# Advanced Process Control and Optimization of Alumina Calciners

**Rodrigo Lopes Monteiro[1], Rodrigo Augusto Carvalho dos Santos[2], Thiago Teixeira Franco[3] and Roberto Seno Junior[4]**
1. Control Specialist Jr.
I.Systems Automação Industrial S.A., Campinas, Brasil
2. Process Consultant.
3. Process Engineer.
4. Technology Manager.
Companhia Brasileira de Alumínio, Alumínio, Brasil
Corresponding author: rodrigo.monteiro@i.systems.com.br

## Abstract

Alumina calciners are one of the greatest energy consumers in an alumina refinery plant. Due to the high temperature needed to remove the hydroxide of the aluminum hydroxide structure, the fuel consumption is extremely high. Regarding this, an accurate process control is essential to achieve an efficient process with low variability, better fuel consumption performance and competitive production costs. The present paper presents the application of advanced control software based on fuzzy logic in Companhia Brasileira de Alumínio (CBA) calciners. Fuzzy logic has the ability of considering multiple variables and the software acts to avoid disturbances. In this way, it was shown in preliminary tests that CBA could improve the calciners performance, reducing the variability of the calcination temperature by 21%, which represents a 0.66% reduction in the specific fuel consumption.

**Keywords:** Process control, fuzzy, alumina calciner, process optimization.

## 1. Introduction

Companhia Brasileira de Alumínio (CBA) is located in Alumínio, 74 km from São Paulo city, and it is one of the biggest integrated aluminum plants in the world. CBA started to operate in 1955 and it belongs to Votorantim Group. The aluminum production capacity of the plant reached 417 kt in 2017 and uses a traditional low temperature Bayer Process.

The Bayer Process, developed in 1888 by the chemist Karl Josef Bayer, is the most used process in aluminum industry for refining ore bauxite into smelting grade aluminum oxide. There are four main stages in the Bayer Process: digestion, clarification, precipitation and digestion [1].

Calcination is the last stage of Bayer Process, where the aluminium trihydroxide ($Al(OH)_3$), formed and separated in the preceding process stages, has its hydroxides removed, forming the aluminum oxide ($Al_2O_3$) and water. The reaction occurs at high temperatures, around 960 °C, and is presented below [1]:

$$2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O$$

In CBA, natural gas is the second largest cost for the alumina production. Also, calcination has an important influence on the product quality. Because of that, an optimized operation of the calciner is crucial from the economic point of view of the whole alumina refining plant. In CBA, two fluidized bed calciners are responsible for the calcination process. A generic schematic diagramme of a fluidized bed calciner is shown on Figure 1, with the calcination stage (Circulating Fluidized Bed Furnace and Recycling Cyclone) highlighted in gray [2]:

