Integration of Nonlinear CDU Models in Refinery Planning Optimization

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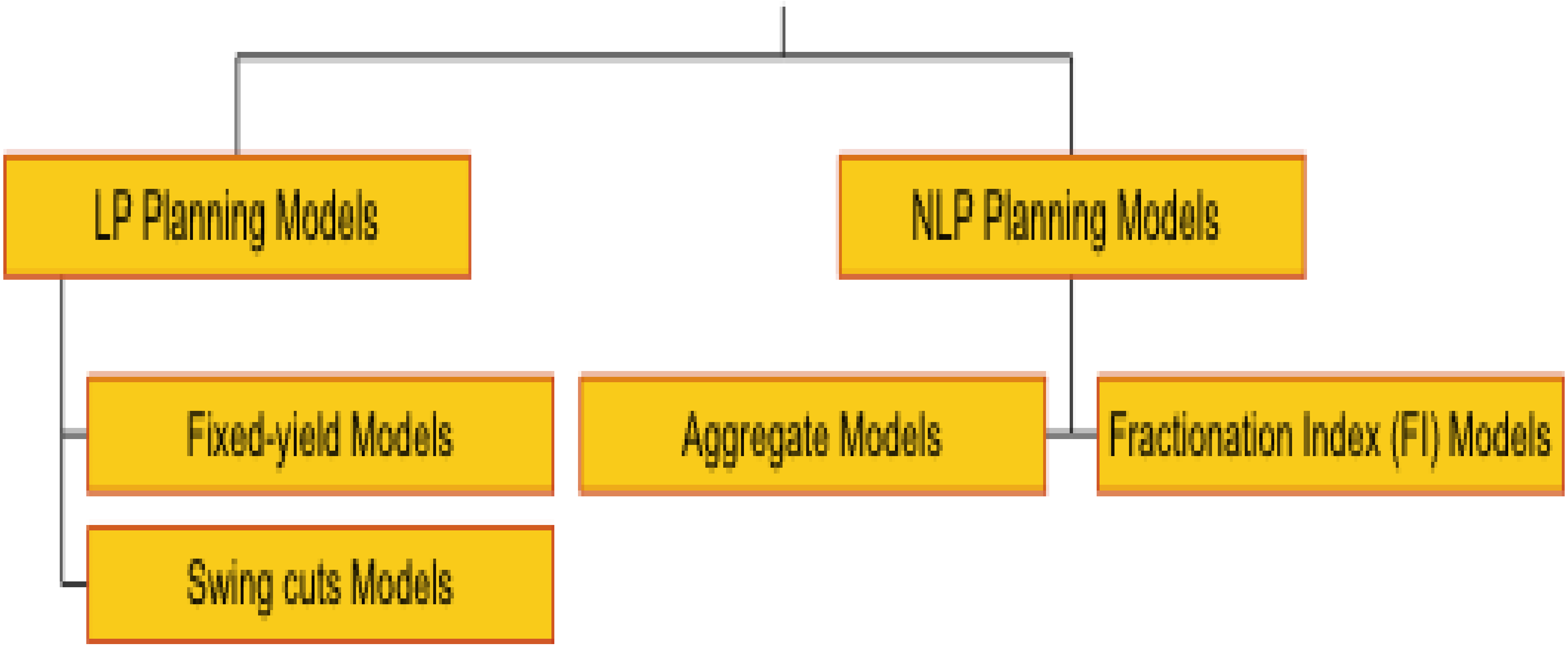
Introduction

- 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
  - Develop a refinery planning model with nonlinear process unit equations
    - integrate scheduling elements

