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Performance analysis of bauxite beneficiation process in Juruti Mine. Part 2: Simulation and optimization alternatives

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Abstract

The simulation process was applied to the industrial circuit of the Juruti Bauxite Mine using mathematical models calibrated for the equipment and based on information from industrial sampling. The sampling campaign, mass balance routines and quantification of the process efficiency were discussed in Part I of this study and the model calibration and simulations process were the Part II objective. Simulation scenarios were defined considering the possible particle size curves for feeding the plant. Based on the simulated results, it was possible to observe which operations may be impacted by the increase in production, impacting the percentage of contaminants in the final product, indicating the necessity of equipment interventions to support increases in capacity. Another group of scenarios were established with the objective to evaluate the possibility of increasing the mass recovery and improving the quality of the fine product, by variations in the opening diameters of the apex and vortex finder of the five cyclone stages. Considering the simulated scenarios, the points of attention identified in the simulations were: (a) the washing efficiency could be reduced, in view of a consequent reduction in residence time connected to the change in characteristics of the ore fed to the plant; (b) increase capacity of the primary and secondary screens need to be done; (c) to keep the classification efficiencies, it is necessary install more cyclone units; and (d) changes in the apex diameter and vortex finder could generate results in terms of mass recovery and product quality.

keywords: mathematical modeling, simulation, process optimization, bauxite.

1. Introduction

This article is Part II of an article about sampling, simulation and optimization of the processing plant at the Juruti Bauxite Mine, that is an integrated operation of the scrubbing, screening, and cyclone circuits. The sampling process, mass balance and quantification of the efficiency of the processes were studied in Part I and the model calibration and carrying out simulations are the Part II objective. The second part addresses the simulations conducted to assess the need for interventions in the beneficiation stages as a function of the intended increases in production and alternatives for improving the performance of the classification stage.

The simulation process is based on mathematical models calibrated for the selected operation. It begins with the planning and execution of the flow sampling in each process equipment. Following the treatment of samples from the sampling, mass balance routines are applied, the consistent dataset of which will be the basis for calibrating the mathematical models of the process equipment. Such calibrated models integrated into a process flowchart are then employed for simulations aimed at improving the local or global performance of the industrial circuit. One of the great advantages of a simulation is the saving of time and resources in the identification of alternatives, enabling the improvement in the process performance or even the definition of new beneficiation routes for projects under development (Napier-Munn *et al*., 1999).

In this sense, the present study considered the sampling carried out and the balanced data presented in the first part of this article (Performance analysis of the beneficiation process of bauxite from the Juruti Mine. Part 1: Industrial sampling and performance evaluation) to calibrate represented mathematical models of each unit operation and for the integrated process. To this end, the typical steps of the mathematical models calibration, modeling and simulations of industrial processes proposed by Napier-Munn *et al*. (1999) were applied, in order to define the circuit flowsheet, set material and machine parameters, define models (in simulator), simulate, analyze product characteristics and circuit performance, and to verify if the desired performance has been achieved.

2. Bibliographical review

One of the significant and common applications of the process simulation is in the evaluation and diagnosis of operations. The objective of process diagnostics is to obtain a more detailed understanding of the current condition of a process. To this end, an investigation and characterization of the current condition must be carried out using data collection of the operation, material characteristics, sampling during the production circuit, operation strategies, and existing control loops, among other information that can contribute to the understanding and definition of the existing condition. Based on a robust evaluation of the existing conditions, it is possible to propose a set of recommendations, such that the stipulated condition can be achieved, that is, the operational stability and optimization of the performance indices, among other improvements required by the study. The process diagnosis allows verifying which problems, or bottlenecks, are more critical in the production process, whether related to the efficiency of the unit operations or incorrect modes of operation, i.e., impacts of the material characteristics, the pressures, or dilutions.

The simulation consists in the calibration of a mathematical model that translates, in the most faithful manner, a process in an integral way. From this model, it is possible to simulate situations and verify the results that they may or may not generate. The interpretation of these, as well as the choice of the best option and application of this “change”, allow an optimization of the studied process to be performed. Not immediately, although effectively, optimization comes as a “long term” result that can currently be considered extremely small, given the technological developments and the demand of the current market for practically instantaneous responses (Napier-Munn *et al*., 1999).

