Refining

Outline

- Refinery processes
- Refining Markets: Capacity, Cost, Investment
- Optimization of Refinery Operations

Based on
Crude Oil $\rightarrow$ Gasoline, Fuels, LPG, Chemicals

### Inputs: Crude Oils

<table>
<thead>
<tr>
<th>Molecules</th>
<th>Wght %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkanes (Paraffins)</td>
<td>30</td>
</tr>
<tr>
<td>Cycloalkanes (Naphthenes)</td>
<td>49</td>
</tr>
<tr>
<td>Aromatics</td>
<td>15</td>
</tr>
<tr>
<td>Asphalitics</td>
<td>6</td>
</tr>
</tbody>
</table>

### Final Products
- Gasoline
- Jet and Heating Fuels
- Liquefied Petroleum Gas
- Chemicals

Offsite Facilities: Electric power distribution; Fuel oil and fuel gas facilities; Water supply, treatment, disposal; Plant air systems; Fire protection systems; Flare, drain and waste containment systems; Plant communication systems; Roads and walks; Railroads; Buildings.
Inland Refinery: Holly Frontier’s Tulsa

Holly Frontier Cooperation (HFC)
$8 Billion revenue, publicly traded, Dallas headquartered.
HFC has refineries also in NM, KS, WY, CO; all inland and complex refineries
Refinery capacity 443 K barrels/day
0. Tulsa capacity 125 K barrels/day
1. Crude oil brought by railways encircling the Tulsa refinery
2. Oil is offloaded to Storage Tanks
Crude Oil Operations, Refining Operations, Final Product Storage

I. Crude Oil Operations
- Receive Crude Shipments
  - Continuous or in Parcels
- Store Crude in Storage Tanks
  - Hedge against crude unavailability risk
    - 15-day throughput storage often adequate
- Use Staging Tanks
  - Mix different crudes
  - Remove Brine (Salts)
  - Hedge against input unavailability
    - 3-4 day throughput storage often adequate
- Pump Crude to the Distillation Unit

II. Refining Operations
- 4 processes, to be detailed later
- Refining is the process of converting crude to usable products.
- Refining operations are continuous processes

Final Product Storage
- Until train, tanker truck, tanker ship pick up or pipeline shipments
- Capacity with 10 days of throughput
Crude Distillation Unit (CDU)

- Hydrocarbons in crude have different boiling temperatures.
  - At 20 °C boiling are few-carbon alkanes: methane (1C), ethane (2C), propane (3C), butane (4C)
  - Around 70 °C boiling are cycloalkanes: pentane (5C), hexane (6C),
  - Around 120 °C boiling is heptane (7C). Liquids are octane (8C), nonane (9C)

- Heated crude turns into vapor and rises in the distillation tower.

- As rising, it cools & condenses on trays.
  - At 20 °C, 1C-4C are in the gas phase and exit from the top of the distillation (fractioning) column.
  - At 120 °C. Some of 5C-9C exit as gas, some as gasoline.
  - At 170 °C, Kerosene condenses & flows out from its tray.
  - At 600 °C, Fuel oil condenses & flows out from its tray.
  - Residue (bottom) is asphalt & liquid when heated, but solidifies in room temperature.

Source: www.energyinst.org.uk
1. Distillation Process: Physical separation
1.A. Atmospheric towers & 1.B. Vacuum towers

Crude Oil

Dehydration and Desalination

1. Distillation

Atmospheric Pressure

- < 30 °C: Butane C₄ and lighter
- 30-150 °C: Gasoline (low octane) and Naphtha
- 150-230 °C: Kerosene
- 230-340 °C: Light Gas Oil (No. 1-4 Fuel Oil)
- 340-430 °C: Heavy Gas Oil (No. 5-6 Fuel Oil)
- > 430 °C: Residual Fuel Oil, Asphalt

Vacuum Unit
Reduced Pressure

Low pressure facilitates boiling

Intermediate Products

Final Products

Refinery fuel gas, propane, NGL (Natural gas liquids)

Gasoline (high octane), Jet fuel

Kerosene, Jet fuel, Diesel, Fuel oil

Gasoline (high octane), Diesel, Fuel oil

Further processing 2-4

Further processing 2-4
2. Conversion Processes: Decompose (Crack), Unify, Reform

Intermediate Products

- Butane and lighter
- Gasoline (low octane)
- Naphtha
- Kerosene
- Light Gas Oil (No. 1-4 Fuel Oil)
- Heavy Gas Oil (No. 5-6 Fuel Oil)
- Residual Fuel Oil
- Asphalt

