Reconciliation of sampling data and heterogeneity analysis of a bauxite mine in Poços de Caldas/MG, in Brazil

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Abstract

Reconciliation plays a key role in controlling and analysing mine operations. It consists in comparing model estimates with actual results produced by the plant, being used as an indicator, a monitoring tool. Discrepancies between these values are common in the mining industry and they highlight problems during processing steps. However, these discrepancies do not necessarily need to be brought to zero, as long as their order of magnitude is understood. Prognostication, a new concept that seeks to replace reactive reconciliation, aims to raise and correct the real causes of these variations. A common cause of this type of problem is sampling, which in most cases is not performed correctly, providing biased samples and compromising reconciliation analyses. The present study reports, evaluates and improves reconciliation in a bauxite mine located in the city of Poços de Caldas/MG, in Brazil and reports on a study of the heterogeneity of the ore. A common practice of the bauxite mines in Poços de Caldas is to carry out the last stage of sampling manually from the trucks before the ore goes to the treatment plant. The data evidenced that this sampling is biased and systematically overestimates the planned ore grades. In addition, it has been confirmed that the best alternative for the company is to implement a conveyor belt sampler collecting increments every 15 minutes. This method shows the best adherence to the plan, that is 100.7% for available alumina and 83% for reactive silica.

Keywords: reconciliation, sampling, Theory of Sampling, TOS, sampling errors, automatic sampler, prognostication.

1. Introduction

Reconciliation is a fundamental activity in the operations of any mining enterprise. It is defined as a comparison between an estimate and a measurement, for example, among the ore grades estimated by models and the grades produced at the beneficiation plant (Hajj, 2013). Discrepancies among these values are common in mining, especially regarding precious metals, and it is often necessary to adopt measures that minimize this problem (Chieregati *et al.*, 2008). So, these discrepancies do not necessarily need to be brought to zero, as long as their order of magnitude is understood. Historically, reconciliation has been reactively used by applying "factors", such as the mine call factor (MCF), to future estimates in an attempt to improve prediction of an operation's performance. However, according to Morley (2003), this is not the best indus-trial reconciliation practice to be applied.

Reconciliation is understood as a quality test of model estimates, being used as an indicator, a monitoring tool. Nevertheless, without adequate sampling capable of generating reliable representative data, any reconciliation analysis is structurally compromised. A good sampling should generate non-biased samples, that is, all particles belonging to a given batch should have the same chance of being collected. Failure to use the fundamentals of the Theory of Sampling (TOS) causes companies to lose millions of dollars per year due to reconciliation failures. Even small rectifi-cations in sampling procedures are known to result in significant improvements in the overall operation (François-Bongarçon and Gy, 2002 apud Chieregati *et al.*, 2008).

Estimating ore grades is not a simple task. For example, the aluminium grades indicated from mine planning in bauxite mines are often not reproduced in the plants, where periodic sampling on conveyor belts is the best approach for quality control. It is necessary to focus on TOS' principles to guarantee representative sampling, including knowledge about the fundamental-sampling errors in each mass-reduction step, representative increment mass levels, correct increment extraction intervals, and the fatal incorrect errors: delimitation, extraction, preparation as well as the analytical pro-cedures (Bortoleto *et al.*, 2019).

Non-compliance issues regarding standards, guidelines, good practices as well as regulatory and legal requirements must be handled with insight. When they do not comply with TOS' stipulations, it will be necessary to start a process of revision or update of the relevant stan-dards. When the documented sampling

variances are too high (a key issue in quality control and assurance, QC/QA), it is always an option to employ more stringent quality criteria from a TOS-based approach. DS 3077 has the objective of establishing comprehensive motivation and competence for taking the stand, relying only on fully TOS-compliant sampling procedures and equipment, irrespective of the theoretical, practical, technological, industrial or societal context under the law. In this context, prognostication acts on the causes of variations from the analysis of available data through the reconciliation process, providing an understanding of the impact of various decisions made in the mining operation,

in mineral processing and in obtaining the final product. This understanding can be used to ensure that the variation between original estimates and actual results remains within acceptable ranges, which depends on the ore to be handled, in bauxite for instance, it should remain within 5% of variation (Morley, 2003; Chieregati *et al.*, 2019).

