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# Advance process control in chemical recovery operation (evaporation plant, recovery boiler, white liquor plant) in kraft pulp mills

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**Abstract:** *The chemical recovery process, particularly in kraft pulp mills, is a critical, highly interactive, and multivariable operation responsible for recycling cooking chemicals (NaOH, $Na_2S$) generating steam and reducing environmental impact. Conventional PID control often struggles to manage the significant time delays and nonlinearities inherent in this process, leading to efficiency losses. This paper presents the application of 'Advance Process Control' (APC), incorporating Model Predictive Control (MPC), soft sensors to optimize recovery operations. By stabilizing key variables—such as liquor density in evaporators and air-to-fuel ratios in the recovery boiler—APC maintains tight control close to operational constraints. Implementation results demonstrate reduced variability, significantly minimized fouling of convection surfaces, and higher white liquor throughput. Ultimately, this translates into increased liquor firing capacity, improved energy efficiency, lower emissions, and substantial economic benefits.*

**Keywords:** *Advanced Process Control (APC), Model Predictive Control (MPC), Chemical Recovery Boiler, Kraft Pulping, Optimization, Soft Sensor.*

## 1. Introduction

Advance Process Control (APC) in chemical recovery optimizes kraft pulp mill operations by using multivariable predictive algorithms to manage complex interactions, such as those in evaporation and recovery boilers. It reduces variability, allowing units to operate closer to efficiency constraints, maximizing throughput, reducing steam usage, and lowering emissions

Process Automation Systems (PAS) are widely known to be a crucial element in processing plants worldwide. Chemicals, petrochemical, oil refining, and power generation industries are vast and complex and said to be controlled by just a handful of significant players worldwide. In an ever-changing environment, industry leaders employ state-of-the-art PASs when possible to mitigate complexities -- with Advanced Process Control (APC) systems explicitly leading to higher efficiency, less operator interaction and increased profits.

APC is a powerful technology that utilizes mathematical algorithms and computer software to optimize production yield while minimizing energy consumption. It can be used in various industries, including chemicals, oil and gas, and manufacturing. By continuously monitoring and adjusting production processes, APC can help companies achieve significant cost savings, improve product quality, and enhance overall efficiency. Most engineers will agree that stabilizing control loops, with significant process dead time and strong process interactions, is complicated. APC has become a standard solution for realizing stable control processes – and to be put in layperson's terms – APC is the added value upgrade to a Process Automation System.

"MPC (Model Predictive Controllers) rely on dynamic models of the process, most often linear empirical models obtained by system identification. The main advantages of MPC is that it allows the current timeslot to be optimized, while keeping future timeslots in account."

"Soft Sensor or (inferential analyzer) is a common name for software where dozens of measurements are processed together. The interaction of the signals can be used for estimating properties of material being processed."

APC is typically comprised of MPC or Soft Sensors (Inferential property estimation), enabling more advanced stability and control by utilizing the multivariate analysis and estimated product properties in real-time (such as Dew point, RVP, Density, etc.)

The information gathered is then used to stabilize the process control without user interaction and adjust the set point closer to the limit - as shown below. Changing the specification point of the operation from high energy consumption to a point with less energy consumption creates the opportunity to use energy much more efficiently and improve profit margins.

## 2. Key Aspects of APC in Chemical Recovery

- **Purpose:** The primary goal is to maximize profitability by increasing operational efficiency (e.g., maximizing throughput while managing constraints) and reducing energy costs (e.g., steam consumption).
- **Key Units:** APC is applied to critical areas including the multiple-effect evaporator plant (solid concentration control), the recovery boiler (combustion efficiency), and causticizing/lime kiln operations.
- **Core Technologies:**
    - o **Model Predictive control:** Calculates optimal moves to predict and manage future process behavior.
    - o **Inferential Sensors (Soft Sensors) :** Estimate properties in real-time (like liquor density or dry solids content) that are difficult to measure directly.
    - o **Feed Forward Control:** Anticipates disturbances (such as load changes) before they affect process stability.
- **Benefits:** Typical benefits include significantly reduced variation in dry solids content, reduced steam consumption in evaporators, increased fuel efficiency in recovery boilers, and increased production capacity.
- **Implementation:** APC integrates as a level two optimization application above the distributed control system (DCS) or programmable logic controllers (PLC).

## 3. Common Applications in Recovery Operations

1. Evaporation plant : Stabilizes dry solids content to maximize efficiency while ensuring the liquor does not exceed safety constraints before firing.
2. Recovery Boiler: Balances combustion, controls the reduction efficiency of inorganics, and manages steam production.
3. Causticizing & Lime Kiln : Improves white liquor quality by reducing fluctuations in causticizing efficiency and controlling TTA (Total Titratable Alkali) in the green liquor

## 4. Advanced Process Control for high production and energy efficiency of multiple-effect evaporator plants

APC solution essentially is controlling and monitoring of the multiple-effect evaporation plant in an organized manner. Using a multivariable model-based approach, the solution controls the strong liquor production rate and dry solids content to minimize energy consumption and increase evaporation plant capacity.

Black liquor evaporation is a very important part of the recovery process. The evaporation unit provides the link between the fiber line and recovery sections and plays a major role in the operation of pulp mills.

Ensuring the production of strong black liquor with on-target dry solids content and minimum variability is the key to stabilizing the recovery section and optimizing steam utilization. The multi-effect evaporators use low and medium steam pressure to transform weak black liquor with a dry solids content of 15-20% into strong black liquor with a dry solids content of 80-85%.

Expert Optimizer Vapor solves these challenges by providing tighter control of the evaporation process, reducing variability of the black liquor quality while also lowering operating costs and increasing capacity.

