EWO in the Petroleum Industry - challenges and opportunities

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Core Areas:

- Refining
  - Add value to Brazilian heavy oil exports
- E&P: West Africa (Nigeria and Angola) & Gulf of Mexico:
  - Apply deep water and deep well drilling technology.
- Latin America:
  - Leadership as an integrated energy company
New frontier in crude oil production: Sub-salt

- **Post-salt layer**: holds most of Brazil’s reserves of crude
- **Salt layer**: irregular layer with thickness varying from 1,000 to 2,000 metres
- **Pre-salt layer**: Due to its geological characteristics, defines a new exploration model, with technologies that provide better corrosion resistance and capable to work at higher T and P.
Petrobras will increase the importance in the industry through growing the oil production and expanding the Downstream.
As Petrobras continues to grow its upstream business, the need for a compatible refining infrastructure becomes more critical.

With limited investment over the last 20 years, Petrobras will increase capacity to meet the needs of a growing domestic market.
MIDDLE DISTILLATE DEMAND EVOLUTION

Strong diesel and jet fuel consumption growth in Brazil have been observed following the economic growth...

Diesel Sales (2006 to 2011)

Jet Sales (2006 to 2011)
# Production, Downstream and Demand in Brazil

Construction of new refineries to meet local market demand

<table>
<thead>
<tr>
<th>Year</th>
<th>Oil and NGL Production – Brazil</th>
<th>Total Crude Oil Processed – Brazil</th>
<th>Oil Products Market (2 scenarios)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>1,792</td>
<td>2,004</td>
<td>1,971</td>
</tr>
<tr>
<td>2010</td>
<td>1,798</td>
<td>2,147</td>
<td>2,004</td>
</tr>
<tr>
<td>2011</td>
<td>2,100</td>
<td>2,208</td>
<td>2,100</td>
</tr>
<tr>
<td>2015</td>
<td>2,205</td>
<td>2,643</td>
<td>3,327</td>
</tr>
<tr>
<td>2020</td>
<td>4,910</td>
<td>3,217</td>
<td>3,095</td>
</tr>
</tbody>
</table>

**Construction of New Refineries:***

- *Abreu e Lima Refinery (RNE)*
  - 230,000 bpd (2013)

- *PREMIUM I (1st phase)*
  - 300,000 bpd (2016)

- *PREMIUM I (2nd phase)*
  - 300,000 bpd (2019)

- *PREMIUM II*
  - 300,000 bpd (2017)

- *COMPERJ (1st phase)*
  - 165,000 bpd (2014)

- *COMPERJ (2nd phase)*
  - 165,000 bpd (2018)
LOGISTICS

Distance from the Brazilian coast to refining centers is at least 5,000 miles, or 16 to 33 days of travel

Freight cost ($/bbl)

1 Petrobras estimates in October 2011
Business Environment 1- Crude Oil market

Crude Oil Prices (US$/Bbl - IMF/IFS)
Business Environment: Biofuels ➔ Ethanol

![Ethanol, Sugar and Petroleum Prices](chart.png)
Provide flexibility in the entire supply chain in order to capture benefits in an increasingly volatile market.
Supply Chain

Crude oil supply

Long term contracts

Spot market

Domestic - offshore

Domestic - onshore

Main Terminals

Refineries

EtOH

Product terminals

Distribution companies

National consumption

Products imports/exports
Challenges for a flexible Supply-Chain

- Traditional optimization structure tends to optimize the usual production mode.
- It is necessary to create a structure adapted also to search novel operations. Ex:
  - Transfers of streams among refineries, and terminals;
  - Use of intermediate streams for non-usual operations.
TECHNOLOGICAL PROGRAMS

New Exploratory Frontiers
Basin Modeling
Deep and Ultra-deep Waters
Carbon Capture and Storage
Enhanced Oil Recovery
Pre-salt
Refining
Reliability
Fuel Innovation
Transportation
Natural Gas
Bio Fuels
Environment
Climate Changes
Main results and current issues
Multivariable Predictive Control:
✓ Developed Linear and nonlinear predictive control algorithms
✓ Developed software solutions for MPC implementation
✓ implemented APC on major Downstream units (Distillation, FCC, Delayed Coker)
✓ Implementing on NG Processing units, Hydrotreaters and Upstream
✓ Developed APC tuning tools
✓ Further developments in robust and nonlinear MPC ➔ Fast NMPC
✓ We still need better product quality inferences and dynamic inferential models
✓ Developing Mixed-Integer MPC algorithms
Real Time Optimization

