Novel Model Reduction Techniques for Refinery-Wide Energy Optimization

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An oil refinery is an industrial process plant where crude oil is processed and refined into more valuable petroleum products, such as:

- LPG
- Naphtha
- Kerosene
- Diesel
- Fuel Oil

The entire oil production and distribution channel includes crude evaluation and selection, production planning and product logistic planning.

The Oil Refinery is a key component of the global oil production and distribution process.
Oil refining challenges

- The selection of optimum crude feed mixture is extremely important in order to achieve higher margins and to meet the final products specifications.

- The operating process parameters will impact the $/bbl (dollars per barrel) for the crude input (Distillation cut points, severities, etc.).

- Oil refineries can be very complex having a combination of various technologies for heavy ends conversion, product quality blending, efficient fuel usage etc.

- Uncertainty in the current economical context (crude, products and utility prices)

Refinery-Wide Optimisation key to NextGen Performance
Refinery optimization

- Optimize refinery Crude feed mixture
- Minimize fuel production, Optimize Gasoline and Distillates Blending
- Minimize Quality Giveaway
- Optimize Fuel Consumption, Minimize Losses
- Optimize utilization of the process units and shutdown planning
- Optimize Unit operations maintaining highest standards of safety, catalyst life activity etc
Refinery model structure

- Large number of variables and constraints
- Nonlinear process units
- Large scale optimisation problem

NLP optimisation without compromising computational time

LP models limitations:
- Non-linear nature of refinery processes
- Data overload
Refinery configurations

Refinery Units:
- NHT: Naphtha Hydrotreater
- CCR: Catalytic Reforming
- DHT: Diesel Hydrotreater
- FCC: Fluid catalytic cracking
- MHC: Mild Hydrocracker
- HCR: Full conversion Hydrocracker
- ALK: Alkylation
- RFCC: Residue Fluid catalytic cracking
- VBU: Visbreaker

Refinery Margin
ANN approach

- ANN Training/Testing of refinery process units through the use of KBC Non-linear rigorous kinetic models (Crude distillation, Hydrotreaters, Catalytic reformers, etc.)

- The ANN will be used as an approximate model to the Rigorous one into the Refinery optimisation model
MIPANN approach

Selection of the Crudes

Rigorous Simulation
Crude Synthesis, Tray to tray column, Side Strippers, pumparounds

Data Generation
Training and Testing data

Data Scaling

NLP network Training

MINLP Nodes Reduction

MINLP Interconnections Reduction

NLP Network Training with the Optimised Structure

Vary inputs

Add more training points

Target met

Do While MSE > Target

Neural network model ready

YES

NO
MIPANN model for temperature prediction
ANN Refinery-Wide optimization model

Crude oil

CDU

Gas Plant

NHT

Splitter

HDS

Isom

CCR

LPG

Gas Plant

Gasoline

Jet

Diesel

Coke

Faster real time refinery optimization

CDU

MHC

HCK

FCC

SDA

Coker
ANN – CDU unit: Prediction of Brent Fractionation

Kerosene Properties Predictions
ANN vs Petrosim

Fuel Oil Properties Predictions
ANN vs Petrosim

Diesel Properties Predictions
ANN vs Petrosim

Naphtha Properties Predictions
ANN vs Petrosim

ANN gives good predictions
Gross Margin ($/BBL) = Crude Price - \( \sum \) Yields x Products Prices
Operating conditions optimization

<table>
<thead>
<tr>
<th>Current Properties</th>
<th>Optimised Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naphtha / Kero</td>
<td>152</td>
</tr>
<tr>
<td>Kero / Diesel</td>
<td>240</td>
</tr>
<tr>
<td>Diesel / Fuel Oil</td>
<td>372</td>
</tr>
<tr>
<td>Margin</td>
<td>48.5 $/Ton</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene</td>
<td>SPG &lt; 0.84, &gt; 0.775</td>
</tr>
<tr>
<td></td>
<td>0.84, 0.84</td>
</tr>
<tr>
<td></td>
<td>0.806, 0.806</td>
</tr>
<tr>
<td>Diesel</td>
<td>SPG &lt; 0.82, &gt; 0.865</td>
</tr>
<tr>
<td></td>
<td>0.88, 0.88</td>
</tr>
<tr>
<td></td>
<td>0.865, 0.865</td>
</tr>
<tr>
<td></td>
<td>359, 386.6</td>
</tr>
</tbody>
</table>

ANN-NLP optimisation

Operating conditions
- **Current**
  - Naphtha / Kero: 150
  - Kero / Diesel: 232
  - Diesel / Fuel Oil: 360
- Margin: 45.9 $/Ton

Operating conditions
- **Optimal**
  - Naphtha / Kero: 152
  - Kero / Diesel: 240
  - Diesel / Fuel Oil: 372
- Margin: 48.5 $/Ton

ANN model impact on a Typical European refinery: 15 MT/y
37.5 M$ / year savings (+2.5$/ton)
Crude mixing optimization

