Optimal Model-Based Production Planning for Refinery Operation

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Outline

- Introduction
- Problem Statement
- Refinery Planning Model Development
  - LP Planning Models
  - NLP Planning Models
- Conclusion
Introduction

- Refinery production planning models
  - Optimizing refinery operation
    - Crude selection
  - Maximizing profit; minimizing cost
  - LP-based, linear process unit equations

- Current Project
  - Collaboration with BP Refining Technology
  - Goal: develop a refinery planning model with nonlinear process unit equations, and integrated scheduling elements
Problem Statement

Typical Refinery Configuration

(Adapted from Aronofsky, 1978)
Problem Statement

- **Information Given**
  - Refinery configuration: Process units
  - Feedstock & Final Product

- **Objective**
  - Select crude oils and quantities to process
    - Maximizing profit
    - Single period time horizon
Refinery Planning Model

LP Planning Models
- Fixed-yield Models
- Swing cuts Models

NLP Planning Models
- Aggregate Models
- Other Models
- Fractionation Index (FI) Models
LP Refinery Planning Models

- **Fixed yield models:**
  - Simplest planning models
  - Linear equation for calculating process unit yield
    \[ F_{outlet} = a_{unit,feed,outlet} \times F_{feed} \]
  - Models are robust and simple
    - Do not represent the process non-linearity
  - Different coefficients for different operating modes and feedstock
LP Refinery Planning Model

- Swing cut models:
  - Improvement from the fixed-yield approach
  - Crude oil cuts are allowed to change
    - Front and back of each cut is optimized
      \[ F_{\text{outlet}} = a_{\text{CDU}, \text{feed}} \times F_{\text{feed}} + b_{\text{CDU}, \text{outlet}, \text{front}} + b_{\text{CDU}, \text{outlet}, \text{back}} \]
    - Better representation for the operating modes
    - Uses existing LP tools
    - Different coefficients for different crude oils
    - Models do not represent the process non-linearity
LP Refinery Planning Model

Example

- Complex refinery configuration
  - Processing 2 crude oils & importing heavy naphtha

- Swing cut model
  - Offers lower net cost & different feed quantities
  - Shows benefits of better equations

<table>
<thead>
<tr>
<th>Crude Feedstock</th>
<th>Fixed yield</th>
<th>Swing cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude1 (lighter)</td>
<td>142</td>
<td>0</td>
</tr>
<tr>
<td>Crude2 (heavier)</td>
<td>289</td>
<td>469</td>
</tr>
<tr>
<td>Other Feedstock</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy Naphtha</td>
<td>13</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Refinery Production</th>
<th>Fixed yield</th>
<th>Swing cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Gas</td>
<td>13</td>
<td>17</td>
</tr>
<tr>
<td>LPG</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Light Naphtha</td>
<td>6</td>
<td>6</td>
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<tr>
<td>Premium Gasoline</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Reg. Gasoline</td>
<td>80</td>
<td>92</td>
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<tr>
<td>Gas Oil</td>
<td>163</td>
<td>170</td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>148</td>
<td>160</td>
</tr>
<tr>
<td>Net Cost</td>
<td>89663</td>
<td>85714</td>
</tr>
</tbody>
</table>
NLP Refinery Planning Models

- Focus on the front end of the refinery
  - Crude distillation unit (CDU)
- Types
  - Aggregate model
  - Fractionation index (FI) model
  - Other models
CDU & Cascaded Columns

Typical Crude Distillation Column
(Gadalla et al, 2003)

Cascaded Columns Representation of a Crude Distillation Column
(Gadalla et al, 2003)
NLP Refinery Planning Models

- **Aggregate model**
  - Conventional distillation
    - Based on work of Caballero & Grossmann, 1999
    - integrated heat and mass exchangers
    - sections around the feed location
      - Assuming equimolal flow in each section
  - Nonlinearity in equilibrium constant
  - Single & cascaded columns arrangements
    - Model is robust
    - Results in good agreement with rigorous calculation
NLP Refinery Planning Models

- **Aggregate model**
  - Conventional distillation example
    - 4 columns
    - Feed: 18 components (C3-C20)
    - Results: product temperature matching simulation results
NLP Refinery Planning Models

- Aggregate model
  - Steam distillation
  - Modified aggregate model
    - 3 Equilibrium stages
    - 2 multi-stage sections
    - Assuming non-equimolal flow in each section
  - Nonlinearity in equilibrium constant
  - Single & cascaded columns arrangements
    - Model is robust
    - Results show predicted temperature peak at the feed stage
NLP Refinery Planning Models

- **Aggregate model**
  - Steam distillation example
    - 2 columns, both with steam distillation
    - Feed: 4 components
    - Results: temperature trend successfully predicted for both columns
NLP Refinery Planning Models

