# Optimal Model-Based Production Planning for Refinery Operation

Abdulrahman Alattas
Advisor: Ignacio E. Grossmann

Chemical Engineering Department
Carnegie Mellon University

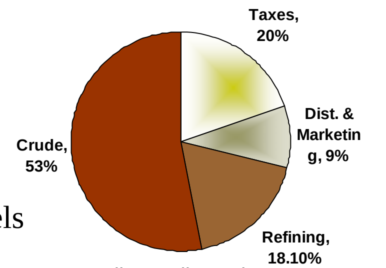


## Presentation Outline

- Introduction
- Problem Statement
- LP-Based Planning Model
- Process Unit Models
- Aggregate Model
- Conclusion

# Motivation

- Refining Operation and crude cost
  - variable cost of production
  - Largest product price components
  - Key to refinery profit and economics
- Refinery production planning models
  - Operation optimization
  - Crude selection
  - maximizing profit; minimizing cost
  - LP-based, linear process unit equations
  - comprise accuracy for robustness and simplicity




2005 Retail Gasoline Price Components (*Grant et al, 2006*)

3

# Motivation

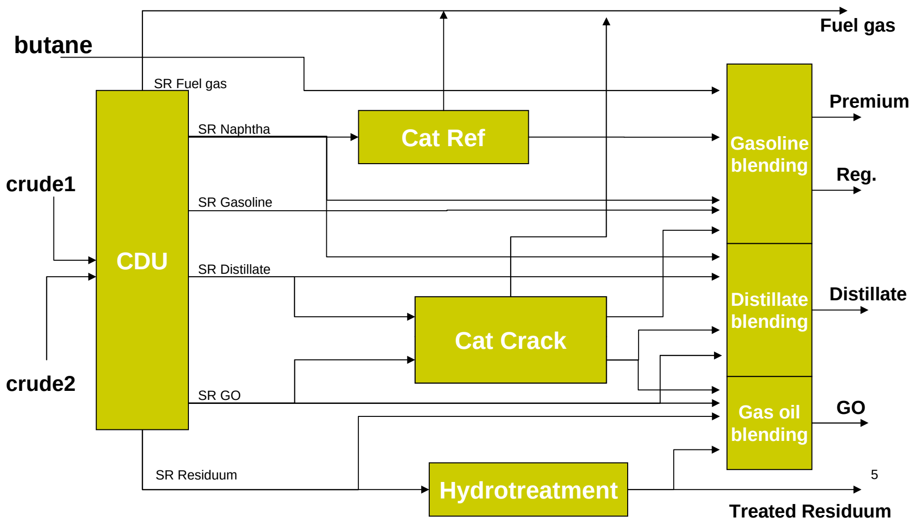
- Issues
  - Improvement to current models
    - Upgrade LP models to NLP
    - Integrate scheduling into planning model
- Current Project
  - collaboration with BP
  - Goal: develop a refinery planning model with nonlinear process unit equations, and integrated scheduling elements

4

# Problem Statement

Typical Refinery Configuration

*(Adapted from Aronofsky, 1978)*




5

# Problem Statement

- Information Given
  - Refinery configuration: Process units
  - Feedstock: crude oils & others
  - Final Product: Specs & demand
  - Economics
    - Feedstock & operating cost
    - Final product prices
- Objective
  - Select crude oils and quantities to process
    - Maximizing profit
    - single period time horizon

6

# LP-Based Planning Model (1)

- Planning model
  - Typical elements
    - Process Units
      - yield equation $F_{outlet} = a_{unit,feed,outlet} * F_{feed}$
        - Base model: fixed yield for all units
        - Capacity check $\sum_{feed} F_{feed,unit} \leq Cap_{unit}$
    - Separators:

      $$F_{i,sep-in} = \sum_{i'} F_{i',sep-out}$$
    - Mixers:

      $$\sum_{i} F_{i,mix-in} = F_{i',mix-out}$$
    - Product blending:

      $$\sum_{i} F_{i,p} = F_p$$
    - Product Specifications $\Pr_p = \sum_i \Pr_i F_{i,p}$ // $\Pr_p (\leq or \geq) Spec_{pr,p} F_p$



# LP-Based Planning Model (2)

- Economics
  - Feedstock Cost

    $$\sum C_{feedstock} * F_{feedstock}$$
  - Operating cost $\sum C_{unit} * F_{unit,feed}$
  - Income: product sales

