

Evaporation Plant And Recovery Boiler Optimization Utilizing Model Predictive Control Technology – A Case Study At Suzano Três Lagoas Mill

Vinicius Bassan Sierra, Suzano S/A, Três Lagoas, MS, Brasil

Marcio Andre de Lima Silveira, BTG, São Paulo, SP, Brasil

Renato Camarosano Onofre, BTG, São Paulo, SP, Brasil

Demi N. B. Lidorikiotis, BTG, Seattle, WA, USA

ABSTRACT

The Evaporation Plant and Recovery Boiler Optimization project has revealed a potential to increase energy revenues. By using a predictive control model in an evaporation plant, it was possible to reduce the dry solids content variations of the heavy black liquor by 50 % and increase the content average from 81.2 % to 82.0 %. By controlling the inflow of the high secondary and tertiary air flows to the recovery boiler, the residual oxygen was reduced from 3.0 to 2.3 %, with a standard deviation reduction from 0.32 to 0.14 %, i.e. a 56 % reduction. Overall, this resulted in an increase of 2.7% high pressure steam generation on the recovery boiler. This increase correlated to a gain in revenue and estimated delivery of electricity to the grid, worth about 2 million USD per year.

INTRODUCTION

Heavy black liquor, the output from the evaporation plant, is the main input to the recovery boiler. Optimization of the evaporation plant is crucial when reducing the variability of the burning process in the recovery boiler. Optimum control minimizes steam usage in the evaporation plant while maximizing the heavy black liquor dry solid content. Using a dynamic model of the evaporation train, the model predictive control accounts for interactions between steam flow, product solids, feed solids and liquor tank levels, resulting in an improved heavy black liquor with less dry solids % variability. This superior heavy black liquor correlates to an increase in calorific power and steam production. [1] The recovery boiler control relies on air optimization, both high secondary and tertiary levels, to optimize the residual oxygen in the furnace, leading to a further increase in steam generation.

BACKGROUND

Suzano Três Lagoas pulp mill, located in the Mato Grosso do Sul state of Midwest Brazil, is one of the largest pulp mills in the world with a total capacity of 3.3 million tonnes. The mill has two fiber and recovery lines. Line 1 began operation in 2009 and has a capacity of 1.35 million tonnes of bleached eucalyptus pulp. Its evaporation plant has six effects and the recovery boiler has a capacity of 6,000 tds/d. Line 2 started in 2017 and has a capacity of 1.95 million tonnes of bleached eucalyptus pulp. The evaporation plant has seven effects the recovery boiler a capacity of 8.950 tds/d.

The cooking process dissolves about half of the wood and together with the used chemicals, forms the weak black liquor. This liquor is washed away from the pulp and sent to the recovery system where the inorganic fraction can be recovered while the organics are burned to generate steam and power [1].

Black liquor has a higher boiling point than water. The temperature difference between the water boiling point and the liquor boiling point is called Boiling Point Rise (BPR). This property strongly influences evaporation plant operations, as the BPR depends on the inorganic content of the liquor. The higher the content of solids, the higher the BPR will be. Therefore, the solids contents of an evaporation stage can be estimated from the calculated BPR for that stage. [2]

Três Lagoas has a significant surplus of electricity generation. This electricity is sold to the Brazilian grid and is regarded as a high priority product. Increasing its output provides a revenue gain to the mil, but requires a higher steam production from the recovery boiler. This work aimed to increase power generation through the optimization of Line 1 evaporation and recovery boiler processes.

Studies on the evaporation plant, recovery boiler, recausticizing plant and steam/power network were done, as those areas can affect the power generation. After ranking them, it became clear that the evaporation plant and the recovery boiler had better return and would have larger impact on mill operations.

An optimized evaporation plant control minimizes steam usage while maximizing dry solids content in the heavy black liquor, which later reduces variability in the burning process of the recovery boiler. A higher dry solids content produces more steam, making it a significant path to increased steam generation. [3] Due to the interaction between the process variables and the long residence time, a solution that uses a predictive model is suitable.

Model Predictive Controls (MPC) is appreciated in the industry as one of the main control methods for the kraft process. MPC is a multivariable control algorithm which uses a set of linear dynamic models representing the process to predict the effect of future control moves on the output variables (controlled and constraint). An optimization routine is used to compute a set of future control moves that minimizes the performance index while simultaneously ensuring that the process constraints are satisfied. [4]

Using a dynamic evaporation train model, the MPC accounts for interactions between steam flow, product solids, feed solids and liquor tank levels. Predictive control compensates for disturbances from the upstream processes, such as changes in brown stock washing. Using the model, the controller “understands” how fresh steam usage, feed liquor solids, product solids and liquor inventories respond to the process changes. The controller uses this built-in knowledge to improve the evaporator economy, stabilize the product solids, and maximize the product solids to the desired level.

Heavy black liquor is the output from the evaporation plant and is the main input to the recovery boiler. A higher quality heavy black liquor results in increased calorific power, stable volumetric flow, and better control of droplet size. This increase in quality and stability of the heavy black liquor allows the air flow to be more easily optimized.

A typical operating strategy for recovery furnaces is to base load the solids mass flow with adjustments for inventory management. Constant solids mass flow does not always translate to a constant heat input or stable furnace. As liquor properties vary the liquor heating value and firing properties will fluctuate. This variation requires ongoing adjustments of boiler inputs such as air flows, liquor and temperature.

Três Lagoas’ recovery boiler control relies on air optimization, using both high secondary and tertiary levels to optimize the residual oxygen in the furnace. Additionally, the control slightly manipulates the black liquor flow in order to aid oxygen optimization. The air inside the furnace is not held constant but rather, moves to accommodate the incoming liquor characteristics.

In this project no extra online measurement modules or other mechanical equipment was needed as the MPC used the sites existing measurement signals to control different valves feeding steam and black liquor in the evaporation plant as well as air and black liquor to the recovery boiler.

THE EVAPORATION APPLICATION

The control matrix must be tailor-made for each process, using the results from bump tests and process knowledge. The concept behind the evaporation plant in Três Lagoas is the following: the concentrator (the 1st stage) is the only point throughout the plant where fresh steam is used, while the consecutive stages (2nd-6th stage) receive the evaporated steam from the previous one. Thus, if the concentrator is well controlled the ensuing stages will be as well.

The main goal for the evaporation application was to reduce the heavy black liquor dry solids variability to the recovery boiler, increasing the average dry solids content. Bump tests were done for each controllable steam valve to the concentrator. From this data models were created between steam valve position and estimated solids for each first stage (1D, 1C, 1B and 1A). The estimated solids were calculated based on BPR, which already existed in the DCS. The biggest difference between the previous DCS controls and the new MACSevap controller is the DCS had simple PIDs

that would control each 1st stage estimated on solids error, while the new controller has dynamic models for each stage and uses the previous stage estimated solids and concentrator flow as a feedforward to the next stage. A simplified schematic of the control is presented in Figure 1.