**Features:**

Dry solids control to optimize steam economy and provide higher evaporation capacity

Production rate controls

Real-time adaptive modelling: Automatic adjustments based on process changes

Higher-order model support: Captures process dynamics accurately

Cost optimizer: Looks for ways to optimize operational costs within process constraints

Evaporators performance monitoring

KPI Dashboard and control usage reports by day/shift

Performance monitoring, with both on-site and remote access for customers and ABB

Task oriented and user friendly customizable operator displays

**Benefits**

- Increased production rates
- Removes bottlenecks
- Reduced strong liquor dry solids variations
- Decreased energy consumption, giving steam savings

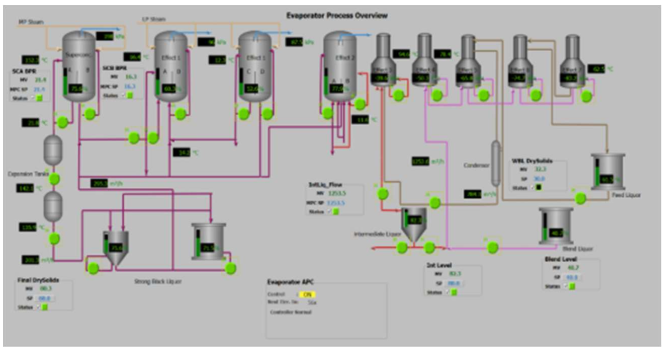
**How it works – Stabilizing black liquor quality and lowering costs**

This APC control effectively uses a multivariable model-based approach to optimize the black liquor dry solids profile across the multi-effect evaporation process.

APC coordinates the gradual rise of the boiling point of the individual effects (or evaporators) as well as the feed and intermediate liquor flows. By reducing the variability in the black liquor dry solids, the APC solution minimizes overall steam consumption while stabilizing operations. This results in fewer upsets and longer intervals between cleanings.

The included production rate control ensures fast and smooth changes during swings in the production rate by efficiently coordinating the various operating parameters (i.e., flows and boiling point rise) to ensure minimal disturbance to the system.

The liquor tank levels are also maintained within desired levels to ensure optimum inventory levels and smooth transitions during disturbances and process upsets. Control performance will not degrade over time with always-on monitoring and analysis of the APC solution.



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## 5. Advance Process Control for Recovery boiler

### 5.1 Introduction

Consumed air optimization for recovery boilers has several potential benefits including better stability, improved efficiency and increased throughput. Multivariable, model predictive control technology has proven very effective at optimizing consumed air. With this technology, minimum excess air can be achieved while all other process constraints are honored. Each one percent (1%) decrease in boiler excess oxygen yields a 0.5 – 1.0% increase in efficiency.

In mills with more than one recovery boiler maximizing firing rate of the more efficient boiler may replace some fossil fuel. In recovery limited mills increased boiler efficiency allows burning more liquor, which, in turn, allows increased pulp production.

An example of before and after boiler excess oxygen is shown in Figure 1.

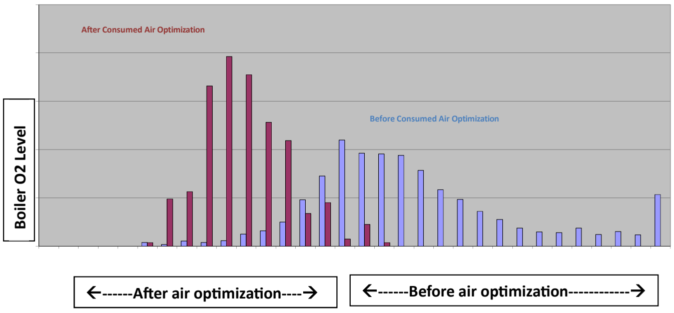



*Figure 1 – Boiler $O_2$ Distribution*

### 5.2 What is consumed air control?

A model predictive controller is derived from a dynamic model, which describes the principal features of the process responses such as:

- time delays,
- interactions between inputs and outputs,
- and complex responses ( for example: inverse, second order and integrating) A multivariable controller includes three classes of variables:

1. Controlled Variables (CV): Process variables that we want to keep within a range (constraints) or at a target, e.g. dry solids rate, oxygen
2. Manipulated Variables (MV): Process variables (valves) that can be manipulated through basic PID (proportional-integral-derivative) controllers and have an effect on one or more CVs, for example black liquor flow and air flows.
3. Feedforward Variables (FV): Process variables that have an effect on one or more CVs but cannot be controlled by the multivariable controller, for example black liquor %solids

The multivariable controller includes models of the impact of manipulated and feed forward variables (MVs and FVs) on controlled variables (CVs). These models are generated from response tests of the system in a similar manner as tests for tuning single level loops. The tuning of the multivariable controller establishes desired response rates of manipulated variables and desired process "objectives". Constraints and targets (setpoints) are prioritized within the consumed air controls to achieve the desired results. As an example, a high priority on CO will override the need to lower $O_2$. Once the CO is within the limits, the $O_2$ is quickly lowered to within the operating target.

The typical objectives of a consumed air optimizer include:

- Boiler O2 Reduction - Every 1% of $O_2$ reduction yields 0.5 – 1% Boiler efficiency increase
- Minimize Steam Flow Variability – Critical for steam limited mills or boilers operating close to MCR
- Maximize Throughput – Critical for recovery limited mills
- Increase Boiler Efficiency by controlling feedwater inlet temperature
- Maintain emissions below environmental limits – $SO_2$, TRS

Models are "identified" by relating changes in CVs to changes in MVs (and FVs). Models are expressed in time series format. There is one model for each CV and includes contributions from each MV and FV.