✓ implementing commercial static RTO on major Downstream units (Distillation and FCC)
✓ studying better ways to characterize the feed and do feed reconciliation
✓ Developing dynamic RTO
✓ implementing RTO on systems with great complexity (Distillation + FCC together)
✓ Developing models for conversion processes for use in RTO systems
Planning and Scheduling
✓ Developed a software platform for refinery scheduling (SIPP)
✓ Implemented SIPP in several refineries
✓ Developed specialized scheduling optimizers using MIP models
✓ Studying optimization of crude allocation into the refineries
✓ terminal-refinery integrated crude planning
✓ integrated optimization of process – blending
✓ routing and scheduling of crude ships
✓ routing and scheduling of helicopters and platform boat supplies (pre-salt increases distance and size of wells; more people to transport)
✓ Long-term planning (Process synthesis)
Other areas:
- Abnormal situation management in real time
- On-line product certification
- Product blending optimization and control
- Detailed furnace modeling (coker)
- Dynamic simulation of refining processes
- Virtual process units integrating 3D visualization and process simulation
- Automated startup and shutdown of process units
- Robotic inspection of industrial equipment
- Crude blending systems to optimize feed composition according to the demand of finished products
- Production planning under uncertainty
Motivation

• Commercial MPCs \(\rightarrow\) QP formulations.
• Some practical consequences:
  – No preferential manipulation sequence \(\rightarrow\) inputs are changed simultaneously;
  – No minimum limit for the absolute change on the inputs \(\rightarrow\) hysteresis may prevent actual application.
  – No preferential order of relaxation of the outputs \(\rightarrow\) choice made by heuristics.

Moro and Grossmann, FOCAPO-2012
• Mixed-integer MPC formulation:
  – Assignment of explicit priorities for the outputs ➔ preferential order of constraint relaxation in case the initial steady-state problem proves infeasible.
  – Assignment of explicit priorities for the outputs ➔ order in which the inputs are to be moved to adjust each output.
  – Minimum limit for control moves ➔ adequate for valves subject to hysteresis.
  – Deal with discrete inputs, either manipulated variables or disturbances ➔ on/off variables.
Background

• MPC functions:
  – reduce process variability;
  – Move closer to the constraints or towards a predefined optimum.

• Hierarchical structure with two layers.

• Hybrid MPCs not new:

• Our approach:
  – MI algorithms based on the traditional MPC that can be advantageously applied even to continuous systems.
MIQP – Steady State Optimization

Obj. function: 
\[ \min_{\Delta \tilde{u}} \varphi_{\text{miss}} = \frac{1}{2} y_v^T \sigma y_v - \pi_i^T z_y + \frac{1}{2} \Delta \tilde{u}^T \mu \Delta \tilde{u} - \lambda_u^T \Delta \tilde{u} + \pi_u^T (z_{u+} + z_{u-}) \]

Output violations: 
\[ y_v + G \Delta \tilde{u} + \hat{y} - y_{LB} \geq 0 \]
\[ y_v - G \Delta \tilde{u} + y_{UB} - \hat{y} \geq 0 \]

Bounds for the outputs: 
\[ \tilde{y} \geq y_{LB} + M (z_y - 1) \]
\[ \tilde{y} \leq y_{UB} - M (z_y - 1) \]

Minimum input change: 
\[ \Delta \tilde{u}_+ \geq \Delta u_{LB} \circ z_{u+} \]
\[ \Delta \tilde{u}_- \geq \Delta u_{LB} \circ z_{u-} \]

Priorities for inputs: 
\[ (\pi_{u1} - \pi_{u2})(z_{u1+} + z_{u1-}) \leq (\pi_{u1} - \pi_{u2})(z_{u2+} + z_{u2-}) \]