Operating Feed compositions

**Optimal**
- Bonny Light: 0.00%
- Forcados: 0.00%
- Kuito: 57.64%
- Cabinda: 42.36%

Market Data

**Driving Force**
Monthly Prices (Aug - 2008)

<table>
<thead>
<tr>
<th>Crude</th>
<th>Price ($/BBL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bonny Light</td>
<td>115.17</td>
</tr>
<tr>
<td>Cabinda</td>
<td>107.82</td>
</tr>
<tr>
<td>Forcados</td>
<td>115.26</td>
</tr>
<tr>
<td>Kuito</td>
<td>97.23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Product</th>
<th>Price ($/BBL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPG</td>
<td>83.42</td>
</tr>
<tr>
<td>Napthana</td>
<td>108.37</td>
</tr>
<tr>
<td>Kerosene</td>
<td>137.65</td>
</tr>
<tr>
<td>Diesel</td>
<td>135.94</td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>104.60</td>
</tr>
</tbody>
</table>
Energy Applications

Heat integration to preheat crude oil feed
General approach for integrating Rigorous simulators with reduced models

- Integration of Rigorous simulation and reduced models for refinery-wide energy optimisation
Optimal operating conditions for energy minimization

\[
\min \text{ Op} = P_w \cdot Q_{\text{duty}}
\]

Subject to:
Mass and Energy balances
(through MIPANN models)
\[
Z_{C_{\text{Escravos}}} = 40 \text{ kbpd}
\]
\[
Z_{C_{\text{Mondo}}} = 40 \text{ kbpd}
\]
\[
Z_{C_{\text{Shengli}}} = 20 \text{ kbpd}
\]
\[
130 \leq C_{\text{nk}} \leq 160
\]
\[
220 \leq C_{\text{kd}} \leq 230
\]
\[
340 \leq C_{\text{dr}} \leq 355
\]
\[
Q_{\text{duty}} = f(Y_{\text{Res}}, Y_{\text{Dsl}}, \text{API}, T_{\text{Dsl}}, T_{\text{Res}})
\]

Optimal cut points for energy minimisation

<table>
<thead>
<tr>
<th>Optimum cut points</th>
<th>Normal operation</th>
<th>Minimum energy mode</th>
<th>Energy savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naphtha/Kero</td>
<td>160</td>
<td>130</td>
<td>-</td>
</tr>
<tr>
<td>Kero/Diesel</td>
<td>225</td>
<td>227</td>
<td>-</td>
</tr>
<tr>
<td>Diesel Residue</td>
<td>340</td>
<td>375</td>
<td>-</td>
</tr>
<tr>
<td>Furnace Duty, G cal/h</td>
<td>10.7</td>
<td>9.9</td>
<td>7.50%</td>
</tr>
</tbody>
</table>
min $O_p = P_w \cdot Q_{duty}$

Subject to:
Mass and Energy balances (through MIPANN models)
$\text{CAP}^{LB} \leq \sum_{k} Z C_k \leq \text{CAP}^{UB}$
$C_{nk} = 155$
$C_{kd} = 230$
$C_{dr} = 355$
$Q_{duty} = f(Y_{Res}, Y_{Dsl}, API, T_{Dsl}, T_{Res})$

### Optimal feedstock selection for energy minimisation

<table>
<thead>
<tr>
<th>Crude oil feedstocks</th>
<th>Normal operation</th>
<th>Minimum energy mode</th>
<th>Energy savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cinta, kbps</td>
<td>5.0</td>
<td>5.0</td>
<td>-</td>
</tr>
<tr>
<td>Arabian Heavy, kbps</td>
<td>5.0</td>
<td>5.0</td>
<td>-</td>
</tr>
<tr>
<td>Mondo, kbps</td>
<td>66.0</td>
<td>5.0</td>
<td>-</td>
</tr>
<tr>
<td>Shengli, kbps</td>
<td>24.0</td>
<td>85.0</td>
<td>-</td>
</tr>
<tr>
<td>Furance Duty, Gcal/h</td>
<td>9.69</td>
<td>8.87</td>
<td>8.4%</td>
</tr>
</tbody>
</table>
Normal operation and the minimum energy mode feedstock composition have been verified by the rigorous simulator to calculate accurately the heat duty of the furnace.

This approach allowed finding an optimum crude selection that minimises the Furnace duty in a much reduced computational time (CPU = 0.217 s) while the simulator failed to find any optimal solution and would require extensive efforts to converge.

The duty predicted by the reduced model implemented in GAMS is very close to the duty rigorously calculated in Petrosim®.
Concluding remarks

• ANN developed for refinery models

• Topping refinery model suitable for preliminary crude and gross margin evaluations

• ANN integrated into an NLP optimisation model for refinery margin maximisation and crude selection whilst meeting products specifications

• The usefulness of the proposed approach was demonstrated by using the topping refinery model for feedstock selection, process optimization and energy minimization cases
Future Directions

- Overall refinery models for the different refinery configurations

- Refinery and Energy optimisation under uncertainty

- Disaggregation and aggregation techniques for large scale ANNs training