The Mesozoic Poços de Caldas alkaline complex is circular shaped with a mean diameter of about 33 km and it was developed during continental break-up and drift. It is constituted mainly by phonolites and their subvolcanic and plutonic counterparts (tinguaites and nepheline syenites), forming

a felsic undersaturated suite, associated with minor amounts of mafic-ultramafic rocks. Intense weathering of the bedrock helped forming the gibbsite that is abundantly found on the edge and in the interior of the Plateau, accompanied by amorphous aluminum hydroxide (cliarchite) (Valeton *et al.*, 1997; Comin-Chiaramonti and Gomes, 2005).

The current operations can be illustrated by the flowchart in Figure 1. Quality control is carried out based on samples collected manually from the mine-to-stockyard transportation trucks. There is a conveyor belt sampler at the beginning of the plant, but it is currently inactive.
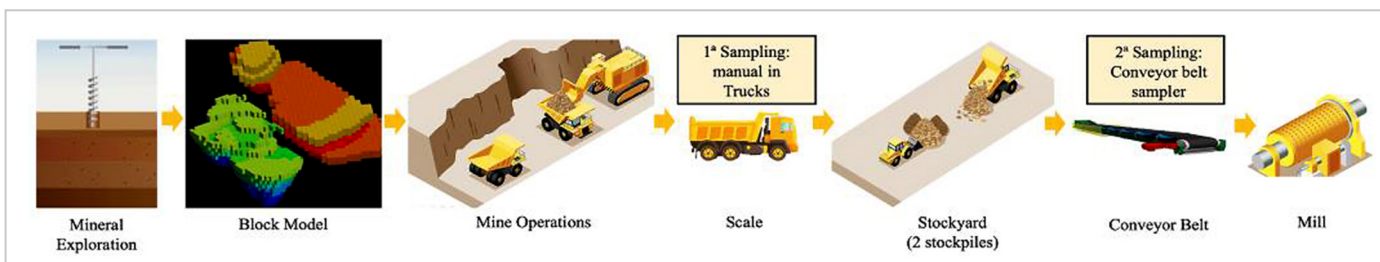

Figure 1 - Bauxite operations flowchart.

The objective of the present was to analyse the heterogeneity of the bauxite ore

and to check for discrepancies in the sampling reconciliation approach adopted by the

mine, comparing the current manual sampling with improved conveyor belt sampling.

2. Methodology

2.1 Heterogeneity test

A fundamental step to start the diagnosis of reconciliation practices is to assess the heterogeneity of the

ore, which enables calculation of the minimum mass of the samples to be collected more accurately than using

the standard literature parameters for material characteristics.

2.1.1 Minimum representative mass

The heterogeneity study used a primary sample of approximately one ton of bauxite ore that was collected from three

different mining fronts, respecting the real mass proportions practiced in the operation. The homogenization was then executed

using an elongated pile (Figure 2a). This operation, while reducing the $DH_{primary\ sample}$, maintains the $CH_{primary\ sample}$.
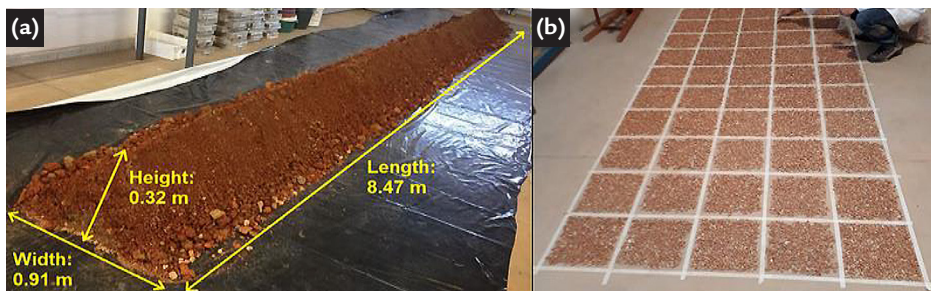

Figure 2 - (a) Homogenization pile for 1 ton of material. Source: Adapted from Freitas and Simões (2019). (b) Example of procedure used for heterogeneity test. Source: Silva (2019).