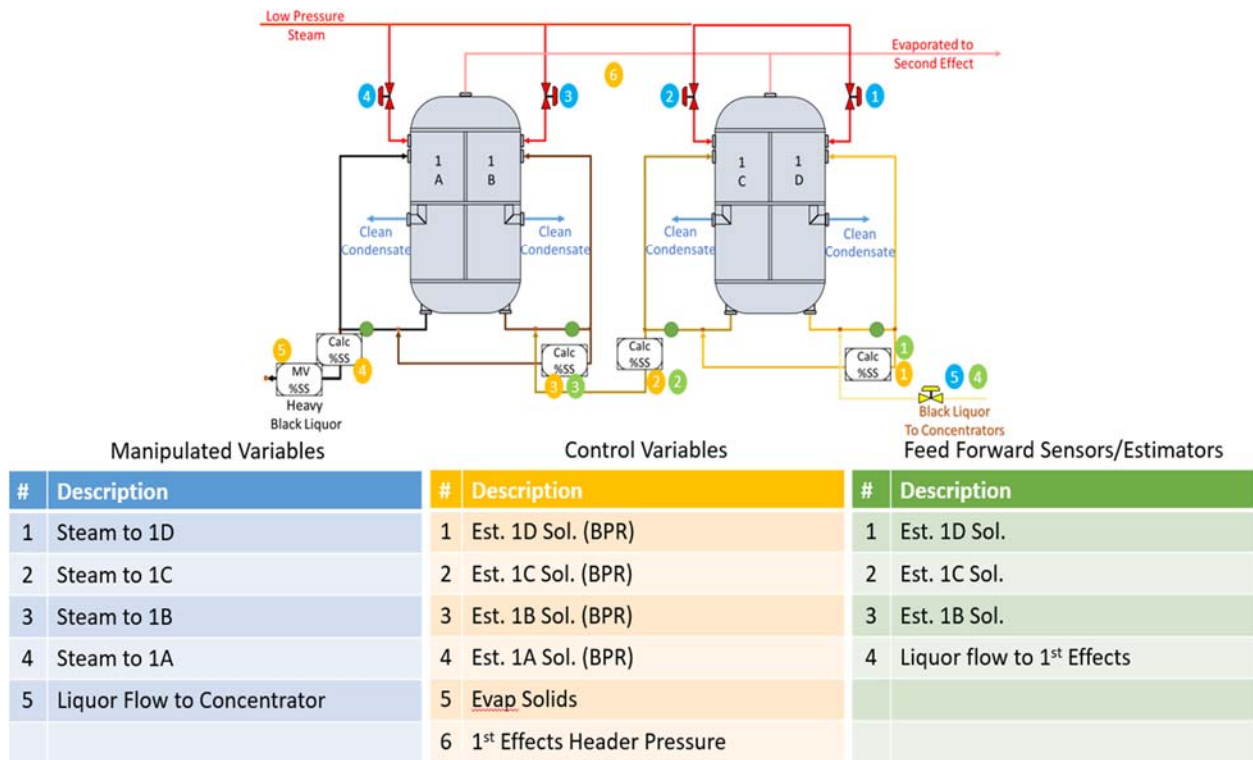


Figure 1. Evaporators model predictive control scheme.

THE RECOVERY BOILER APPLICATION

The main goal of the recovery boiler application, MACSrecovery, was to reduce the residual oxygen in the furnace region. All air and heavy black liquor flows underwent bump tests to get models for each variable. From here it was clear that the primary air and low secondary air had a significant impact on the boiler bed shape with no immediate response on the residual oxygen. These two levels were used according to the boiler load air curve. The bump tests also showed that high secondary and tertiary air flows had a good response on the residual oxygen, therefore those two air levels were adjusted accordingly to boiler load. When needed the controller could offset it from its target, i.e. from air curve to control residual oxygen. A simplified schematic of this control is presented in Figure 2.

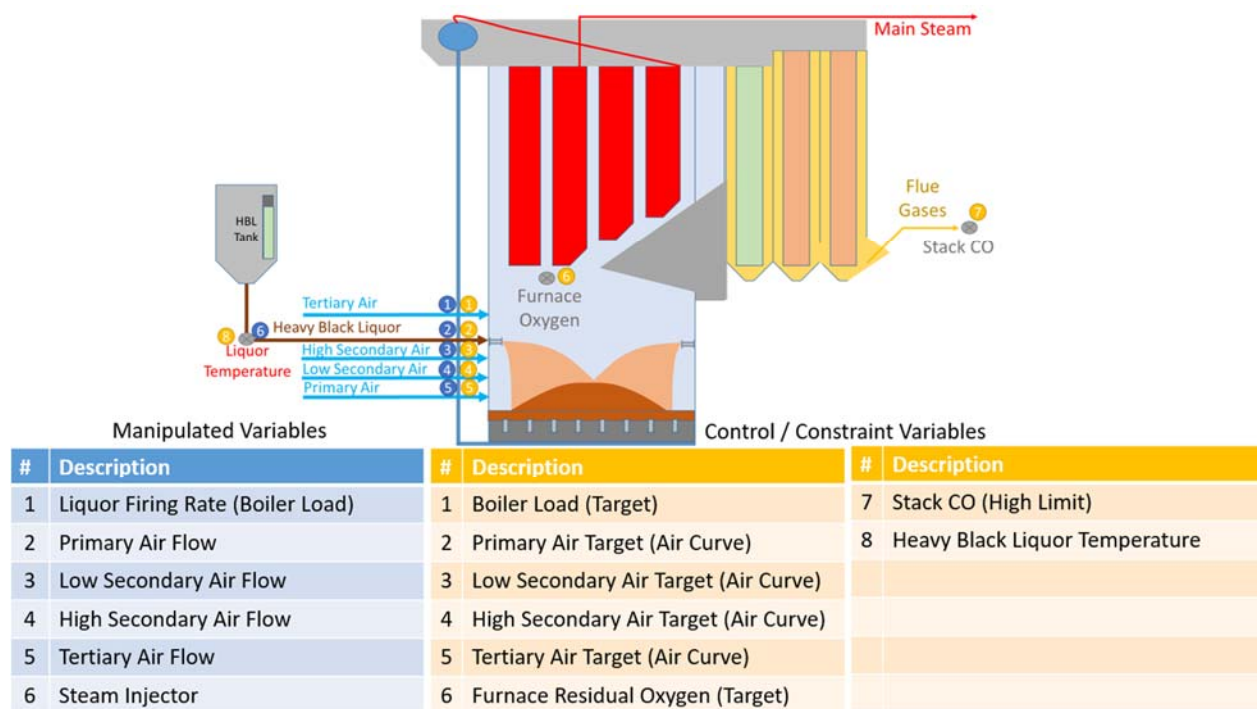


Figure 2. Recovery boiler model predictive control scheme.

The heavy black liquor flow has a very good response to residual oxygen due to oscillations in liquor quality, such as dry solids content and the organic/inorganic ratio. The control can offset black liquor flow to help with residual oxygen control. Keeping residual oxygen constant contributes to a more stable burning process without wasting energy on excess air. The control checks CO on the stack, preventing peaks and keeping it well within legal limits. The application also controls the direct steam injector through calculations based on dry solids content to keep liquor temperature on target. This is done to reduce the variation of liquor droplet size.

The solution provider had one key person watching the process, evaluating its performance and discussing it with the operators, technical assistants and area supervisor. Based on the resulting assessment, the control would be tuned accordingly. After evaluating the preliminary performance and making the necessary adjustments, both applications worked as expected. MPC methodology was used for both applications; as such, it is recommended that the control models are revalidated whenever a major process change is made.

RESULTS

Before the project started, a calculation model was agreed upon in order to standardize the baseline and how the performance would be calculated. This included how data would be pooled, i.e. the frequency, filters, formulas, corrections and coefficients used to translate process data to steam ratio and steam generation increments. This was used to evaluate the power generation incremental economic benefit.

The project was finalized in June 2019 when the recovery boiler optimization package received final acceptance. The project was evaluated by three main Key Performance Indicators (KPIs): heavy black liquor dry solids average and standard deviation, furnace residual oxygen average and standard deviation, and steam ratio average. The first two KPIs were chosen because they are direct measurements that the application is controlling. The steam ratio was chosen as it translates to increments of steam generation and therefore energy generation. The steam ratio was the KPI used to calculate the projects financial return.

The advanced control system utilized to optimize the heavy black liquor dry solids in the evaporation plant increased the dry solids content average from 81.2 % to 82.0 % (Figure 3), while reducing the standard deviation from 1.4 % to 0.7%. Translating to a 50 % liquor quality variability reduction. That increment was possible through the quality improvement of the heavy black liquor without increasing the number of high dry solids content excursions. This proves that utilizing an advanced process control system based on a predictive model is an effective way to reduce the dry solids' oscillations in the heavy black liquor going to the recovery boiler.