Refinery Planning Model

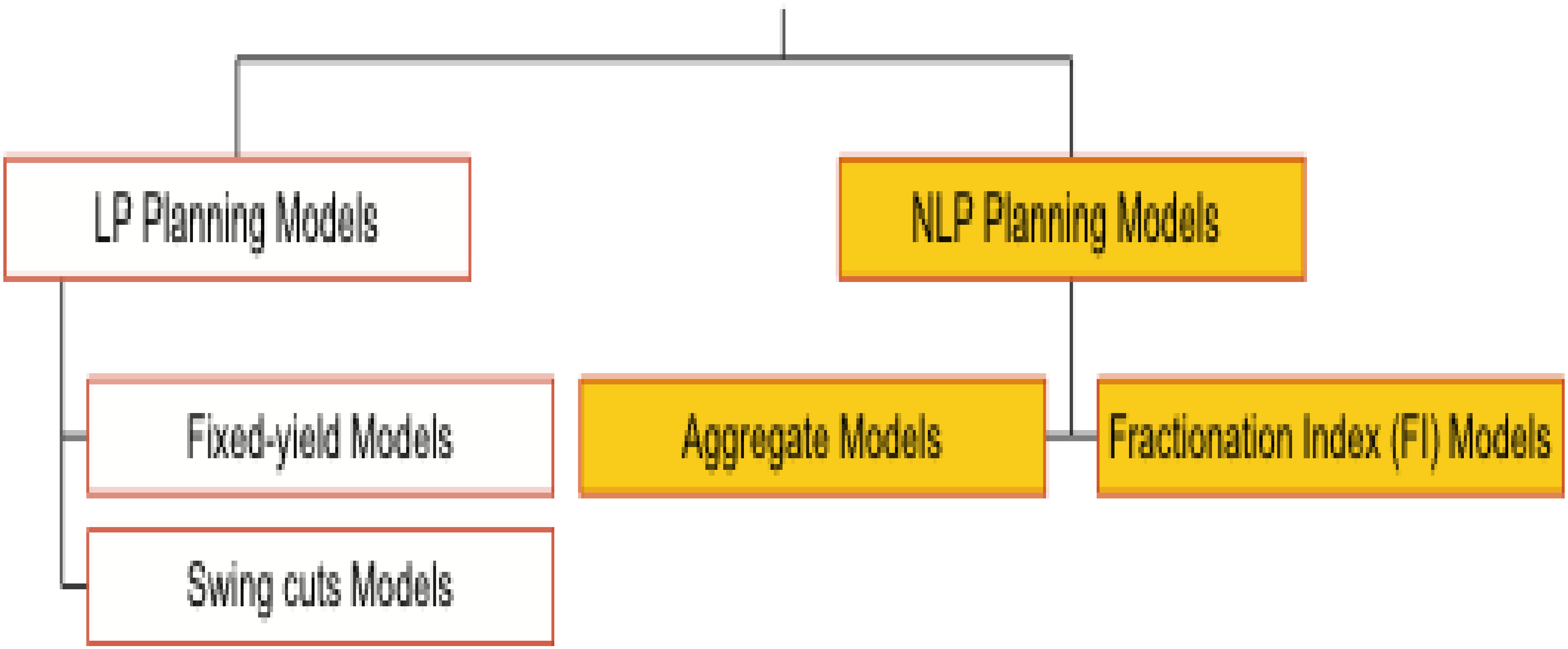


LP Refinery Planning Model Example

- **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

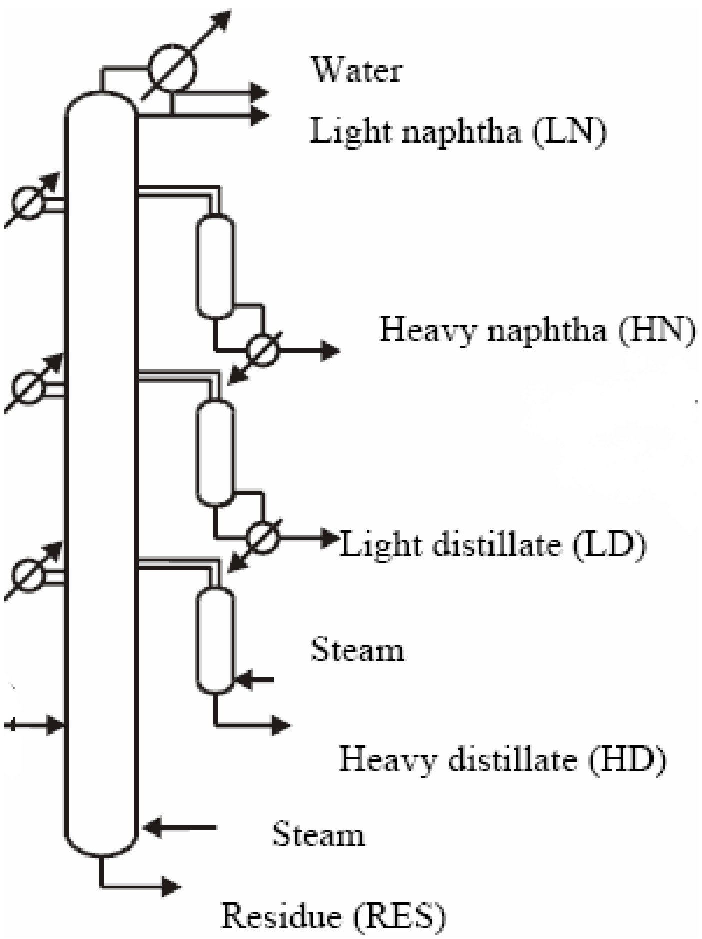
		Fixed yield	Swing cut
Crude Feedstock	**Crude1 (lighter)**	**142**	**0**
	Crude2 (heavier)	**289**	**469**
Other Feedstock	**Heavy Naphtha**	13	9
Refinery Production	**Fuel Gas**	13	17
	LPG	18	20
	Light Naphtha	6	6
	Premium Gasoline	20	20
	Reg. Gasoline	80	92
	Gas Oil	163	170
	Fuel Oil	148	160
	Net Cost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

