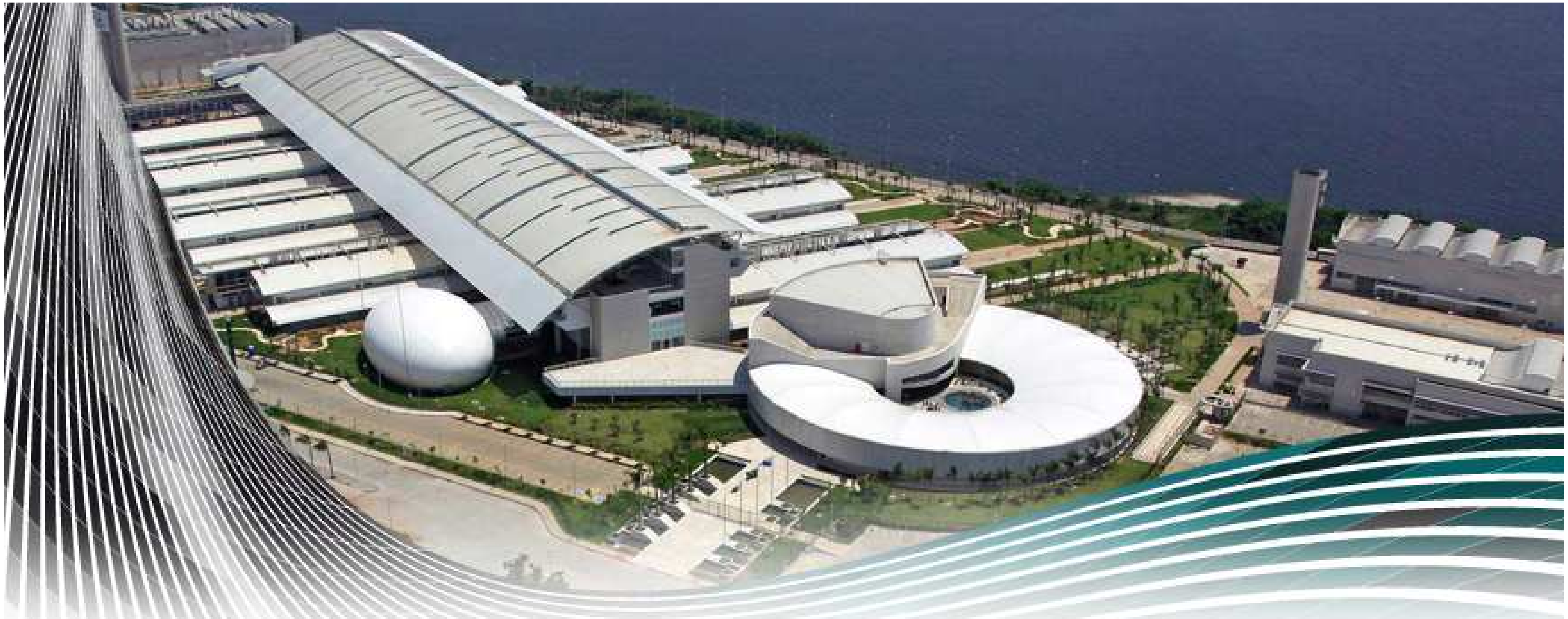
EWO in the Petroleum Industry - challenges and opportunities

Lincoln F. Lautenschlager Moro
Fábio dos Santos Liporace
Euclides Almeida Neto



CMU – March 2012

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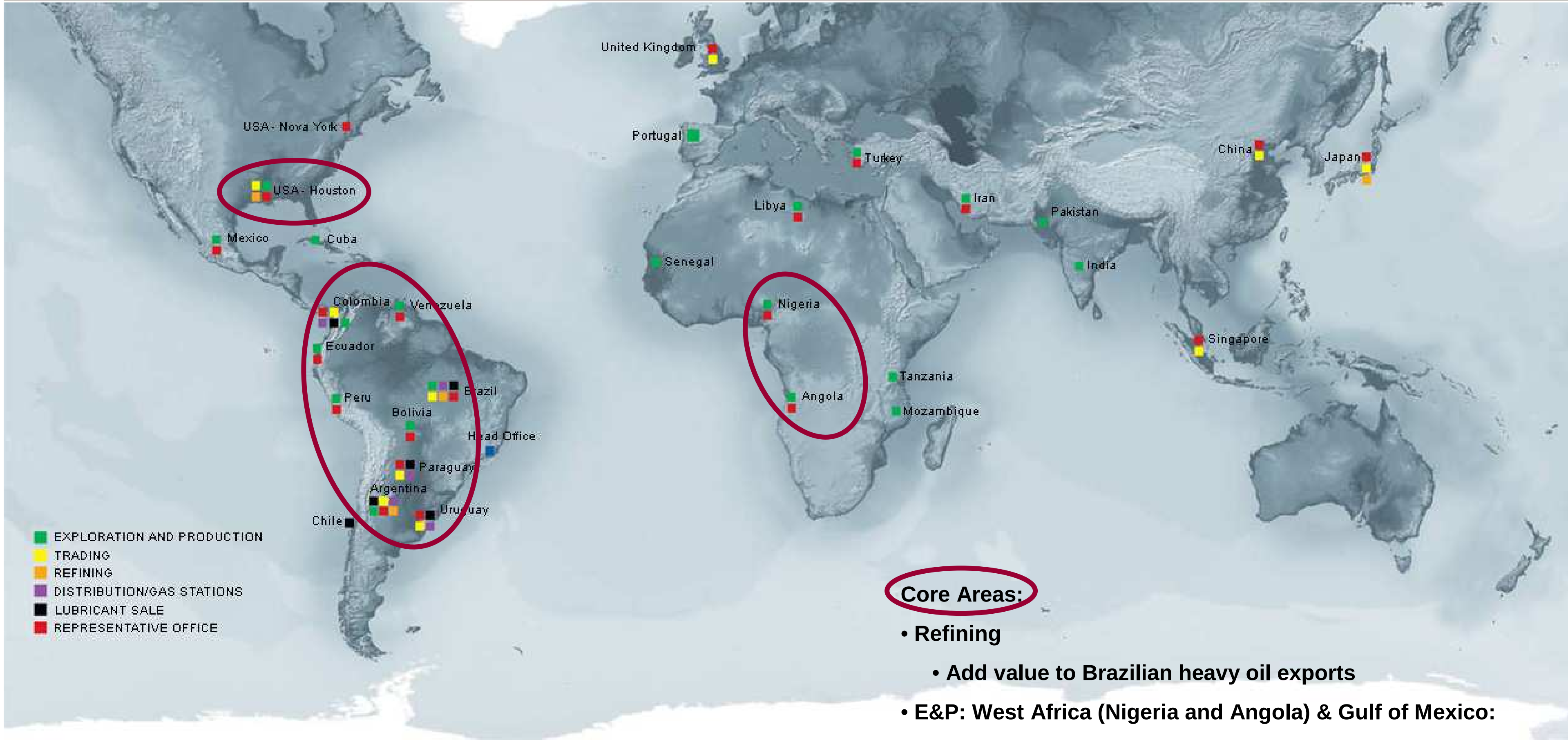
INTERNATIONAL COMPANY

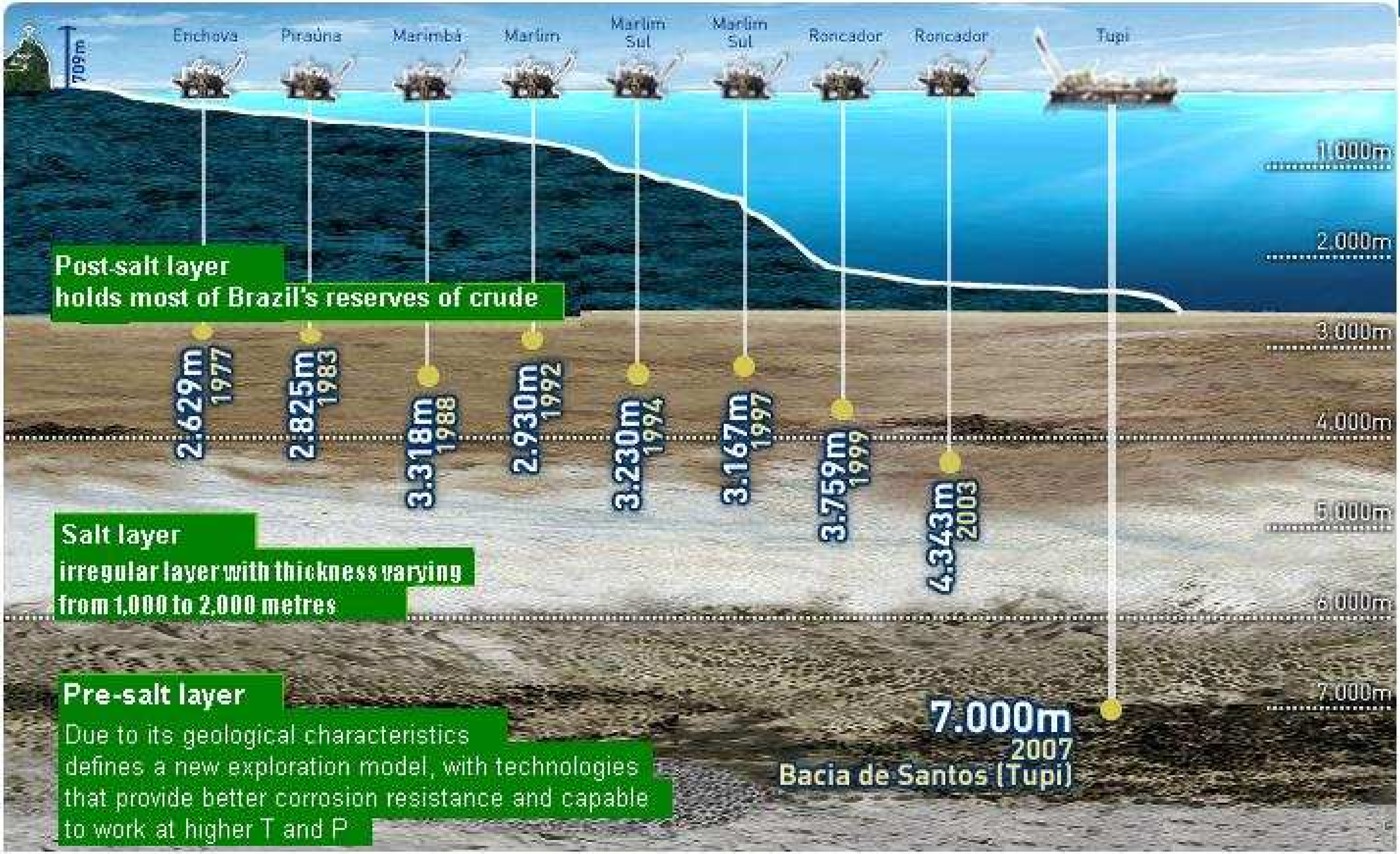


Core Areas:

- **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**

PETROBRAS

New frontier in crude oil production: Sub-salt



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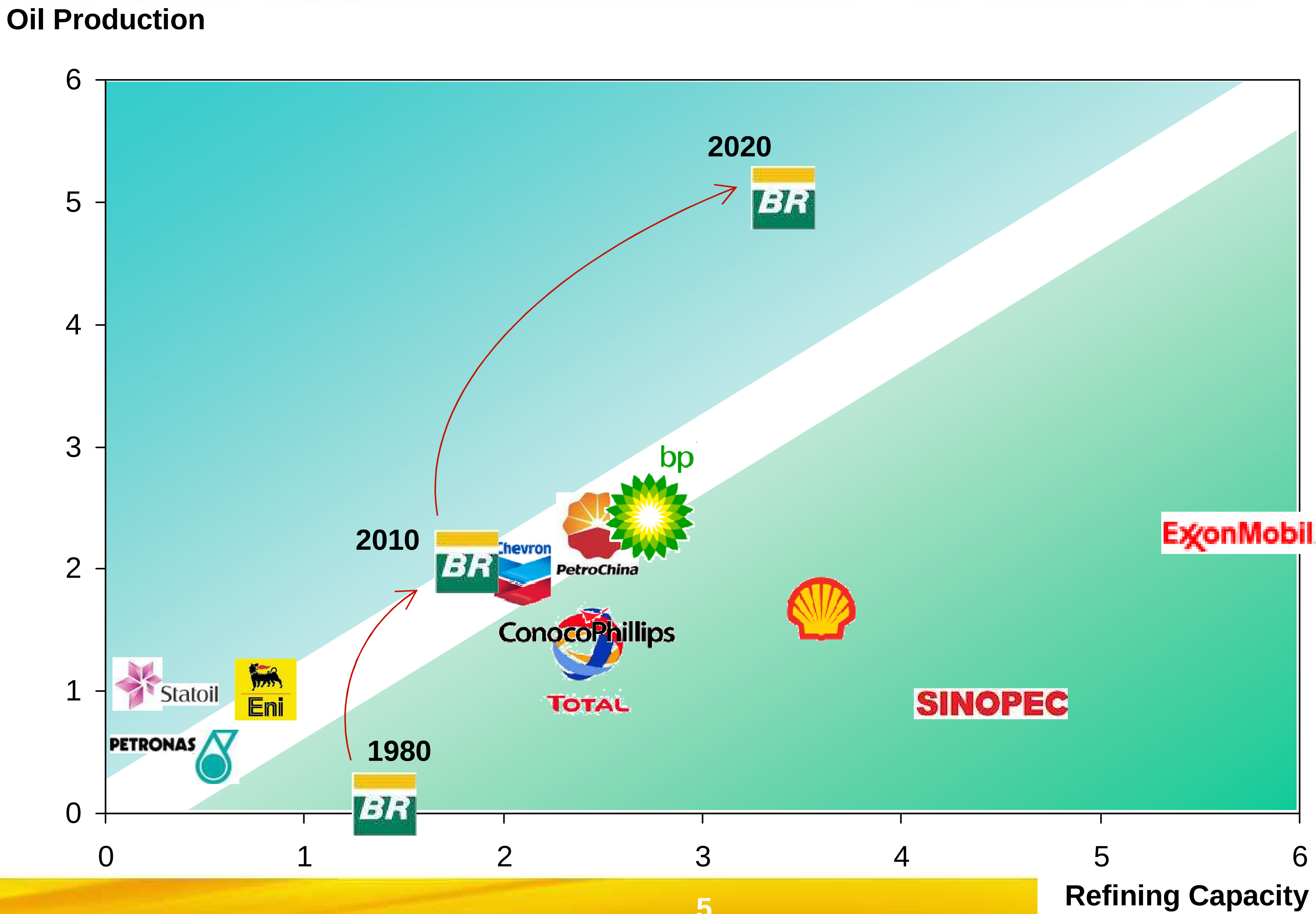
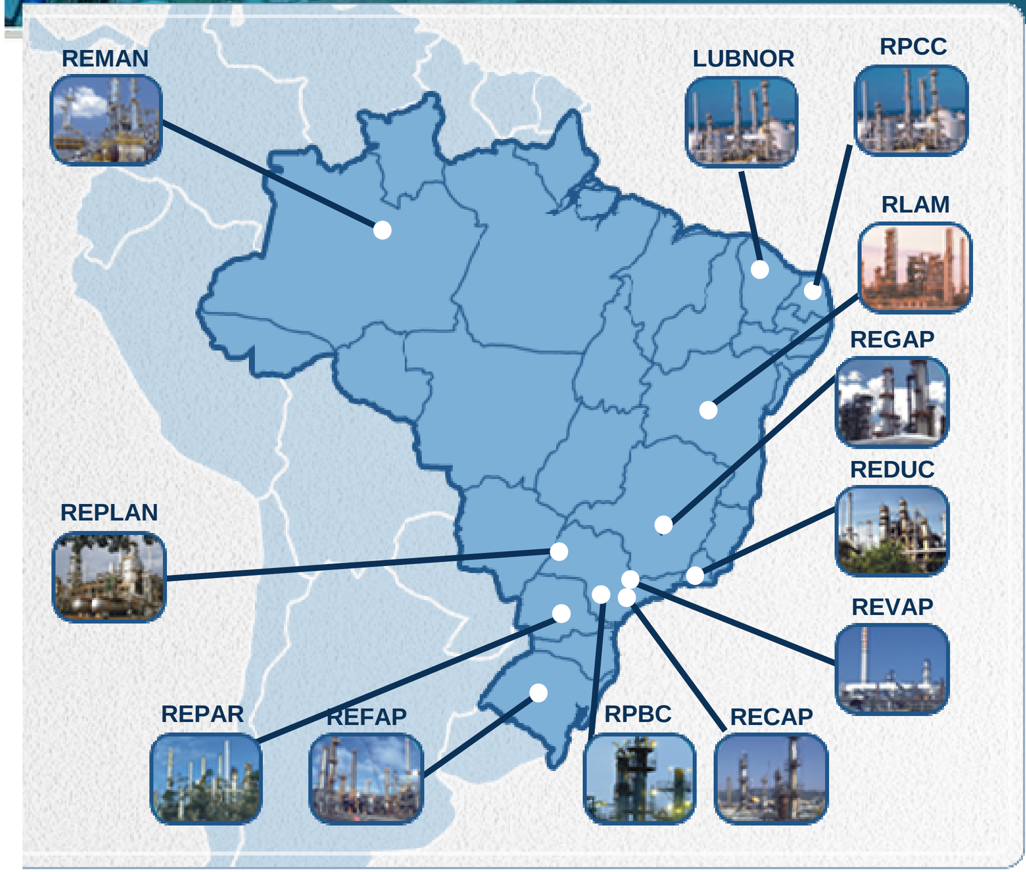
BUSINESS INTEGRATION

Petrobras will increase the importance in the industry through growing the oil production and expanding the Downstream



Note: For other companies, capacity in 2010.

Petrobras' Refining Infrastructure



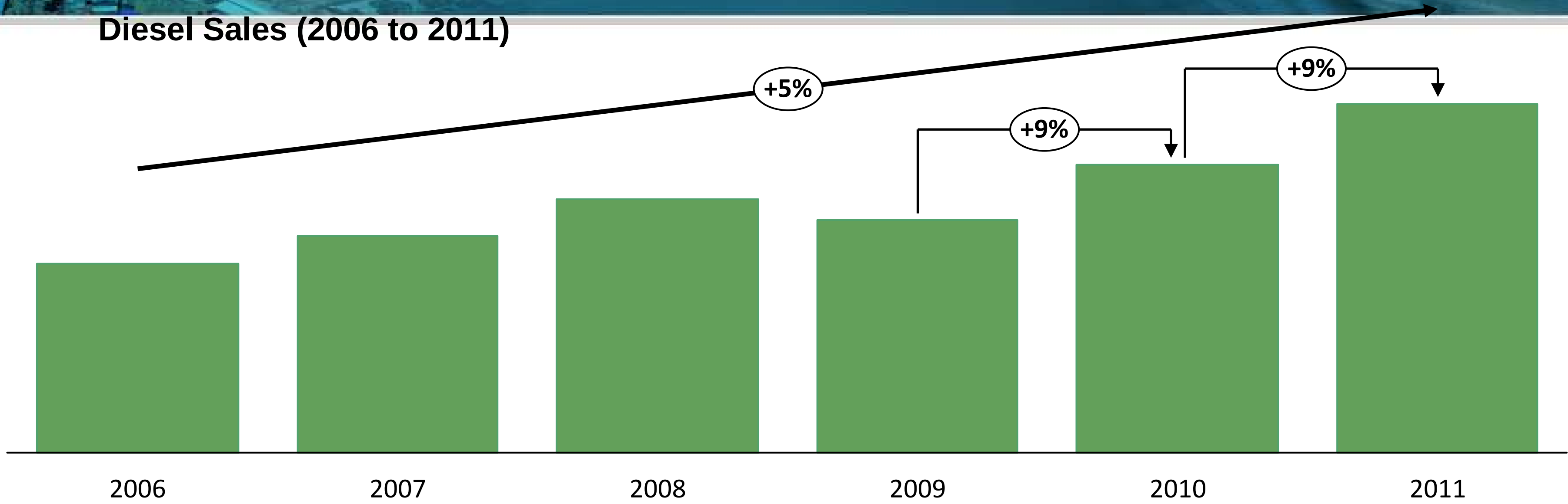
Refineries	Capacity (Mbpd) Original	Upgraded	%
Paulínia - Replan (SP)	252	396	57%
Landulpho Alves - Rlam (BA)	218	281	29%
Henrique Lage - Revap (SP)	189	252	33%
Duque de Caxias -Reduc (RJ)	191	239	25%
Pres. Getúlio Vargas - Repar (PR)	126	195	55%
Alberto Pasqualini - Refap (RS)	142	189	33%
Pres. Bernardes - RPBC (SP)	139	172	24%
Gabriel Passos - Regap (MG)	110	151	37%
Capuava - Recap (SP)	20	49	145%
Manaus - Reman (AM)	37	46	24%
Clara Camarão - RPCC (RN)	25	35	40%
Fortaleza - Lubnor (CE)	3	8	167%
Total Brazil	**1,452**	**2013**	**38%**
United States		100	
Argentina		81	
Okinawa		100	
Total Petrobras		**2,289**	

