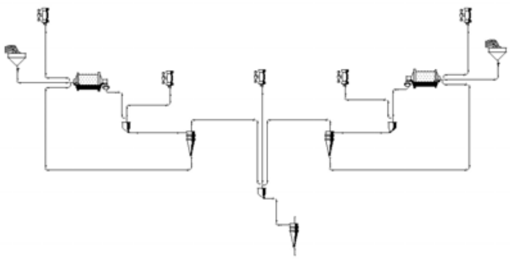

Figure 1. Carajas grinding circuit.

The circuit has two independent grinding lines and their product, in this case the overflow of the “classification” cyclones, is sent to a desliming stage. The equipment items that compose this circuit are:

- Two ball mills (20.0' x 34.5'),
- Eight “classifying” cyclones (26”) grouped in two clusters of four cyclones for each grinding line,
- Three hundred and sixty “desliming” cyclones (4”) grouped in ten cyclone clusters.

This nomenclature to denominate cyclone clusters (“classifying” cyclones and “desliming” cyclones) is adopted to prevent any misunderstanding.

2.1.2 Sampling practice

Obtaining good representation of a process stream is the main objective of sampling. Therefore, the circuit was held as constant as possible during the sampling campaign. This means that the grinding circuit ran at reasonably steady state conditions (tonnage, feed sizing and ore hardness).

Three complete surveys on the grinding circuit were conducted by the authors and VALE’s technical team.

There were a number of potential error sources affecting the data collection. Each variable required to model the ball mills and cyclones, together with variables related to the ore were observed in detail.

2.1.3 Sample analysis

As sample analysis was conducted at VALE´s facilities, the methodology adopted for sample analysis was their internal standard procedures.

The complete size analyses were conducted using a stack of $\sqrt{2}$ spaced sieves, starting with the bottom size of the feed size interval. The fines were then analyzed with a cyclosizer. Samples were oven-dried and size distribution was determined from dry weights of material retained on each sieve. The fines from the cyclosizer were collected, filtered on a filter paper and oven-dried.

2.2 Rock Breakage Characterization

Two techniques were used to characterize ore breakage. The first technique was the Bond grindability test. The second is the JKRMC method in which breakage is obtained on an impact cell by impacting individual rock particles. Both tests were conducted in the facilities of the Escola Politécnica from the Universidade de São Paulo.

2.2.1 Bond´s grindability test

The grindability test developed by Fred Bond in 1952 is a standard test for determining the ball mill Work Index (WI) of an ore sample, which expresses the resistance of a material to ball milling. It is a “locked cycle” test conducted in closed circuit with a laboratory screen for estimating the energy required for grinding, and for ball mill scale-up.

In the determination of the Work Index, 15 kg of representative ore is staged crushed until 100% of the material passes the screen aperture of 3.35 mm. A standard ore volume is added to the mill and dry ground. The product is sized on a closing screen selected to close the circuit and to target the desired product size. New feed is added to replace the screen undersize and the procedure is continued until a 250% circulating load is achieved.

The average of the last three net grams of product per revolution (Gbp) is the ball mill grindability. The Bond mill work index is calculated from the following equation:

$$\mathbf{WI = 1.102} \times \frac{44.5}{(P_1)^{0.23} \times (Gbp)^{0.82} \times \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}}\right)} \quad (8)$$

Where:
Gbp = Ball mill grindability (in g/revolution)
P =Product P_{80} (in microns)
F = Feed P_{80} (in microns)
P_i = Opening size of the sieve size used (in microns)

2.2.2 Impact breakage testing

The Impact Cell device comprises a steel frame which is raised to a known height. Once released the weight falls and impacts individual rock particles which are placed onto a steel anvil. By varying the height of fall as well as the mass of the weight, an extensive range of energy inputs is used. The Impact Cell Test is particularly suitable for characterizing drill core samples which are inherently size limited.

A typical test begins by preparing a number of individual particles within a strict size range. Three lots of particles are prepared in a given size range and each lot is subjected to impact breakage at different specific energy levels. Once impacted, the broken particles are screened and the respective size distributions are calculated.

The resulting distributions are then normalized in order to obtain the IQ parameter which is subsequently correlated to the A and b parameters, as described by Napier-Munn (1996). The low energy abrasion parameter, t_a, is determined by tumbling ore fragments.

As described by Chieregati and Delboni Jr.(2001), where there is inadequate sample mass or there are no large fragments available it is not possible to execute the test in all size ranges and a simplified method can be used. The authors showed that it is possible to establish a relationship between breakage parameters (IQ) obtained for a simplified test with those calculated for the complete test.