Inputs x Outputs priorities: 
\[ z_{yi} \geq 1 - (z_{uj+} + z_{uj-}) \quad \forall i \in CV, \quad j \in MV \mid \pi_{yi} > \pi_{uj}, G_{ij} \neq 0 \]

\[ \tilde{u} = \text{SS targets for the inputs} \]
\[ z_{u+}, z_{u-} = \text{decision to move the input} \]

\[ \tilde{y} = \text{SS targets for the outputs} \]
\[ z_y = \text{decision to enforce the output bounds} \]

\[ G = \text{Gain matrix} \]
\[ \mu, \pi_y, \pi_u, \sigma = \text{tuning factors} \]
MIQP – MPC (dynamic layer)

Obj. function:

\[
\min_{\Delta \bar{u}_k} \phi^{qdmc} = \frac{1}{2} \Delta \bar{u}_k^T (A^T QA + \Lambda) \Delta \bar{u}_k + A^T Q (\hat{y}_k - y_{sp}) \Delta \bar{u}_k + \frac{1}{2} (\bar{u}_k - \bar{u})^T R (\bar{u}_k - \bar{u})
\]

Bounds for the inputs:

\[
\Gamma_i \Delta \bar{u}_k + u \geq u_{LB} \quad u_{LB} \geq \Gamma_i \Delta \bar{u}_k + u
\]

Max/min input rate-of-change:

\[
\Delta \bar{u}_k - \Delta u_{LB} \circ \bar{z}_{u+} + \Delta u_{UB} \circ \bar{z}_{u-} \geq 0
\]
\[
- \Delta \bar{u}_k + \Delta u_{UB} \circ \bar{z}_{u+} - \Delta u_{LB} \circ \bar{z}_{u-} \geq 0
\]

Future time-instants with nonzero control moves:

\[
h \geq z_h^T \cdot 1
\]
\[
\Delta u_{UB} \circ z_h \geq \Delta \bar{u}_k
\]
\[
\Delta \bar{u}_k \geq -\Delta u_{UB} \circ z_h
\]

- QDMC formulation with the inclusion of binaries to allow:
  - definition of minimum rate-of-change;
  - Selection by the algorithm of the future time-instants when the control action will be placed.

- Still using the Hierarchical structure with two layers.
MIQP Solver

- Outer-Approximation method (Duran and Grossmann, 1986) → series of QP subproblems and MILP master problems;
- DLL built in FORTRAN:

\[
\begin{align*}
\min \varphi &= \frac{1}{2} x^T C x + D^T x \\
\text{s.t.} \quad &Ax + B \geq 0 \\
&x^L \leq x \leq x^U \\
&x_i \in [x_i^L, x_i^U] \forall i \in I^c \\
&x_i \in \{0,1\}, \forall i \in I^B
\end{align*}
\]

- DLL also includes the option of solving a QP at each B&B node
Tests on a Simulated System

Air injected in the second stage of the regenerator: smaller influence on the temperature

Secondary air: should be used frequently to deal with small temperature fluctuations

Main air: should be used only for aggressive control moves

- The MPC from the actual industrial implementation:
  - 33 outputs and 11 manipulated inputs
- Steady State layer $\rightarrow$ MIQP with 55 continuous and 44 binary variables $\rightarrow$ solved in 0.25 sec. in a 2.4GHz PC
- Dynamic layer $\rightarrow$ MIQP with 11 continuous variables, 23 binary variables $\rightarrow$ solved in less than 0.1 seconds.
After steady state the minimum limit is raised from 680°C to 700°C.

Traditional MPC (T-QP) and MIQP (T-MI) exhibit similar behavior.

The MIQP uses the main air flow only for aggressive moves, as desired.

MIQP inputs are more stable, but can be vigorously moved when necessary. The traditional formulation changes the inputs frequently, even when little improvement in the system behavior can be obtained.

Traditional MPC makes frequent small adjustments in the main air, which can result in wear and tear in the valve.
Currently: Integration of scheduling and MPC

Scheduling formulation to guide the MPCs of several units.