Refinery Planning Model

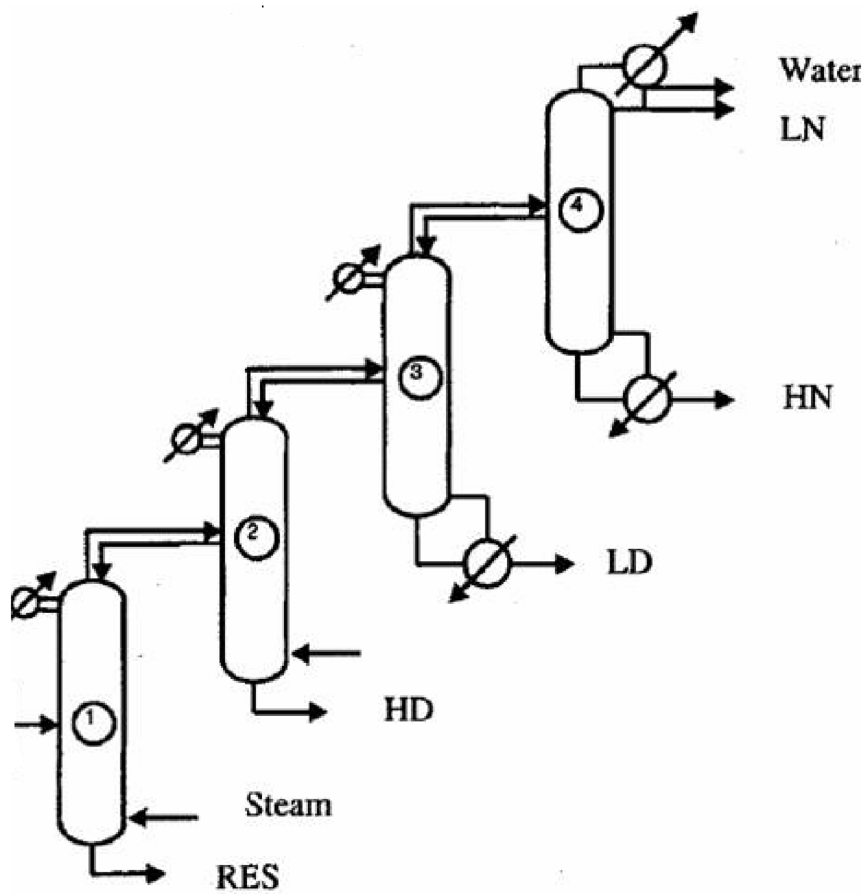


- Focus on the front end of the refinery
  - Crude distillation unit (CDU)

CDU & Cascaded Columns

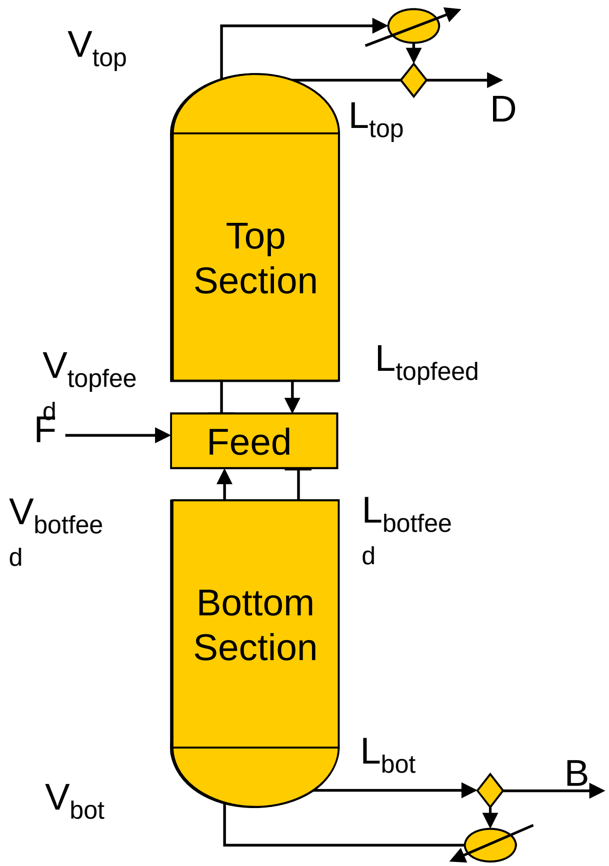


Typical Crude Distillation Column
(Gadalla et al, 2003)