- **Aggregate model**
  - Mixed-type distillation
    - Combines conventional and steam distillation
    - Can be solved for a limited number of cascaded columns
    - Initialization
NLP Refinery Planning Models

- **FI model**
  - CDU is a series of binary separations
  - Cut point temperature is the separation temperature
  - Based on Geddes’ fractionation index method (Geddes 1958)
    - FI replaces $N_{\text{min}}$ in Fenske equation
      \[
      \left( \frac{\text{Dist}}{\text{Prod}} \right)_{i,j} = \left( \alpha_{i/\text{ref}} \right)_j^\text{FI} \left( \frac{\text{Dist}}{\text{Prod}} \right)_{\text{ref},j}^\text{ref}, \quad i \in \text{comp}, j \in \text{stage}
      \]
    - Model is crude-independent
NLP Refinery Planning Models

**FI model**

- FI model example
  - Venezuelan crude (Watkin 79)
  - 40 Pseudo-components, 4 cuts
  - 4 runs: Maximizing naphtha (N), heavy naphtha (HN), light distillate (LD), heavy distillate (HD)
- Cut-point temperature and product quantities reflect the different business objectives

**Stats**

- Equations: 562
- Variables: 568
- Solver: CONOPT

```
<table>
<thead>
<tr>
<th>Run</th>
<th>Gas OH</th>
<th>Naphtha</th>
<th>H Naphtha</th>
<th>L Dist.</th>
<th>H Dist.</th>
<th>B. Residue</th>
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<tbody>
<tr>
<td>Max Naphtha</td>
<td>272.7</td>
<td>417.0</td>
<td>426.4</td>
<td>526.8</td>
<td>595.3</td>
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<tr>
<td>Max H Naph.</td>
<td>272.7</td>
<td>386.2</td>
<td>487.8</td>
<td>526.8</td>
<td>595.3</td>
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<tr>
<td>Max L Dist.</td>
<td>272.7</td>
<td>386.2</td>
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<td>386.2</td>
<td>398.3</td>
<td>526.8</td>
<td>650.5</td>
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<table>
<thead>
<tr>
<th>Product</th>
<th>Fee</th>
<th>Prod 1</th>
<th>Prod 3</th>
<th>Prod 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Naphtha</td>
<td>6.2</td>
<td>112.9</td>
<td>35.1</td>
<td>68.6</td>
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<tr>
<td>Max H Naph.</td>
<td>6.2</td>
<td>107.4</td>
<td>53.0</td>
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<tr>
<td>Max L Dist.</td>
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<td>111.5</td>
<td>10.7</td>
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<tr>
<td>Max H Dist.</td>
<td>6.2</td>
<td>111.5</td>
<td>10.7</td>
<td>94.0</td>
</tr>
</tbody>
</table>
NLP Refinery Planning Models

**FI Model**

- *FI model in the planning model*
  - Venezuelan crude only (Watkin 79)
  - Model calculates feed quantity and final products for maximum profits at the given prices
  - Model also generates the cut point temperature settings
- Stats
  - Equations: 686
  - Variables: 707
  - Solver: CONOPT

<table>
<thead>
<tr>
<th>Feedstock</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Crude oil</td>
<td>100.0</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Final product</th>
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</thead>
<tbody>
<tr>
<td>Fuel gas</td>
<td>13.4</td>
</tr>
<tr>
<td>Prem. Gasoline</td>
<td>12.2</td>
</tr>
<tr>
<td>Reg. Gasoline</td>
<td>52.0</td>
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<tr>
<td>Distilate</td>
<td>0.0</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>6.8</td>
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<tr>
<td>HT Residue</td>
<td>16.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Economics</th>
<th></th>
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<tbody>
<tr>
<td>income</td>
<td>701</td>
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<tr>
<td>OpCost</td>
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<tr>
<td>purchases</td>
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</tr>
<tr>
<td>Profit</td>
<td>20</td>
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</table>

<table>
<thead>
<tr>
<th>Cut</th>
<th>Cut point Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naphtha</td>
<td>287</td>
</tr>
<tr>
<td>H Naph.</td>
<td>398</td>
</tr>
<tr>
<td>L Dist.</td>
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<tr>
<td>H Dist.</td>
<td>552</td>
</tr>
<tr>
<td>B Residue</td>
<td>628</td>
</tr>
</tbody>
</table>
NLP Refinery Planning Models

- Other Models
  - All limited to empirical approaches
    - Alhajeri & Elkamel (2008):
      - Empirical correlation
    - Dua & Gueddar
      - Artificial neural networks
Future work

- NLP Aggregate model
  - Investigate better initialization scheme and additional constraints

- NLP FI model
  - More runs using the FI model
    - Additional FI parameters
    - Manage property blending for the intermediate streams

- NLP models
  - Assess the benefit of the different modeling approaches in terms of accuracy, robustness & simplicity
  - Upgrade process model for other important units

- Extend the model to multi-period
- Add scheduling elements