One third of the pile was separated for this specific test with enough calculated mass, approximately 300kg, which was dried before being sieved with the following openings (mm): 25.4, 12.7, 6.3 and 1.2. Figure 2b

demonstrates the procedure employed, which is the traditional heterogeneity test proposed by Pitard (1993). The calculation of the minimum mass considers the fundamental sampling error and a variance of the fundamen-

tal sampling error (FSE) considered acceptable for the ore characteristics. Equation 1 shows the simplified Gy's formula, which is used to calculate this minimum representative mass value (Pitard, 1993).

$$M_s = \frac{IH_L}{S^2_{FSE}} \qquad (1)$$

Where Ms is the minimum mass, IH_L refers to the constant factor of constitution heterogeneity (aka the Heterogeneity Invariant) and S^2_{FSE} is the accepted maximum variance of the FSE. Through the heterogeneity test, it was possible to draw up the IH_L graphs for both available alumina and reactive silica (Figure 3), which allowed calculation of the minimum mass required for a representative sampling of the flow through the conveyor belt.
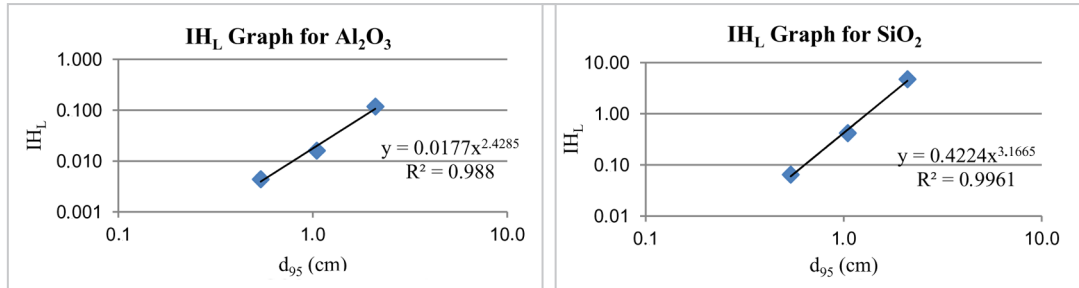

IH$_L$ Graph for Al$_2$O$_3$

$y = 0.0177x^{2.4285}$
$R^2 = 0.988$

IH$_L$ Graph for SiO$_2$

$y = 0.4224x^{3.1665}$
$R^2 = 0.9961$

Figure 3 - IH_L graphs as a function of d_{95} – bauxite ore from Poços de Caldas. Source: Silva (2019).

Analysing the Figure 3 concerning the material IH_L, it can be noted that it is a function of the d_{95}, making it also necessary to know this value (41.5 mm).

Thus, Figure 4 shows the particle size distribution used as a reference for the present work. It is important to highlight that the bauxite ore from Poços de Caldas is much finer than other typical Brazilian bauxites reported in literature, e.g. the ore from Juruti that presents d_{95} close to 5 cm (Bortoleto *et al.*, 2014).
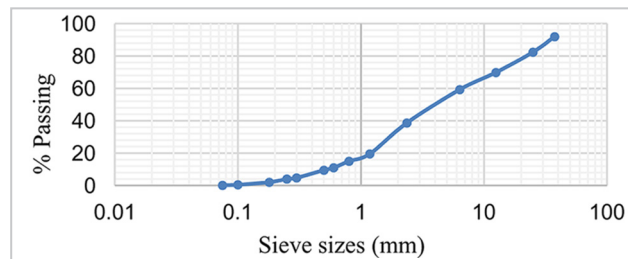

Figure 4 - Particle size distribution for the blended bauxite ore. Source: Silva (2019).

2.2 Conveyor belt sampler assessment

2.2.1 Stockpile formation

In order to conduct the conveyor belt sampler assessment study and the subsequent analysis for comparison between the two types of data obtained, it was necessary to collect samples at two locations at different times. Sample collection was carried out at two separate occasions: those collected during the stacking of the test stockpile and those collected from its reclaim onto the conveyor belt.

A test stockpile of approximately 600 tonnes was formed in the stockyard so its material could be identified, studied and sampled separately, in order for it to be tracked throughout the subsequent process.