Currently: Integration of scheduling and MPC

Straight-run streams

Coker-1

Coker-2

FCC

LKGO1

LKGO2

LCO

LCO storage

HDT-D

HGU

Diesel storage

H₂
Thank you
The objective function includes terms maximizing the decision to enforce the upper/lower limits on the outputs, \((\text{binary variable})\) and minimizing the decision to move the inputs in the positive and negative directions, and \((\text{binary variables})\):

\[
\min_{\pi, \eta} \sum_{i=1}^{Nc} \left[ \pi_i \delta_i \right] + \sum_{i=1}^{Nc} \left[ \eta_i \delta_i \right]
\]

Equations defining the amount of upper \((\pi_i)\) and lower \((\eta_i)\) limit violations for each output:

\[
\begin{align*}
\pi_i &= \sum_{j=1}^{Nm} L_i \left( u_{ij} - u_{j}^{\text{min}} \right) \quad \forall i \in \mathcal{Nc} \\
\eta_i &= \sum_{j=1}^{Nm} L_i \left( u_{ij} - u_{j}^{\text{max}} \right) \quad \forall i \in \mathcal{Nc}
\end{align*}
\]

Violations of limits are always positive numbers:

\[
\pi_i \geq 0 \quad \forall i \in \mathcal{Nc} \\
\eta_i \geq 0 \quad \forall i \in \mathcal{Nc}
\]

If the decision to enforce the limits of output \(i\) is taken then the target for this input must remain within the allowable range:

\[
\begin{align*}
\pi_i + u_{ij}^{\text{max}} - u_i^{\text{min}} &\leq 0 \quad \forall i \in \mathcal{Nc}, j \in \mathcal{Nm} \\
\eta_i - u_{ij}^{\text{max}} + u_i^{\text{min}} &\leq 0 \quad \forall i \in \mathcal{Nc}, j \in \mathcal{Nm}
\end{align*}
\]

The values of the inputs \(u_{ij}\) can only be changed if the corresponding binary decision variable \((\pi_i \text{ or } \eta_i)\) is selected:

\[
\begin{align*}
\delta_i &\in \{0, 1\} \\
\pi_i \delta_i &\geq 0 \\
\eta_i \delta_i &\geq 0
\end{align*}
\]

Once the decision to move an input is taken, the change must be greater than the minimum threshold limit \(\Delta u_i^{\text{th}}\):

\[
\begin{align*}
\Delta u_i &= \text{sign}(\delta_i) \pi_i \delta_i \Delta u_i^{\text{th}} \\
\Delta u_i &= \text{sign}(\delta_i) \eta_i \delta_i \Delta u_i^{\text{th}} \\
\forall i \in \mathcal{Nc}
\end{align*}
\]

An input cannot be simultaneously moved in the positive and negative directions:

\[
\delta_i \pi_i \delta_i + \eta_i \delta_i \delta_i \Delta u_i^{\text{th}} \leq 1 \\
\forall i \in \mathcal{Nc}
\]

The movements to be applied on the inputs are subject to a sequence of priorities according to:

\[
\begin{align*}
\pi_i^{\text{th}} &\leq \pi_i \quad \forall i \in \mathcal{Nc} \\
\eta_i^{\text{th}} &\leq \eta_i \quad \forall i \in \mathcal{Nc}
\end{align*}
\]

where \(i\) and \(j\) \((\text{input variables indices})\) so that the priority of \(j\) is greater that the priority of \(j\). This means that the input \(j\) can only be moved if \(j\) has also already been moved.

The decision to relax a limit of any output can only be selected when all inputs with lower priority than this output have already been moved:

\[
\begin{align*}
\pi_i^{\text{th}} + \pi_i \delta_i + \eta_i \delta_i \Delta u_i^{\text{th}} &\leq 1 \\
\forall i \in \mathcal{Nc}, j \in \mathcal{Nm}
\end{align*}
\]

The lower layer (dynamic controller) was not modified in this work.
Investments in R&D

Revenues from oil fields defined as special participation:

1%

R&D

0.5%

Internal

0.5%

External institutions [e.g.: Universities]

about US$ 250 million/yr
Types:

- Contracts and agreements with Universities and Research Centers
- Networks of excellence

Over 120 Brazilian Institutions

Types:

- Joint Industry Projects
- Cooperating Research
- Strategic Alliances
- Technology Interchange

Over 70 International Institutions
Optimization Structure

- Planned x actual
- Corporate production planning
- Refinery production planning
- Refinery scheduling
- Optimization
- Advanced control
- Regulatory control
- Process data acquisition
- Performance monitoring
- Data reconciliation
- Plant
Pre-salt discoveries

Source: Petrobras Business Plan 2009 - 2013