2.3 Simulation Exercises

The JKSimMet simulation program was used for the mass balance, model fit and simulation exercises. This program contains a variety of mathematical models for each of the unit operations, and the models used in this work were:

- Ball mill: Perfect Mixing Model
- Cyclone: Nageswararao Model

The experimental data obtained in circuit surveys were submitted to mass balance routines for verification of data consistency. In the mass balance step, nonmeasured values such as stream flows and size distribution were calculated. Those samples which resulted in balanced data with adequate quality were used in the process equipment model fit.

A model fit routine was used so that the adjusted models truly represent the industrial circuit. In this way, each equipment item was fitted separately and afterwards the circuit was fitted as one. With model parameters fitted, simulation exercises were carried out, and predicted ore type performance was compared.

3 RESULTS AND DISCUSSION

The results include the ore type characterization results, the analysis of industrial grinding circuit sampling data, model fitting and simulation exercises for ores that come from mine faces that are usually not fed to the grinding circuit.

3.1 Ore Types Characterization

3.1.1 Bond´s grindability test

Samples of ores that are commonly fed to the mill were submitted to Bond´s grindability test. Those samples were sinter feed (in this work called SFCK), a blend composed by N5W ore and lump ore (denominated in Carajas as NP2). Samples of lump ore and N5W ore were used to compose two blends: one with 15% NP2 and the other with 30% NP2. Also, samples from different mine faces were submitted to Bond´s grindability test: N5W, N4W Central, N4WN and N4E.
All results are presented in Table 1. Values listed in the table bellow presented a significant variation, with one sample around 8.5 kWh/st (N4E) and other with 18 kWh/st (N4W Central).

Table 1. Bond´s tests results.*

Sample	WI (kWh/st)
SFCK	14.6
N5W + NP2 (85-15%)	12.1
N5W + NP2 (70-30%)	12.3
N5W	11.4
N4W Central	18.1
N4WN	11.8
N4E	8.4

This set of values resulted in a mean of 12.7 kWh/st and a standard deviation 3 kWh/st. This means that the variation coefficient is around 20%, which is a considerably high value.

3.1.2 DWT

One composite sample was submitted to the complete drop weight test. This sample was composed by N5W and N4W Central ore (50-50%), both from mines faces which physically close to the grinding plant. The figure below shows the curve obtained for values from the test (specific energy - Ecs (kWh/t) and resultant fragmentation - t_{10})).

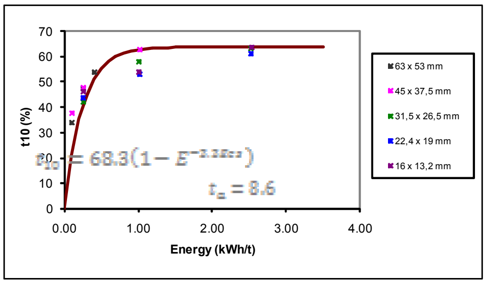

Figure 2. Parametric curve of energy and fragmentation.

The composite sample presented a value of A*b of 225, which is considered high indicating an incompetent ore. The parameter referring to fragmentation through abrasion, t_a, was 8.6, which indicates an exceptionally low resistance to abrasion.
The relationship with complete test and simplified test follows:

$$Ab = IQ + 79.5 \tag{9}$$

Five samples from Carajas mine faces were submitted to simplified drop weight test (DWT). The A*b values are listed in Table 2.

Table 2. Drop weight test results.*

Sample	Axb
N5W	194.4
N5E	194.5
N4W Central	189.1
N4WN	265.3
N4E	146.8

The mean Axb value obtained was 278, with a standard deviation of 43. This means that Carajas samples present an extremely low resistance to impact. It can be observed that the sample from N4WN has a lower resistance compared to the other samples. On the other hand, sample from N4E presented the higher resistance.

3.2 Mass Balance

To make experimental data coherent, a mass balance for each size fraction was conducted. The routine used in JKSimMet is based on the Morrisson solution and data values are adjusted to minimize the true weighted sum of squared errors between the actual and balanced data sets. To weight the importance of size distribution errors, Whiten's values for standard deviations (0.1% plus one tenth of the fraction, up to a maximum weighing of 1%) were set for each experimental size distribution and mass balancing was carried out to check on survey data accuracy.
Mass balancing was first conducted around each equipment item, then for each grinding line and finally as one circuit. Final errors for each stage are presented in Table 3.

Table 3. Mass balance weighted sum of squares.

Survey	1	2	3
Classifying cyclones I	139.9	15.9	17.7
Classifying cyclones II	253.7	2.2	13.5
Desliming cyclones	116.5	28.5	11.7
Grinding line I	291.5	59.9	45.5
Grinding line II	397.6	12.5	50.6
Griding circuit	1017.0	162.8	124.8

Discrepancies between the experimental and balanced data for the first survey were significant can be seen by comparing values in Table 3. Survey 1 was not used for further studies as the data was considered inaccurate.