Cracking Processes

- Thermal Cracking
- Catalytic Cracking
- Visbreaker
- Coking

Intermediate Products: Butane and lighter, Gasoline (low octane), Naphtha, Kerosene, Light Gas Oil (No. 1-4 Fuel Oil), Heavy Gas Oil (No. 5-6 Fuel Oil), Residual Fuel Oil, Asphalt

Final Products

- Refinery fuel gas
- Propane
- NGL
- Regular Gasoline
- Premium Gasoline
- Solvents
- Jet fuel
- Diesel
- Heating/Fuel oil
- Lubricants oils
- Greases
- Asphalts
- Coke: Similar to Coal

Vapor Recovery: Capturing gasses physically

Isomerization

Reforming

Alkylation

3. Treating

4. Blending

Cracking Processes
2. Conversion Process Descriptions

2.A. Cracking

- **Cracking**: Breaking down heavier and larger HCs into lighter and smaller HCs.
  - **Thermal Cracking**: Using heat to crack.
    - **Steam-cracking**: Using steam to crack; sound-like steam flooding in EOG.
    - **Coking**: Using extreme heat to crack residue to obtain coke and heavy oil.
    - **Visbreaking**: Using moderate heat to crack with the purpose of reducing viscosity
  - **Catalytic cracking**: Using a catalyst (facilitator) under high temperature.
    - **Fluid catalytic cracking (FCC)**: Using zeolites (aluminium + silicates) powder as catalyst
    - **Hydro cracking**: Using water (hydrogen) as catalyst

<table>
<thead>
<tr>
<th></th>
<th>Fluid catalytic cracking</th>
<th>Hydro cracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use zeolites &amp; hydrogen ↑ gasoline yield &amp; kerosene yield.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPG</td>
<td>14%</td>
<td>6%</td>
</tr>
<tr>
<td>Gasoline</td>
<td>45%</td>
<td>4%</td>
</tr>
<tr>
<td>Kerosene</td>
<td>1%</td>
<td>40%</td>
</tr>
<tr>
<td>Diesel (Gasoil)</td>
<td>23%</td>
<td>38%</td>
</tr>
<tr>
<td>Other: gas, naphta, residue, coke</td>
<td>17%</td>
<td>12%</td>
</tr>
</tbody>
</table>

Based on Figure 240 on p.171 of GOGI.
2. Conversion Process Descriptions

2. B. Reform and 2. C. Combine (Unify)

- **Higher Octane Level** ⇒ Better combustion under pressure.
  - Level indicates the amount of pressure a HC can withstand before self-ignition.
  - Octane levels are defined relative to iso-octane.
  - As there can be more pressure resistant HCs, octane levels >100 ok for them.
  - E.g.: Methane has octane number 120.

- **Isomerization** is changing the geometry of the molecule.
  - This increase the octane level.

- **Reforming** is obtaining cyclic HCs from chains.

- **Alkylation** is obtaining alkanes (saturated) HCs from non-saturated ones.
  - This yields larger molecules with higher octane levels.
3. Treating

1. Distillation ✓  2. Conversion ✓

3. Treatment: Preparation of HCs and finished products by using chemical / physical separation.
   - Removing unwanted substances: Salt, Sulfur, nitrogen, oxygen, metals (lead, mercury)
     » Desalting
     » Hydrodesulfurization: Sulfur removal yields elemental sulfur that is used in agriculture (as fertilizer) and in pharmaceuticals. Some sulfur can remain in fuel oil and coke.
   - Dewaxing to avoid solidification under low temperature and to improve gasoline flow in winters.
4. Blending

1. Distillation ✓  2. Conversion ✓  3. Treating ✓
4. Blending: Mixing of HCs in certain fractions to obtain finished products with specific properties.