To carry out the simulations, it is necessary to calibrate a representative model of unit operations in an integrated manner. In this way, mathematical models that describe the phenomena that occur in the equipment are used and represent the reality of the operation within acceptable limits of representativeness. To model the screening stages, a model based on partition curves and water partition between the products was used. According to Napier-Munn *et al*. (1999), screening performance can be obtained from the size distribution and mass of the feed and the calibrated partition curves. In this study, the partition curves followed the parameterization proposed by Whiten (1980), according to Equation 1. It is important to emphasize that Equation 1 describes the standard partition curve for the overflow. The concept is similar to the partition curve for the underflow, with both curves mirroring each other with respect to the line y = 0.5.

$$Eo(x) = C\left[\frac{(1+\beta\beta^{*}x)(exp(\alpha)-1)}{\exp(\alpha\beta^{*}x)+exp(\alpha)-2}\right] \quad (1)$$

where, x is d/d_{50c}., C is 100 – βa, α is the parameter that modulates the slope of the curve in the segment near d_{50c} - the dispersion parameter α is associated with the so-called separation sharpness, β is the parameter that modulates the so-called "fish-hook effect" profile of the partition curve for fine particles, and β^* is the parameter that adjusts the standard partition curve so that it has an ordinate equal to 0.5 C for the abscissa $d = d_{50}$.

Even though partition curve models are useful to describe the size separation process that occurs in vibrating screens, they are not suitable for assessing specific aspects, such as feed size distribution or feed flow rate on screen capacity. Modelling screen capacity requires specific parametric equations that associates operating conditions and screen design with capacity and performance. In order to cope with efficiency variations, throughout this study, since no specific modelling was carried out for screening capacity, screening efficiency was simulated by means of varying the partition curve parameters. Such an aspect is further discussed in section 4.2.

The Nageswararao model (1978), which was developed directly from the Lynch and Rao model (1975), was used for the cyclone operation. It is an empirical model and is based on the four equations related to operational variables, namely, median partition diameter, water partition and slurry partition for the underflow, and the relationship between volumetric flow and pressure during cyclone feeding. Each particle size range was assigned real partition values, which define two populations of particles in the products and those that are determined from the first three abovementioned parameters. These, in turn, are linked to the fourth parameter through the influence of the relationship between volume flow and pressure in the equipment. To apply the Nageswararao model, at least one sampling of the specific operation and at least one value of solid flow value from any of the three flows are necessary to obtain the α value of the partition curve; this partition curve is related to the classification sharpness and is dependent on the ore-equipment set, the parameters that adjust the slurry and water partition equations, and the pressure and flow relationship (Chaves, 2012). After calibration of the parameters, it is possible to simulate this model by changing both the feed flow conditions and geometric variables of the cyclones.

The Table 1 shows the models selected in the JKSimMet software for each unit operation.

Table 1 - models applied for each unit operation, as presented in the JKSimMet model list.

Unit Operation/Equipament	Model Name (JKSimMet v6.0.1)
Washers	Variable Rates - AG Mill (adapted)
Trommels	Efficiency Curve - Water & Fines
Re-crushing	Crusher (Andersen-Whiten)
Screening	Efficiency Curve - Water & Fines
Cyclones	Nageswararao Cyclone

To perform screens capacity analysis that support the intended production increase, considering the flow increase in each screen from simulation results, the *Allis-Chalmers* method was used. The *Allis-Chalmers* method supports an analysis of the diagnosis and efficiency, and defines the repowering and/or addition of screens to the beneficiation route of the Juruti plant. The *Allis-Chalmers* sizing method is considered an empirical method and consists mainly of using a standard unit capacity curve as a function of the effective opening of the screen mesh, applying correction factors to the value read in the curve that depend on deviations from standardized conditions. These conditions were defined by the manufacturer when defining the standard unit capacity curve for screens (Domingues, 2019).

This method considers the calculation of two main parameters for evaluation (Nunes, 2017): i) area required for all undersized screens, and ii) screen width such that the bed height at the discharge of an oversized screen reaches a maximum of four-times the opening of the screen.

3. Method

The methodology used in this study consisted of calibrating an integrated model of the beneficiation process at the Juruti Bauxite Mine, known as the base case, based on samples taken at the industrial plant specifically for this purpose, followed by a mass balance, performance analyses, and model adjustments. The JKSimMet 6.0.1 simulator, developed by Julius Kruttschnitt Mineral Research Centre (JKMRC) of the University of Queensland, Australia, was used for the calibration of the mathematical models of the individual equipment, as well as the integrated beneficiation processing. Using the calibrated model, simulations were conducted to assess bottlenecks in the production process, given the increase in production, and alternatives to improve the performance of the classification stage.