3.3 Model Fit

As the balanced data, rather than raw data, was used in model fitting, surveys 2 and 3 were considered accurate enough to be submitted to model fitting analysis. During each survey, the grinding circuit was being feed different types of ore:

- Second survey: run of mine (N5W);
- Third survey: a blend composed of run of mine (N5W) and lump ore (NP2).

In the model fit routine, equipment was first fitted as isolated units and afterwards the whole circuit was fitted. Ball mills were fitted using JKSimMet´s master/slave approach, in which the same parameters were fitted to both units. This approach could be used as data were collected simultaneously from both grinding lines. Figure 3 shows breakage functions for the second and third survey.

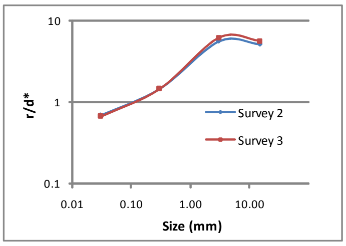

Figure 3. Master/slave fitted breakage function.

Grinding efficiency was evaluated by comparing the operational work index with the measured ore work index Wi. Work indices calculated from operating data shown as WIoc. This index was used in this grinding study for:

- Calculating mill performance during surveys;
- Comparing grinding lines in the same plant.

The following Table 4 shows the energy efficiencies that were calculated based on the fitted power at the mill pinion shaft.

Table 4. Energetic efficiency.

Survey	Grinding line	Wi (kWh/st)	Fitted power (kW)	Wi_{oc} (kWh/st)	Grinding efficiency (%)
2	I	11.42	7146	16.0	71
	II	11.42	7145	14.2	80
3	I	12.14	7144	14.1	86
	II	12.14	7146	17.4	70

For cyclone fitting the master/slave approach was not adopted because clusters from different lines had different vortex and apex diameters. Parameters for the Nageswararao model were fitted and are listed below in Table 5.

Table 5. Cyclone fitted parameters.

Survey	2			3		
Parameter	Classifying cyclones		Desliming cyclones	Classifying cyclones		Desliming cyclones
	Line I	Line II		Line I	Line II	
K_{D0}	3.82E-5	3.61E-5	4.29E-5	5.49E-5	5.22E-5	3.63E-5
K_{Q0}	1151	1031	763	894	1198	872
K_{V1}	11.7	8.48	13.0	9.31	7.62	14.5
K_{W1}	22.6	16.5	73.6	17.5	13.5	84.9
α	2.40	0.62	0.431	2.09	2.05	0.64

For classifying cyclones, the parameter related to water (K_{W1}) and volume pulp recovery to underflow were greater for line I in both surveys. Other parameters were very similar from one survey to another.

In particular, the desliming cyclone model gave relatively major deviations between the two surveys, but both models represented the experimental data well. A relatively high variation was observed for parameter α, which is the parameter related to the sharpness of cut. As desliming cyclone feed is composed from both grinding line products, it is very important to collect the combined sample. As a sample from cyclone feed slurry was taken only in the third survey, the variations may be explainable because in the second survey, the cyclone feed stream was back-calculated.

Survey number 3 was selected for simulation exercises as it presented the lowest weighted sum of squares in mass balance and also achieved the highest grinding efficiency. In Figure 4 are shown third survey's fitted reduced efficiency curves for both classifying cyclones and for desliming cyclones. It can be noted that for both lines, classifying cyclones present similar performance.

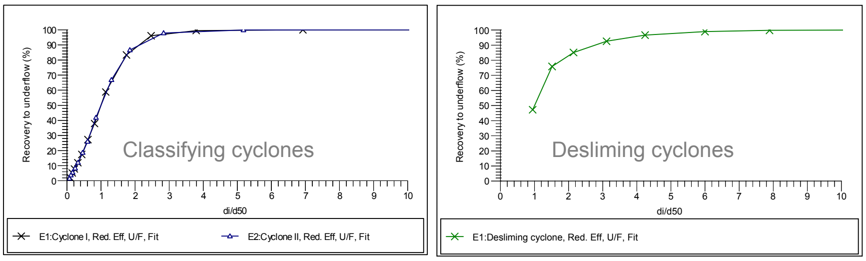

Figure 4. Fitted Reduced Efficiency curves fitted for the third survey.

3.4 Simulation

The circuit fitted to the operational conditions of the third survey was taken as the Base Case (BC) in simulation exercises. The objective of simulation exercises was to evaluate the grinding circuit's performance when fed with ore types that were never before used for pellet feed production.
Five ore types were sampled from different mine faces and were submitted for both of the breakage characterization tests. The samples were N5W, N4W Central, N4WN e N4E.
Two parameters were used to simulate each ore type. Those parameters were:

- Size distribution – determined by size analysis of the run of mine.
- Work index – obtained through Bond`s grindability standard test and JK drop weight test.