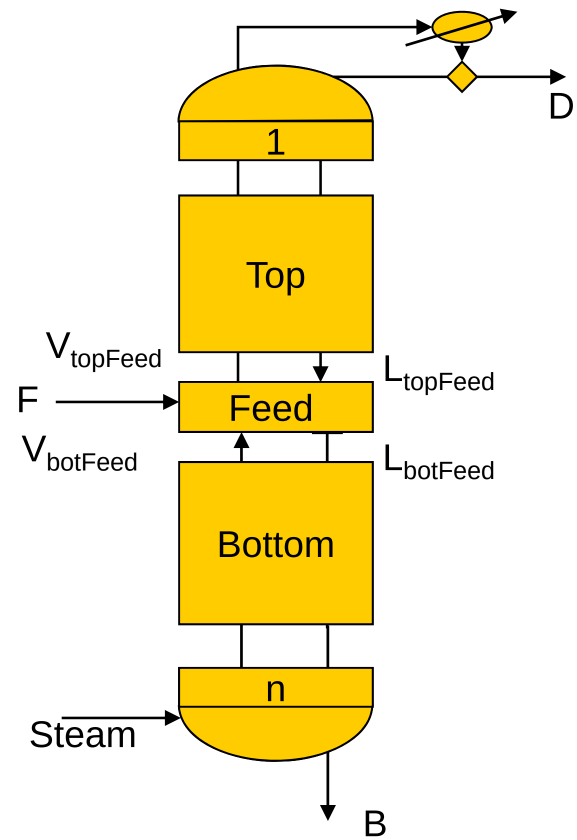


Cascaded Columns Representation of a Crude Distillation Column
(Gadalla et al, 2003)