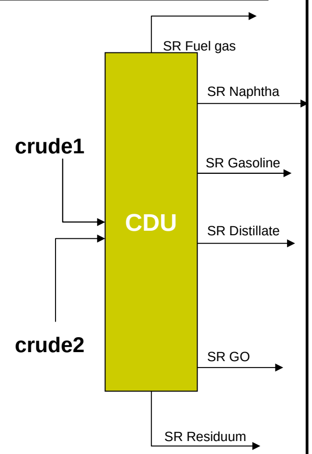
    $$\sum C_{product} * F_{product}$$
- Objective function:
  - Profit

    $$profit = \sum C_{prodcut} * F_{product} - \sum C_{feedstock} * F_{feedstock} - \sum C_{unit} * F_{unit,feed}$$
  - Cost

    $$\text{cost} = \sum C_{feedstock} * F_{feedstock} + \sum C_{unit} * F_{unit,feed} - \sum C_{prodcut} * F_{product}$$

# Process Unit Models

- Overview
  - Predicts products quantities and properties
  - Function of feed and operating conditions
  - Inherently nonlinear
- Process Models in Refinery Planning Model
  - Linear yield calculation assumption: LP requirement
  - Tradeoff: accuracy vs. robustness & simplicity
  - Area for nonlinear upgrade
- Initial Focus on CDU
  - Front end of the every refinery
  - Dictates final products and their quality
  - Affects downstream units




Typical Crude Distillation Unit (CDU)

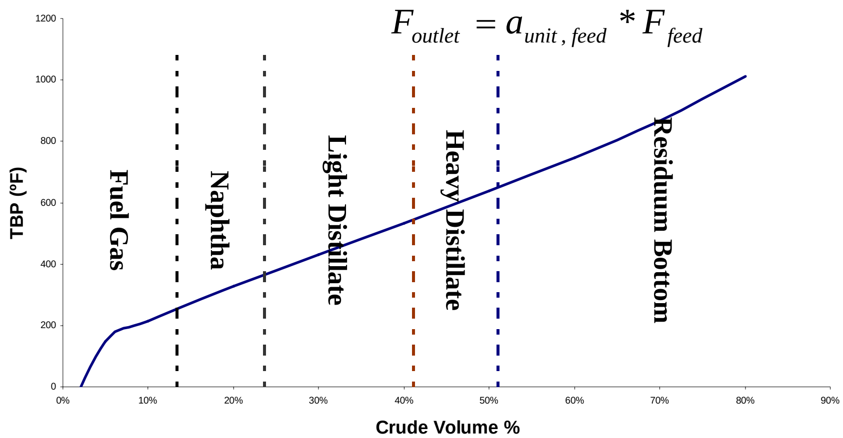




# CDU Fixed Yield Model (1)

- Fixed yield approach
  - Linear equation, for LP-based models
  - Similar approach in other units
  - Simple & robust
  - Issues
    - Linear model
    - No parameters for operating conditions or cuts property calculations
    - Single operating mode

# CDU Fixed Yield Model (2)




Crude true boiling point (TBP) curve showing crude cuts
(*adapted from Watkins 1979*)

11

# CDU Swing Cut Model (1)

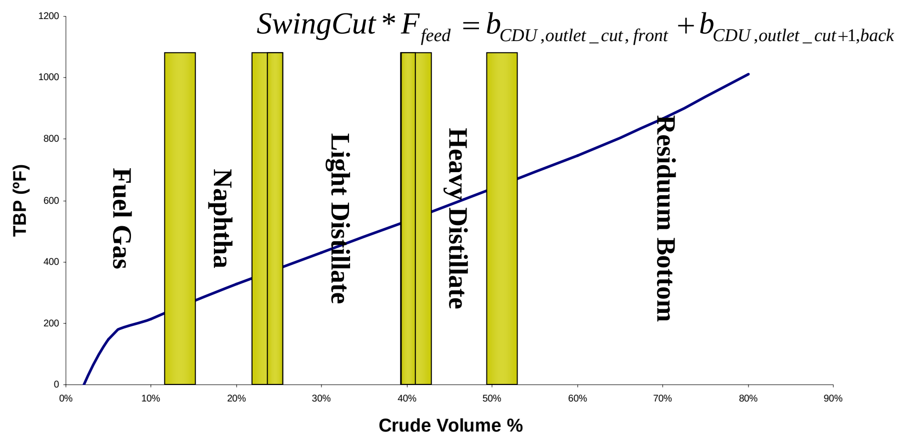
- Swing cut approach
  - Upgrade from fixed yield
  - Similar to fixed yield, with optimized cuts
  - Suitable for existing LP-based models
  - Reflects operating modes
  - Limitation
    - Linear model
    - No parameters for operating conditions or cuts property calculations