- **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.**

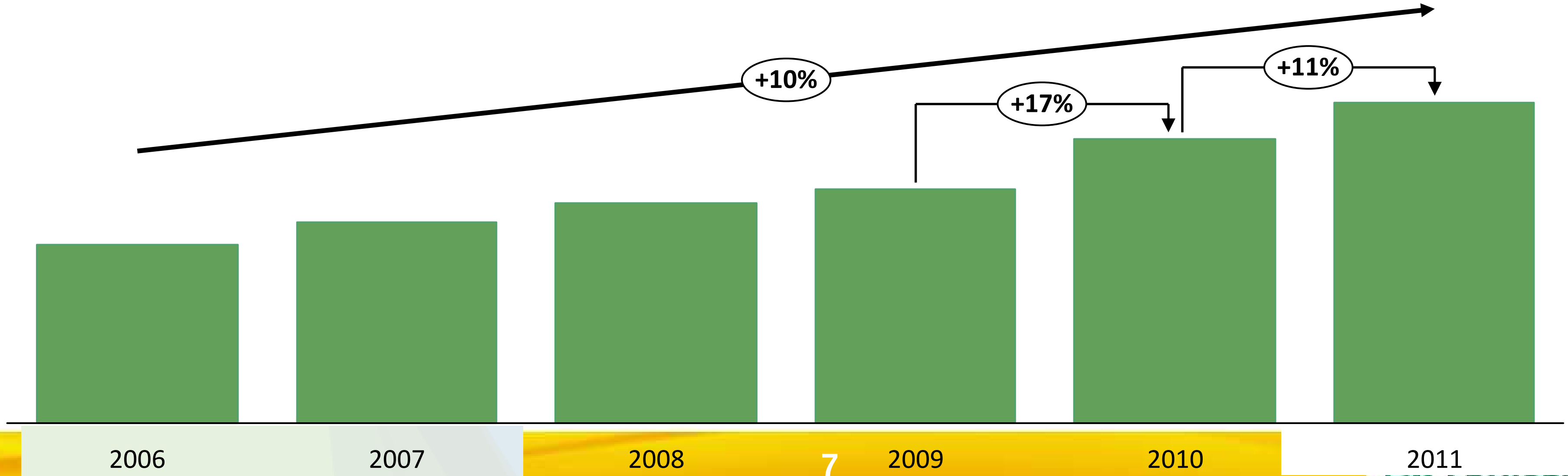
MIDDLE DISTILLATE DEMAND EVOLUTION

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

Diesel Sales (2006 to 2011)

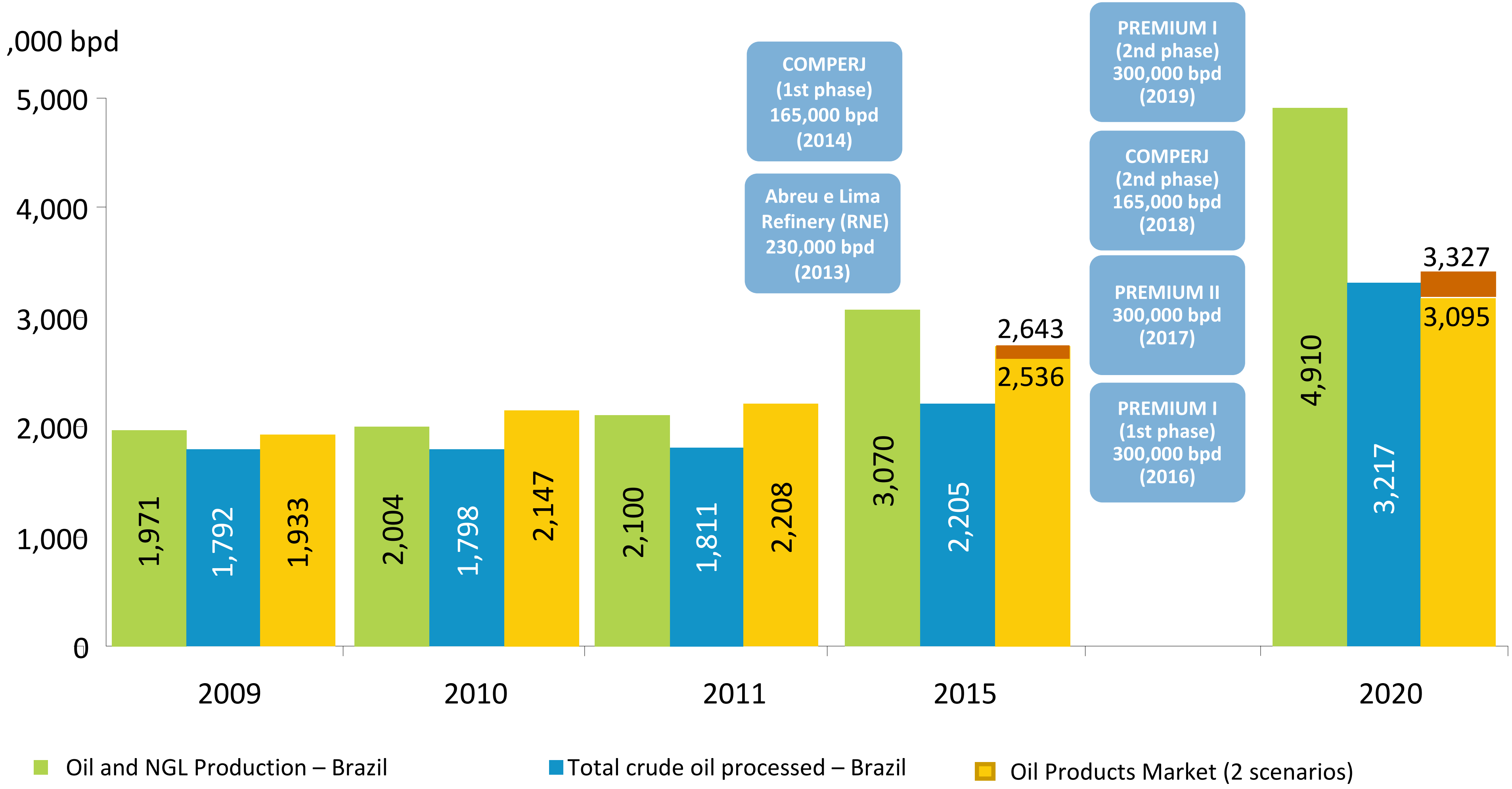


Jet Sales (2006 to 2011)



PRODUCTION, DOWNSTREAM AND DEMAND IN BRAZIL

Construction of new refineries to meet local market demand



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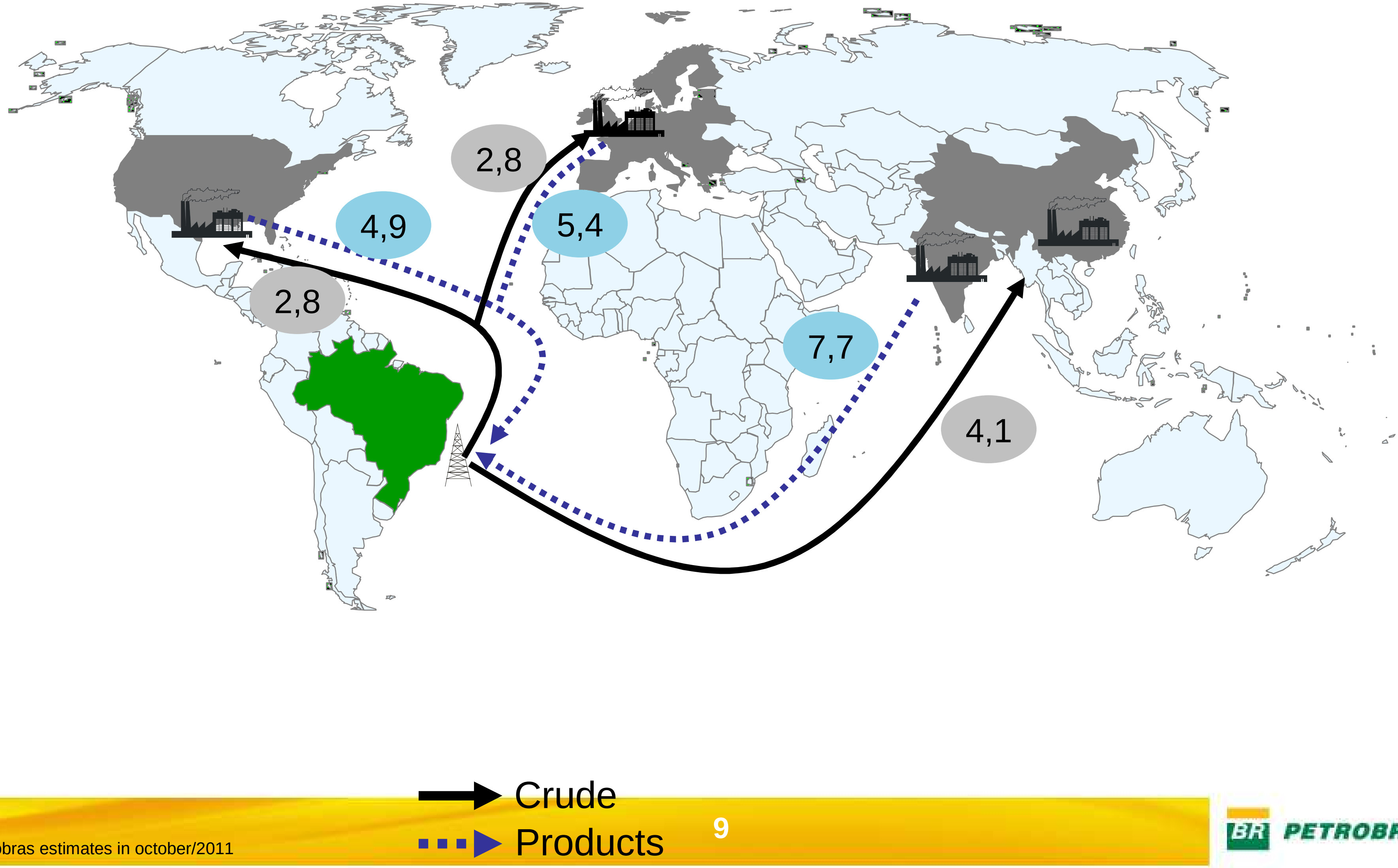
LOGISTICS