The following are the simulation assumptions made to evaluate the operational bottlenecks given the intended increase in production, as well as alternatives to improve the performance of the classification stage in terms of the mass recovery and reduction of the contaminants (the amount of material below 0.037 mm; that is. considered contamination in the product due to the high reactive silica content and low available alumina content present in this mass fraction).

Because the physical characteristics of the bauxite fed to the plant are determinants of the process performance, impacting the global mass recovery and removal of contaminants as indicators, granulometric distribution curves were defined to represent coarse, medium, and fine distributions of the industrial feed, considering the granulometric distribution as a reflection of the physical characteristic of the material (ore), as shown in Table 2.

Table 2 - Particle size distribution for medium, coarse and fine ore.

Mesh (mm)	Medium Ore	Coarse Ore	Fine Ore
127.0	100	100	100
101.6	98.9	86.1	98.9
76.2	95.0	72.3	97.6
50.8	83.6	60.6	94.3
25.4	71.0	51.0	84.5
12.7	60.2	43.6	73.8
8.0	54.3	39.8	68.8
6.35	52.2	38.5	67.0
2.38	44.0	31.4	58.0
1.19	40.0	27.0	53.0
0.59	36.7	23.2	47.2
0.212	33.5	19.3	40.8
0.15	32.5	18.6	39.7
0.105	31.7	18.1	38.9
0.074	30.8	17.0	37.6
0.053	30.2	16.1	36.7
0.037	29.7	15.4	36.0

In view of such considerations, a set of simulations was defined to analyze the capacity of the equipment installed at the Juruti plant for a scenario of increased production, as shown in Table 3. The feed flow rate of the simulated solids was kept fixed for all the simulated cases, considering a 7.7% increase in relation to the base case.

Table 3 - Scenarios selected for simulation.

Scenario (Simulation = SIM)	Particle size distribution
SIM A	Medium
SIM B	Coarse
SIM C	Fine

One more group of scenarios was established to be simulated in this study with the objective of evaluating the possibility of increasing the mass recovery and improving the quality of the product by reducing the contaminants (fraction below 0.037 mm). Thus, variations in the opening diameters of the apex and vortex finder of the five cyclone stages (primary fines (PF), secondary fines (SF), primary super-fines (PSF), secondary super-fines (SSF) and tertiary super-fine) were applied, as shown in Table 4.

Table 4 - Selected scenarios for simulation of the classification stage.

Simulations focusing on increasing mass recovery	Simulations aiming to increase product quality
SIM 1C: PF Cyclone- *Apex* 100 mm	SIM 1D: PF Cyclone - *Apex* 20 mm
SIM 2C: PF Cyclone - *Apex* 120 mm	SIM 2D: SF Cyclone - *Apex* 20 mm
SIM 3C: SC Cyclone - *Apex* 120 mm	SIM 3D: PF Cyclone - *Vortex finder* 240 mm
SIM 4C: PSF Cyclone - *Apex* 32 mm	SIM 4D: SF Cyclone - *Vortex finder* 240 mm
SIM 5C: SSF Cyclone - *Apex* 32 mm	SIM 5D: PSF Cyclone - *Vortex finder* 100 mm

4. Results and discussion

4.1 Model calibration

In calibrating the representative model of the bauxite beneficiation operations at the Juruti plant, the efficiency curve models (Napier-Munn *et al*. (1999) were used for the screening operation and Nageswararao (1978 and 1995) for the cyclone classification operation. Tables 5 and 6 show the constants and parameters obtained for the calibrated model, considered the base case in the present study.

Table 5 - Parameters of the efficiency curve model applied to the screening.

Efficiency Curve Parameters	Trommel	Primary Screening	Re-crushing Screening	Secondary Screening
Efficiency curve - Alpha	13.82	9.72	80.51	6.92
Efficiency curve - Beta	0.00	0.00	23.38	0.00
Water Partition - Fine Product	99.51	97.70	92.34	98.43
D50 corrected - d50c (mm)	54.45	8.66	1.10	2.09
Beta calculated	1.00	1.00	1.10	1.00

Table 6 - Parameters of the Nageswararao model applied to the five cyclone stages.