12

## CDU Swing Cut Model (2)

$$F_{outlet} = a_{CDU,feed} * F_{feed} + b_{CDU,outlet,front} + b_{CDU,outlet,back}$$

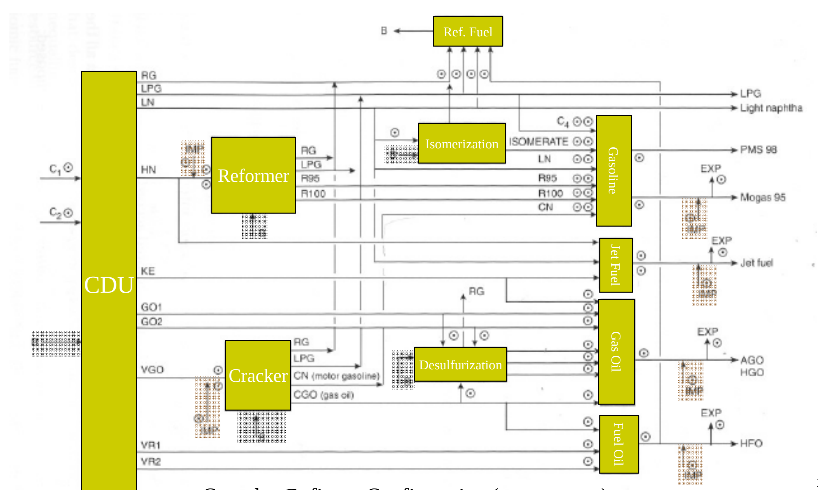
$$SwingCut * F_{feed} = b_{CDU,outlet\_cut,front} + b_{CDU,outlet\_cut+1,back}$$




Crude TBP curve showing crude cuts and swing cuts
(*adapted from Watkins 1979*)

13

## Complex Refinery Example - Configuration for Heavy Crude Processing




Complex Refinery Configuration (*Favennec, 2001*)

14

# Complex Refinery Example - Data

**Final Products Demand**

| Final Products | Demand (*kt*) |
|---|---|
| LPG | 11 |
| Light naphtha | 6 |
| Premium Gasoline (98 mogas) | 20 |
| Regular Gasoline (95 mogas) | 80 |
| Jet Fuel | 70 |
| Gas Oil | 160 |
| Fuel Oil | 148 |
| Fuel Oil (Refinery use) | 15.2 |

**Unit Capacity and Crude Availability**

| *kt* | Min | Max |
|---|---|---|
| Crude Distillation Unit | | 700 |
| Reforming Capacity | | |
| 95 severity | 2 | |
| Total | | 60 |
| Total Cracking Capacity | | 135 |
| Desulfurization Capacity | | 150 |
| Crude 1 (lighter) | | 400 |
| Crude 2 (heavier) | 260 | |

15

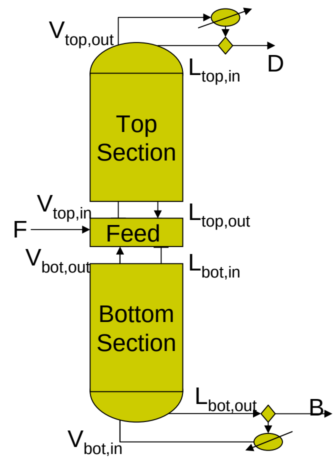
# Complex Refinery Example - Results

| | | Fixed yield | Swing cut |
|---|---|---|---|
| Crude Feedstock | Crude1 (lighter) | **142** | **0** |
| | Crude2 (heavier) | **289** | **469** |
| Other Feedstock | Heavy Naphtha | 13 | 9 |
| Refinery Production | Fuel Gas | 13 | 17 |
| | LPG | 18 | 20 |
| | Light Naphtha | 6 | 6 |
| | Premium Gasoline | 20 | 20 |
| | Reg. Gasoline | 80 | 92 |
| | Gas Oil | 163 | 170 |
| | Fuel Oil | 148 | 160 |
| | Net Cost | **89663** | **85714** |