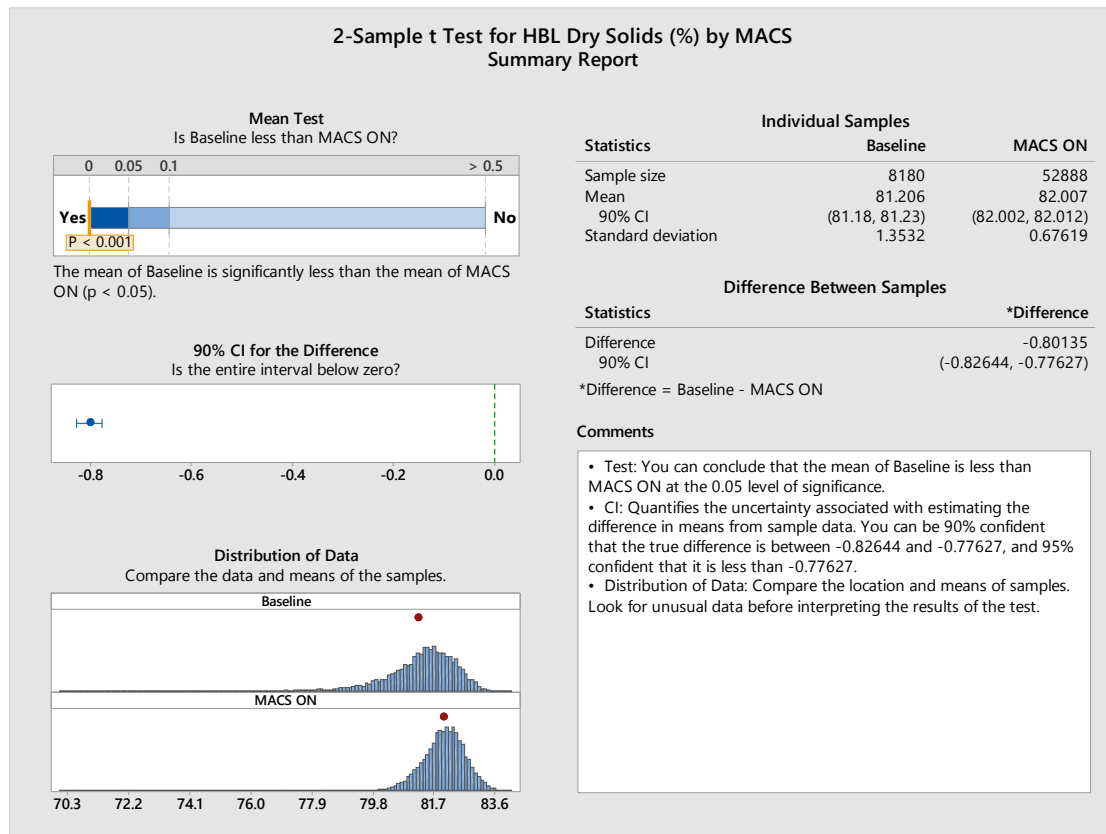


Figure 3. Dry solids content statistical analysis.

The second KPI was the furnace residual oxygen average and standard deviation. These parameters are important indicators as both should be kept as low as possible for an optimized process in the recovery boiler. By controlling the inflow of the high secondary and tertiary air flows in an optimized way, the residual oxygen decreased from 3.0% to 2.3% (Figure 4 and Figure 5), while the standard deviation was reduced from 0.32 to 0.14 %. Translating to a 56% reduction and a confirmation of a more stable process at a higher steam production rate.

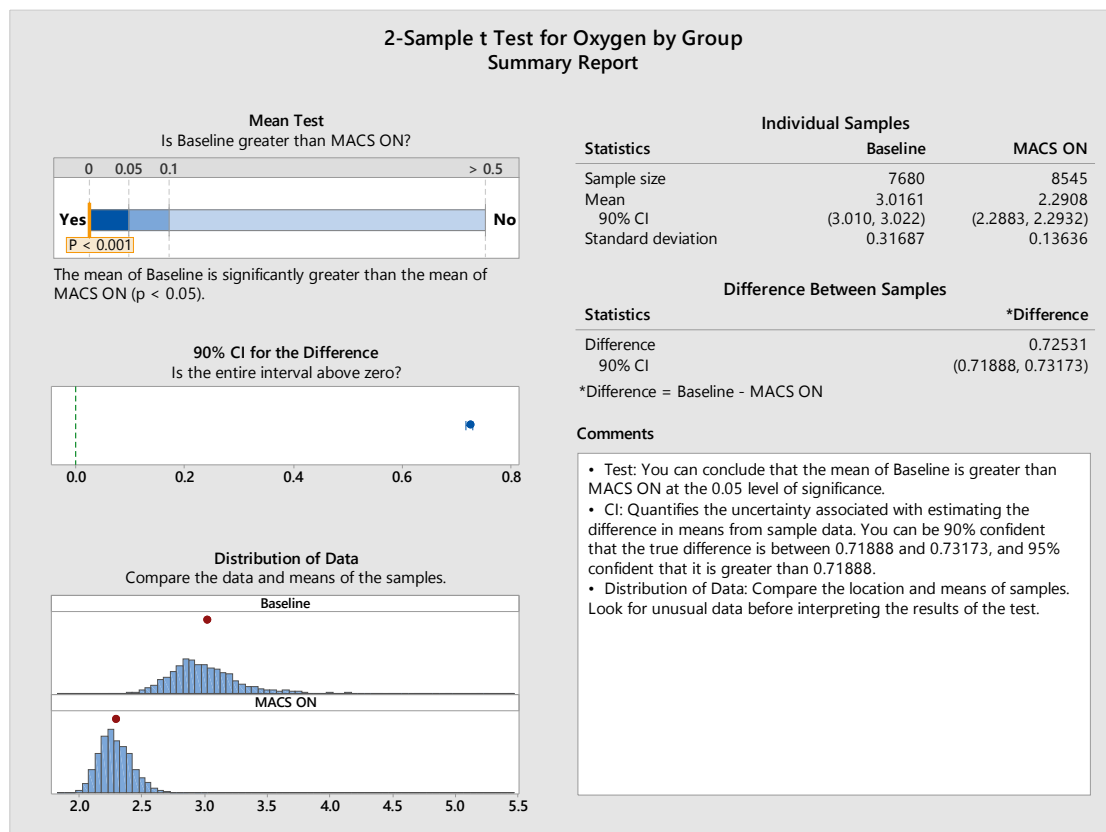


Figure 4. Oxygen statistical analysis.