Aggregate Model



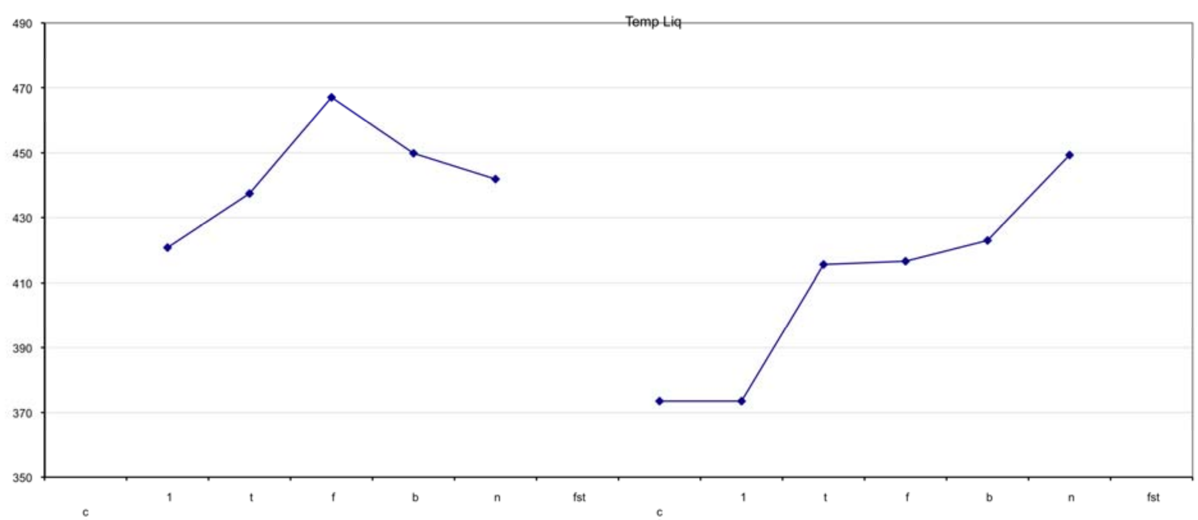
Conventional distillation

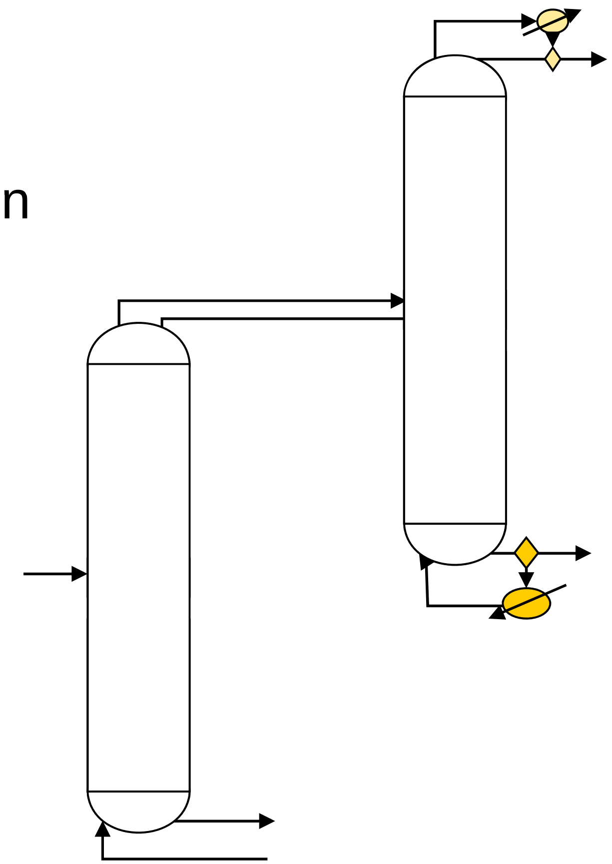


Steam distillation

NLP Refinery Planning Models

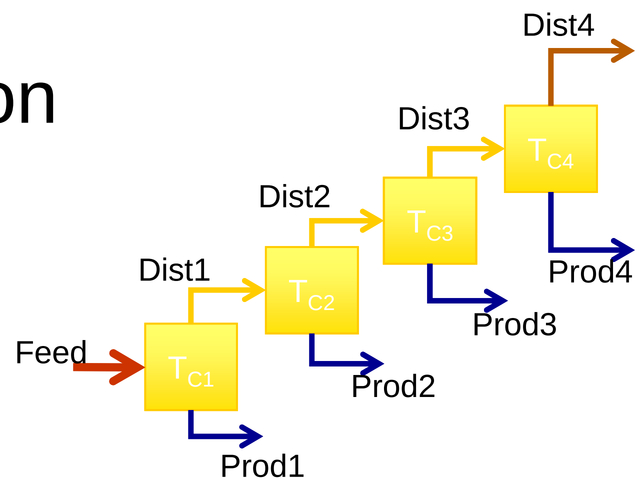
- **Aggregate Model**
  - Mixed-type distillation cascade
    - Combines conventional and steam distillation
    - Challenges with full CDU model
      - 4+ cascaded columns
      - 32+ components

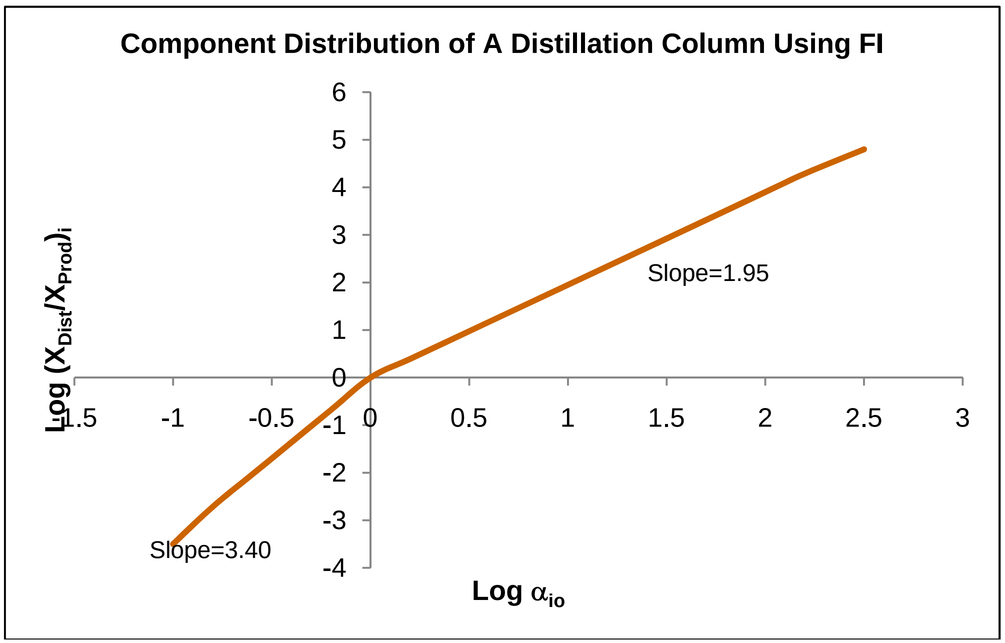




FI Model - Intro

- CDU is a series of fractionation units
  - Cut point temperature is the separation temperature





- Based on Geddes' fractionation index method (Geddes 1958)

FI Model - Equations

- Mass balance

$$F_{j,i} = PD_{j,i} + PB_{j,i}$$

$$F_{j+1,i} = PD_{j,i}$$

- Component distribution

$$PD_{j,i<LK_j} = F_{j,i}$$

$$PB_{j,i>HK_j} = F_{j,i}$$

$$PB_{j,LK_j \le i \le HK_j} = \frac{F_{j,i}}{\frac{PD_{j,total}}{PB_{j,total}} \alpha_{j,io}^{FI_j} + 1}$$

- Temperature

$$Tc_j = \frac{TE_j + TI_{j+1}}{2}$$

$$Tc_{j+1} < Tc_j$$

- Vapor pressure

$$Pv_{j,i} = Exp\left(\left(PVA_i - \frac{PVB_i}{T_j + PVC_i - 273.15}\right) * 2.303\right)$$