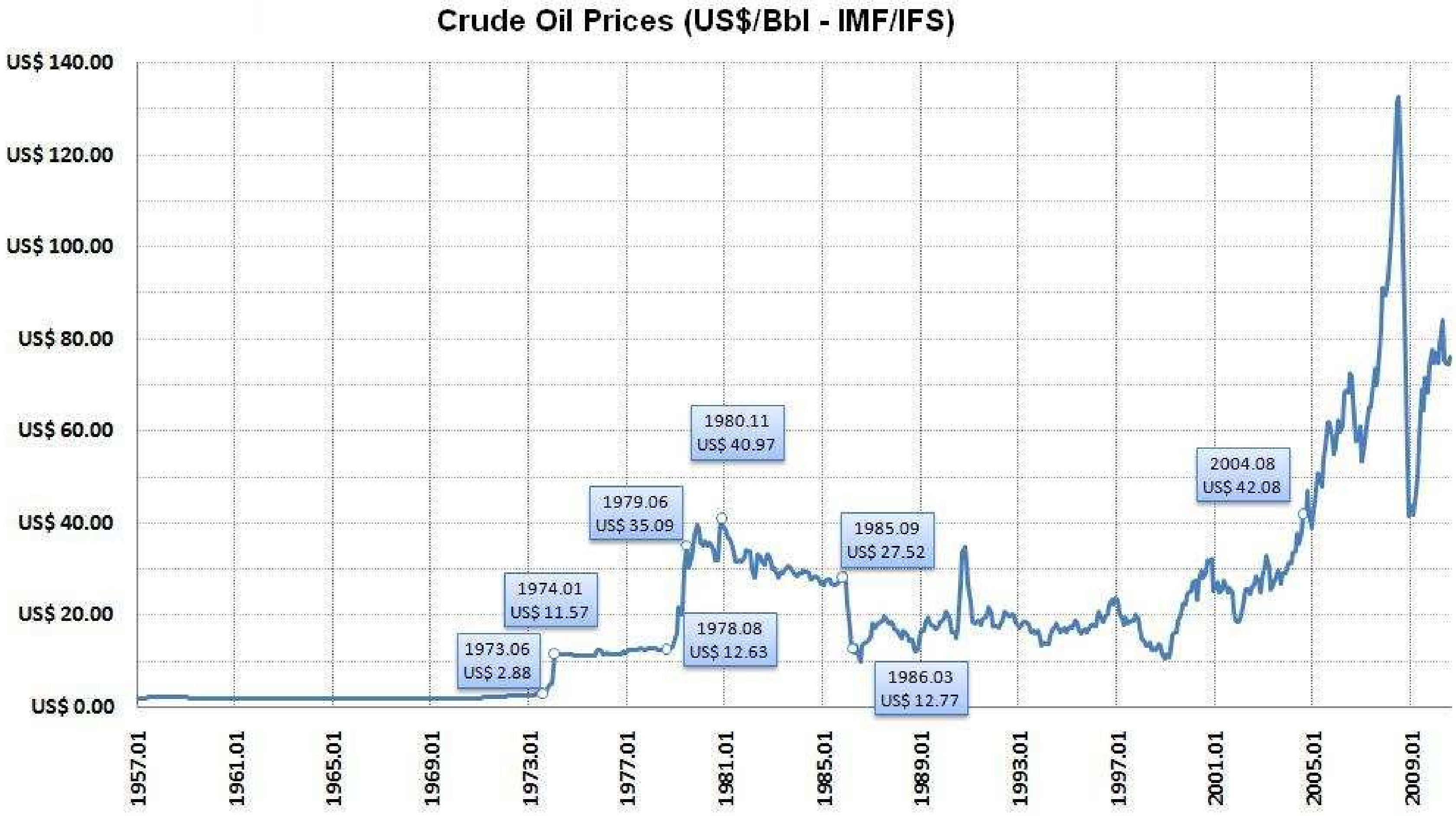
Distance from the Brazilian coast to refining centers is at least 5.000 miles, or 16 to 33 days of travel

Freight cost ($/bbl)[1]



[1]Petrobras estimates in october/2011

Business Environment 1- Crude Oil market



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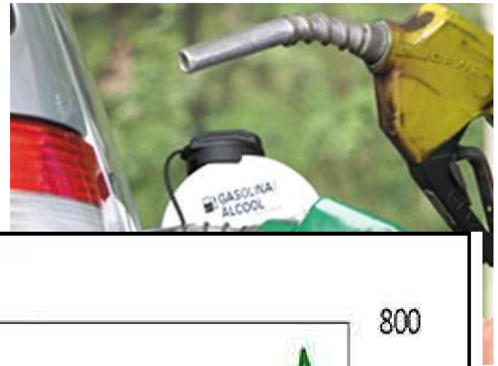
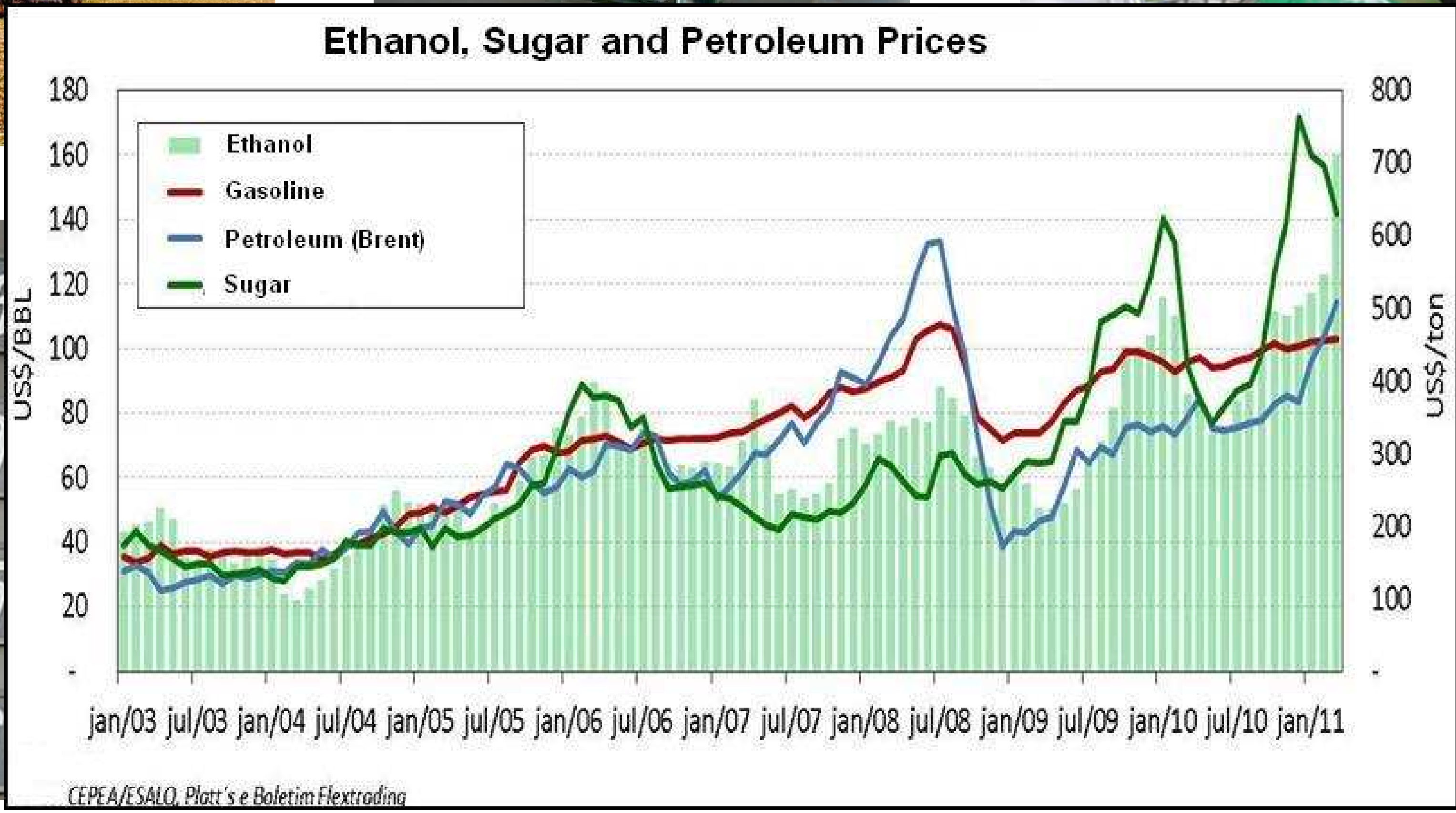
Business Environment: Biofuels→Ethanol