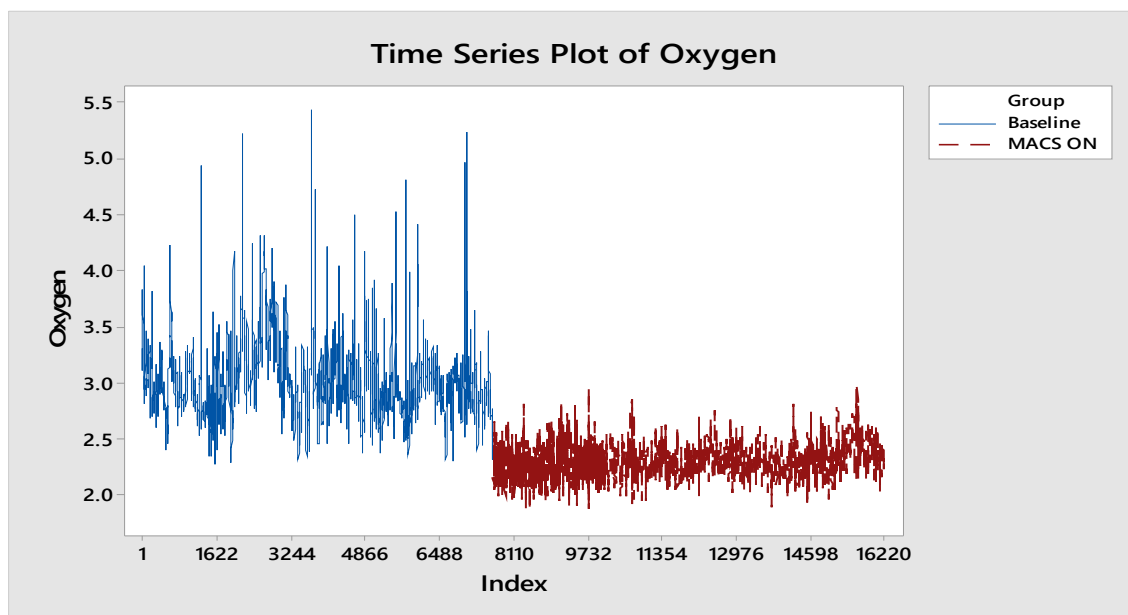


Figure 5. Oxygen time series trend.

Heavy black liquor with a greater dry solids content has a greater calorific power. Therefore, the high pressure steam generation in the recovery boiler is also greater. The project results showed an increase of 2.7 % on recovery boiler steam generation. This figure is based on a comparison of results achieved between April and May 2019 when the recovery boiler application was running. April had a steam ratio of 3.294 t/tds (tons of steam per tons of dry solids

burnt) and May a steam ratio of 3.342 t/tds, which shows an improvement of 0.048 t/tds of the steam ratio. The evaporations' application increment was 0.037. Adding both, it means an increment of 0.085 t/tds, which would represent a 2.7 % improvement over the baseline (Figure 66). The excess high pressure steam generated is used for power generation in a condensation turbine, providing significant financial return to the site.

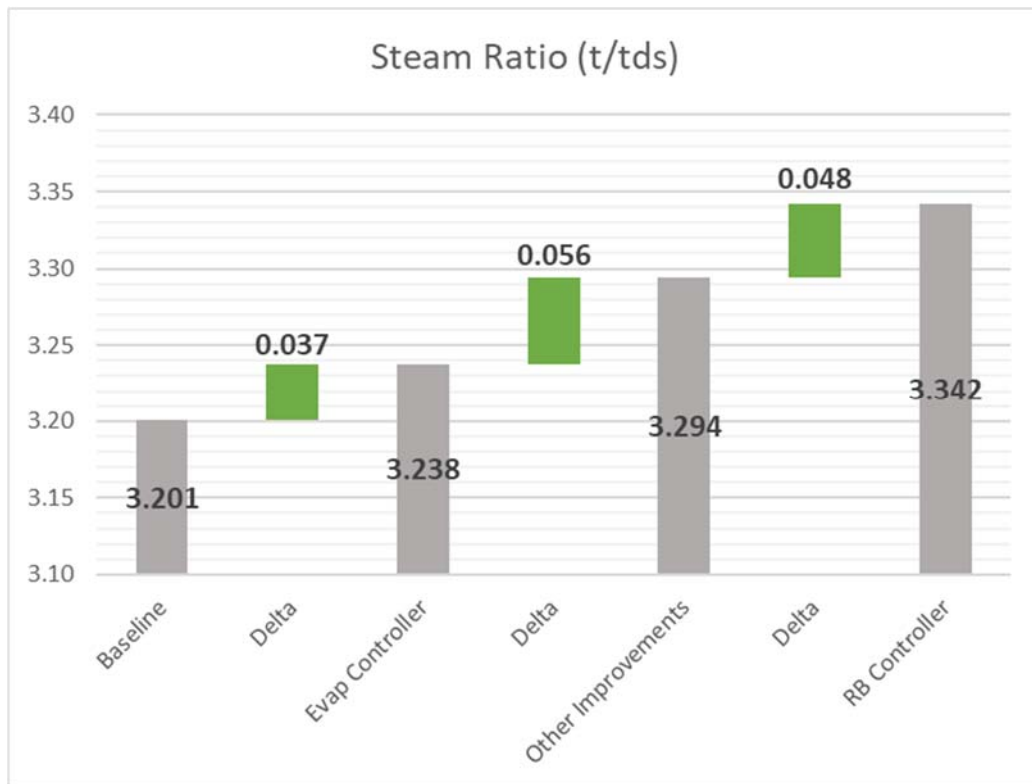


Figure 6. Steam Ratio Increment.

The steam amount used in the evaporator plant was not considered as it used low pressure steam, the impact on steam generation occurs at the high pressure header. It is also impacted by weak black liquor quality. If the weak black liquor solids coming to the evaporation plant have lower solids content, the plant will need more overall steam to reach to the same heavy black liquor dry solids target. Thus, the focus was to increase the steam generation of the recovery boiler as that would overcome any increment on steam utilization in the evaporation plant.

The heavy black liquor dry solids content was close to the upper limit when considering the standard deviation. If an average higher than 82.5% was set as target, problems downstream would occur. During the project period no major impact was noted in the fiber line.

REVENUE BENEFITS

The increment was calculated comparing the steam ratio average from the baseline period to a period after the controls implemented. The steam ratio increment using both applications was calculated in 0.085 t/tds. The steam ratio during both periods was corrected by white liquor sulfidity, as during the studies it had a large impact on the generation. All steam ratios, baseline, and performance evaluations considered the sulfidity at a 32%.

An increase of 0.085 t/tds and 1,611,600 tds/year burned using both controls correlates to an incremental economic benefit of 136,986 tonnes steam. This amount of steam corresponds to a power increase of 39,139 MWh which with an estimated energy price of 51 \$/MWh means a total estimated savings of ~ 2,000,000 USD per year. The project met its targets and Line 1 in Três Lagoas is now running according to control expectations.

ACKNOWLEDGEMENTS

The authors wish to thank Suzano Três Lagoas' Automation Team and Evaporators and Recovery Boiler operators for providing the support necessary to implement both applications.

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4. Seborg, D. E., "Process Dynamics and Control", Chapter 20, (2011).