Four cycle engine: 4-step engine:
1. Intake (injection)
2. Compression
3. Power
4. Exhaust

Piston goes back to the same position twice to complete 4 steps
4. Blending for Specific Properties

Ignition Properties:

- **RVP (Reid Vapor Pressure)** specifies evaporation characteristic of gasoline.
  - RVP measures the surface pressure that keeps a liquid from vaporizing.
    - High RVP ⇒ Liquid vaporizes easily. Low RVP ⇒ Liquid does not vaporize easily
  - Liquid gasoline does not burn easily. Spraying charcoal igniter liquid on your barbecue ok, if the liquid is cold.
  - A **fuel injector** sprays gasoline & oxygen at the right mix and pressure into the engine block for combustion.
    - Injector needs 6-12 psi RVP; Higher RVP for lower temperatures and lower RVP for higher temperatures
  - Vapor vaporizes easily under high temperature
    - RVP of 12 psi for Fargo, North Dakota in winters; less RVP, gasoline remains as liquid and does not burn.
    - RVP of 6 psi for Dallas, TX in summers; more RVP, gasoline vaporizes while pumping or transferring to the injector
  - EPA needs less RVP to reduce evaporative emissions. The limits are stricter during the summer ozone season.

- **Octane level**: Gasoline mostly has octane C₈H₁₈ and some heptane C₇H₁₆ & others.
  - Gasoline with octane number 90 has the same combustion properties as 90% iso-octane and 10% heptane.
  - Similarly octane number 80 indicates the same combustion properties as 80% octane and 20% heptane.
  - Knocking: Ignition of gasoline in the engine block on its own before being ignited by a spark plug.
    - Self-ignition is more likely if the pressure on the gasoline is high
    - The pressure on the gasoline is high in engines with high compression ratio
    - Compression ratio = Highest volume of an engine block / Lowest volume of the engine block
    - Sport cars: high compression ratio engines to obtain more power ⇒ high risk of self-ignition
      - Sport cars need less combustible gasoline, which is high octane gasoline
  - High octane rating ⇒ smooth & sustained combustion with less combustible gas to avoid knocking

Corrosion Properties:

- **Sulphur level**: Crude with > 0.5% Sulphur is corrosive (sour).
- **TAN (Total Acid Number)** is the concentration of potassium hydroxide (KOH, a base) needed to neutralize the acid in the crude. Crude with TAN > 1 mg KOH/g is corrosive.
4. Blending Computations

4. Blending:

- **Octane level:**
  - Gasoline with different octane levels can be blended
  - 50-50 Blending of 90 octane gasoline with 80 octane gasoline yields 85 octane gasoline.
  - 20-80 Blending of 90 octane gasoline with 80 octane gasoline yields 82 octane gasoline.
    - \[82 = (0.2)90 + (0.8)80\]
  - Suppose we are selling mid-grade gasoline with 88 octane. In what proportions should we blend 90 octane gasoline and 80 octane gasoline to obtain 88 octane gasoline?
    - \[88 = 90x + 80(1-x)\] gives \(x = 0.8\).

- These linear blending computations are assumed to be valid for sulfur content, TAN & RVP, i.e., for a characteristic \(C_{blend}\), we obtain it from the characteristic \(C_i\) of the ingredient \(i\) by using volume (or weight) \(V_i\).
  - Take a weighted average of characteristics where weights can be relative volumes (weights)
    \[C_{blend} = \sum_{i \in \text{Ingredient}} \left( \frac{V_i}{\sum_{j \in \text{Ingredient}} V_j} \right) C_i\]
  - There also is a nonlinear but more exact formula for RVP:
    \[RVP_{blend} = \left( \frac{\sum_i V_i}{\sum_j V_j} RVP_i^{1.25} \right)^{\frac{1}{1.25}}\]
  - The nonlinear blending equation above is suggested by William Jackson, Merit 18.
Blending then and now: Preference for Alcohol over Lead in the Engines

Ethyl Cooperation (www.ethyl.com) founded in 1923 ran ads like the one on left. This ad is from National Geographic 1931 – 8 years after Ethyl’s founding.

The “Ethyl Fluid” mentioned in the ad is to
- “deliver power … with a smoothly increasing pressure”
- rather than “sharp, irregular bursts (that cause power-waste, harmful knock and overheating)”

Ethyl component $\text{CH}_3\text{CH}_2 - [?]$ has an open bond to connect with $[?]$

- Lead $\text{Pb}$ (Plumbum in Latin) in “Ethyl Fluid” of then.
- Gasoline is lead-free now in most countries.
- Now Ethyl alcohol (octane number 108) is blended with gasoline up to 25% in Brazil & 10% in the USA.