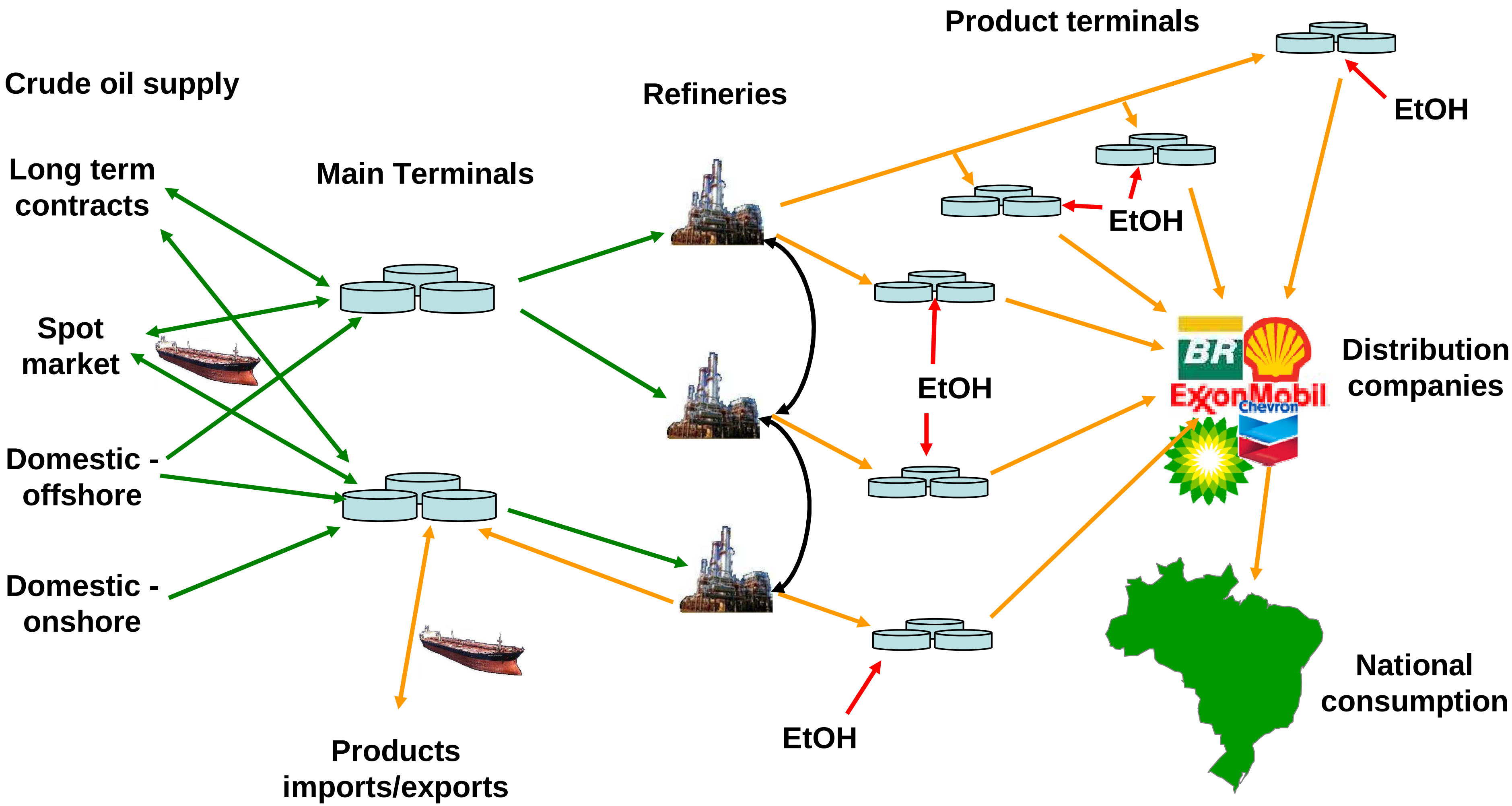




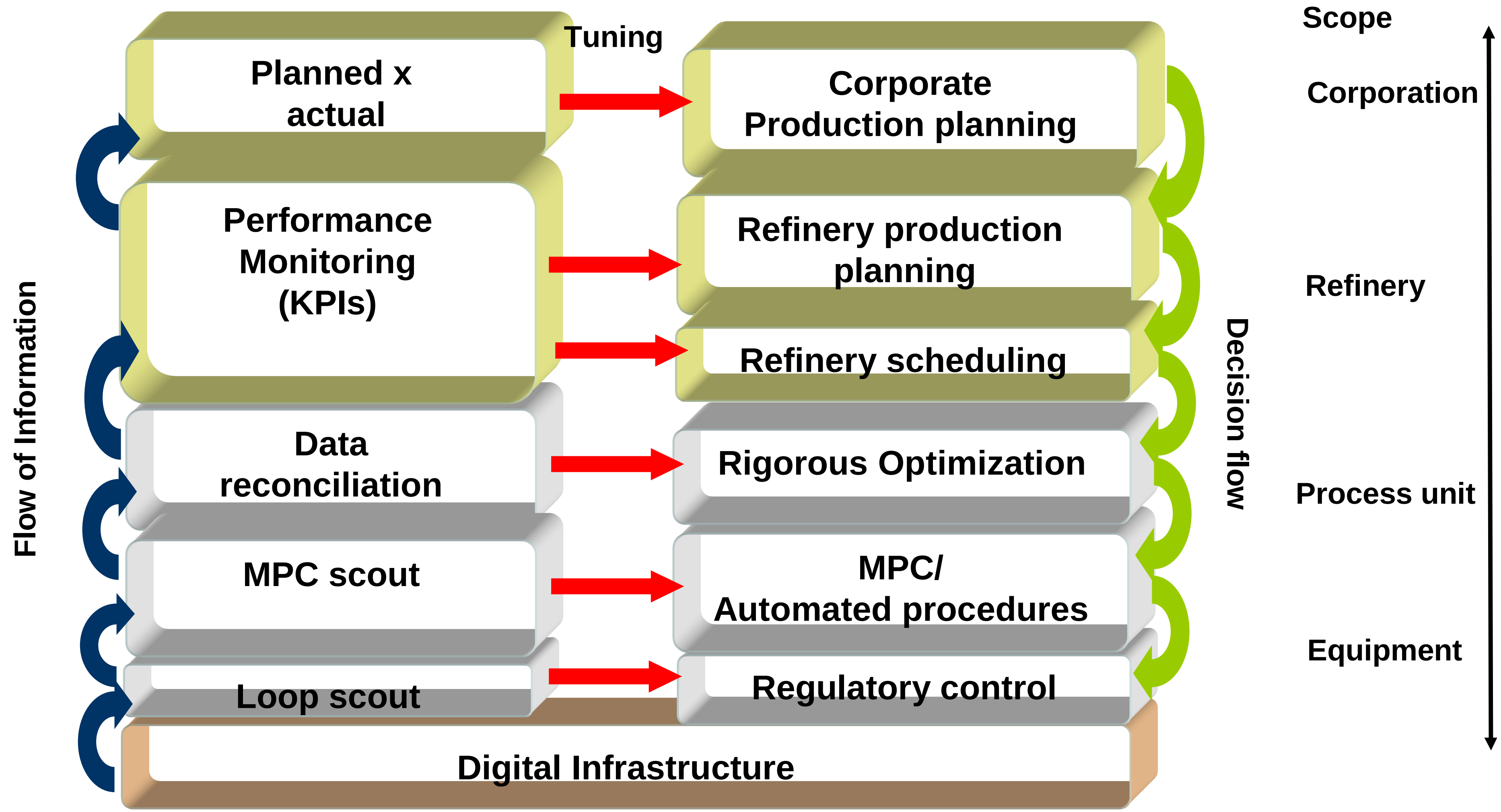
BUSINESS OBJECTIVE

Provide flexibility in the entire supply chain in order to capture benefits in an increasingly volatile market.

Supply Chain



Optimization Structure



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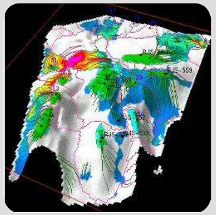
Challenges for a flexible Supply-Chain

- 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

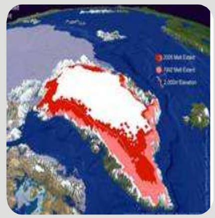
Fuel Innovation

Transportation

Natural Gas

Bio Fuels

Environment



Climate Changes

Main results and current issues

OPTIMIZATION ISSUES BEING ADDRESSED

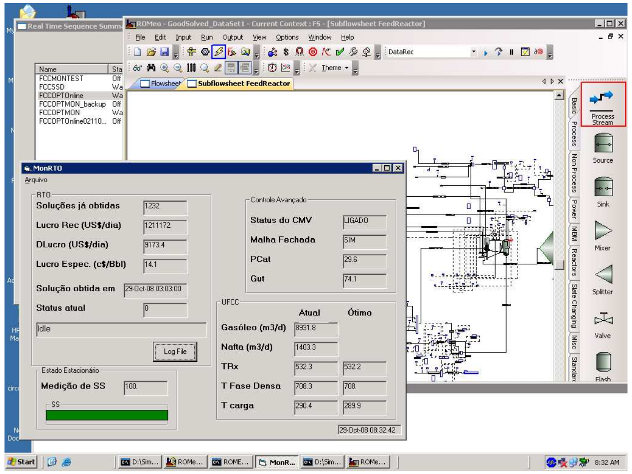
Multivariable Predictive Control:

- ✓ 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

OPTIMIZATION ISSUES BEING ADDRESSED

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



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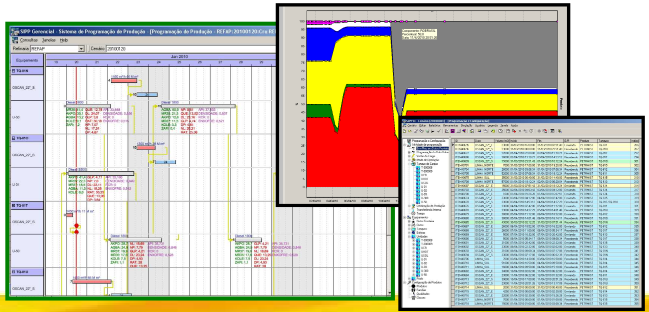
OPTIMIZATION ISSUES BEING ADDRESSED

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)



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OPTIMIZATION ISSUES BEING ADDRESSED

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 ➔ QP formulations.
- Some practical consequences:
  - No preferential manipulation sequence➔ inputs are changed simultaneously;
  - No minimum limit for the absolute change on the inputs ➔ hysteresis may prevent actual application.
  - No preferential order of relaxation of the outputs ➔ choice made by heuristics.

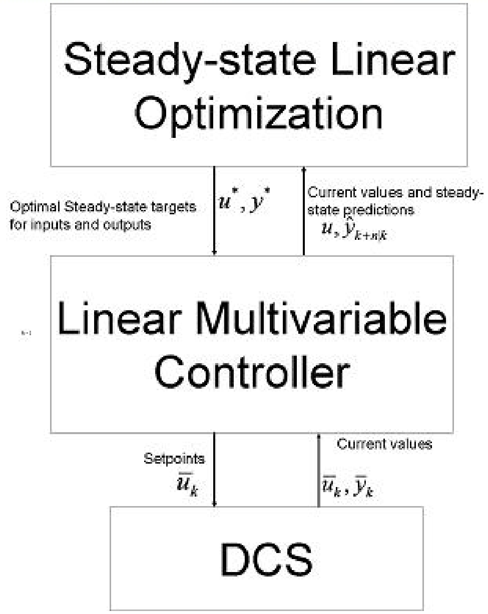
Moro and Grossmann, FOCAPO-2012

Goals

- 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:
  - Bemporad and Morari (1999), Morari and Barić (2006), Zabiri and Samyudia (2006).
- Our approach:
  - MI algorithms based on the traditional MPC that can be advantageously applied even to continuous systems.

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MIQP – Steady State Optimization

Obj. function:

$$\min_{\Delta\tilde{u}} \varphi_{miss} = \frac{1}{2} y_v^T \varpi y_v - \pi_i^T z_y + \frac{1}{2}\Delta\tilde{u}^T \mu \Delta\tilde{u} - \lambda_u^T \Delta\tilde{u} + \pi_u^T (z_{u+} + z_{u-})$$

Output violations:

$$y_v + G\Delta\tilde{u} + \hat{y} - y_{LB} \geq 0 \qquad y_v - G\Delta\tilde{u} + y_{UB} - \hat{y} \geq 0$$

Bounds for the outputs:

$$\tilde{y} \geq y_{LB} + M\left(z_y - 1\right) \qquad \tilde{y} \leq y_{UB} - M\left(z_y - 1\right)$$

Minimum input change:

$$\Delta\tilde{u}_+ \geq \Delta u_{LB} \circ z_{u+} \qquad \Delta\tilde{u}_- \geq \Delta u_{LB} \circ z_{u-}$$

Priorities for inputs:

$$(\pi_{u1} - \pi_{u2})(z_{u1+} + z_{u1-}) \leq (\pi_{u1} - \pi_{u2})(z_{u2+} + z_{u2-})$$

Inputs x Outputs priorities:

$$z_{yi} \geq 1 - (z_{uj+} + z_{uj-}) \quad \forall i \in CV, j \in MV \mid \pi_{yi} > \pi_{uj}, G_{ij} \neq 0$$

$\tilde{u}$ **= SS targets for the inputs**

z_{u+}, z_{u-} **= decision to move the input**

$\tilde{y}$ **= SS targets for the outputs**

z_y **= decision to enforce the output bounds**

G **= Gain matrix**

$\mu, \pi_y, \pi_u, \varpi$ **= tuning factors**

MIQP – MPC (dynamic layer)

Obj. function:

$$\min_{\Delta\bar{u}_k} \varphi^{qdmc} = \frac{1}{2}\Delta\bar{u}_k^{\;T}\left(A^T Q A + \Lambda\right)\Delta\bar{u}_k + A^T Q\left(\hat{y}_k - y_{sp}\right)\Delta\bar{u}_k + \frac{1}{2}\left(\bar{u}_k - \tilde{u}\right)^T R\left(\bar{u}_k - \tilde{u}\right)$$

Bounds for the inputs:

$$\Gamma_l \Delta\bar{u}_k + u \geq u_{LB} \qquad u_{LB} \geq \Gamma_l \Delta\bar{u}_k + u$$