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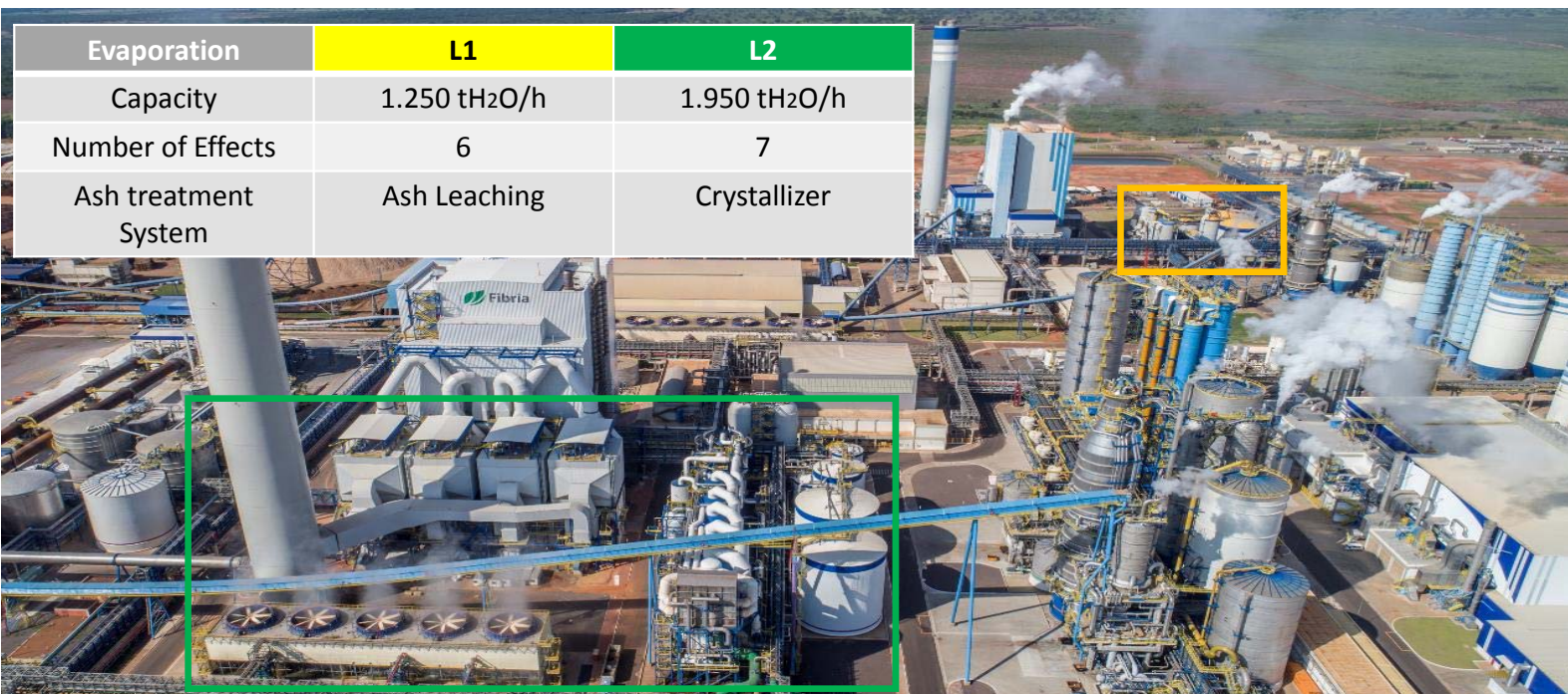
Demi N. B. Lidorikiotis, BTG, Seattle, WA, USA

Agenda:

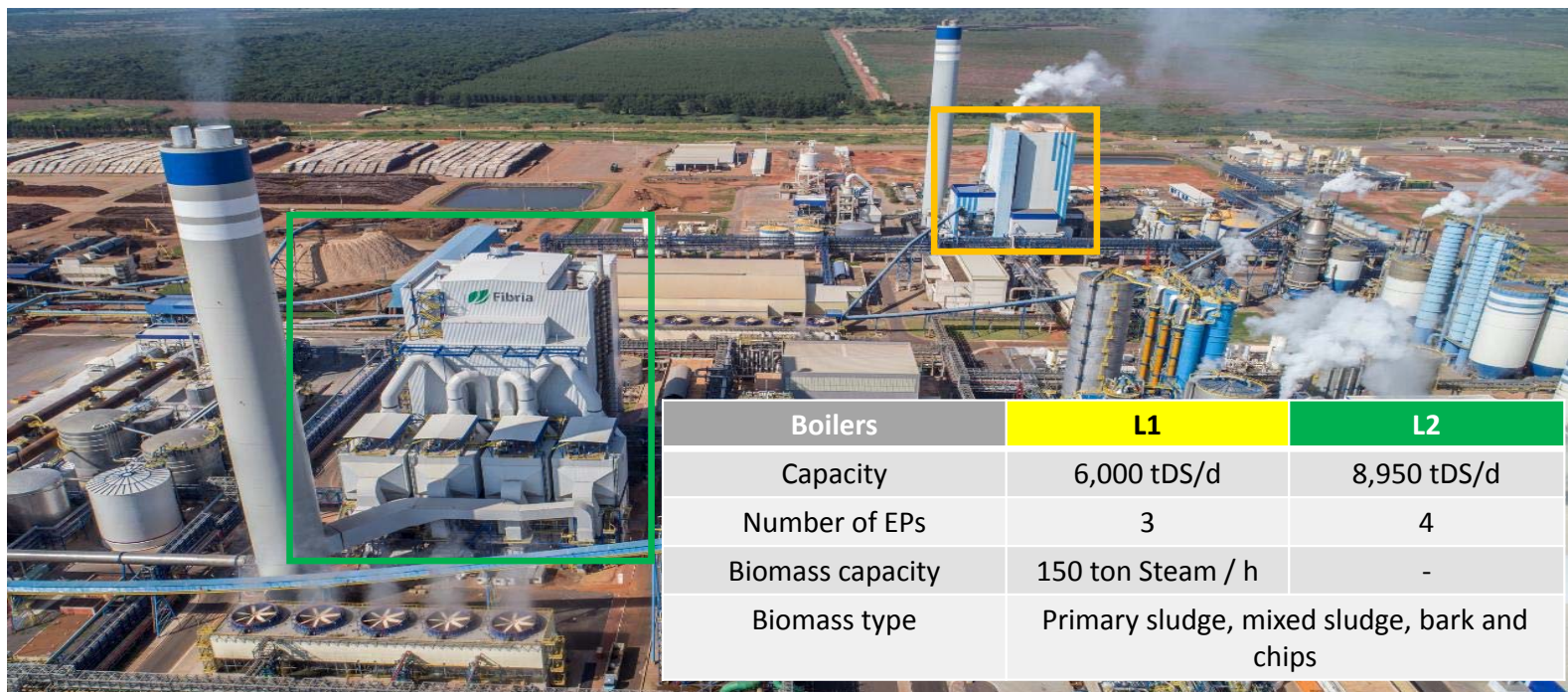
- Evaporation and recovery boiler area overview
- Couple of variables which impact on RB steam ratio
- Evaporation plant advanced control
- Recovery boiler advanced control
- Conclusion