Model Parameters	Primary Fine Ore	Secondary Fine Ore	Primary Super-fine Ore	Secondary Super-fine Ore	Tertiary Super-fine Ore
K_{D0} (D_{50} - total)	0.00022	0	0.00015	0.00013	0.00013
K_{Q0} (capacity)	686.01	412.41	599.03	361.51	361.51
K_{V1} (volume partition)	4.61	11.11	2.23	19.87	19.87
K_{W1} (water partition)	15.59	26.45	13.84	109.86	109.86
Efficiency Curve - Alpha	0.01	0	1.81	3.74	3.74
Efficiency Curve - Beta	0.84	0.23	0	0	0

To evaluate the calibration quality, the particle size distributions of the coarse and fine product obtained from the sampling process were plotted, together with the distributions obtained in the calibrated base case, as shown in Figure 1. Good adherence of the experimental and simulated curves can be observed, indicating that the calibrated model is representative of the operations that compose the bauxite beneficiation process at the Juruti plant.

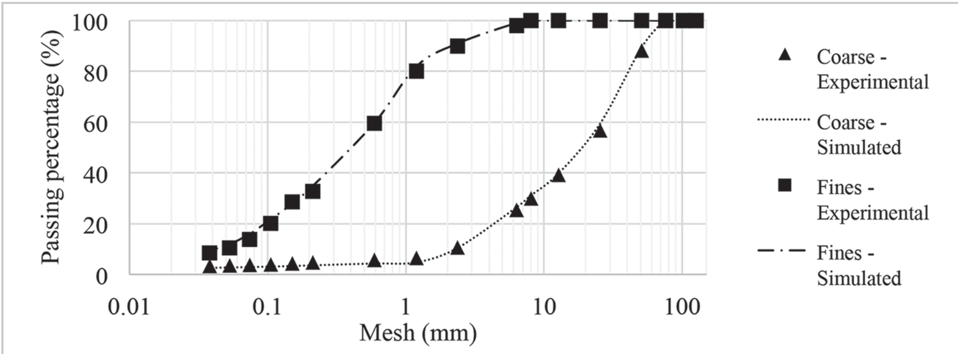

Figure 1 - Experimental and simulated particle size distribution of the coarse and fine product for the base case.

4.2 Simulations for evaluating the increase in production

Using the set of proposed simulations, mentioned in Table 3, it was possible to evaluate the impact of the characteristics of the material fed to the plant in terms of the particle size distribution, and the screening efficiency on the efficiency of the processes that constitute the bauxite beneficiation route. Figures 2 and 3 show the particle size distributions of the coarse and fine products for the simulations with reduced screening efficiency and those of the sampling, respectively.

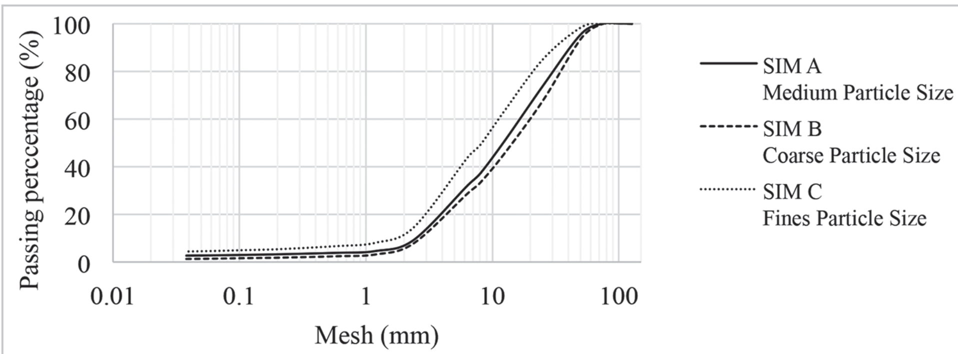

Figure 2 - Particle size distribution of the coarse product for coarse, medium, and fine ore particle size in the plant feed.

