

## Advanced process control application in VM-CBA bauxite digestion unit

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### Abstract

Bauxite slurry and heated caustic liquor are fed into digestion reactors for alumina extraction. The main parameter of the reactor output, the A/C (alumina/caustic) ratio is adjusted manually through the bauxite flow, based on laboratory analyses that are made to calibrate the system every two hours. Since many variables interfere in the A/C ratio, such as bauxite and liquor composition and scaling process, the measurements have low reliability, making this control not effective. The current work presents an advanced process control application, based on Fuzzy Logic technology, in a bauxite digester in order to control the bauxite slurry. The software does not require phenomenological knowledge to control the A/C ratio and uses empirical rules to estimate it. By anticipating production variances, the process variability was reduced by 50 %, which saved 3.2 % of the steam used for caustic liquor heating.

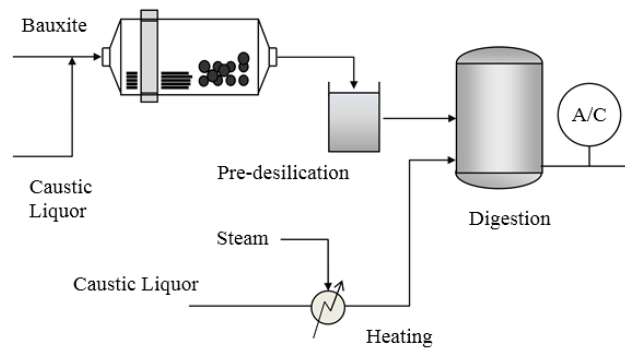
**Keywords:** bauxite digestion, fuzzy logic, advanced process control.

### 1. Introduction

Companhia Brasileira de Alumínio (CBA), of Votorantim Group, is located in Alumínio, 74 km from São Paulo city, and it is the biggest integrated aluminium plant in the world. CBA started to operate in 1955 and it belongs to Votorantim Metais, leading Brazilian producer of primary aluminium, which is part of the Votorantim Group, one of the largest Brazilian conglomerates operating in the industrial market segment. The aluminium production capacity of the plant reached 0.415 Mt in 2013, by using a traditional low temperature Bayer Process.

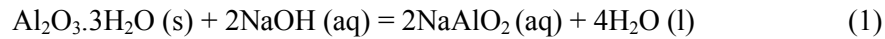
The Bayer Process, developed by Karl Josef Bayer in 1888, is used for refining ore bauxite into smelting grade alumina ( $\text{Al}_2\text{O}_3$ ) [1]. This process can be divided into two parts, popularly known as red side and white side. To briefly summarize, in the red side occurs the alumina trihydrate ( $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ ) dissolution in caustic solution and the residue separation of bauxite ore; in the white side occurs the alumina trihydrate precipitation and afterwards the removal of structural water in this hydrate (next step to Bayer Process called calcination), generating the compound known as alumina ( $\text{Al}_2\text{O}_3$ ).

Digestion is one of the steps of Bayer Process and in CBA it consists of three series of autoclaves that receive the bauxite slurry and the heated caustic liquor. This equipment promotes the alumina trihydrate ( $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ ) dissolution of the ore, under high pressure and temperatures close to 418 K, according to Figure 1.

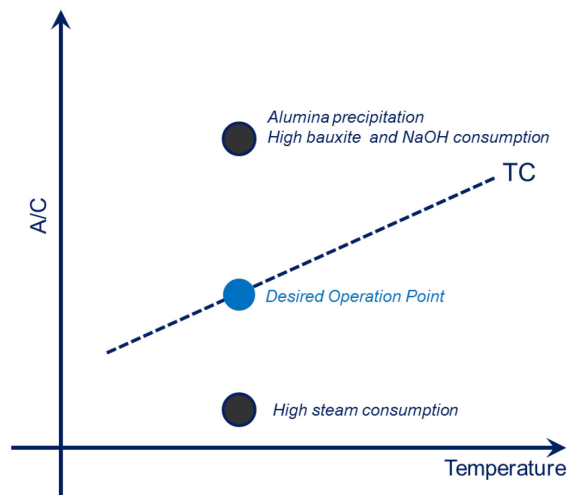


**Figure 1. Process diagram of the digestion unit.**

The chemical reaction is presented as follows (1):