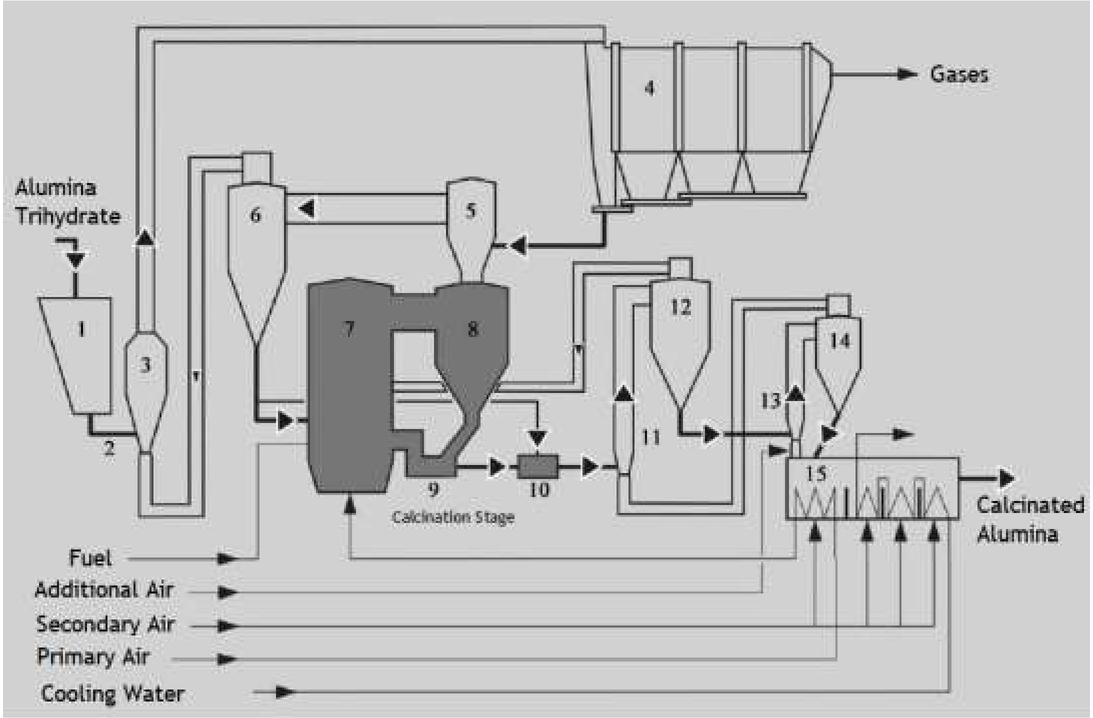

**Figure 1. Generic schematic of a fluidized bed calciner, with the calcination stage highlighted.**

The feed is fed from the feed bin (equipment 1 in Figure 1) via a feed screw into the first venturi preheating stage (equipment 3, in Figure 1). After passing a series of cyclones the material is fed into the CFB furnace (indicated by the number 7 in Figure 1) by a chute. The fuel (in CBA´s calciners natural gas) is fed by gas lances and controlled with a valve into the CFB furnace. Primary and secondary air are fed by eight blowers (three for the primary air and five for the secondary air). The material is calcined and recirculated in the CFB system, a special discharge device is responsible for discharging product alumina to the cooling stages.

As there are a plenty of heat transfer and chemical reactions (combustion and calcination) occurring at the same time in the CFB furnace, a successful control system must deal with many variables at the same time, as an actuation in one manipulated variable, may have a direct influence on more than one process variable and one process variable may suffer influence from more than one manipulated variable.

The combustion reaction of the fuel is responsible for providing the heat necessary for the calcination of the aluminium trihydroxide into smelter grade alumina, so it is important to control the flow of fuel and air to keep the calcination temperature stable and close to the setpoint. However, the bottom temperature and the secondary air temperature may also interfere with the calcination temperature, as they reflect the amount of heat retained with the recirculated solids and the amount of heat provided to the calciner by the air. That said, it is important that the control system can stabilize all these variables to achieve a stable heat flow in the calciner, optimizing its energetic efficiency and fuel consumption leading to important economic savings on the equipment operation.

## 1.1. Fuzzy Logic

Fuzzy logic is a powerful artificial intelligence method, as explained by Franco [3]:

*"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."*

Consider, for example, a steam boiler in which we have one main variable to control (the steam pressure). As a human thinking we can divide the information about this variable in different states and make a gradient transition between then. An example is shown in Figure 2 below:

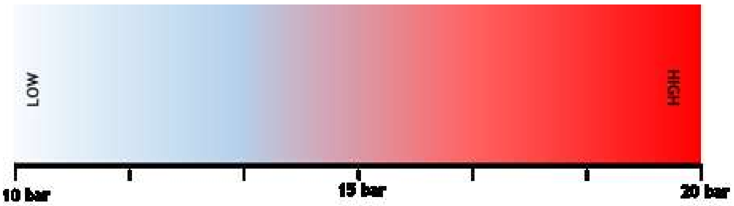

**Figure 2. Gradient transition between the states regarding steam pressure in a boiler.**

As it is impossible to determine precisely where one state ends and another begins we can say that any specific level is a member of two states at the same time, in different percentages. As an example, we can classify a 12.5 bar steam pressure value and a 17.5 bar steam pressure value as:

- 12.5 bar pressure is 75 % low and 25 % high.
- 17.5 bar pressure is 25 % low and 75 % high.

We call this rating percentages membership functions. In real processes there are plenty of membership functions (commonly hundreds or thousands) to this mapping [3].

To develop a functional Fuzzy control, we first need to classify variables in labels (or triangles), indicating how they change regarding the setpoint. These triangles will define a range of values for the control [3]. Figure 3 shows the labels defined to the boiler example.

**Figure 3. Steam pressure variation classification.**

In this case, values close to the reference (15 bar) are solely labeled as "ideal". However, values between 10 bar and 15 bar can have more than one label: "very low", "low" or "ideal". For example, a value of 11 bar can be labeled as "very low" and "low" at the same time but cannot be labeled as "ideal" (as this label starts to be defined at 12.5 bar). In the same way, a value of 14 bar can be labeled as "low" and "ideal" but not "very low" (as this label ends to be defined at 12.5 bar).