Ethanol = Ethyl Alcohol
= $\text{CH}_3\text{CH}_2\text{OH}$

Lead is toxic
+ But radiation shield
Refinery Operations and Yields

I. Crude oil receipt and operations
   1. Mix
   2. Desalt

II. Refining operations
   1. Distillation
      a) Atmospheric
      b) Vacuum
   2. Conversion
      a) Cracking
         i. Thermal Cracking: Steam-cracking, Coking, Visbreaking
         ii. Catalytic cracking: Fluid catalytic cracking, Hydro cracking
      b) Reforming
         i. Isomerization
         ii. Reforming
      c) Combining (Alkylation)
   3. Treating
      a) Desalt
      b) Hydrodesulfurization
      c) Dewax
   4. Blending

III. Final product storage and shipment

◆ Refinery yields in US in 2003:
   - 46.9% Gasoline
   - 23.7% Distillate fuel oil (inc. Diesel)
   - 4.2% Residual fuel oil (heating & ship fuel)
   - 9.5% Jet Fuel
   - 5.1% Coke
   - 3.2% Asphalt
   - 4.2% Liquefied gas

◆ Refinery yields in Europe p.168 of GOGI:
   - 21% Gasoline + 6% Naphta
   - 36% Distillate fuel oil
   - 19% Residual fuel oil
   - 6% Kerosene used in Jet Fuel
   - 9% Residuals like Asphalt
   - 3% Petroleum gas like Liquefied gas

More gasoline in US. More Diesel & Fuel oil in Europe.
Refinery Markets: Capacity, Cost, Investment
Refinery Characteristics: Types and Products

- Simple refineries have low margins and are owned by small & niche companies.
- Complex refineries have higher margins.
  - Their margins ↑ when the spread (light sweet crude price − heavy sour crude price) ↑
- Refinery outputs are commodities
  - Gasoline (aviation, car and light distillates); Middle distillates (diesel fuel, jet fuel, heating oil); Other products (lubricants, wax, solvents, machine oils)
  - Output markets are more segmented by location, regulation, season, quality.
  - Product prices are related to crude prices whose prices are volatile.
  - Product prices are volatile as demand is inelastic in the short-term.

<table>
<thead>
<tr>
<th>Study</th>
<th>Product</th>
<th>Short-term elasticity</th>
<th>Long-term elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dahl &amp; Sterner 1991</td>
<td>Gasoline</td>
<td>0.26</td>
<td>0.86</td>
</tr>
<tr>
<td>Espey 1998</td>
<td>Gasoline</td>
<td>0.26</td>
<td>0.58</td>
</tr>
<tr>
<td>Graham &amp; Glaister 2004</td>
<td>Gasoline</td>
<td>0.25</td>
<td>0.77</td>
</tr>
<tr>
<td>Brons et al. 2008</td>
<td>Gasoline</td>
<td>0.34</td>
<td>0.84</td>
</tr>
<tr>
<td>Dahl 1993</td>
<td>Oil</td>
<td>0.07</td>
<td>0.30</td>
</tr>
<tr>
<td>Cooper 2003</td>
<td>Oil</td>
<td>0.05</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Refining Characteristics: Margins

- Refineries, capital-intensive, long lifetime, very specific physical assets
  - Cost of a refinery.
  - High initial investment and exposure to financial risk: interest rate, investment cycle, crude cost.
  - Gross margin = Revenues from product sales – Cost of crude was $8.68 per barrel in 2004.
  - Net Margin = Gross margin – Cost of (marketing + internal energy + operating) was $3 per barrel in 2004.
  - Booms and Busts: Profitability of refinery peaked in 1988 and 2001: 15%. It plunged to -1.7% in 2002.

- Crudes are becoming heavy and sour (high-sulfur).
  - Recent capacity expansion of US refineries is to provide bottom-of-the-barrel processing to handle heavy crude.
  - This is profitable and required by environmental regulations.
  - Cracking refineries are becoming coking refineries over time with the capacity and process expansions.