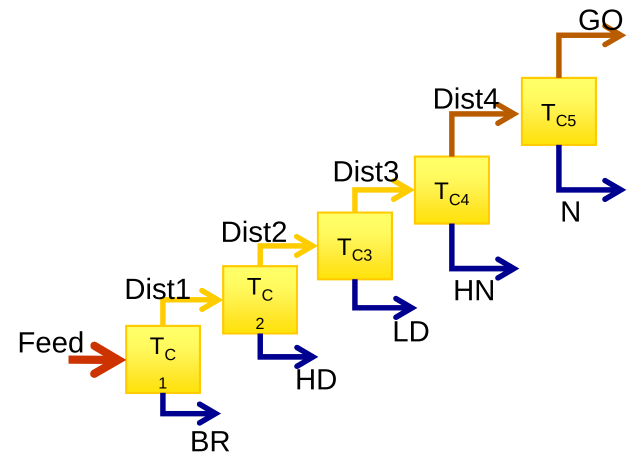
$$Pv_{j,i} = Pc_i * Exp\left(\begin{aligned}&\begin{bmatrix}-5.96346(1-Tr_{j,i}) + 1.17639(1-Tr_{j,i})^{1.5} \\ -0.559607(1-Tr_{j,i})^3 - 1.319(1-Tr_{j,i})^6\end{bmatrix} / Tr_{j,i} \\ &+\omega_i \begin{bmatrix}-4.78522(1-Tr_{j,i}) + 0.413999(1-Tr_{j,i})^{1.5} \\ -0.891239(1-Tr_{j,i})^3 - 4.98662(1-Tr_{j,i})^6\end{bmatrix} / Tr_{j,i}\end{aligned}\right)$$

FI Model - Remarks

- FI Model is crude independent
  - FI values are characteristic of the column
  - FI values are readily calculated and updated from refinery data
- Avoids more complex, nonlinear modeling equations
- Generates cut point temperature settings for the CDU
- Adds few additional equations to the planning model

FI Model – CDU Example

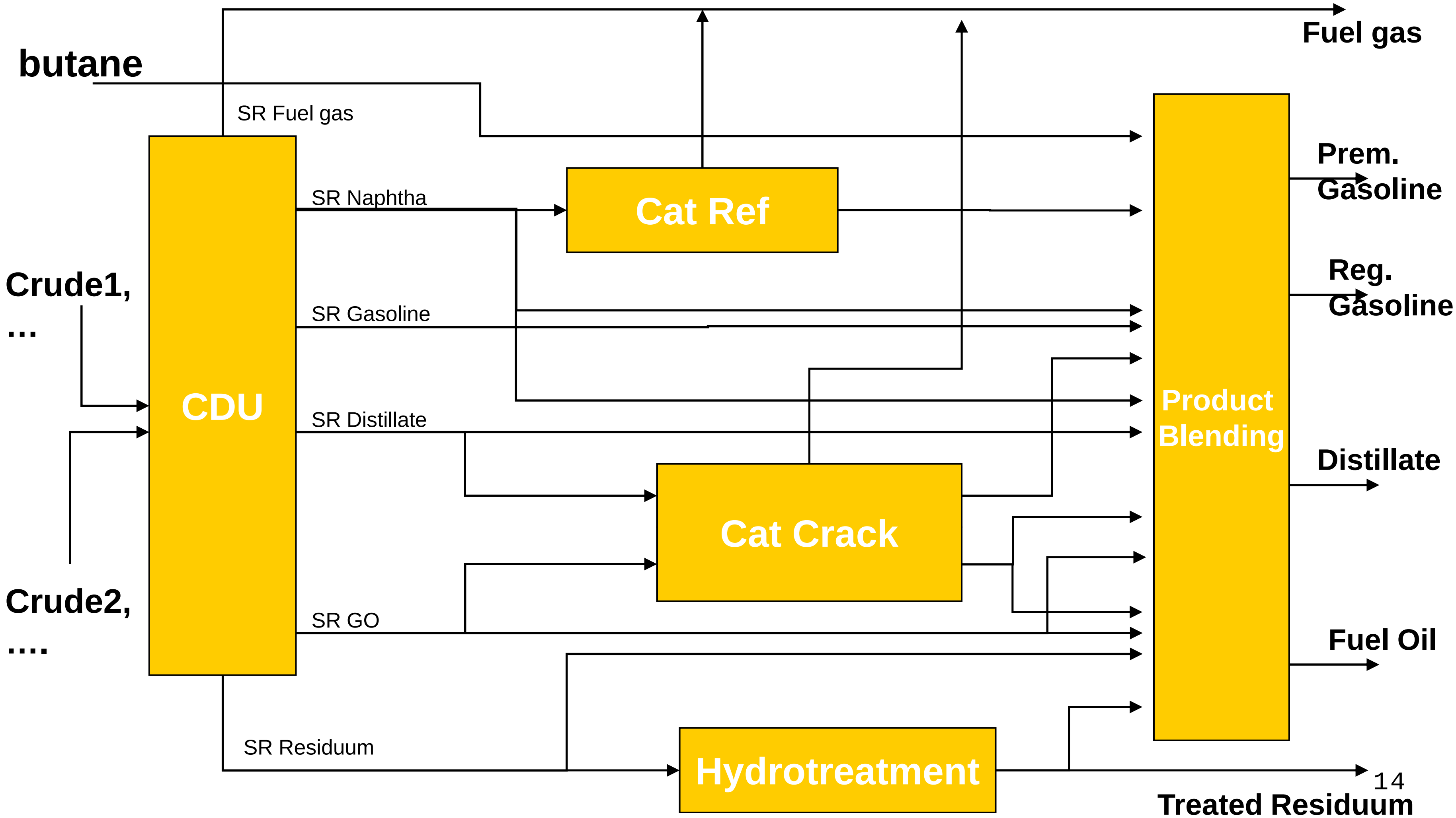
- **FI model**
  - FI model example
    - Venezuelan crude
    - 40 Pseudo-components, 5 cuts
    - 4 cases:
      - Maximizing naphtha (N), heavy naphtha (HN), light distillate (LD), heavy distillate (HD)
    - Cut-point temperature and product quantities reflect the different business objectives
    - Stats
      - Equations: 562
      - Variables: 568
      - Solver: CONOPT
      - Time: 0.360 sec