Gateway to the Future

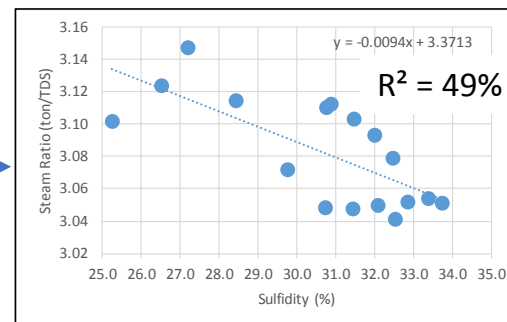
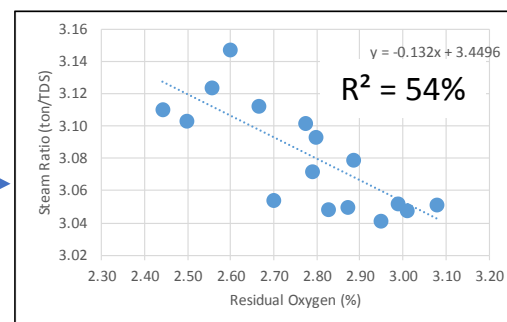
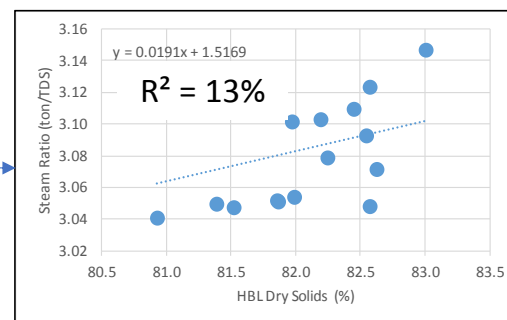
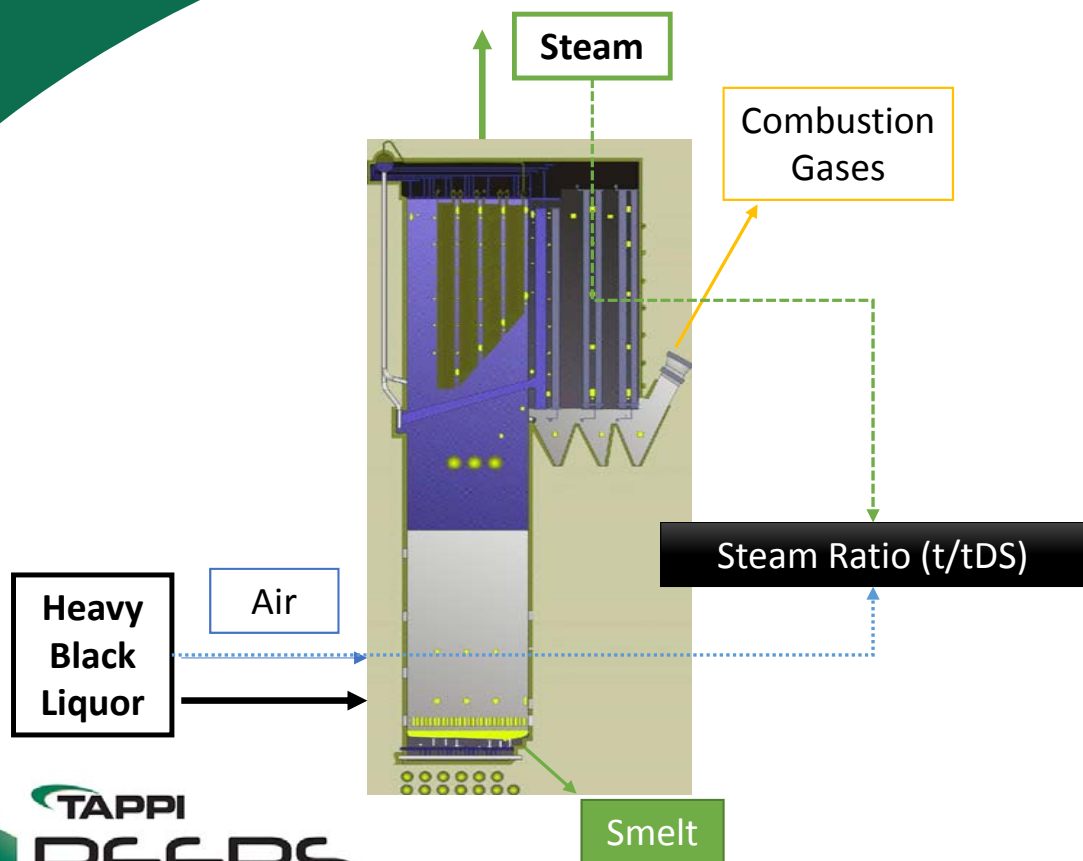
Evaporation	L1	L2
Capacity	1.250 tH ₂ O/h	1.950 tH ₂ O/h
Number of Effects	6	7
Ash treatment System	Ash Leaching	Crystallizer



Gateway to the Future



Steam Ratio (t steam/tDS)



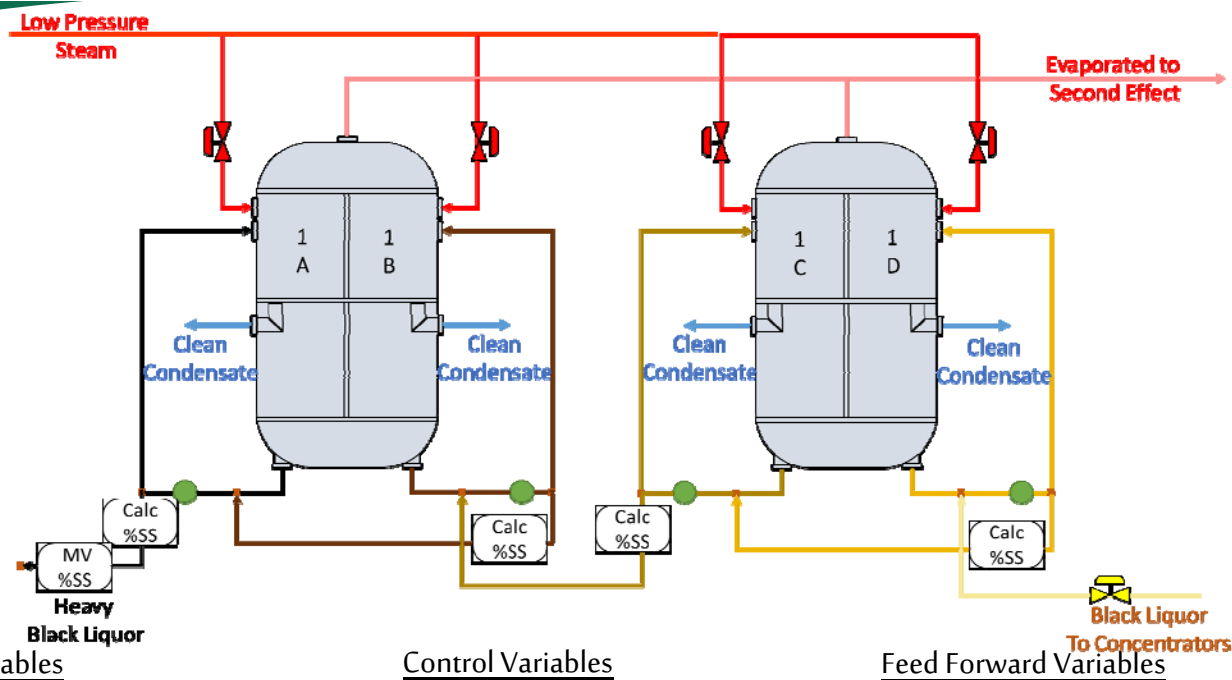
Control Concept

Model Predictive Controls (MPC) - multivariable control algorithm which uses a set of linear dynamic models representing the process to predict the effect of future control moves on the output variables (controlled and constraint). An optimization routine is used to compute a set of future control moves such that a performance index is maximized.

Evaporation plant MPC:

- ✓ Control accounts for interactions between steam flow, product solids and feed solids;
- ✓ Predictive control compensate for disturbances from the upstream processes, such as changes in brown stock washing;
- ✓ Controller “understands” how fresh steam usage, feed liquor solids and product solids respond to the process changes;
 - ✓ Controller uses this built-in knowledge to both improve the evaporator economy, stabilize the product solids and maximize the product solids to the desired level.