Historical data cannot be reliably used to identify robust models. This is because operators typically change MVs in a coordinated way such as increasing air flows as they increase black liquor flow. Models based on such data would be "biased" and will not provide good estimates of the CVs. A technique known as PRBS (pseudo random binary series) testing provides robust models with superior predictive properties.

The model predicts the future trajectory of the process outputs for any variation in the process inputs. A change in one of the MVs or FVs results in a dynamic response in one or more CVs.

Models are typically linear, multivariable, time-series. The multivariable control can also include logic for interlocks and model switching.

Figure 2 shows actual data from a typical PRBS test. The time interval between successive setpoint moves is set by software based on an engineering estimate of the process time constant. Compared to typical bump tests the magnitude of the setpoint changes are smaller but procedure is run for a longer time period.

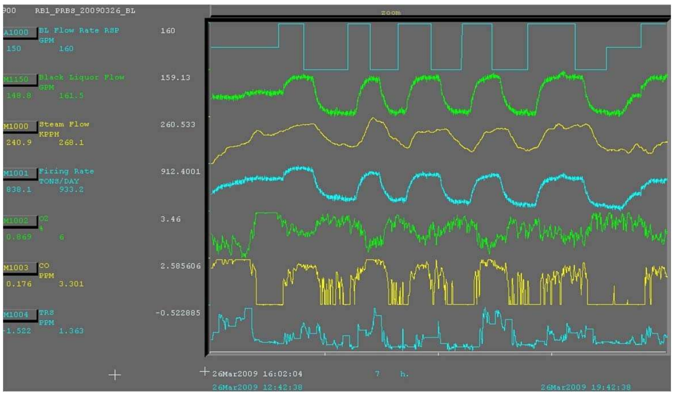


*Figure 2 – Example PRBS Test*

Trends shown from top to bottom:

Blue - Black liquor flow setpoint, which was set at 155 gpm prior to test.

Greeen – Black liquor flow

Brown –Steam flow

Bold Cyan – Firing rate (dry solids)

Bold Green – Boiler %O2

Yellow - Combustibles

Cyan - TRS

A resulting model will look similar to the matrix shown in Figure 3.

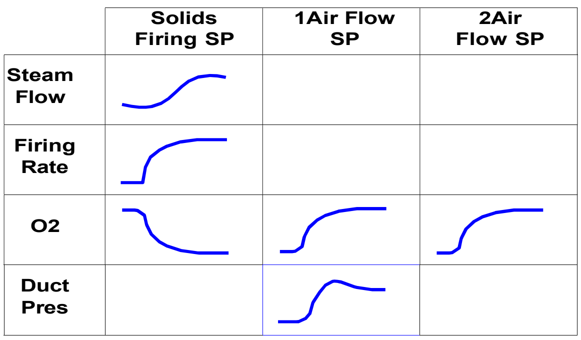



*Figure 3 – Example Model Matrix*

The input/output signal structure of the controller is determined by reversing the roles of CVs and MVs in the model. By "inverting" the models, one can calculate future MV moves that would move the CVs to their setpoints or constraints as shown in Figure 4.

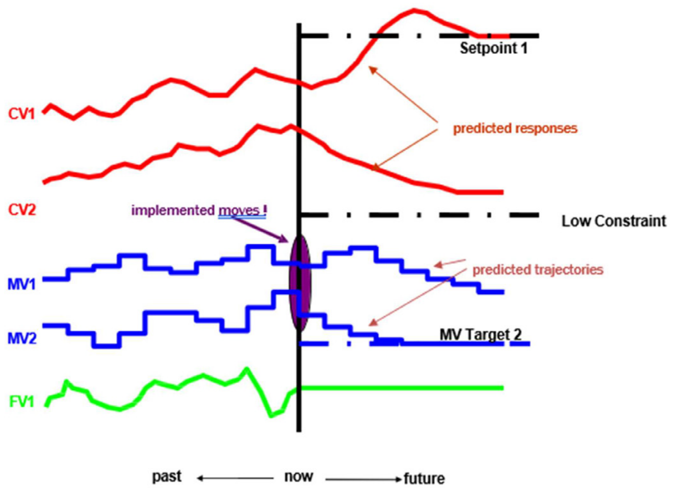



*Figure 4 – Example of Model Predictions*

Reducing variability alone provides limited economic benefits. Targets should be shifted to achieve economic benefits as depicted in Figure 5. This is achieved by an optimizer that is linked to the multivariable controller.

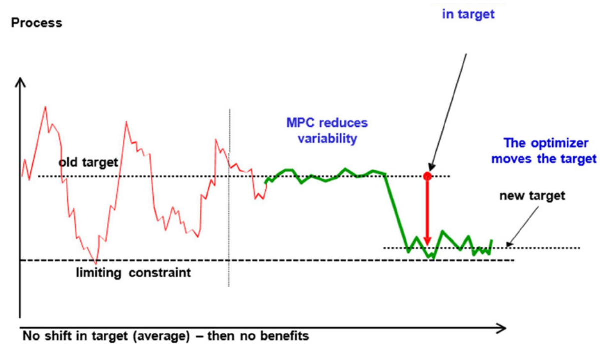



*Figure 5 – Taking Advantage of Reduced Variability to Shift the Target*

Optimization approach shall be as explained in fig 6 below

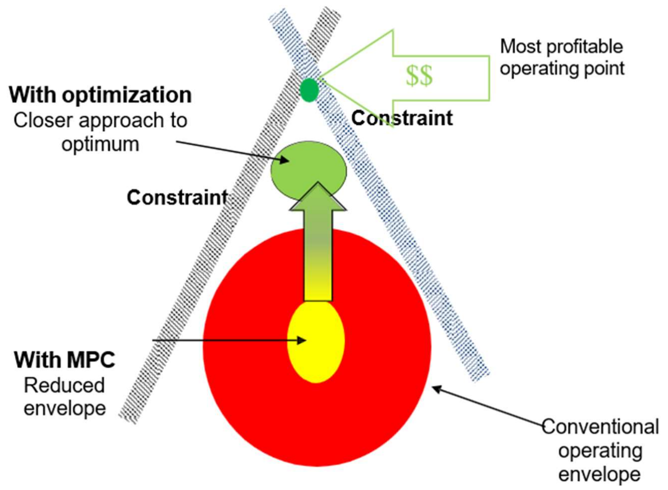



*Figure 6 - Reduce variability and push closer to optimum*

### 5.3 Regulatory control versus multivariable control

Typical regulatory or basic control is volumetric flow or dry solids control. Excess oxygen trim control is often attempted, but seldom successful.