This same thinking can be used for values greater than 15 bar, that can be labeled as "ideal", "high" or "very high".

This label classification can also be used for manipulated variables. Considering a fuel valve on the boiler that can be manipulated by an operator, the Fuzzy controller uses a set of rules to determine what valve opening should be used (output) for every steam pressure data (input). A schematic example of the rules is shown on Figure 4.

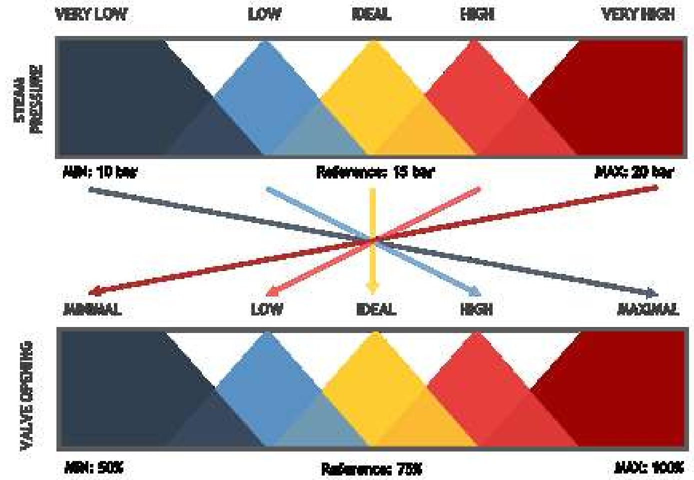

**Figure 4. Control rules regarding the steam pressure.**

It is important to note that the number of Fuzzy rules has a huge impact on the controller precision. With more rules, mores states can be defined, which allows the description of more complex scenarios, making the controller had a better performance.

## 1.2. Technology Development and Application

To deal with the control challenges concerning the calciner, and to improve the equipment's efficiency, CBA´s engineering team decide to apply I.Systems' solution Leaf, which is an advanced control platform based on Fuzzy logic. Leaf was installed to replace the PID controls in the feed flow, the natural gas flow, the product alumina discharge flow and the manual control of the primary and secondary air blowers.

The implementation steps are described below and illustrated by Figure 5, and were as follows:

1) Automation structure analysis and adaptation: creation of a safety and writing logic and an on/off switch button. Leaf was installed "above" the Distributed Control Systems (DCS);
2) Data analysis and control logic creation;
3) Control logic evaluation, with analysis of Leaf in open loop;
4) Leaf activation. From this point, Leaf started controlling the calcination unit. Afterwards, the implementation benefits were evaluated for a 31 day period.

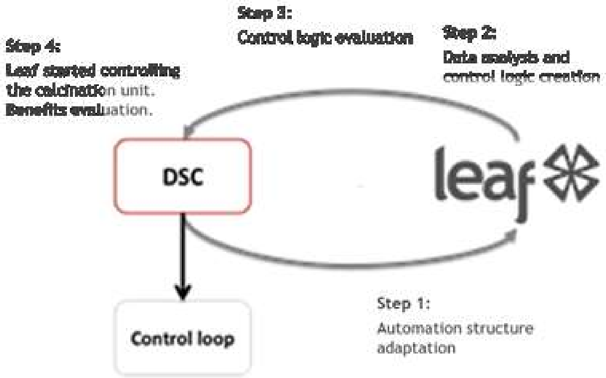

Figure 5. Leaf's implementation steps.

The advanced control system was first implemented only in one calciner (called calciner 6) for validation of the benefits. After the confirmation of the gains, it will be installed on the other calciner as well.

Due to the number of control loops to be optimized and the complexity of the calcination process, in which every variable has a strong influence on the others, the first step on the control implementation is to determine what parameters have the strongest influence in each process variable to create the better strategy for every control loop.