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:

$$h \geq z_h^T .1$$

$$\Delta u_{UB} \circ z_h \geq \Delta\bar{u}_k$$

$$\Delta\bar{u}_k \geq -\Delta u_{UB} \circ z_h$$

- 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:

$$\min_{x} \varphi = \frac{1}{2} x^T C x + D^T x$$

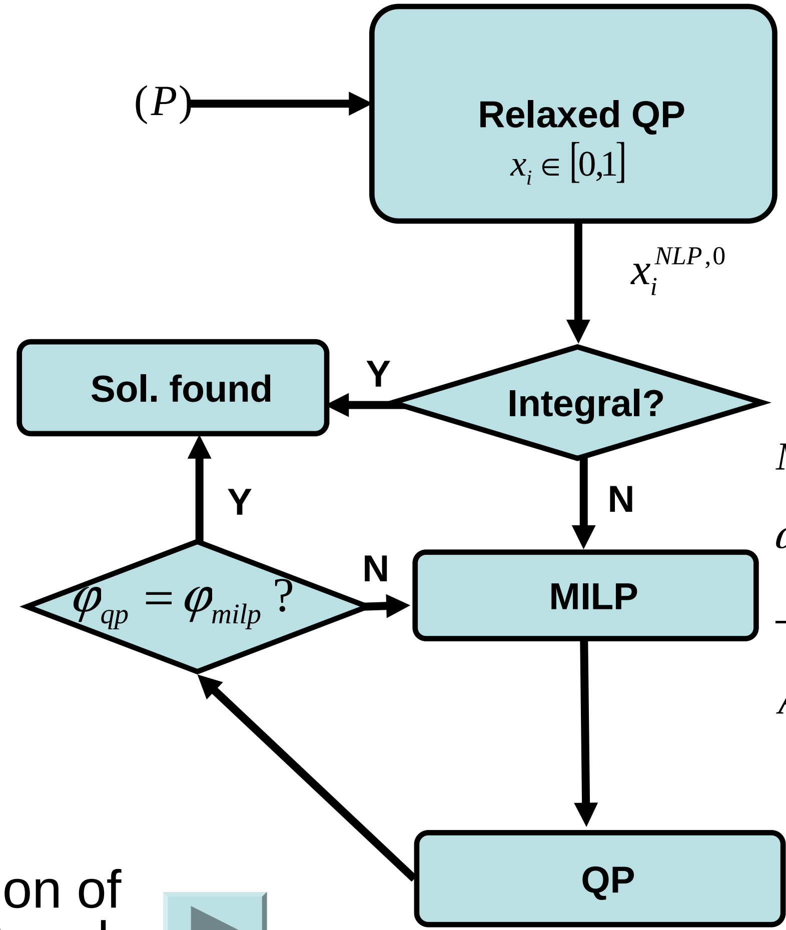
$$s.t.$$

$$Ax + B \geq 0 \qquad (P)$$

$$x^L \leq x \leq x^U$$

$$x_i \in \left[x_i^L, x_i^U\right], \forall i \in I^c$$

$$x_i \in \{0,1\}, \forall i \in I^B$$



$$Min\, \varphi_{milp} = \alpha$$

$$\alpha \geq \left(x^{NLP,j^T} C + D^T\right) x + $$

$$-\frac{1}{2} x^{NLP,j^T} C x^{NLP,j}, \; j = 1, \cdots k$$

$$Ax + B \geq 0$$

$$\min_{x} \varphi_{qp} = \frac{1}{2} x^T C x + D^T x$$

$$Ax + B \geq 0$$

$$x_i^k = x_i^{MILP,k}, \forall i \in I^B$$

- DLL also includes the option of solving a QP at each B&B node

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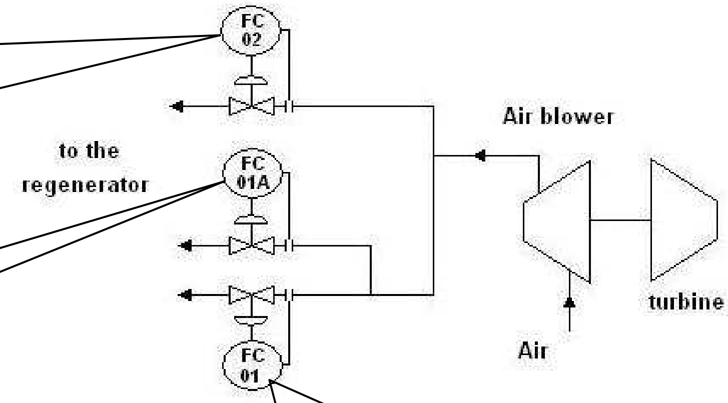
Tests on a Simulated System

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

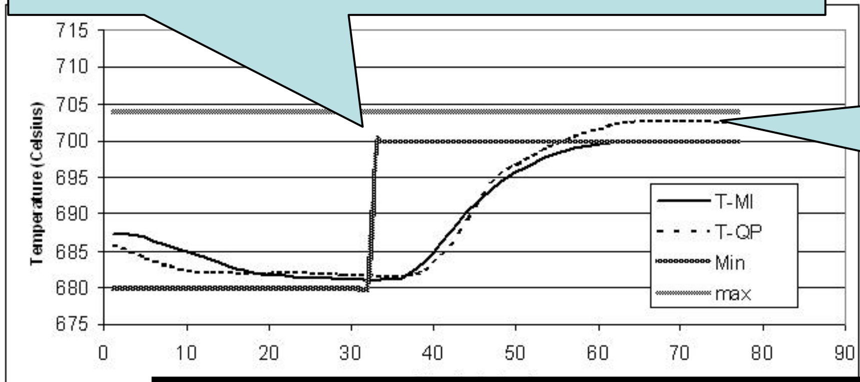
FCC Regenerator air subsystem

- The MPC from the actual industrial implementation:
  - 33 outputs and 11 manipulated inputs
- Steady State layer ➔ MIQP with 55 continuous and 44 binary variables ➔ solved in 0.25 sec. in a 2.4GHz PC
- Dynamic layer ➔ MIQP with 11 continuous variables, 23 binary variables➔ solved in less than 0.1 seconds.

Behavior

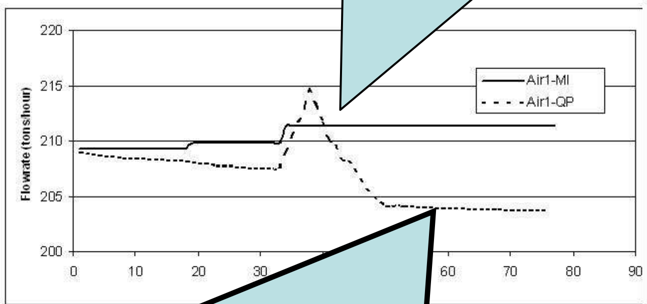
After steady state the minimum limit is raised from 680ºC to 700ºC.

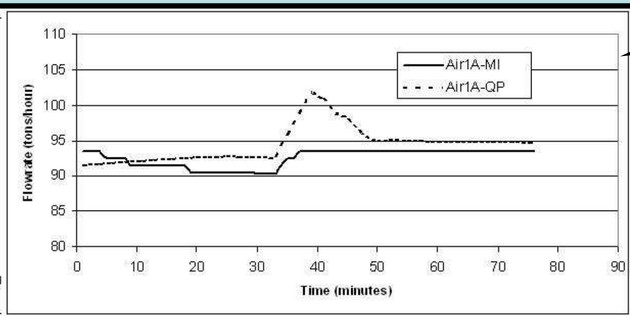
Traditional MPC (T-QP) and MIQP (T-MI) exhibit similar behavior

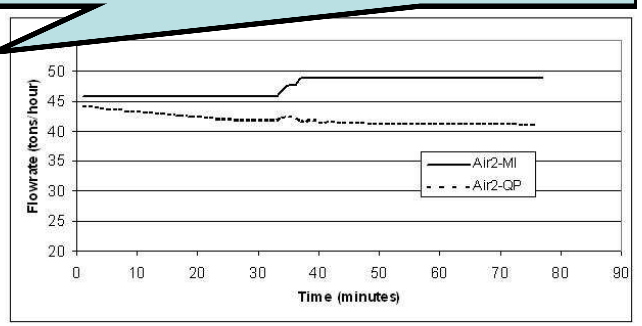


The MIQP uses the main air flow only for aggressive moves, as desired.

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.

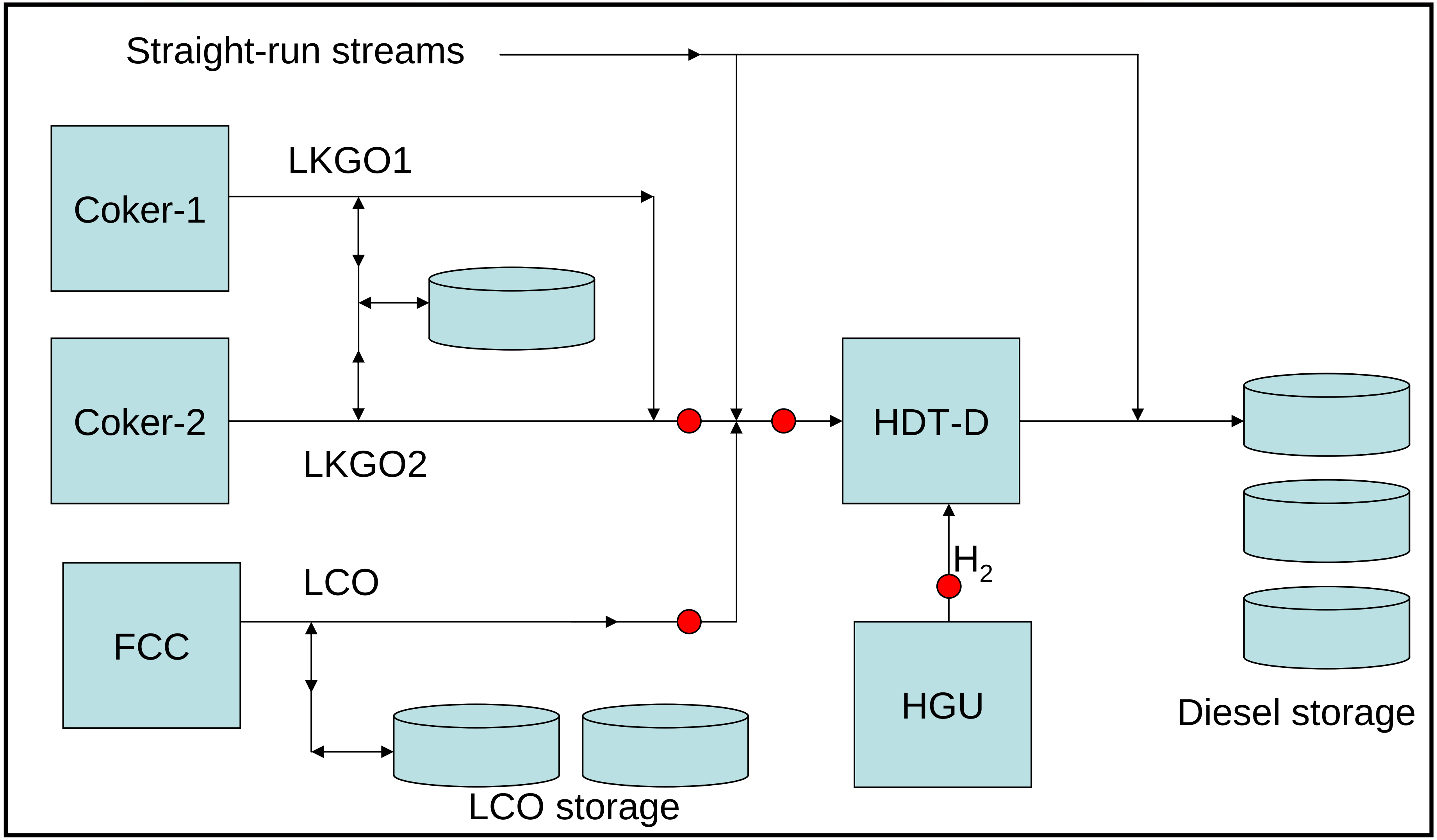






Traditional MPC makes frequent small adjustments in the main air, which can result in wear and tear in the valve

Currently: Integration of scheduling and MPC



Thank you

USE OF MIXED-INTEGER FORMULATIONS IN PREDICTIVE CONTROL ALGORITHMS

Paper #99

Lincoln F. L. Moro[a] and Ignacio E. Grossmann[b] .