Volumetric flow control includes black liquor flow controlled automatically to a setpoint and air flows controlled automatically, but often on manual. Dry solids control includes black liquor flow controlled to a setpoint calculated to keep the firing rate at a target with the current solids concentration and air flows controlled automatically, but often on manual.

Excess oxygen trim control is usually not successful due issues such as TRS, blackouts and limited inclusion of other boiler constraints. Advanced regulatory strategies that attempt to include multiple constraints are too complicated to be maintained by in-house staff. These strategies are very dependent upon maintaining strict relationships between variables and they become unmanageable as constraints are added.

Multivariable, model predictive control (MPC) takes a higher-level view of the process and addresses issues not covered by regulatory control. Control is based on models between each manipulated variable (MV) and all controlled variables (CV). Most CVs are constraints rather than setpoints and operation is allowed within the range of these constraints.

Models are developed empirically and they may also include feedforward variables (FV). A steady state optimizer pushes the process to the optimum conditions

Under normal conditions, the optimum is at a low level of boiler oxygen, similar to a O2 trim setpoint; however, high or low limit of any CV may stop the controller from reaching the "theoretical" optimum.

The controlled variables for MPC typically include the following

Production

Firing Rate

Steam Flow

Efficiency

Boiler Oxygen

CO/Combustibles

Environmental

TRS

Safety

ID Fan Speed

Mixing

Tertiary Air Windbox pressure

Secondary Air Windbox pressure

Primary Air Windbox pressure

Air Distribution

Tertiary /Total Air

Secondary/Total Air

Primary/Total Air

Air Dampers

Tertiary Air Damper Position

Secondary Air Damper Position

Primary Air Damper Position

The controlled variables for production set a firing or steam production rate, but not both. Usually, these are the only CVs that are setpoint variables. Black liquor inventory is managed by firing rate. If steam flow is controlled it is possible to run the boiler closer to its rated capacity MCR (maximum continuous rating). Steam flow must be compensated for changes in header pressure so that liquor flow is not changed for temporary changes in steam header pressure.

The controlled variables for efficiency have the objective of decreasing boiler oxygen as much as possible based on constraints. Boiler oxygen can be decreased to the point combustibles peaks are observed. The air - combustibles relationship tends to be highly nonlinear.

The variables for environmental control are the focused on TRS. The inability to manage TRS excursions is the primary reason why some supervisory control strategies have not been successful. However, TRS is very difficult to model. A rule-based strategy (fuzzy logic controller) is used to partially bypass the multivariable controller and increase air flows at a faster rate until TRS is reduced. The rule-based controller switches into the waiting mode and air flows are decreased slowly back to their previous values as TRS returns to its normal range. The operator can selectively disable the rule-based controller.

The controlled variables for safety assure that the boiler is kept under negative pressure. The induced draft (ID) fan is used to control boiler pressure. All other factors being constant, increasing air flow results in increased boiler pressure which, in turn, increases the ID fan speed to remove more flue gas from the boiler and the boiler pressure is reduced back to the setpoint. If ID fan is already at maximum speed air flows should not be increased.

There must be sufficient mixing in the combustion zone in order to increase boiler efficiency. Air must be introduced into the boiler at a sufficiently high pressure so that it penetrates into the center of the boiler, so windbox pressure at each level must be kept above its corresponding low constraint. In addition, this minimum windbox pressure constraint is different for each level.

Air flow should not be reduced if windbox pressure drops below the low constraint. Manual damper positions may have to be adjusted so that lower air flow is delivered at a higher pressure. These damper positions may change as a function of firing rate.

The typical manipulated variables employed to satisfy the aforementioned control variables are:

Black liquor flow

Tertiary Air

Secondary Air

Primary Air

This yields a control matrix similar to that depicted in Figure 7. In this case, % solids to recovery boiler, black liquor flow and ID fan pressure are feedforward variables.

| | | Black Liquor Flow SP | Primary Air Flow SP | Secondary Air Flow SP | Tertiary Air Flow SP | %Solids to RB | Black Liquor Flow | ID Fan Pressure |
|---|---|---|---|---|---|---|---|---|
| | | FIC0113 | FIC100 | FIC102 | FIC101 | 50DR1761 | 50PIC201 | PI0109 |
| Steam Flow | FI0116 | + | | | | + | + | |
| Solids Firing Rate | CX0113 | + | | | | + | + | |
| O2 | AI0169<br>AI0169B | - | + | + | + | - | - | + |
| Combustibles | AI0169C | + | - | - | - | + | + | |
| TRS | AI1175 | | | | | | | |
| Primary Air Duct Pressure | PI0100A<br>PI0100B | | + | | | | | |
| Secondary Air Duct Pressure | PI0102A<br>PI0102B | | | + | | | | |
| Tertiary Air Duct Pressure | PI0101A<br>PI0101B | | | | + | | | |
| ID Fan Speed Controller Output | PIC0109.OT PIC0110.OT | | + | + | + | | | |