To evaluate simulation results fitted and simulated values were compared. In this way, for comparison purposes deviations between fitted and simulated values were calculated through the following equation:

$$Deviation = 100 \times \frac{F-S}{F} \quad (10)$$

Where
F = fitted value
S = simulated value
During simulating certain operating parameters such as cyclone underflow percent solids (prevent roping in the cyclones), cyclone overflow sizing, cyclone feed volumetric flow rate and cyclone pressure were controlled within limits that place on circuit operation. Simulation exercises consisted of varying the new feed rate to achieve a maximum throughput for each ore type. Simulations were carried out so that the optimum feed rates were achieved with each ore.
To compare the products and analyze which ore type recovered more to final product at the required. The following simulated parameters were assessed: recirculating load, solids flowrate and size related parameters (percent retained on 106 micron, percent passing on 45 and 7 micron). Results are presented in Table 6.
The feed size distributions have high deviations for fine particles. That was expected as the circuit was fitted for a feed composed by run of mine and lump ore, which is coarser than simulated ores. In fact, smaller deviations were observed for N5W mine face.

Table 6. Deviations obtained for flowrates and size distribution parameters in simulation exercises.

Mine face	Parameter	Stream				
		New feed I	New feed II	O/F Clas. Cyclones I	O/F Clas. Cyclones II	U/F Desl. Cyclones
N5W	Solids flowrate (t/h)	5%	8%	5%	8%	6%
	Percent retained on 106 micra	-1%	0%	8%	19%	18%
	Percent passing on 45 micra	-6%	1%	-1%	-1%	-1%
	Percent passing on 7 micra	-7%	5%	0%	0%	0%
	Recirculating load (%)	-25%	-30%	-	-	-
N4W central	Solids flowrate (t/h)	-30%	-28%	-30%	-28%	-28%
	Percent retained on 106 micra	-7%	-6%	-3%	7%	4%
	Percent passing on 45 micra	10%	18%	-1%	-1%	-1%
	Percent passing on 7 micra	31%	47%	-4%	-4%	-2%
	Recirculating load (%)	8%	-1%	-	-	-
N4WN	Solids flowrate (t/h)	5%	8%	5%	8%	7%
	Percent retained on 106 micra	5%	6%	36%	40%	40%
	Percent passing on 45 micra	-30%	-25%	-3%	-3%	-4%
	Percent passing on 7 micra	-29%	-20%	-3%	-2%	-3%
	Recirculating load (%)	-23%	-29%	-	-	-
N4E	Solids flowrate (t/h)	39%	44%	39%	44%	39%
	Percent retained on 106 micra	-12%	-11%	86%	67%	76%
	Percent passing on 45 micra	26%	36%	-2%	-1%	-3%
	Percent passing on 7 micra	33%	50%	4%	5%	4%
	Recirculating load (%)	-41%	-46%	-	-	-

When compared to BC, N5W ore type would increase production in up to 8% with a performance very similar to the one obtained in the industrial circuit and final product deviations were relatively small. This exercise can be considered as a validation, given that the simulated ore type fed to the mill is very similar to the actual blend fed to the mill during the survey. Low deviations show that fitted models reliable represent the industrial circuit.

Ore type N4W central presented the highest work index for Carajas samples. As consequence, the circuit would process at an average of only 300 t/h. Therefore a coarser ball mill product was simulated as well as a higher solids recovery in the desliming stage.

Coarser new feed was observed for N4WN, but the ball mill product was very similar to the one industrially obtained, and therefore, simulated pellet feed was also similar to the one obtained in the base case.

Carajás grinding circuit would process N4E ore type with a mean flow rate of 600 t/h per mill. This ore presented higher amount of fines in new feed and lower work index (8.4 kWh/st). On the other hand, solids recovery to desliming cyclone underflow was the lowest obtained in simulation exercises, as shown in Table 7.

Table 7. Simulated solids recovery to underflow (desliming cyclones).

Mine face	Rs (%)
N5W	83.1
N4W Central	84.7
N4WN	83.5
N4E	81.5

4 CONCLUSION

Simulation exercises showed that Carajas' fitted circuit is a very powerful tool for predicting the industrial circuit's performance. The comparative analysis of simulated products showed significant differences between selected parameters depending on the studied mine face. N4WN was the mine face never processed by the grinding plant that resulted in a circuit most similar to the industrial one with a similar recovery of solids.

Further studies is being carried out to identify how iron minerals crystal sizes influence in ore's breakage characteristics. To do so, optical microscopy techniques are being applied.

Acknowledgment

The authors would like to thank:

- FAPESP for the financial support;
- Vale for the technical support, in particular the technician Ercílio Rangel Almeida for his support in the field and the engineer Marco Túlio Santiago.
- Dean David, for his valuable comments on this paper.

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