[a]Petrobras S.A. – Sao Paulo, Brazil, [b]Carnegie Mellon University - Pittsburgh, USA

Motivation

- Model predictive control (MPC) algorithms traditionally use continuous quadratic programming formulations: QP-MPC.
- Some practical difficulties result from this approach:
  - It is not possible to define a preferential order of manipulation of the inputs➔ inputs are changed simultaneously, even when some have only a small influence on the controlled variables that are active;
  - It is not possible to define a minimum limit for the absolute change on the inputs ➔ very small changes may be calculated, but these cannot be implemented in practice due to valve hysteresis;
  - It is not possible to define a preferential order of relaxation of the outputs (controlled variables) in case it is infeasible to keep all of them within bounds➔ choice of which outputs will be relaxed is made by the MPC in an ad-hoc basis.

Goals

- Develop a mixed-integer (MIP) formulation for the MPC problem with the following advantages over the continuous MPC:
  - 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.
  - Set a minimum limit for control moves ➔adequate for valves subject to hysteresis.
  - Deal with discrete inputs, either manipulated variables or disturbances➔ on/off variables.

Background

- Model predictive control (MPC) algorithms have two main functions: reduce process variability and move the operating point closer to the constraints.
- This is achieved via a hierarchical structure with two layers:
  - Upper layer ➔ optimal steady-state targets for inputs and outputs;
  - Lower layer ➔ control moves that drive the system towards the steady-state targets.

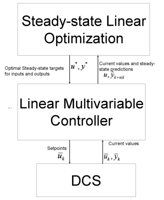


Figure 1- MPC hyerarchical structure

- Both layers ➔ continuous quadratic programming problems.
- Hybrid MPCs already successfully used in industrial applications: Bemporad and Morari (1999), Morari and Barić (2006), Zabiri and Samyudia (2006). We focus on the development of MIQP algorithms based on the traditional MPC that can be advantageously applied even to continuous systems.

MIQP Formulation for the Steady State Optimization

The objective function includes terms maximizing the decision to enforce the upper/lower limits on the outputs, z_i^y (binary variable) and minimizing the decision to move the inputs in the positive and negative directions, z_j^{u+} and z_j^{u-} (binary variables):

$$\min_{\Delta u^*} \varphi^{miss} = \sum_{i=1}^{Nc}\left(\frac{1}{2} y_i^v \varpi_i y_i^v - \sum_{i=1}^{Nc} \pi_i^y z_i^y\right) + \sum_{j=1}^{Nm}\left(\frac{1}{2}\Delta u_j^* \mu_j \Delta u_j^* - \lambda_j^u \Delta u_j^* + \pi_j^u (z_j^{u+} + z_j^{u-})\right)$$

Equations defining the amount of upper (y_i^{LB}) and lower (y_i^{UB}) limit violations for each output, y_i^v :

$$\left.\begin{aligned} & y_i^v + \sum_{j=1}^{Nm} G_{i,j}\left(\Delta u_j^{*+} - \Delta u_j^{*-}\right) + \hat{y}_i - y_i^{LB} \ge 0 \\ & y_i^v - \sum_{j=1}^{Nm} G_{i,j}\left(\Delta u_j^{*+} - \Delta u_j^{*-}\right) + y_i^{UB} - \hat{y}_i \ge 0 \end{aligned}\right\} \quad \forall i = 1,\ldots, Nc$$

Violations of limits are always positive numbers:

$$y_i^v \ge 0 \qquad \forall i = 1,\ldots, Nc$$

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

$$\left.\begin{aligned} & y_i^* \ge y_i^{LB} + M\left(z_i^y - 1\right) \\ & y_i^* \le y_i^{UB} - M\left(z_i^y - 1\right) \end{aligned}\right\} \quad \forall i = 1,\ldots, Nc$$

The values of the inputs u_j can only be changed if the corresponding binary decision variable (z_j^{u+} or z_j^{u-}) is selected:

$$\left.\begin{aligned} & \Delta u_j^{*+} \le M z_i^{u+} \\ & \Delta u_j^{*-} \le M z_i^{u-} \\ & \Delta u_j^* = \Delta u_j^{*+} - \Delta u_j^{*-} \end{aligned}\right\} \quad \forall j = 1,\ldots, Nm$$

Once the decision to move an input is taken, the change must be greater than the minimum threshold limit, Δu_j^{LB}:

$$\left.\begin{aligned} & \Delta u_j^{*+} \ge \Delta u_j^{LB} z_i^{u+} \\ & \Delta u_j^{*-} \ge \Delta u_j^{LB} z_i^{u-} \end{aligned}\right\} \quad \forall j = 1,\ldots, Nm$$

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

$$z_j^{u+} + z_j^{u-} \le 1 \qquad \forall j = 1,\ldots, Nm$$

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

$$z_{j1}^{u+} + z_{j1}^{u-} \le z_{j2}^{u+} + z_{j2}^{u-} \qquad \forall j1, j2 = 1,\ldots, Nm \mid \pi_{j1}^u > \pi_{j2}^u$$

where *j*l and *j*2 are input variables indexes so that the priority of input *j*1 is greater that the priority of *j*2. This means that the input *j1* can only be moved if *j2* 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:

$$z_i^y \ge 1 - z_j^{u+} - z_j^{u-} \qquad \forall i = 1,\ldots, Nc,\ j = 1,\ldots, Nm \mid \pi_i^y > \pi_j^u$$

The lower layer (dynamic controller) was not modified in this work.

MIQP Solver

- The MIQP solver uses the Outer-Approximation method (Duran and Grossmann, 1986) ➔ series of QP subproblems and MILP master problems;
- Algorithm built in C++ using freely available DLLs to solve the QPs and MILPs;
- The resulting DLL was linked to the industrial multivariable controller.
- MIQP described as:

$$P \left\{ \begin{aligned} & \min_x \varphi = \frac{1}{2} x^T C x + D^T x \\ & s.t. \\ & Ax + B \ge 0 \\ & x^L \le x \le x^U \end{aligned} \right.$$

$$x_i \in \left[x_i^L, x_i^U\right] \quad \forall i \in I^c$$

$$x_i \in \{0,1\} \quad \forall i \in I^b$$

Algorithm:

1. Solve P as a relaxed QP ➔ set $x_i \in [0,1]$, $\forall i \in I^b$ and let $x^{NLP,k}$, with *k*=0, be the solution vector. If the solution is integral➔optimal for P. Otherwise, proceed.
2. Linearize the objective function around $x^{NLP,k}$, set $k = k + 1$ and solve the following MILP:

$$\min_x \varphi_{milp} = \alpha$$

$$\text{s.to} \quad \begin{aligned} & \alpha \ge \left(x^{NLP,j^T} C + D^T\right)x - \frac{1}{2} x^{NLP,j^T} C x^{NLP,j}, \ j = 1,\cdots k \\ & Ax + B \ge 0 \\ & x^L \le x \le x^U \\ & \alpha \in \Re^1 \end{aligned}$$

which will result in a new optimal solution $x^{MILP,k}$.

3. Fix the binary variables $x_i^k = x_i^{MILP,k}$, and solve P with only $x_i \in I^c$ as free variables, thus obtaining $x^{NLP,k}$. If the NLP objective function value $\varphi^{NLP} = \varphi^{MILP}$ ➔ the algorithm converged and $x_i^{NLP,k}$ is the optimum solution. Otherwise, proceed to step 2.

Application to an FCC unit

- Formulation used to control an FCC (Fluid Catalytic Cracking) simulator (Moro and Odloak, 1995).
- MPC configuration ➔ taken from the actual industrial implementation: 33 outputs and 11 manipulated inputs.
- Steady-State MIQP with 55 continuous and 44 binary variables and 165 constraints➔ solved in 0.25 sec in an INTEL Core Duo 2.4GHz PC.
- Subsystem to be analyzed: regenerator temperature control.
- Regenerator temperature is mainly affected by the air injection.
- Air is injected through 3 pipes to allow better control.

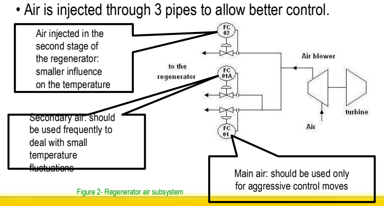


Figure 2- Regenerator air subsystem

Results

- Performance of the MIQP algorithm (MI) compared with the traditional MPC currently used to control the plant (QP).