*Figure 7 – Typical Directional Multivariable Control Matrix*

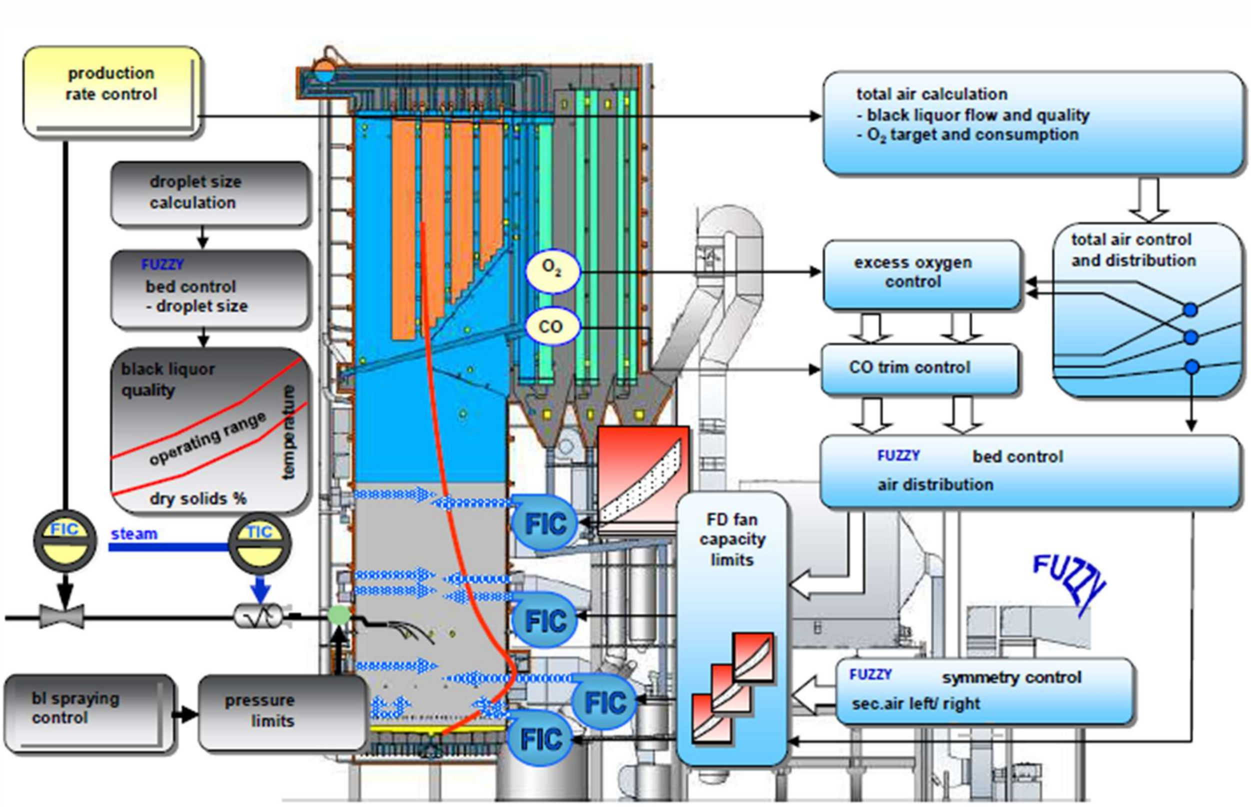



*Figure 8 – Recovery boiler showing advance process control in various sub systems*