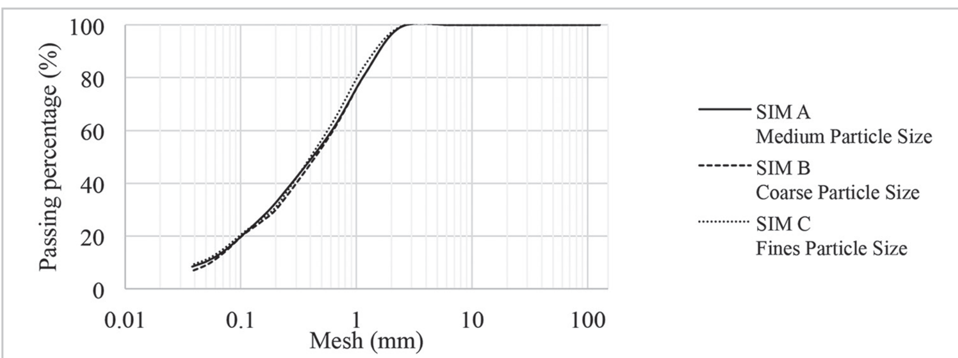

Figure 3 - Particle size distribution of the fine product for coarse, medium, and fine ore particle size in the plant feed.

Table 7 shows the percentage of contaminants in the coarse and fine product in each of the simulated scenarios. It was observed that in the simulations with fine particle size (3B), there is a greater presence of contaminants (mass fraction below 0.037 mm) in the coarse and fine product, i.e., when compared to the simulations with coarse and medium particle size.

Table 7 - The percentage of contaminants
(mass fraction below 0.037 mm) in the coarse and fine product in each of the simulated scenarios.

Scenario Simulated	Contaminants Coarse Product (%)	Contaminants Fine Product (%)
A Medium Particle Size	2.68	8.41
B Coarse Particle Size	1.30	6.77
C Fine Particle Size	4.41	9.10

Table 8 shows the efficiencies of each process step for the three simulated scenarios. It was observed that the efficiencies, calculated based on the reference mesh of each referred stage, varied in accordance with the characteristics of the material fed to the plant, corroborating with the variations in the particle size distribution and variation in the percentage of contaminants (mass fraction below 0.037 mm), as presented in Figures 2 and 3. The secondary fines cyclone (26-inch cyclones) presented the lowest efficiencies under all scenarios. It should be noted that in the base case they also presented a reduced efficiency.

Table 8 - Efficiency (%) of the stages of the beneficiation process.

Stage of the Process	Reference Mesh (mm)	Baseline Case	SIM A	SIM B	SIM C
Trommel	76.2	95.23	95.16	92.41	98.39
Coarse Screening	8.00	95.73	95.66	95.26	96.37
Intermediate Screening	1.20	98.14	98.11	97.97	98.10
Re-crushing Screening	1.20	94.39	94.37	94.65	94.18
Primary Fines Cyclone	0.037	90.13	90.31	86.37	89.27
Secondary Fines Cyclone	0.037	32.29	32.97	25.63	27.72
Primary Super-fines Cyclone	0.037	95.90	95.92	91.46	95.27
Secondary Super-fines Cyclone	0.037	64.29	71.77	69.73	75.45

Thus, through simulations with different granulometric type ores, it was possible to determine which conditions demand more from the equipment, and based on the flow data, layer thickness, and required area versus the available area, it was possible to establish which equipment needs to be repowered or which units need to be added to achieve the stipulated increase in the feed flow of the existing plant, while maintaining the product quality standards.

In the rotary washers, it was observed that the degradation was greater for coarser fractions, as shown in Figure 4.

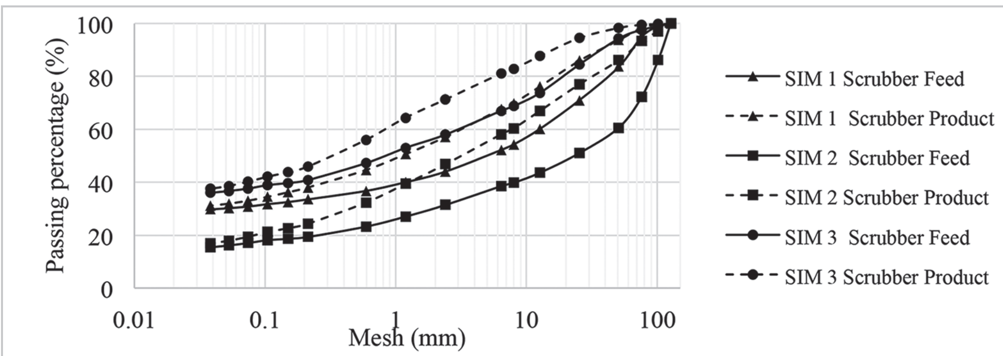

Figure 4 - Particle size curves of feed and washer product for simulations conducted.