First, the mine planning team determined to mine specific areas from different mining fronts, enough to feed the plant during a 9-hour shift. These areas were designated and isolated in the mine fronts for later survey. At this stage, samples taken from the transportation trucks (14.5 tons capacity) that carried the selected material were to be part of the study. Two sampling methodologies were employed: one already used by the company, in which truck samples collected manually by a shovel from each mine are incorporated into a single sample at the end of the day, then are manually quartered using cone piles and sent to the laboratory. The other approach, proposed here for comparison, was to send all samples collected from each of the trucks involved in the test for chemical analysis, separately.

2.2.2 Stockpile reclaim

The ore followed the mine flow path until it reached the conveyor belt, where it was sampled with a frequency of 15 minutes, at the end of the shift totalling 36 samples, always respecting the previously determined minimum sample mass. Cutting and collecting the material on the belt was performed manually with the help of a shovel, taking care to pass it closely enough to the belt in order to collect as much material as possible, including fines, simulating a real cross-belt sampler. All 36 samples were quartered by making elongated piles, generating sub samples to be analysed by different laboratories (internal and external), as well as obtaining duplicates to produce variograms. All these data will be used to set the automated cross-belt sampler in the process.

Samplers extracting increments from a continuous flow (conveyor belt) collect material at regular time intervals. The frequency of extractions will influence the accuracy or error of the sample (integration error) (Grigorieff *et al.*, 2005).

The variogram is built as a function of time between two points located on a

process dimension and it allows to characterize the one-dimensional heterogeneity of chronologically ordered data. The experimental variogram can be calculated as shown in Equation 2 (Chieregati and Pitard, 2012).

$$2\gamma(h) = \frac{1}{n(h)} \sum_{i=1}^{n(h)} [x(z_i) - x(z_i + h)]^2 \qquad (2)$$

Where $\gamma(h)$ is the variogram function for the time interval between two increments h, $x(z_i)$ is the increment content z_i and $x(z_i+h)$ is the increment content separated by h from the increment z_i (contribution to the heterogeneity), and $n(h)$ represents the number of pairs of increment values separated by h (Chieregati and Pitard, 2012). To estimate the $v(0)$ of the variogram (nugget effect), the most appropriate method is to calculate the variance based on the difference in duplicate content (Gomes *et al.*, 2011).

The semi-variogram function allows you to define a minimum interval j_{min} between sample collections to be representative, which can be noted when the semi-variogram curve crosses the sill line, the moment when only pure random phenomena start to act.

The Integration Error is defined as the difference between the actual batch content and the sample content collected over the t time interval. The magnitude of this error depends on the ore heterogeneity and variability (Grigorieff *et al.*, 2005).

Sampling variances can be estimated from four auxiliary functions of the variogram and one error generation function. They are represented by: S (j): simple integral of the variogram; w (j): the mean value of S (j); S '(j): double integral of variogram; w '(j): mean value of S '(j) (Gy, 1998 apud Gomes *et al.*, 2011).

3. Presentation, analysis and discussion of results

3.1 Sample collection

3.1.1 Minimum mass calculation

Taking into account 3% variance of the FSE and 4.15 cm d_{95}, the minimum mass calculated using Equation 1 is 0.62 kg for available alumina and 42.46 kg for reactive silica. However, the total mass collected on the conveyor belt was 89.4 kg, which is more than two times the minimum required, making it representative for both available alumina and reactive silica. As the feed material may differ slightly from the general characteristics assumed in the calculations, a safety factor of 1.2 has been adopted.