The main parameter to be controlled in this process is the A/C ratio (alumina concentration/caustic concentration) in the liquor. Two phenomena happen when controlling the A/C as shown in Figure 2:



**Figure 2. Equilibrium curve to A/C ratio as function of process variables in digestion.**

The equilibrium curve shows the desired A/C ratio operation point from the liquor with a known caustic concentration and at a fixed temperature to digestion. Below this curve, it means a high caustic liquor consumption, which results in a higher steam consumption. On the other hand, above this curve, it means a high bauxite consumption, which implies in a higher caustic liquor consumption besides the risk of alumina precipitation in the next steps of the process, which impacts production and raises plant costs.

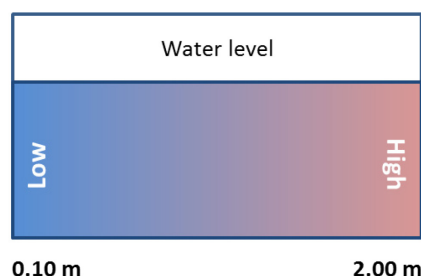
The A/C control was done manually adjusting the bauxite slurry flow by a control room operator, based on laboratory analysis, whose results are available two hours after the samples are collected. Even more, several process variables influence the Digestion, as slurry and liquor

composition and temperature, over-scaled process, precipitation yield and many others involving both the red and the white side.

Due to these factors, the A/C ratio had showed high variability. An advanced control application based on Fuzzy Logic was implemented in a Digestion unit of CBA, through software Leaf, aiming to reduce variability.

Fuzzy logic allows that indeterminate states can be quantified. This way, abstract concepts such as warm, very cold, too high, etc., can be processed by a computer. While dealing with abstract concepts, it's not possible to see a clear distinction between the states or qualifications and a classification issue arises.

Considering the human information about a water tank level (low, high, etc.), for example: the transition between the states is presented in Figure 3 as a gradient, in which it's not possible to say exactly where one state ends and another one begins. It is also possible to categorize a value as something that belongs in both states (with different intensities) at the same time.



**Figure 3. Gradient transition between the states regarding a water tank level.**

Simply put, one can consider that a 0.10 m level is 100 % low and 0 % high. Also, that a 2.00 m level is 0 % low and 100 % high. This way, for example, the 0.48 m and 1.62 m levels are classified as:

- 0.48 m level is 80 % low and 20 % high
- 1.62 m level is 20 % low and 80 % high

This rating percentage is also referred as membership function. Using this method, it's possible to say that a 0.48 m level is lower than a 1.62 m level, as well as a 1.62 m level is higher than a 0.48 m one.

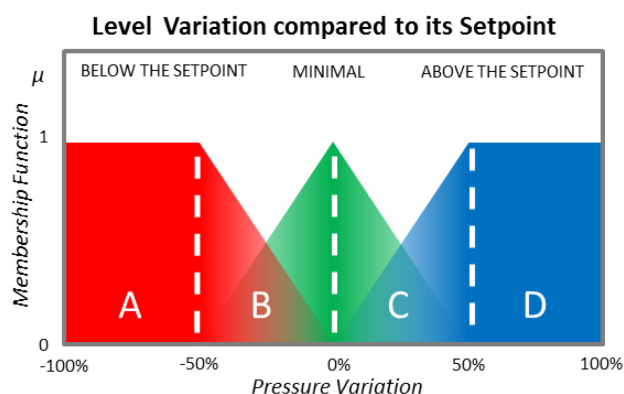
Those rating percentages are called membership functions. It's important to note that the mapping functions in real processes may require a great many membership functions to be functional.

Any closed loop control starts by evaluating the sensors' errors in the process, regarding their setpoints. The result of this evaluation is used to change the process, attempting to reduce the variability. Using Fuzzy logic, it's possible to evaluate which would be the best value to the actuator, following the same operator's rules of control.

The first part of a Fuzzy control development is the variables classification in labels that indicates their intensity and direction regarding the setpoint. A label (also called a triangle) is a state (such as high and low, hot and cold) that will define a range of values. Figure 4 shows the triangles related to the water tank example.

In this case, variations close to the setpoint are labeled “minimal”. In the setpoint mark (where variation equals 0 %), the value is solely labeled as “minimal” (“100 % minimal”). Following the same definition, the bigger is the variation, less sense it makes to get the minimal label and, therefore, less influence it receives.