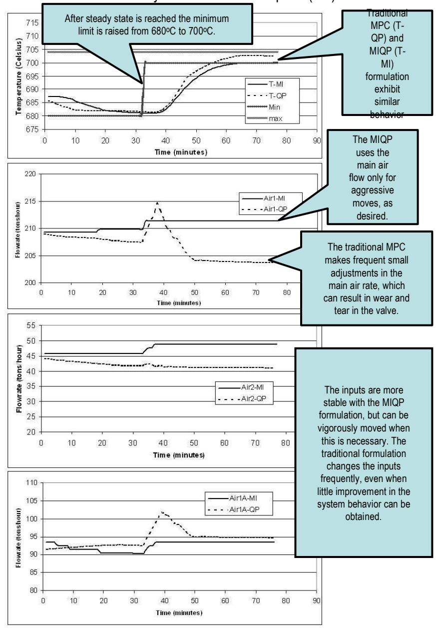


Figure 3- Regenerator temperature and air flow rates with the MIQP formulation (-MI) and with the traditional QP (-QP)

Conclusions and future work

- Developed MIQP formulation for the calculation of steady state targets and for the dynamic MPC layer.
- Formulation applied to a simulated industrial case➔ desired behavior was obtained.
- Future work:
  - Development of an MIQP formulation for the dynamic layer;
  - Evaluate changes in the tuning parameters;
  - Industrial implementation replacing the existing traditional MPC;

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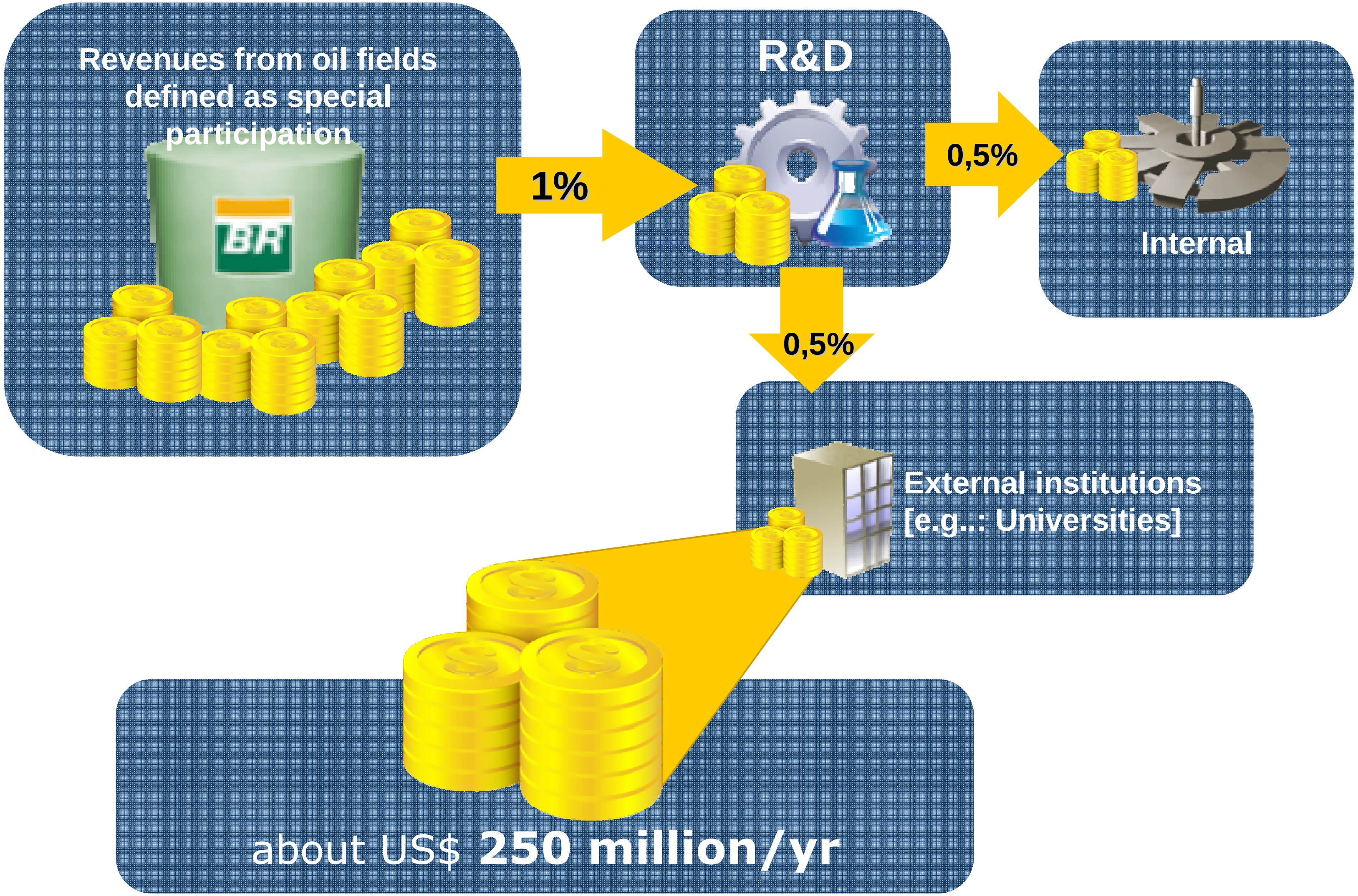
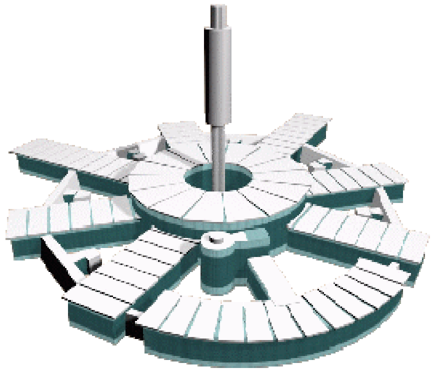
Investments in R&D





R&D
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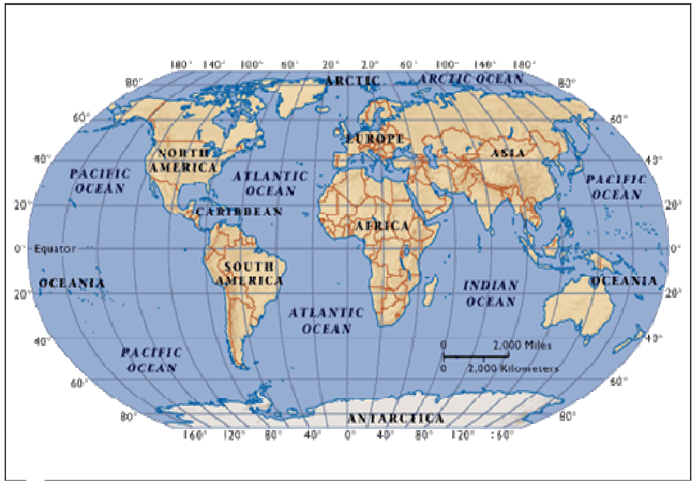

Types:

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

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Types:

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

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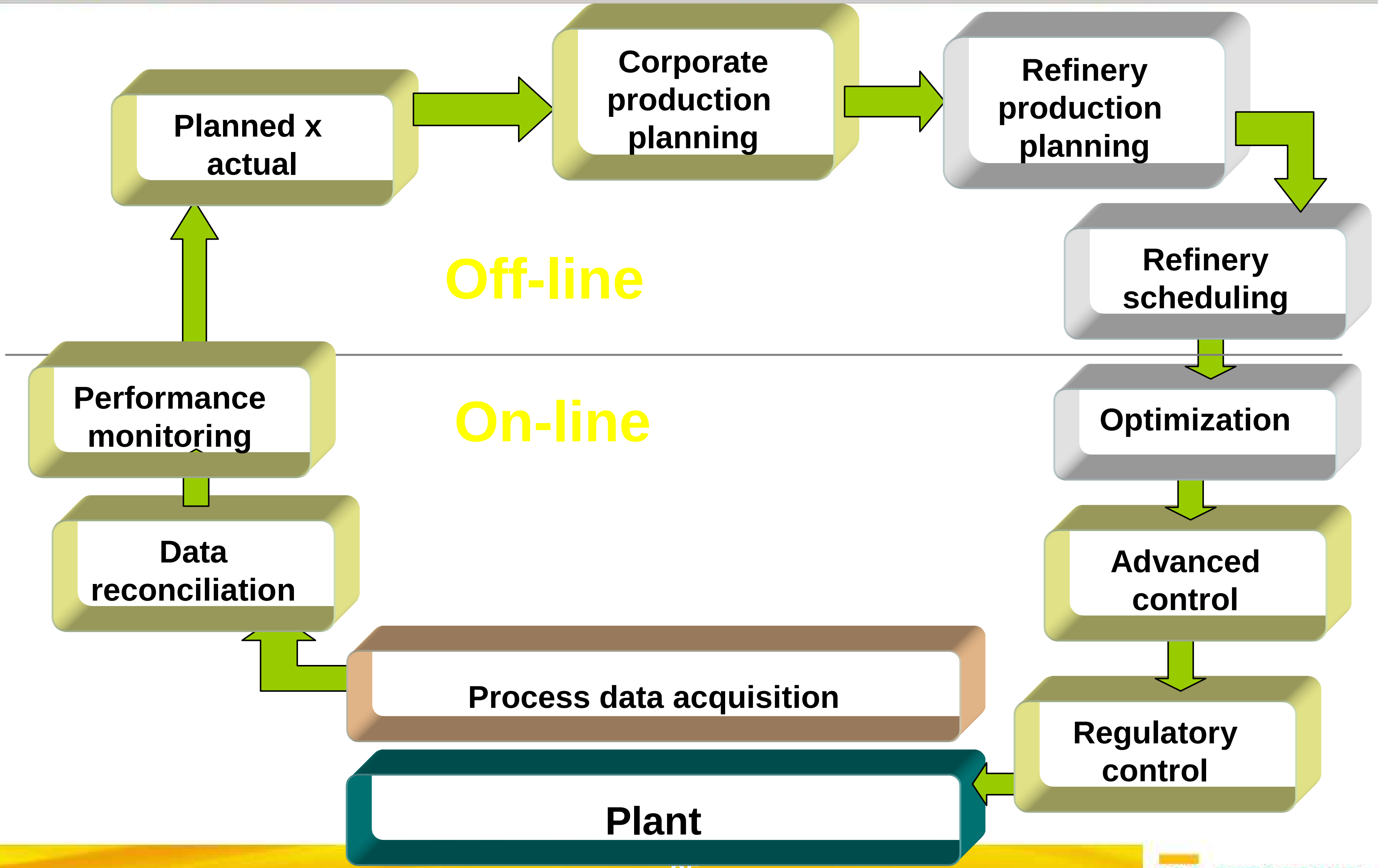
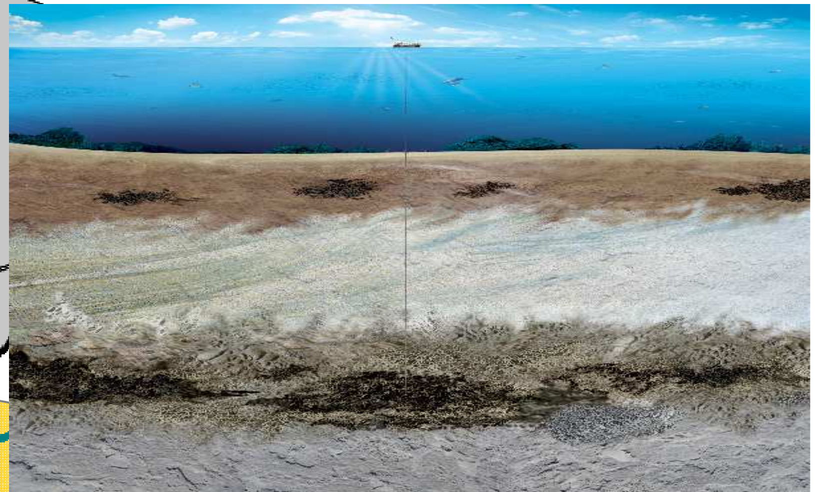
Optimization Structure



Pre-salt discoveries



exciting provinces

Source: Petrobras Business Plan 2009 - 2013

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