Although not proven, this fact was attributed to a greater presence of autogenous grinding bodies inside the washers. The retained percentages accumulated within 76 mm in the internal loads of the washer were estimated to be 10%, 19%, and 57%, respectively, for fine, medium and coarse ores. The generation of material smaller than 0.037 mm varied from 1.3%–1.5%, which is considered low. Calculations of required area versus the area installed in the trommel were carried out, through which it was identified that it would operate close to the maximum theoretical capacity, with only the simulations with fine ore exceeding this value by 0.2%. It is understood from the results obtained that there is a possibility of a reduction in the washing efficiency owing to the increase in the flow rate considered in the feeding of the equipment. For a predominantly fine ore operation, the equipment will need to be repowered.

In the re-crushing, it was observed that for ores with a coarser granulometry, the feed flow will exceed the original project flow. Thus, increases in production with coarser ores indicate the need to repower this equipment.

The minimum area required, and the thickness of the ore layer at the screen discharge, on the first and second deck, were assessed based on the *Allis-Chalmers* method.

In the primary screening, the first deck presented a more satisfying condition than the second, considering the ratio between the required area and the available area. If decreases in performance become evident owing to increased production, the imbalance observed between the two decks can be mitigated by reducing the opening of the upper deck, as well as by relieving the 8.0 mm screens of the lower deck. In these cases, the mechanical resistance of the screens should be checked. In addition, the second deck carries smaller particles, therefore presenting a larger surface area for the same mass. Because silica-rich sludge adheres to the surface of the particles, it is important for the washing sprays on the second deck to access all layers of the ore. In this case, closing the separation mesh of the first deck will contribute to a reduction of the mass fed to the second, and consequently, will increase the exposure of the particles surface to the washing sprays. Thus, in view of the possibility of changes in the sieving screens to absorb increases in production while maintaining the washing efficiency, the simulations indicate that there is no need for intervention in the primary or coarse screening.

In the secondary screening, the area available on the first deck proved to be adequate for all simulations conducted. Regarding the layer thicknesses in the feed, all scenarios presented higher values than the maximum limit indicated by the supplier.

However, the base case itself also exceeded this criterion, and as presented in the first part of this article, the efficiency of the measured stage was 98%, which is considered to be extremely high. In the second deck of the secondary screening, with openings equal to 1.2 mm, the criterion of required area was not met for the fine ore simulations, indicating a necessary increase of 14% in the screening area. This fine screening (1.2 mm) can also impact the quality of the coarse product because it presents significant oversize flows. It was also observed that the utilization ratio of the area in the base case was 84% and that of the SIM C scenario was 114%, which is a significant discrepancy, signaling a necessary point of intervention (addition of equipment).

In the primary fine cyclone (26-inch cyclones), the scenario that demanded the most cyclones was SIM C, with relatively finer feeding. However, the required capacity is met with the current arrangement, leaving one cyclone on stand-by. In the secondary fine cyclone (26-inch cyclones) the scenario that demanded the most cyclones was SIM C, with a fine feed, using all installed units. There was no evidence indicating the need to insert more units at this stage because all cyclones will only be used simultaneously in the case of extremely fine ore being fed to the plant.

In the primary super-fine cyclone (10-inch cyclones) the scenario that demands most cyclones is the SIM C, with fine feeding. In this way, there is a need to insert more cyclone units. Under all scenarios, the super-fine secondary battery (10-inch cyclones) meets the requirements and is maintained with units on stand-by.

4.3 Simulations to assess improvement in the performance of the classification circuit

To evaluate alternatives for increasing the mass recovery, five simulations were carried out by changing the apex diameter of the cyclones that constitute the four batteries of cyclones, as summarized in Table 4.