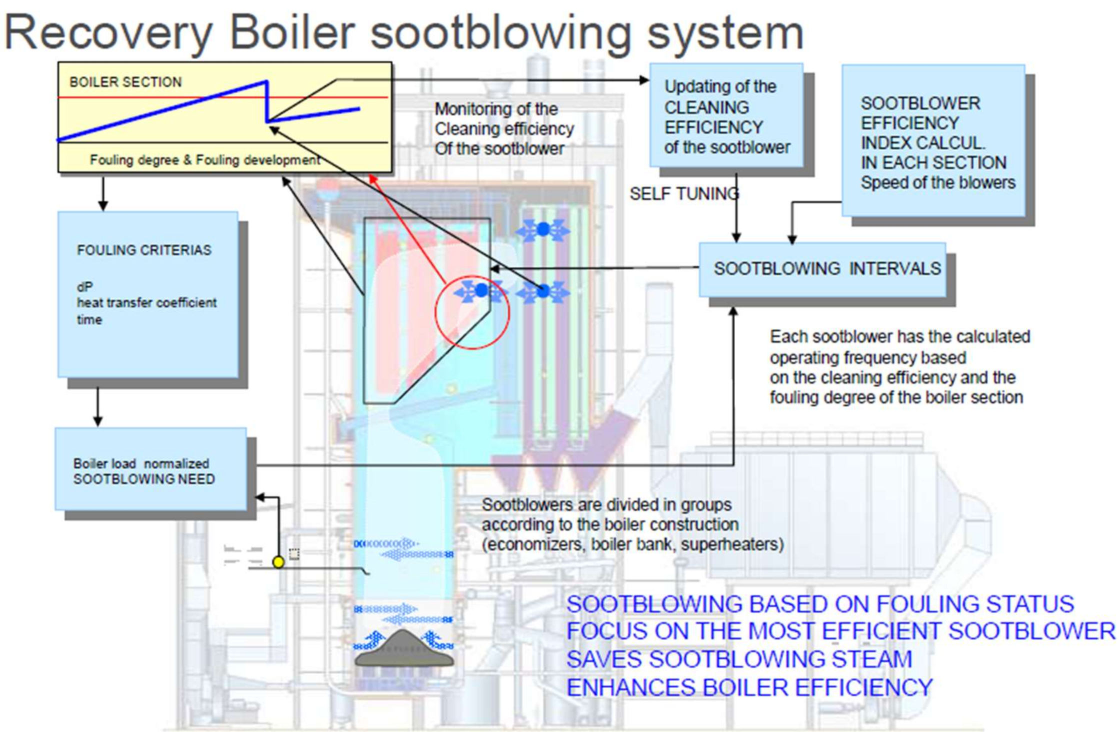


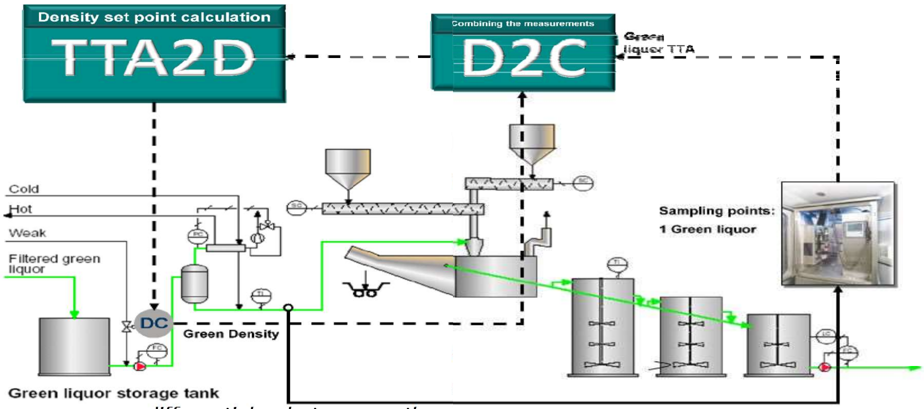

*Figure 9 – Recovery boiler showing advance process control in soot blowing*

## 6. Causticizing process optimization

In the causticizing area, there are two key variables to control – incoming green liquor total titratable alkali (TTA) and the causticizing efficiency (%CE) of the lime mud slurry and white liquor. Metso proposes a different adaptive model-based control strategy for each variable.

The challenges for this process area include the reliability of data, dynamic process parameter relationships, and long process delays.These challenges make it impossible to implement simple static.controls that are robust enough to handle a variety of process conditions.

Ideally, the green liquor TTA control starts at the dissolving tank. At least one control point is required between the dissolving tank and the slaker. The control model is based on comparing an in-line density measurement with an on-line titrator measurement such as a Kajani ALKALI analyzer. The on-line titrator measurement provides an absolute measurement of TTA while the in-line provide a relative continuous measurement. Refer fig 10 below.




differential between the

*Figure 10 – Recausticizing plant showing causticity control*

incoming green liquor and slaker bowl is used as a quick feedback for the lime

reactivity and is modeled to the %CE measurements from on line titrator. This model is once again dynamic and updated in real-time.

The temperature of the incoming green liquor can also be controlled to maximize heat of reaction (dT) in the slaker while preventing boil over. The heat of reaction is also used to ensure proper lime addition to achieve % CE without overliming.

The in-line density measurement is modeled to the on-line measurement to provide a continuous absolute measurement for control. This model is dynamic and adaptive in real-time to changes in operating conditions. If control at both the dissolving tank and the slaker is available, then a slightly higher TTA target is set at the dissolving tank than at the slaker to allow trim control of the TTA to the slaker as explained in fig 11 below.

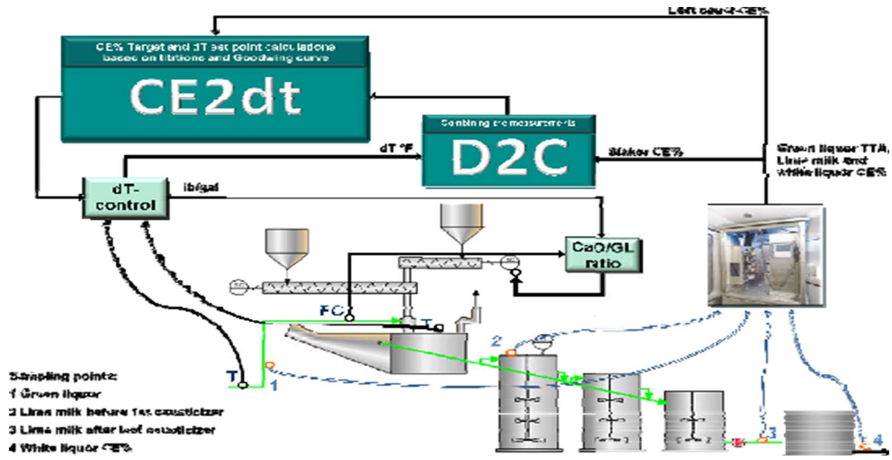



*Figure 11 – TTA control*

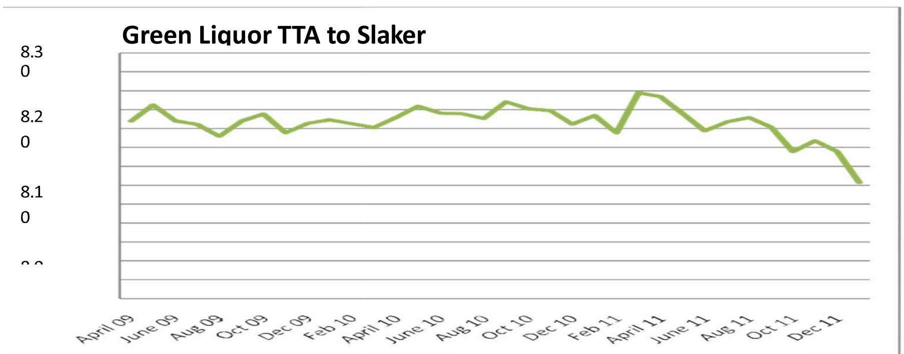
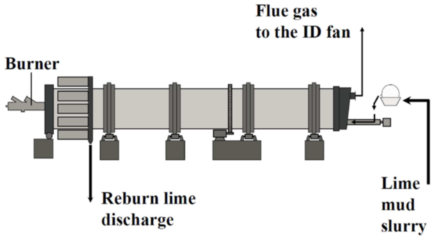