Evaporation Control Matrix



Manipulated Variables

#	Description
1	Steam to 1D
2	Steam to 1C
3	Steam to 1B
4	Steam to 1A
5	Liquor Flow to Concentrator

Control Variables

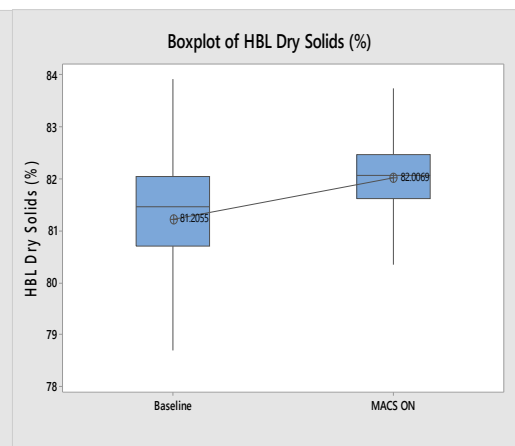
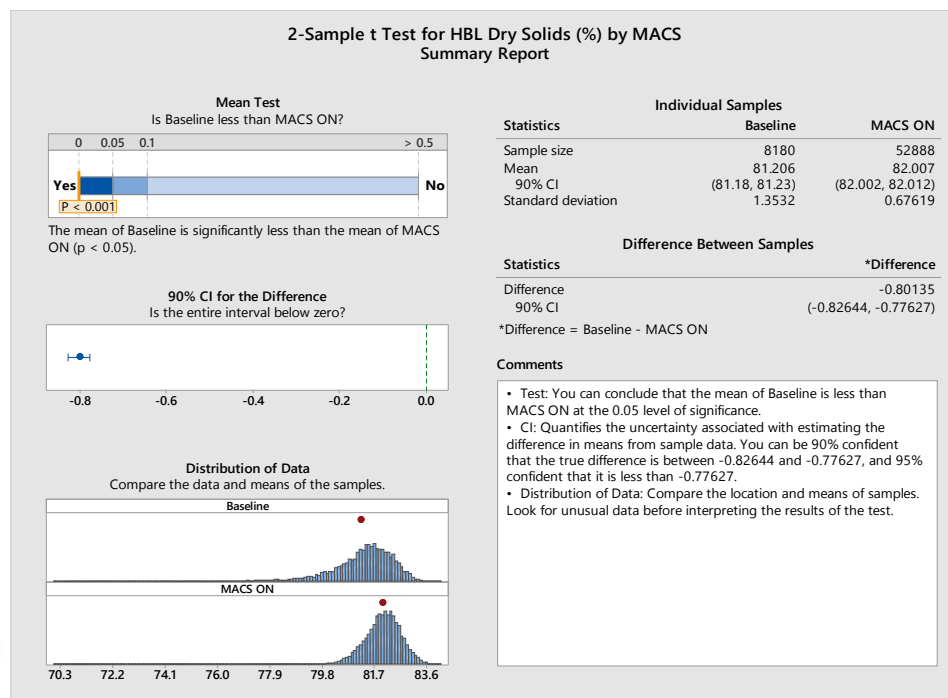
#	Description
1	Est. 1D Sol. (BPR)
2	Est. 1C Sol. (BPR)
3	Est. 1B Sol. (BPR)
4	Est. 1A Sol. (BPR)
5	Evap. Solids
6	1 st Effects Header Pressure

Feed Forward Variables

#	Description
1	Est. 1D Sol.
2	Est. 1C Sol.
3	Est. 1B Sol.
4	Liquor flow to 1 st Effects

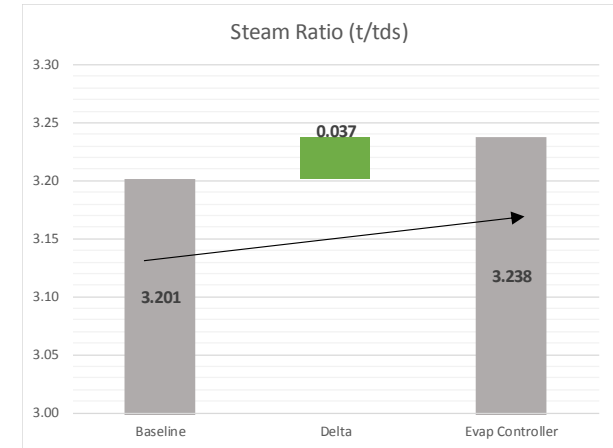
Evaporation Results

- ✓ APC was able to increase dry solids content from 81.2% to 82.0%, reducing the standard deviation from 1.4% to 0.7%, which means a 50% reduction on liquor quality variability;
- ✓ Improvement was possible without increasing the number of too high dry solids content excursions, which are not desirable.



Evaporation Plant – Conclusion

- Utilizing an advanced process control system based on predictive model was effective on reducing the dry solids oscillation of the heavy black liquor going to the recovery boiler;
- Heavy black liquor with a greater dry solids content has a greater calorific power. Therefore the high pressure steam generation in the recovery boiler is also greater;
- The extra high pressure steam generated can be used for power generation in a condensing turbine, enabling significant financial return.



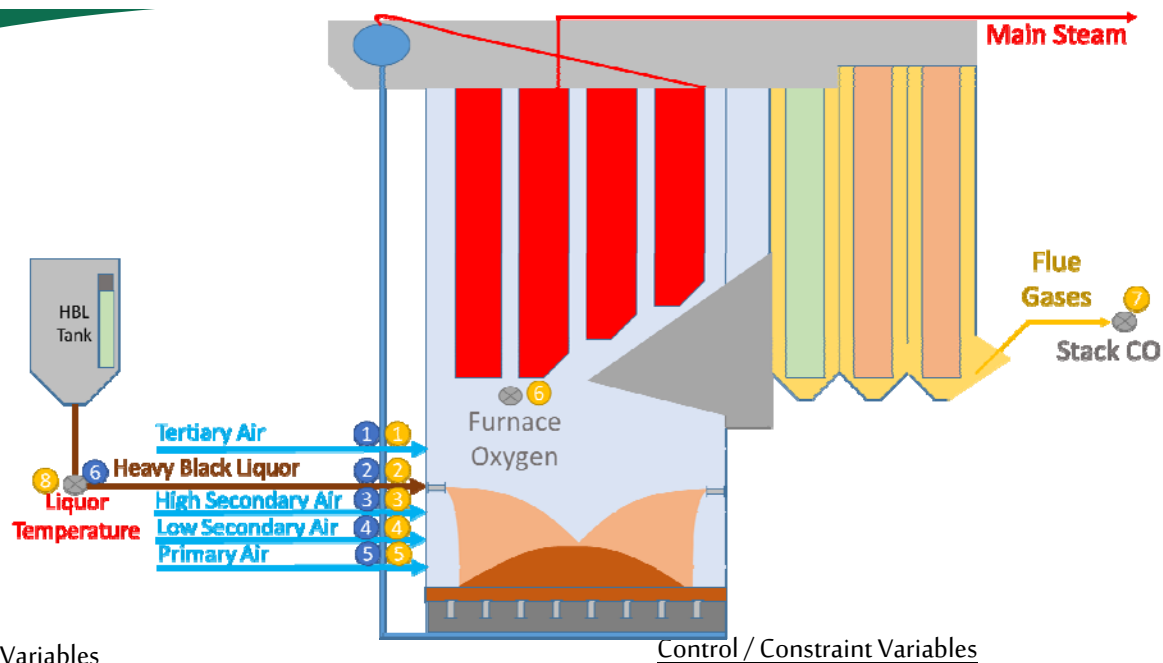
Average increment on the steam ratio (corrected by liquor sulfidity) between June/18 and January/19

Control Concept

Recovery boiler plant MPC:

- ✓ Control accounts for interactions between all intake air flows, boiler load and feed solids;
- ✓ Predictive control compensate for disturbances from the upstream processes, such as changes heavy black liquor dry solids content;
- ✓ Controller “understands” how high secondary and tertiary intake air flows, heavy black liquor solids and boiler load respond to the process changes;
 - ✓ Controller uses this built-in knowledge to both improve the furnace residual oxygen, stabilize the combustion process and maximizing the steam generation.

Recovery Boiler Control Matrix



Manipulated Variables

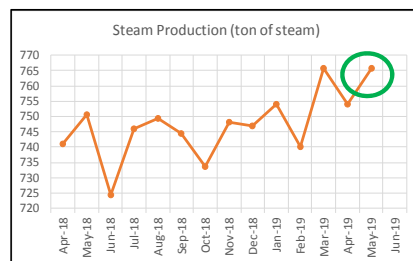
#	Description
1	Heavy Black Liquor Flow (Load)
2	Primary Air Flow
3	Low Secondary Air Flow
4	High Secondary Air Flow
5	Tertiary Air Flow
6	Steam Injector

Control / Constraint Variables

#	Description	#	Description
1	Boiler Load Target	6	Furnace Residual Oxygen (Target)
2	Primary Air Flow (Air Curve)	7	Stack CO (High Limit)
3	Low Secondary Air Flow (Air Curve)	9	Heavy Black Liquor Temperature
4	High Secondary Air Flow (Air Curve)		
5	Tertiary Air Flow (Air Curve)		