Merging I.Systems control and data analysis expertise and CBA's engineers and operators process knowledge it was possible to determine the best control strategy for every loop. Figure 6 shows the control strategies, with process variables (PV), manipulated variables (MV) and disturbance variables (DV) for every control loop optimized by Leaf:

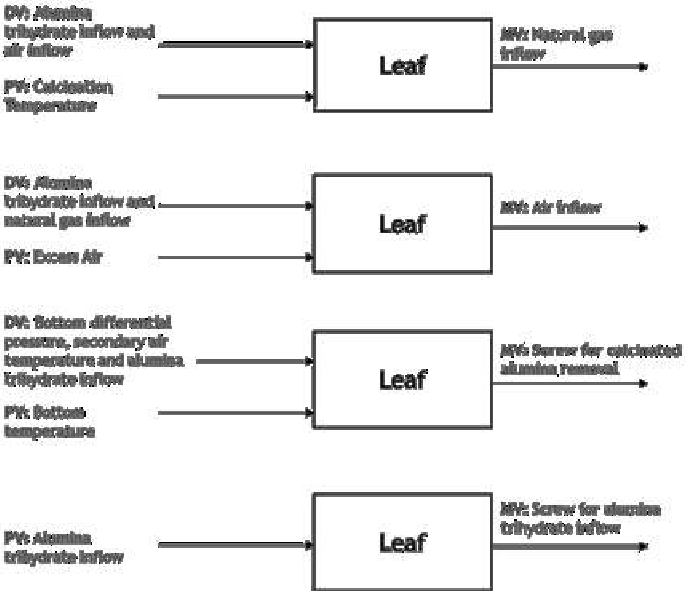

Figure 6. Leaf's control strategy.

In combustion systems is very important to secure a complete combustion of the fuel, resulting in a better energetic efficiency (as a complete combustion delivers more energy for the process than an incomplete combustion) and avoiding formation of carbon monoxide (CO), which is a security necessity as carbon monoxide in elevated concentrations is a flammable compound. Because of that a strategy to avoid incomplete combustion was implemented in the control logic. In this strategy, the molar flows of fuel and air are calculated for each control interaction.

Then they are compared with the stoichiometric proportion needed for complete combustion (also considering a safe margin of excess air) and the lowest value is set for the fuel molar flow and the highest is set for the air molar flow. This way, guarantees that there will always be proportionally more air than fuel in the combustion system, making sure that the combustion will be complete.

Another important control parameter is the starting point, which is called reference value. In the calcination process these reference values vary greatly according to the production. To deal with that and using process data analysis, linear functions that correlate the alumina trihydrate inflow setpoint with every manipulated variable were created. Using this strategy, the control robustness was increased, as it could react quicker to process changes and disturbances.

After the advanced control implementation, the validation step consisted on collecting data of one-month operation with the system on and off, calculate and validate the benefits using statistical methods to guarantee that the benefits were clear and derived only from the implementation of the advanced control system, excluding external factors.

## 2. Results and Discussion

The data presented in Figure 7 shows the comparison of the calcination temperature before and after the advanced control implementation:

Figure 7. Data for the calcination temperature.

It is possible to see the reduction in variability of the furnace temperature after the advanced control implementation. This reduction can be confirmed to be statistically valid by analyzing the box plot of the calcination temperature error for the whole validation period. The results are presented in Figure 8.

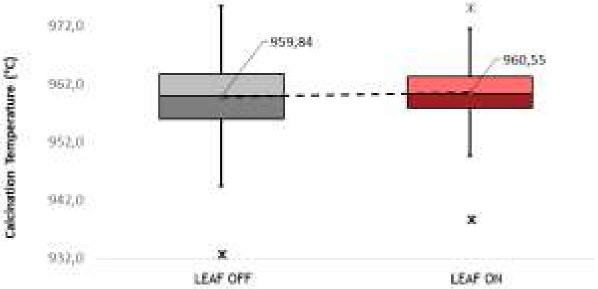

Figure 8. Box plot for the calcination temperature.

The numerical results regarding this data can be seen in Table 1.

**Table 1. Results for the calcination temperature.**

| Control Strategy | Mean (°C) | Standard Deviation (°C) |
|---|---|---|
| Leaf ON | 960.55 | 6.23 |
| Leaf OFF | 959.84 | 7.90 |

As it can be seen, the calcination temperature variability was reduced by 21%, although its mean had remained close to the desired value, around 960°C. Also the box plot shows that, with the advanced control, the temperature was kept closer to the setpoint, with less outliers, wich leads to a improvement in the product quality, as less temperature deviations favour the yield of the calcination reaction.

As the setpoint for the bottom temperature changed during the validation period, it was used the absolute error of this variable to calculate its stability. In Figure 8 the data for the calciner's bottom temperature error are presented.