*Figure 12 GL TTA to Slaker*

## 7. APC for rotary lime kiln




Objectives:

- Produce High Quality Lime
- Maintain Stable Hot End Temperature
- Maintain Stable Cold End Temperature
- Maintain Oxygen within Limits
- Prevent CO Formation
- Achieve Production Targets
- Minimize Energy Requirements

### 7.1 APC for kilns – example

Pulp mill produces 425,000 tons, Totally Chlorine Free (TCF) bleached Kraft pulp

- 95,000 tons of chemical thermo –mechanical pulp for hygiene packaging products
- Multi Fuel Lime Kiln, Saw dust used as main Fuel
- Heavy Oil, Odor Gases, and Stripper gases as auxiliary Fuel

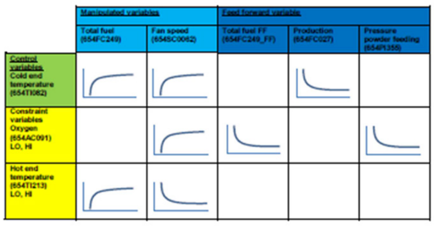


*Fig 13 – Advance process control parameters for lime kiln*

- Cold End Temperature is controlled to setpoint
- Hot End Temperature & Oxygen are controlled within limits
- Fuel Flow & ID Fan Speed are manipulated.
- Oxygen Safety Logics Included
- Production Rate Control Included

Above points are illustrated in fig 13.

## 8. Regulatory versus Advance Process Control

### 8.1 SISO ( Single Input Single Output) – Refer Fig 14

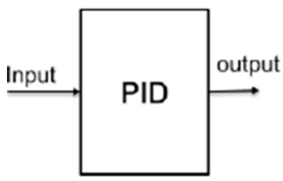
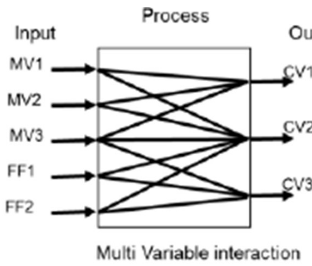
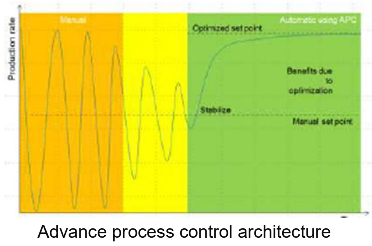



*Fig 14 – Single input single output*

**8.2 MIMO** ( Multi Inputs Multiple Outputs) - Explained in Fig 15



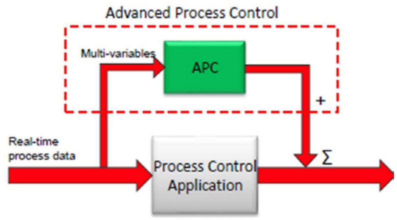




*Fig 15 – Multi input Multi output*

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**8.3 Model predictive control** (Refer Fig 16)