3.2 Belt sampler assessment

Figure 5 shows the variograms for both the internal and external laboratories regarding the available alumina and reactive silica.
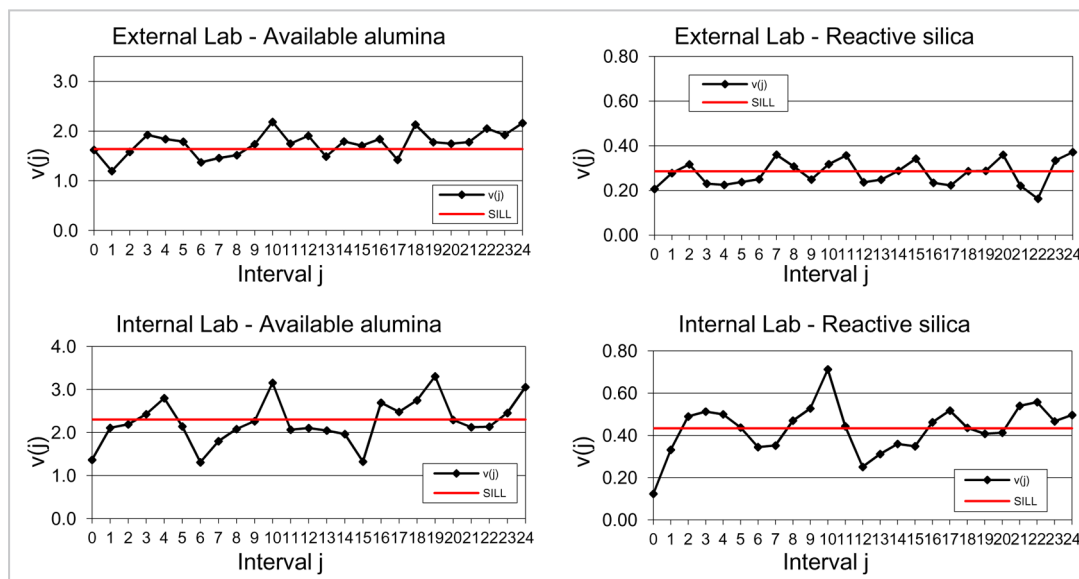

Figure 5 - Variograms for the external and internal lab results of available alumina and reactive silica.

Comparing the results obtained by the two laboratories for the available alumina, it can be said that both indicated a minimum frequency of 30 minutes of sampling. However, the biggest difference is in the nugget effect; much more pronounced in the graph obtained by the external laboratory.

Such behaviour can be explained by the greater variability among duplicate contents found in the external laboratory analysis.

Regarding the reactive silica, it can be said that both laboratories indicated a minimum frequency of 15 minutes of sampling. But again, the external lab had a higher nugget effect (0.21 versus 0.12). Table 1 provides a summary for the integration error for the minimum sample correlation interval defined by variograms, highlighting the error variance values (s^2(IE)sy) and the relative percentage error for a confidence interval of 95% (Sst 95%).

Table 1 - Integration Error summary.

Variable	Laboratory	j_{min}	$s^2(IE)sy$	Sst 95%
Available alumina	Internal	2	0.047	1.05%
	External	2	0.040	0.93%
Reactive silica	Internal	1	0.003	2.91%
	External	1	0.006	4.96%

It is important to note that, for a sampling performed on moving conveyor belts, the integration error corresponds to a significant part of the overall estimation error, but it is not the only one. The differences found might be a reflection of the unstable, bias-afflicted sub-sampling process employed in the last sample preparation steps carried out inside the labs that we do not have control of. Hence, it is important to keep all errors as small as possible to ensure representative sampling.

3.3 Comparison

3.3.1 External Laboratory versus Internal Laboratory

Figure 6 shows the relative difference between the results of chemical analysis from the laboratories used for the study for the 36 samples collected on the conveyor belt.
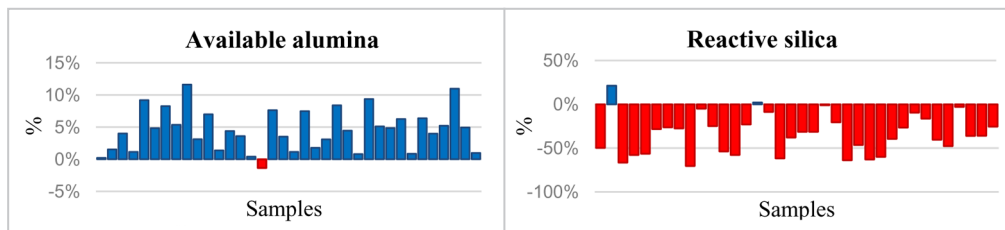

Figure 6 - Graph of relative difference between laboratory contents (External - Internal).