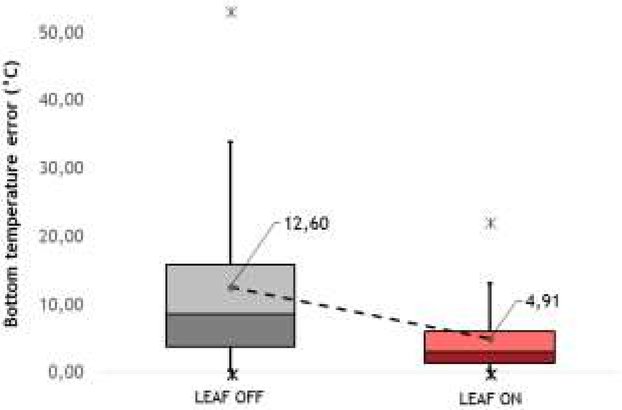

**Figure 9. Histogram for the bottom temperature error.**

For the benefits evaluation, is also important calculate the mean of the bottom temperature. Table 2 presents this results for the bottom temperature.

**Table 2. Results for the bottom temperature.**

| Control Strategy | Mean (°C) | Absolute Error Mean (°C) |
|---|---|---|
| Leaf ON | 911.68 | 4.91 |
| Leaf OFF | 908.13 | 12.60 |

From the data, is possible to see that, with the advanced control, the bottom temperature is more stable and with a higher mean, leading to a gain of 61 % in stability and a increase of 0.4 % in the mean.

With a more stable and higher bottom temperature, the energetic efficiency of the calciner is increased, as more heat is maintained inside the calcination chamber, wich increases the combustion thermal efficiency, reducing the fuel consumption.

This great improvement was mainly achieved by the change on the control logic of the product discharge from the CFB furnace. Before the advanced control the main objective of the control of alumina discharge was to maintain the bottom differential pressure on the setpoint set by the operators. The differential pressure corresponds to the inventory of the fluidised bed furnace and also indicates if there areproblems with the discharge like lack of material inside the calciner (if this diferrential pressures is too low) or obstruction by excess of material at the bottom (if this differential pressure is too high). With this strategy, the bottom temperature was only a result of the control, and not a controlable variable. However, with the advanced control capacity of dealing with multiple variables at the same time, it was possible to create a strategy that optimizes the bottom temperature and keeps the differential pressure inside its limits, leading to the stabilization mentioned above.

Finally, on Table 3 are presented the results comparison regarding the specific fuel consumption of the calciner.

**Table 3. Results for the Fuel Consumption.**

| **Control Strategy** | **Mean ($m^3$/t feed)** | **Standard Deviation ($m^3$/t feed)** |
|---|---|---|
| Leaf ON | 80.12 | 1.27 |
| Leaf OFF | 80.66 | 1.92 |

The data above shows the economic benefits of the advanced control application, by showing the 0.66% reduction on the mean of the specific fuel consumption on the calciner as well as a 34 % reduction in its variability. With that reduction the economic gains derived from the stability of calcination and bottom temperatures could be measured, validating the benefits of the application of the advanced control provided by Leaf.

## 3. Conclusion

By anticipating disturbances and integrating the main control loops of the calciner, it was possible to achieve a more stable and optimized operation of the process, leading to operational and economic gains.

A more stable process leads to an increase in the product quality, since the calcination reaction is affected by temperatures changes, so a stable temperature improves its yield. Also, in the long term, a more stable process can reduce the costs with maintenance and the deterioration of the equipment.

The reduction of 21 % in the variability of the calcination temperature (maintaining the temperature at the desired value of 960 °C), along with the reduction of 61 % in the variability of the bottom temperature stabilized the process. This stabilization summed with the increase of 0.4 % in the mean of the bottom temperature resulted in reduction of 0.66 % of fuel consumption, derived from a better energetic efficiency of the calciner.

## 4. References

1. Eduardo L. G. Filho, Modelagem e Simulação de Calcinadores de Hidróxido de Alumínio em Leito Fluidizado. Rio de Janeiro/RJ: UFRJ/EQ, 2012.
2. Daniella S. Ferreira, Análise e identificação do modelo dinâmico do processo de combustão em um calcinador industrial. Belém/PA: PPGEP/PA, 2015.
Thiago Franco et al., Advanced process control application in VM-CBA bauxite digestion unit. Available at: https://icsoba.org/proceedings-2015.