Variations with intensities bigger than 50 % stop being considered “minimal” (“0 % minimal”). In a similar way, the variations below 0 % are labeled as “below the setpoint” and the variations above 0 % are labeled “above the setpoint”. Thus, a -25 % variation is labeled at the same time as “minimal” (“50 % minimal”) and “below the setpoint” (“50 % below”).



**Figure 4. Level variation classification.**

Considering the presence of a valve being manipulated by an operator to control the water tank level, the same classification method can be applied to the “valve opening” variable.

After the label definition, the Fuzzy controller uses a set of rules to adjust the valve opening (output), from the water level data (input). Table 1 brings the rules created in the water level tank example:

**Table 1. Control rules regarding the water tank level.**

	<b>Water Level (Input)</b>	<b>Valve Opening (Output)</b>
Rule	Label	Label
1	Below	Maximum
2	Minimal	Nominal
3	Above	Minimal

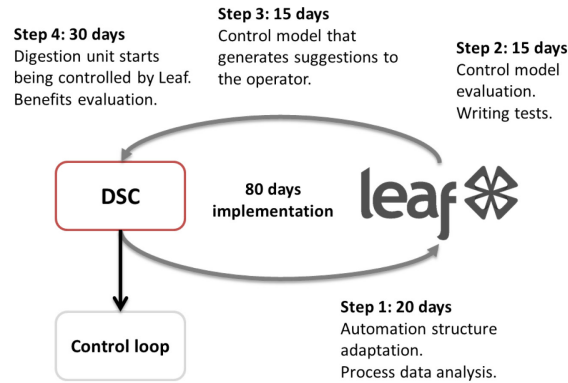
A variation in the value read by the sensor, regarding its setpoint, can activate many labels in different intensities. This way, more than one rule can be activated at once, which creates an output with lots of labels, with different intensities. The controller becomes more precise with an increase of the number of Fuzzy rules being used, which allows describing more complex behaviours from different scenarios.

### 1.1. Technology development and application

In order to improve the process efficiency and to stabilize the control of the bauxite digestion, CBA’s team applied I.Systems’ solution Leaf (“Learning Fuzzy”), which is an advanced control platform based on Fuzzy logic. Leaf was installed to replace the manual control of the bauxite slurry flow that feeds the digester, making optimized control decisions in real time.

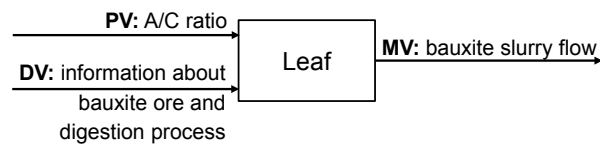
The implementation steps are described below and illustrated by Figure 5. It follows from the automation structure analysis until the moment when Leaf was activated:

- 1) Automation structure analysis and adaptation: creation of a safety logic and an on/off switch button. Leaf was installed “above” the Distributed Control Systems (DCS). The first implementation step also includes the process data and structure analysis (20 days);
- 2) Model evaluation and writing tests (15 days);
- 3) Creation of a model that generates control suggestions to the operator (15 days);
- 4) Leaf activation. From this step, Leaf started controlling the digestion unit. Afterwards, the implementation benefits were evaluated (30 days).



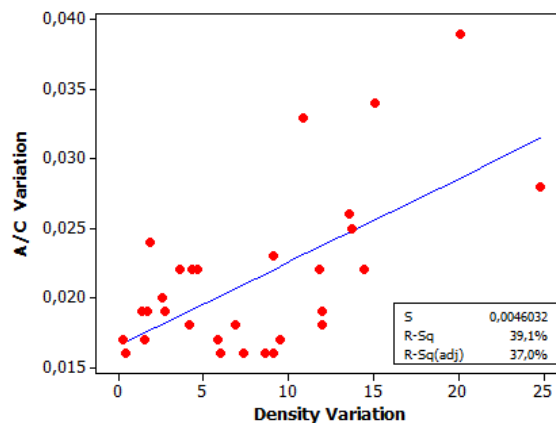
**Figure 5. Leaf’s implementation steps.**

Figure 6 shows the process variable (PV), manipulated variable (MV) and the disturbance variables (DV) of the control strategy:



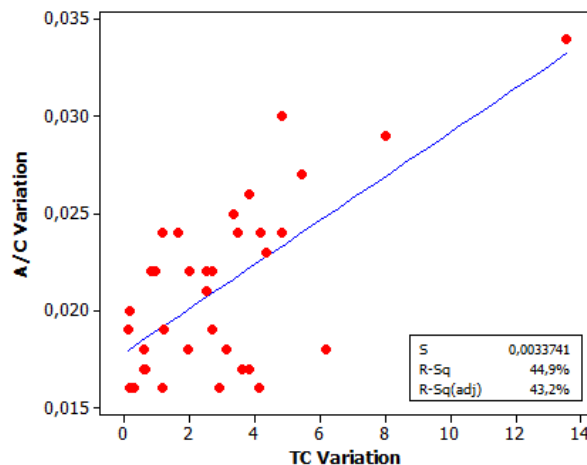
**Figure 6. Leaf’s control strategy.**

Regarding the control strategy, the first step was to determine the parameters that have the strongest impact on the A/C control. There are two main processes before the digestion: the bauxite grinding and the liquor heating as shown in Figure 1. The grinding result is the bauxite slurry which characteristics vary depending on the ore. The slurry density variability increases the digestion A/C variability according to Figure 7.



**Figure 7. Digestion A/C ratio behavior according to slurry density.**

The other main process is the liquor heating. The liquor returns from the white side, after the hydrate precipitation and filtration, and it is adjusted with NaOH solution before passing through the digestion heat exchangers. The caustic concentration (TC) of the adjusted liquor causes variability on the digestion A/C control according to Figure 8.



**Figure 8. Digestion A/C ratio behavior according to liquor TC.**

Both parameters are considered disturbance variables of the process, thus they were imputed in Leaf system. Another important input for the control system is the starting point, which was called reference value.

The reference value is the ratio between the liquor flow and the bauxite slurry flow. It allows the system to consider the digestion productivity target, converging faster and avoiding mistaken outputs from the system. It is given by the equation (2) below:

$$\text{Reference Value} = \frac{\dot{Q}_{\text{liquor}}}{\dot{Q}_{\text{slurry}}} \cdot \frac{(A/C_{\text{target}} - A/C_{\text{liquor}})}{(A/C_{\text{digestion}} - A/C_{\text{liquor}})} \quad (2)$$

$\dot{Q}$  Flow (m/s)

A/C Alumina concentration/caustic concentration

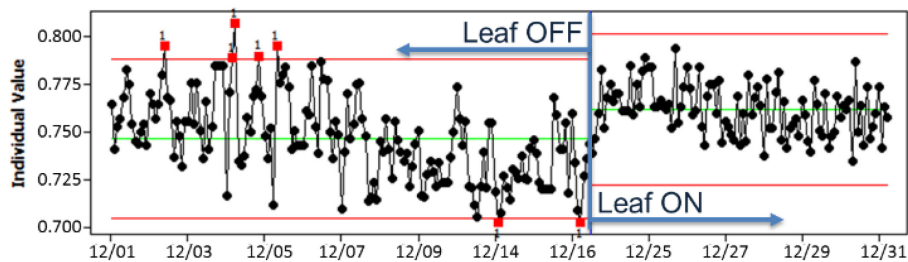
Every 2 hours the laboratory provides new results from the A/C ratio of the attack liquor and of the digestion product. Using these data, Leaf calculates a new Reference Value.

Leaf is able to both estimate the A/C ratio every second and analyze all information related to bauxite composition and the digestion process, allowing the production variances to be anticipated, bringing stability to the operation. Thus, the A/C ratio was set into a higher value within the target safety ranges, to increase the plant productivity or alumina yield [2].

The comparison between Leaf and the traditional control was made during the month of December in 2013 in the third digestion unit of the refinery. The system had been switched on, but the operation control remained manual for the first two weeks and then, on the last two weeks of December, Leaf was activated. This way, both controls were able to work with the same daily disturbances.

## 2. Results and Discussion

The data presented in Figure 9 were collected in real time and shows not only the process variability reduction when Leaf is active, but also the increase in the A/C ratio of the digestion process.