Run	Product									
	Gas Oil	Naphtha	H Naphtha	Cut point temperature					B. Residue	
				H Naphtha	L Dist.	L Dist.	H Dist.	H Dist.	B. Residue	Residue
Max Naphtha	6.2	272.7	112.9	417.0	35.1	426.4	68.6	526.8	16.5	595.3 / 60.7
Max H Naph.	6.2	272.7	107.4	386.2		487.8	56.1	526.8	16.6	595.3 / 60.7
Max L Dist.	6.2	272.7	111.5	386.2	10.7	398.3		606.0	6.0	631.0 / 60.5
Max H Dist.	6.2	272.7	111.5	386.2	10.7	398.3	94.0	526.8	16.9	650.5 / 60.5

Planning Model Example

Typical Refinery Configuration *(Adapted from Aronofsky, 1978)*



Planning Model Example
Problem Statement

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

Crude1	Louisiana	Sweet
Crude2	Texas	Sweet
Crude3	Louisiana	Sour
Crude4	Texas	Sour

Lightest

Heaviest

  - Cases: Processing 2,3 & 4 crude oils

Case 1	Crude1	Crude2		
Case 2	Crude1	Crude2	Crude3	
Case 3	Crude1	Crude2	Crude3	Crude4

- Objective
  - Select crude oils and quantities to process
    - Maximize profit
    - single period time horizon

Planning Model Example Results

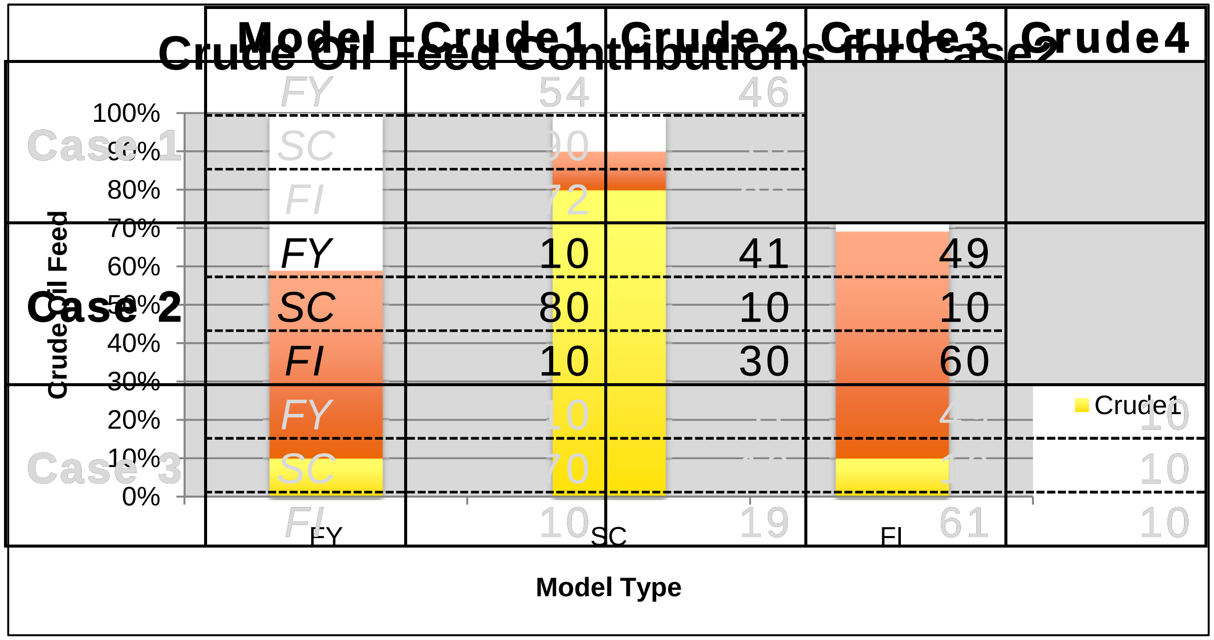
- Comparison with the fixed yield and swing cut models
- Economics
  - FI calculates the maximum profit scenario