Gateway to
the Future

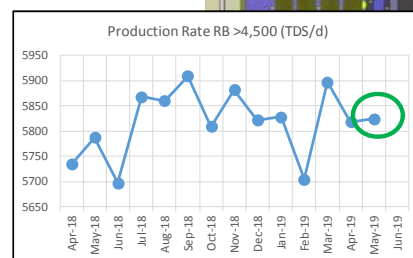
Steam Ratio
(t/tDS)



Steam

Combustion
Gases

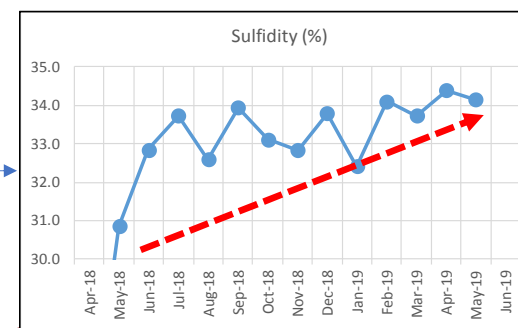
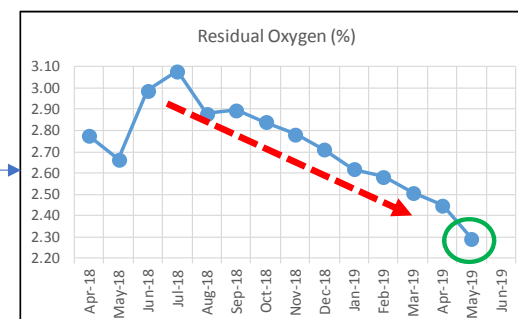
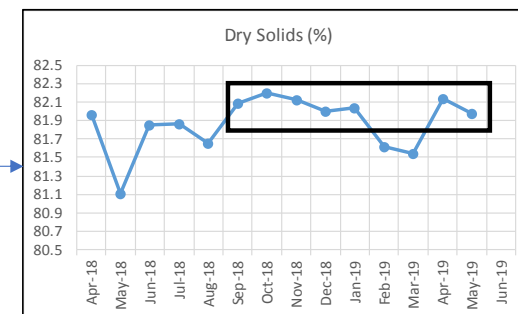
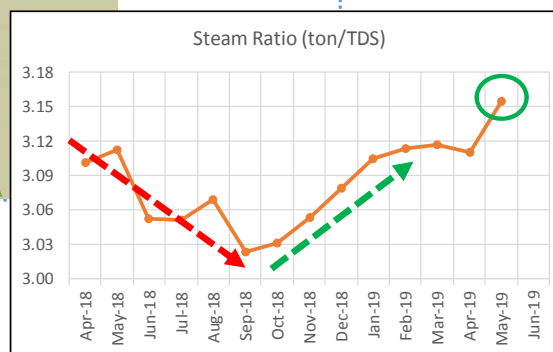
Steam Ratio (t/tDS)



Air

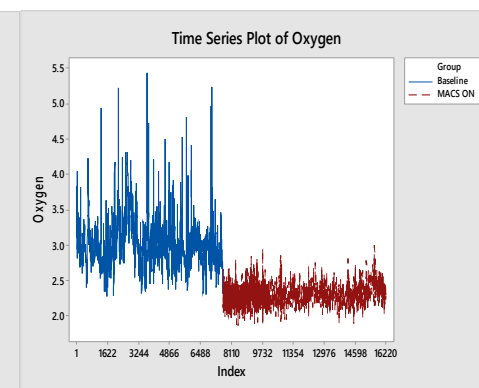
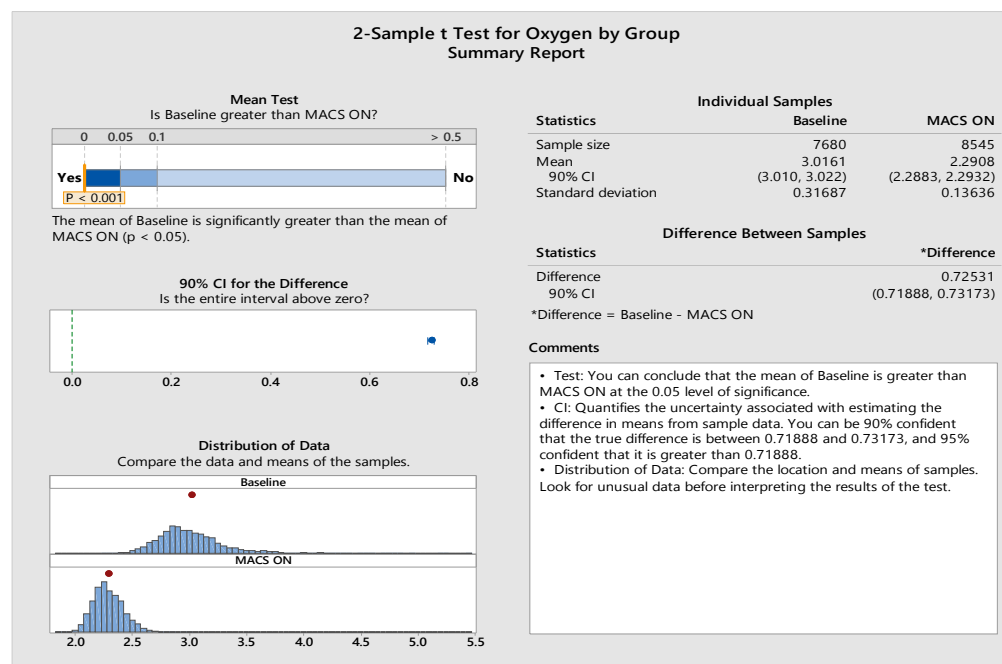
Heavy
Black
Liquor

Green
Liquor



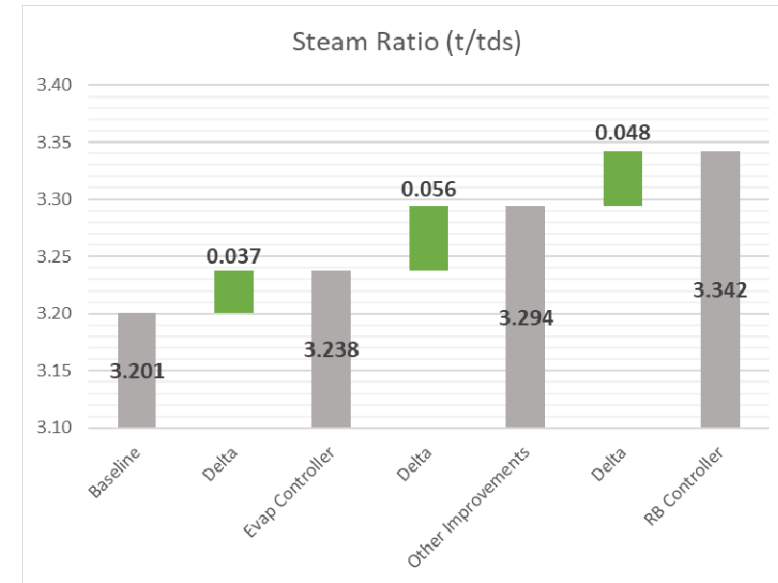
Recovery Boiler Results

- ✓ By controlling the inflow of the high secondary and tertiary air flows in an optimized way, the residual oxygen decreased from 3.0% to 2.3%;
- ✓ Standard deviation was reduced from 0.32 to 0.14 %, translating to a 56% reduction and a confirmation of a more stable process at a higher steam production rate.



Recovery Boiler – Conclusion

- April had a steam ratio of 3.294 t/tDS and May a steam ratio of 3.342 t/tDS, which shows an improvement of 0.048 t/tDS of the steam ratio;
- The steam ratio increment using both applications was calculated in 0.085 t/tDS, which would represent a 2.7 % improvement over the baseline;
- This increase correlates to an incremental economic benefit of 136,986 ton steam/year. This amount of steam corresponds to a power increase of 39,139 MWh, which means a total estimated savings of ~ 2,000,000 USD per year.



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