**Figure 9. A/C ratio points collected during one month with Leaf off and on.**

The results regarding the statistical analysis of Figure 9 data can be found in Table 2:

**Table 2. Results from the comparison between the two control strategies.**

	Leaf ON	Leaf OFF
Mean	0.762	0.747
Standard deviation	0.014	0.023

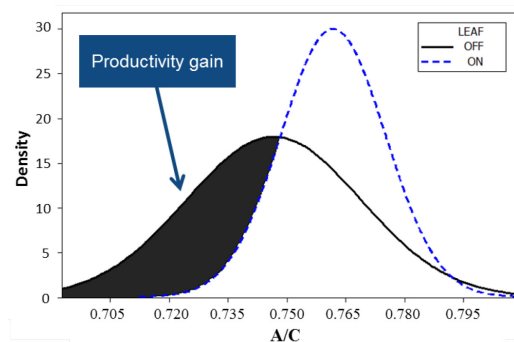
The comparison shows that Leaf was able to reduce the dispersion of the A/C ratio by 38 %, since the standard deviation decreased from 0.023 to 0.014. Also, the average value for the A/C ratio was higher with Leaf on, with an increase of 2 %.

Previously, the caustic liquor flow had to be kept at high levels to guarantee production, because the manual control increased operational variability. With elevated values of caustic liquor flow, the digestion A/C ratio becomes lower and the productivity can be affected.

Caustic liquor flow reduction was achieved after Leaf's implementation, because the process was stabilized and thus, the A/C ratio was increased. By increasing the A/C ratio, the steam consumption decreased, as it directly follows the reduction of the circulated liquor.

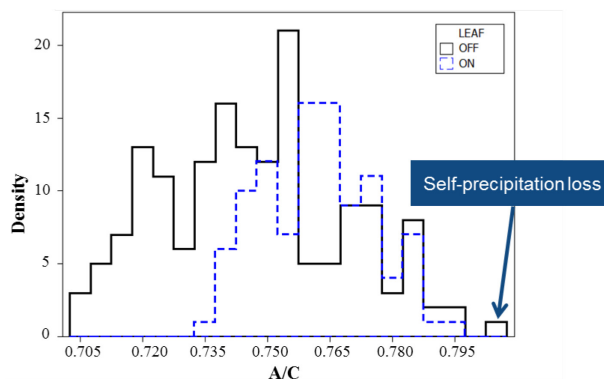
The A/C ratio can't be increased by itself without monitoring the supersaturation on the subsequent process steps, the clarification and filtration. Therefore, it is necessary to establish a safety limit to the digestion A/C ratio increase.

Figure 10 shows that the data density, when Leaf is on, is closer to the average value, which confirms the smaller standard deviation from the data sample.



**Figure 10. A/C ratio comparison between Leaf on and off.**

The same data can be put into a distribution where the damped curve won't be an influence to compare the self-precipitation event. In Figure 11, it is possible to see that Leaf operated closer to the superior limit and within the ideal operation range.



**Figure 11. A/C ratio histogram with Leaf on and off.**

Meanwhile, with manual operation, data points that indicated a self-precipitation event were collected. Figure 11 also shows that the points collected with Leaf off are more scattered, which is the reason they operated with a lower A/C.

The caustic liquor in circulation decreased with the 2 % increase on the digestion A/C ratio, which implied a reduction in steam consumption of 2 %. On Figure 11, it's clearly possible to observe the productivity gain by increasing and maintaining the A/C ratio stabilized.

The process capability increased from 1.95 to 3.26 after the Leaf implementation. By considering the reduction on steam consumption due to productivity elevation, the potential saving to the company is about US\$ 0.4 Million per year, per digestion unit.

### 3. Conclusion

The operating costs have benefited by the process variability reduction in 38%. This made possible a 2 % reduction of the caustic liquor flow, which implies in steam generation savings and economical gains to the plant.

Another gain is the stabilization of the A/C ratio sent to the white side. It provides a better control for the precipitation, impacting on the precipitation yield and on the final product quality.

Leaf was able to stabilize the operation, achieving a higher A/C ratio always within target safety ranges through precise control of the bauxite slurry flow, replacing the manual one.

### 4. References

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2. R. Den Hond, I. Hiralal, A. Rijkeboer, "Alumina Yield in the Bayer Process: Past, Present and Prospects", *Light Metals* 2007, pp 37-42.