16

# CDU Aggregate Model - Overview

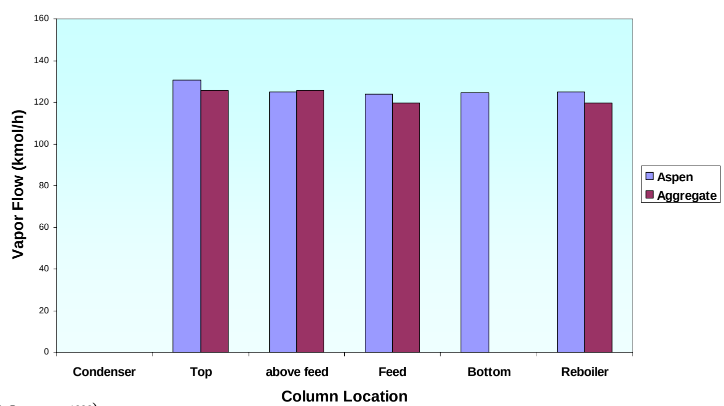
- Aggregate Distillation Column Model
  - Proposed nonlinear implementation
  - Adds simplest process modeling to planning
  - Based on work of Caballero & Grossmann, 1999
  - Principle
    - Top and bottom integrated heat and mass exchangers around the feed location
    - Constant flow in each section
    - Pinch location is at the feed section
    - Nonlinearity in equilibrium constant and stream splits
  - Advantage
    - Nonlinear process equations
    - Simplest modeling form




17

# Aggregate Model Example

- Example from Caballero & Grossmann, 1999
  - Comparison of rigorous (Aspen+) and aggregate model calculation for a distillation column with 4-component feed



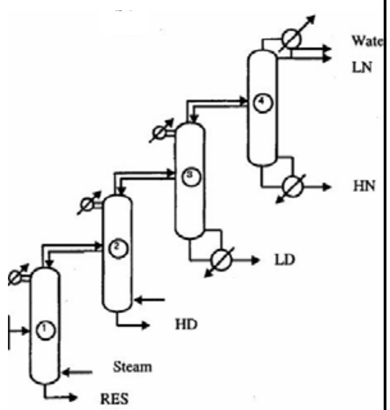

18

(*Caballero & Grossmann, 1999*)

Carnegie Mellon

# CDU Aggregate Model – Issues (1)

- Issues
  - Original work based on only top and bottom product streams
    - CDU: multiple side streams
- Proposal
  - Represent CDU with cascaded sub-columns
    - A sub-column for each section between product streams
    - Indirect sequence to represent side stripper
    - Approach can be applied to aggregate model & shortcut equations



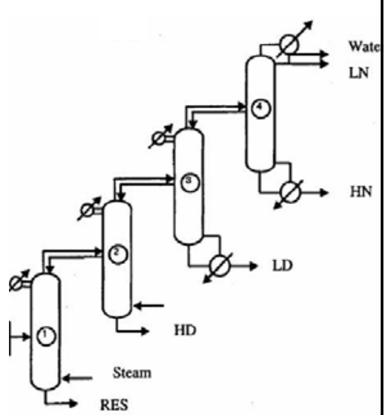

Cascaded Columns Representation of a Crude Distillation Column (Gadalla et al, 2003)



Carnegie Mellon

# CDU Aggregate Model – Issues (2)

- Features
  - Each column is modeled individually
  - The column feed is the combined feed stage inlet & outlet streams
- Steam Stripping
  - Conveniently implemented using the aggregate model
  - Short cut equation implementation
    - Question of application and results
    - Developed for reboiled column
    - Different Temperature profile

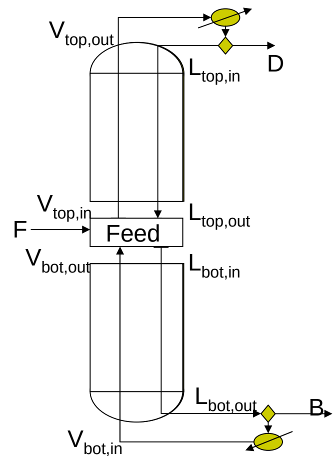



Cascaded Columns Representation of a Crude Distillation Column (Gadalla et al, 2003)

Carnegie Mellon

# Nonlinear Model Initialization

- Important for convergence
- Optimized column material balance
  - Based on recovery of distributed components
  - No energy balance or equilibrium equation
- Identified additional constraints
  - $R_i > R_{j-1}+B_j$
  - $F_1=D_j+\sum_{k=1}^{j}B_k$




21

Carnegie Mellon

# Conclusion

- Preliminary research to build a nonlinear refinery planning & scheduling model
- LP model using fixed yield & swing cut approaches
- Aggregate model equation implementation
  - Assessing the benefit of introducing nonlinearity
  - Explore other nonlinear implementation
- Extend the model to multi-period
- Upgrade process model for other important units

22

# Optimal Model-Based Production Planning for Refinery Operation

Thank you