Figure 6 shows that there is a clear trend of overestimation by the external laboratory, or underestimation of the internal laboratory, when comparing the results of chemical analyses of available alumina and reactive silica for the same samples. The contents obtained by the external laboratory were better (higher for available alumina and lower for reactive silica) than indicated by the internal laboratory.

3.3.2 Planned versus Actual

Table 2 is a summary of the reconciliation between planned and actual data collected during the test.

Table 2 - Reconciliation data (%). Source: from the author.

		Planned (MineSight)	Trucks (Company Methodology)	Trucks (Proposed Methodology)	Conveyor belt sampling (Int. Lab.)	Conveyor belt sampling (Ext. Lab.)
Number of data		-	4	42	36	36
Available alumina	Absolut Value	40.86	42.83	41.37	41.14	43.10
	Reconciliation	-	104.82	101.26	100.70	105.48
Reactive silica	Absolut Value	4.84	3.19	3.64	4.03	3.06
	Reconciliation	-	65.86	75.10	83.18	63.10

Table 2 shows important findings. First, the results that came closest to what was planned were obtained by the sampling conducted on the conveyor belt by the internal laboratory, confirming the theory of sampling. For the available alumina, an excellent adherence of 100.70% was obtained, whereas for the reactive silica, the value was relatively low, of 83.18%, but it was the best among the conducted sampling campaigns.

The sampling in the trucks was biased, wrongly indicating "better values" than the actual ones, that is, indicating a higher available alumina content and smaller reactive silica. Both sampling methodologies presented this behaviour. However, the proposed alternative resulted in a slightly better adherence due to the larger number of analyses conducted, since each sample was analysed separately. The absolute differences of 1.45% for available alumina and 0.45% for reactive silica might have happened because of errors generated in the additional sample preparation steps required in the company's methodology, involving mass loss, homogenization and quartering for the generation of final sample.

According to Table 2, one can observe again a discrepancy between the results obtained by the two laboratories when comparing the contents of the sampling performed on the belt. The external laboratory provided the values with the lowest adherence to the plan. However,

sub sampling errors that can happen inside the labs and that we do not have control of, can also have an impact upon the final results.

The actual impacts of these discrepancies can best be understood by conducting a long-term financial analysis. Through simulations conducted internally by the company, it is possible to obtain the amount of caustic soda - supply of greater financial impact - required according to the bauxite content in the feed. The higher the reactive silica content, the higher the amount of soda needed for bauxite processing in the refinery.

Considering a constant production of bauxite for the next 10 years of 50 thousand tons per month according to the forecasts made by the planning team, an additional amount of approximately 130 tons of soda would be needed during this period, comparing the contents obtained by sampling currently performed on trucks with optimized belt sampling. Since the levels reported from truck sampling are biased better than the actual, this additional cost would not be in the company's financial planning. Considering the current price of 490 USD/ton, this total cost would be almost 70,000 USD for the period considered.

4. Conclusions

Several points of improvement in the sampling system were noticed during this research, which, if implemented, would bring about a more satisfactory reconciliation. First, a discrepancy in the block model regarding the reactive silica was observed when compared to the values found in the test, since the best adherence obtained was only 83%. Therefore, we suggest that the resources and reserves should be re-evaluated using a well-designed TOS-complaint sampling campaign.

During the mining operation stage, the sampling used for quality control should also be reviewed – and improved. Currently, sampling in trucks is used and, as demonstrated by the present results, this is not representative. Alternatively, the auto-sampler on the conveyor belt should be re-established collecting increments every 15 minutes as observed in the semi-variograms shown. This process improvement directly impacts the reconciliation results, making the predictions more reliable.

Another critical issue pointed out in this study, concerns the significant discrepancies found between the company's internal and external laboratories. More than 90% of the samples analysed by the external laboratory presented better contents than the internal laboratory. Therefore, an evaluation of the procedures of both laboratories is necessary, conducting also an interlaboratory comparison program to better control the analytical error. For future works, it's also important to analyse the sub-sampling process steps conducted in the labs for better understanding.

The importance of implementing these process changes is clear in order to achieve greater control, competitiveness, predictability and financial return for the company. More representative sampling generates more confidence in the data and adherent reconciliation is critical for more assertive decision making that enables consistent and continuous business growth.

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