Table 9 shows that the most distant results from the base case were obtained by changing the apex diameter of the primary fine cyclone from 80 to 120 mm. There was an increase in production equal to 1.6% (95.000 TPA), with an increase in the percentage of the passing fraction by 0.037 mm in the fine product from 9.1% to 13.2%. From the 5.8 t/h increase in washed bauxite, 0.4 t/h come from the fraction retained in 0.037 mm of the tailings, and 5.4 t/h are due to the passing fraction of 0.037 mm. This leads to a decrease in the available alumina content and an increase in the reactive silica content. Thus, it was found that it is possible to increase the mass recovery; however, this will require increasing the share of contaminants in the fine product, which will result in a loss of quality in terms of the content of usable alumina (Al_2O_3) and reactive silica (SiO_2).

Table 9 - Results of simulations for increased mass recovery (CB = Base Case).

Scenario	Un	CB	SIM C1	SIM C2	SIM C3	SIM C4	SIM C5
Installed	m	-	0.080	0.080	0.100	0.025	0.025
Simulated	m	-	0.100	0.120	0.120	0.032	0.032
Production Increase	%	-	0.74	1.59	0.12	0.14	0.3
Mass Recovery	%	75	75.6	76.2	75.1	75.1	75.2
-0.037 mm in Coarse Product	%	4.16	4.16	4.16	4.16	4.16	4.16
-0.037 mm in Total Fines Product	%	9.14	11.05	13.18	9.51	9.34	9.75
Removal Efficiency (0.037 mm)	%	85.17	83.4	81.33	84.83	84.97	84.59
Content Al_2O_3 in the Final Product	%	47.5	47.31	47.09	47.46	47.47	47.43
Content SiO_2 in the Final Product	%	4.1	4.13	4.17	4.11	4.1	4.11

To evaluate alternatives to increase the quality of the product, five simulations were conducted by changing the apex and vortex finder diameter of the cyclones, as summarized in Table 4. Table 10 shows that the highest gain estimate, although modest, was obtained when changing the vortex finder of the primary fine battery from 200 to 240 mm. This gain refers to the increase in the content of available alumina by 0.05% and a reduction in the content of reactive silica by 0.01%.

Table 10 - Results of simulations for product quality increase (CB = Base Case).

Scenario	Un	CB	SIM C1	SIM C2	SIM C3	SIM C4	SIM C5
Installed	m	-	0.025	0.025	0.200	0.200	0.080
Simulated	m	-	0.020	0.020	0.240	0.240	0.100
Production Increase	%	-	-0.21	-0.26	-0.21	-0.05	-0.18
Mass Recovery	%	75	74.8	74.8	74.6	75	74.9
-0.037 mm in Coarse Product	%	4.16	4.16	4.16	4.16	4.16	4.16
-0.037 mm in Total Fines Product	%	9.14	8.95	8.73	8.6	9.01	8.98
Removal Efficiency (0.037 mm)	%	85.17	85.38	85.57	85.66	85.28	85.35
Content Al_2O_3 in the Final Product	%	47.5	47.53	47.55	47.55	47.51	47.52
Content SiO_2 in the Final Product	%	4.1	4.1	4.09	4.09	4.1	4.1

5. Conclusions

o The mathematical modeling adopted proved to be adequate to represent the unit operations of the Juruti beneficiation plant, as well as the integrated ore washing process. Adherence was observed between the balanced experimental values and those resulting from the calibration of the mathematical models used.

o The simulations of the circuit capacity increase had as reference an increase of 7.7% in relation to the capacity of the base case. In addition to the increase, the simulation scenarios included a variation of the characteristics of the ore fed and the different screen efficiencies. Based on the results obtained in the simulations, it was possible to identify which stages of the process require repowering, as is the case of the re-crusher, or in the case of the intermediate screening, even the addition of new equipment, to maintain the washability of the plant to at least the same level as that obtained during the sampling operations.

o Simulations were also conducted to evaluate the opportunities to improve the performance of the fine circuit by changing the apex and vortex finder diameters of the cyclones. The results demonstrated the potential impact on the quality of the products generated in Juruti: i) changing the apex diameter an increase in the production could be achieved. However, the increase comes from the fraction retained in 0.037 mm, material that is considered contaminants and could impact in the product quality; and ii) a small improvement in product quality can be verified by changing the vortex finder. Considering the annual production, this small change in reactive silica content can generate significant financial savings.

o With the use of the process simulator, it was possible to present scenarios that allowed the identification of opportunities for improving the performance indexes of the circuit, as well as necessary interventions in the unit operations to support capacity increases while maintaining the same levels of product quality, and allowing the validation of a process optimization study.

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