Model	Case1	Case2	Case3
FI	245	249	247
SC	195	195	191
FY	51	62	59

Planning Model Example Results *(cont.)*

- Feedstock results:
  - Different crude purchase option

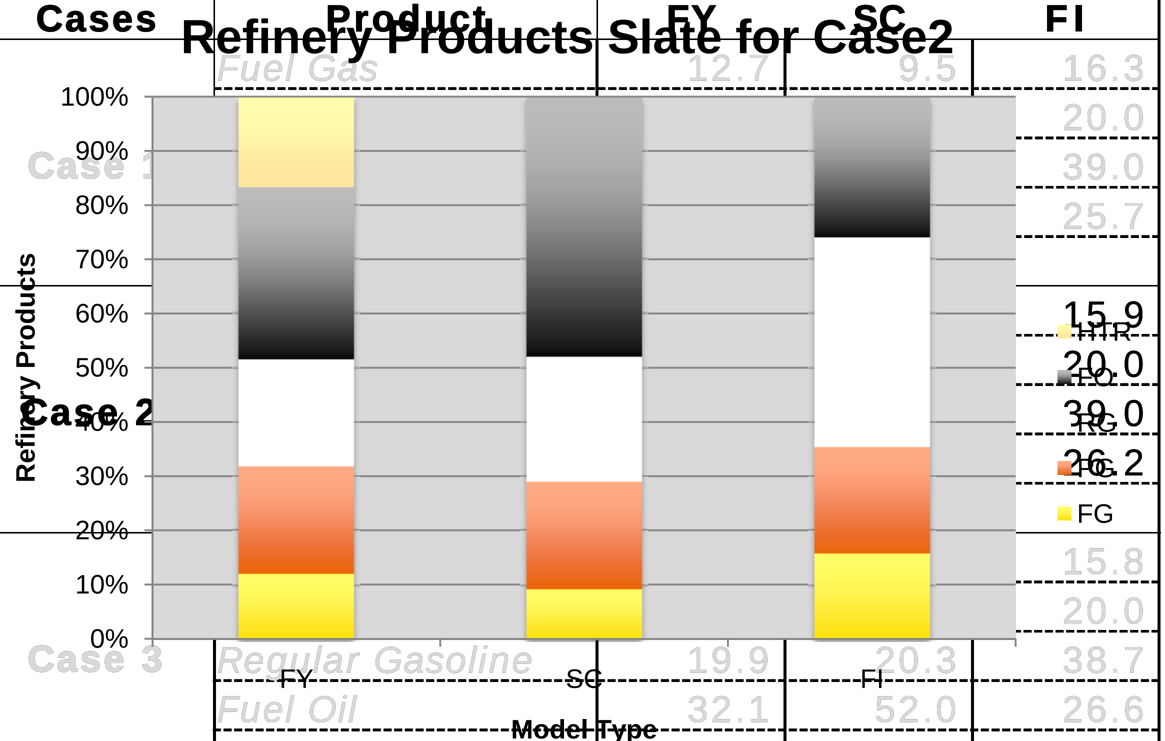
	Model	Crude1	Crude2	Crude3	Crude4
Case 1	FY	54	46		
	SC	90	[illegible]		
	FI	72	[illegible]		
Case 2	FY	10	41	49	
	SC	80	10	10	
	FI	10	30	60	
Case 3	FY	10	[illegible]	[illegible]	10
	SC	70	[illegible]	[illegible]	10
	FI	10	19	61	10



Planning Model Example Results *(cont.)*

- Products
  - Increased reg. gasoline
  - Different fuel oil rates and treated residue

Cases	Product	FY	SC	FI
Case 1	Fuel Gas	12.7	9.5	16.3
				20.0
				39.0
				25.7
Case 2				15.9
				20.0
				39.0
				26.2
Case 3				15.8
				20.0
	Regular Gasoline	19.9	20.3	38.7
	Fuel Oil	32.1	52.0	26.6
	HT Residuum	17.4		



Planning Model Example Results *(cont.)*

- Model statistics
  - FI model increased the number of equations and variables
  - ~30% nonlinear variables
  - Solution time is short

	Model	Variables	Equations	Nonlinear Variables	CPU Time	Solver
Case 1	*FY*	14	130		6.7	CPLEX
	SC	163	140		7.3	
	FI	1225	1204	348	7.3	CONOPT
Case 2	*FY*	185	161		8.4	CPLEX
	SC	215	176		9.0	
	FI	1808	1772	522	8.8	CONOPT
Case 3	*FY*	231	194		9.8	CPLEX
	SC	271	214		10.3	
	FI	2395	2342	696	10.8	CONOPT

Conclusion

- Proposed FI model
  - Crude independent
  - Calculates cut point temperature settings
  - Successful in CDU calculations
  - FI-based planning model calculates higher profits using different crude oil purchase decision
    - Limited increase in solution time
- Aggregate model
  - Successful models for Conventional distillation and steam distillation
  - Resolving modeling full CDU with mixed type columns
- NLP models
  - Assess the benefit of the different modeling approaches in terms of accuracy, robustness & simplicity

Thank You