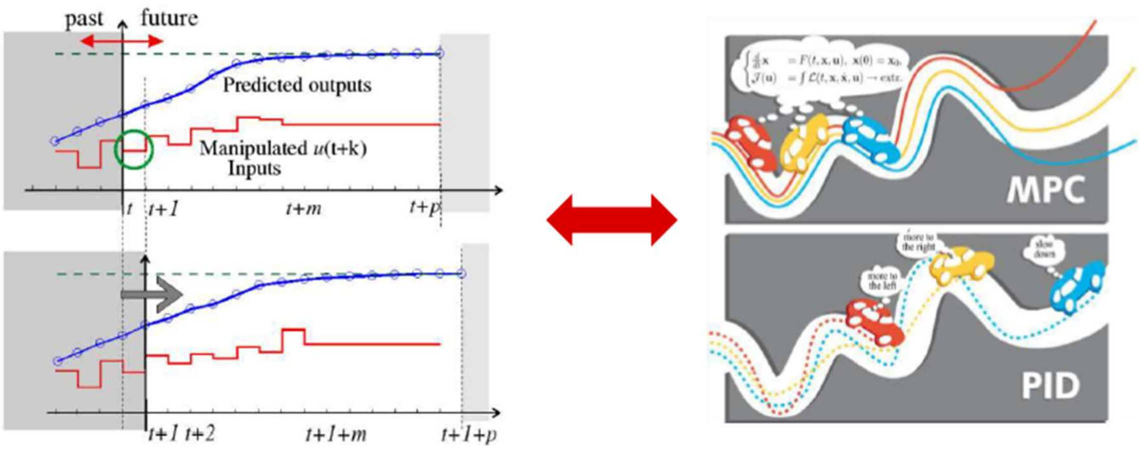


*Fig 16 – Model predictive control depiction*

**8.4 How APC will improve the performance and lower costs?**

Refer Fig 17 below which illustrates APC performance and cost control

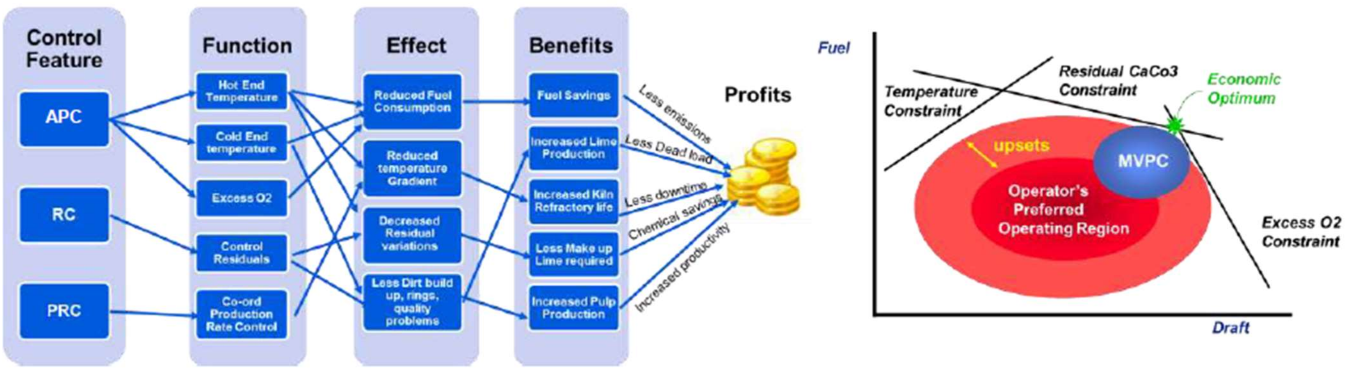


*Fig 17 – Performance and cost control*

## 9. Advance process Control - Economic and Market Context

- **Volatility of Chemical Inputs:**

  Fluctuating costs for makeup chemicals like sodium sulfate, sodium hydroxide, and lime threaten mill operating margins.

  APC stabilizes recovery furnace and causticizing operations to minimize chemical losses and reduce dependence on expensive purchased raw materials.

- **Decarbonization Markets:**

  Selling excess green energy (steam and electricity) to the grid is a major secondary revenue stream.

  APC tightens steam headers and limits boiler variability, allowing mills to optimize cogeneration without compromising pulping capacity.

- **Biorefinery Integration:**

  Advanced controls enable the extraction of lignin and tall oil without destabilizing the recovery boiler. This aligns with the transition toward high-margin biomaterials.

### Return on Investment (ROI) Metrics

- Capital and Timeline:

  Typical APC implementations in recovery islands range from $500,000 to $2.5 million, depending on the scale and number of unit operations (evaporators, recovery boiler, lime kiln). Projects routinely achieve full payback within 6 to 18 months.

- **Energy Efficiency:**

  APC reduces the variability in black liquor dry solids, optimizing the recovery boiler's thermal efficiency. Mills typically see a 1% to 3% increase in steam generation, translating to significant annual savings in supplementary fossil fuels.

- **Throughput and Chemical Yield:**

  By maintaining optimal reduction efficiency in the furnace and balancing the causticizing plant, APC limits production bottlenecks, directly increasing pulp mill throughput

## Circular Economy Framing

**Zero-Waste Operations:**

The Kraft recovery cycle is inherently circular, recycling 95% to 97% of cooking chemicals. APC optimizes this loop by minimizing the need for makeup chemicals and reducing wastewater discharge through tighter control of the effluent footprint.

**Fossil-Free Production:**

By maximizing the combustion of concentrated black liquor and utilizing biomass waste, APC helps mills shrink their carbon footprints and produce renewable energy.

- **Resource Management:**

  Modern systems use predictive logic to control non-condensable gases (NCGs) and lime kiln temperatures. This lowers greenhouse gas emissions and decreases the amount of waste sent to landfills.

## 10. Results & discussion

**1. Evaporator Train Optimization**

- Stability: Implementing Model Predictive Control (MPC) reduces the variability of dry solids in heavy black liquor . Exact percentage by which disturbances in the final solids content were reduced will depend on the mill base value and potential. available for improvement.
- Energy Efficiency: Similarly the reduction in specific steam consumption (kg of steam per kg of evaporated water) across the multiple-effect evaporators. Can be 3 to 5 % depending on the potential available

**2. Recovery Boiler Stabilization & Throughput**

- **Bed & Furnace Management:** implementing multivariable control, balances combustion air and black liquor spraying to maintain optimal char bed temperatures.
- Steam Generation: Implementing APC optimizes steam generation finally based on heat input into furnace and optimization of combustion air. This could be typically 3 to 5 % increase depending on base value before optimization and varies from mill to mill.

**3. Causticizing and Lime Kiln Efficiency**

- **White Liquor Quality:** Implementing APC improves the causticizing efficiency by optimizing control in slaking and causticizing tanks.
- **Lime Kiln Fuel Savings:** Implementing PC gives the opportunity for reduction in fuel consumption (e.g., reduced natural gas/oil usage per ton of reburned lime) and reduction of total reduced sulfur (TRS) emissions.

**4. Overall Economic and Environmental Impact**

- **Variability Reduction:** APC gives the opportunity for closing critical control loops which in turn allows the operation to run closer to safety and operational limits without operator intervention .

- **ROI & Emissions:** Implementing APC could result in economic benefits typically could be 12 to 24 months (ROI) depending on the base value prior to implementation and could result in CO and Sox/ Nox or Totally reduced sulphur emission reduction.

## 11. Conclusion

Successful implementation of an APC system requires strong plant-level ownership, proper planning, and continuous support. Establishing an APC Champion with adequate authority and budget ensures effective coordination and execution. Early involvement of operators helps in better acceptance and smooth operation of the system. Prior verification of existing conventional control performance is essential before APC installation. Proper initial and refresher training should be provided to all concerned personnel. Maintaining transparency regarding APC benefits and real-time value encourages operator confidence. Long-term support from suppliers for critical APC components is also necessary for sustained performance and reliability.

*Courtesy : TAPPI , VALMET , ANDRITZ*