### Complexity US Capacity Gross Margin $/barrel Net Margin $/barrel

<table>
<thead>
<tr>
<th>Complexity</th>
<th>US Capacity</th>
<th>Gross Margin $/barrel</th>
<th>Net Margin $/barrel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topping</td>
<td>5.6%</td>
<td>0.5 to 1.5</td>
<td>-0.5 to 1.5</td>
</tr>
<tr>
<td>Cracking</td>
<td>28.7%</td>
<td>3 to 4.5</td>
<td>0 to 2.5</td>
</tr>
<tr>
<td>Coking</td>
<td>65.7%</td>
<td>5 to 7</td>
<td>0.5 to 4</td>
</tr>
</tbody>
</table>

- Refining is energy intensive.
  - US refining consumed 6.4 quads (10^{15}) BTU in 2004. This is 28% of energy consumption in US manufacturing.
  - 30-40% of refining energy is spent on distillation.
  - 20% spent on hydrotreating (removal of sulfur, nitrogen, oxygen and metals).
  - Close to 60% of operating expenses are for the energy.
Refining Characteristics: Pollution

🔹 Refineries create pollution
  - Pollution gases emitted during refining operations: Particle matter (dust, dirt, smoke, soot), Sulfur dioxide, Carbon monoxide, Nitric oxides, Volatile organic compounds (paints, adhesives). All of these are created by catalytic cracking and coking units.
  - Pollution created by refinery products such as gasoline. Reducing the pollution from burning gasoline?
  - Refineries are subject to several regulations.

🔹 Each refinery is unique and evolve with expansions over time.
  - ConocoPhillips’ Borger Refinery is located in Borger, TX, in the TX Panhandle about 50 miles north of Amarillo and includes an NGL fractionation facility. The refinery’s gross crude oil processing capacity is 146 MBD, and the NGL fractionation capacity is 45 MBD.
    » Facilities: coking, fluid catalytic cracking, hydrodesulfurization and naphtha reforming that enable it to produce a high percentage of transportation fuels.
    » Input: Primarily medium sour crude oil and natural gas liquids received through pipelines from West TX, the TX Panhandle, WY and CA. It can receive foreign crude via company-owned and common-carrier pipelines.
    » Output: A high percentage of transportation fuels (gasoline, diesel fuel and jet fuel), coke, NGL and solvents.

  - ConocoPhillips’ Sweeney Refinery located in Old Ocean, TX, 65 miles southwest of Houston, has a crude oil processing capacity of 247 MBD. It processes mainly heavy, high-sulfur crude oil, but also processes light, low-sulfur crude oil.
    » Facilities: fluid catalytic cracking, delayed coking, alkylation, a continuous regeneration reformer and hydrodesulfurization units.
    » Input: Domestic and foreign crude oil, received primarily through wholly and jointly owned terminals on the Gulf Coast, including a deepwater terminal at Freeport, TX.
    » Output: A high percentage of transportation fuels (such as gasoline, diesel fuel and jet fuel). Other products include petrochemical feedstocks, home heating oil and coke.
    » The refinery operates nearby terminals and storage facilities in Freeport, Jones Creek and on the San Bernard River, along with pipelines that connect these facilities to the refinery.
**Investment Cost for a Refinery in 1994 by Major Equipment Estimates**

- **Onsite facilities** of a refinery cost: $82,976 K:
  - Desalter $1,800 K for 30,000 BPSD (=barrels per stream day)
    
  Barrel per stream day BPSD = max # of barrels of input a distillation unit can process
  - Atmospheric distillation unit $27,000 K for 30,000 BPSD
  - Vacuum distillation unit $14,500 K for 18,000 BPSD
  - Naphtane desulfurization unit $6,600 K for 4,000 BPSD
  - Reforming unit $11,000 K for 3,000 BPSD
  - Catalytic reformation unit $600 K.
  - Cold water system $824 K for 8,240 gallons per minute.
  - Steam system $2,472 K for 30,900 pound per hour.
  - Storage $18,000 K for 12 days throughput
    
    Storing 360,000=12*30,000 barrels at the cost of $50/bbl storage capacity

- **Offsite facilities:** Electric power distribution; Fuel oil and fuel gas facilities; Water supply, treatment, disposal; Plant air systems; Fire protection systems; Flare, drain and waste containment systems; Plant communication systems; Roads and walks; Railroads; Buildings.
  - For a midsize refinery offsite costs are 30% of onsite facility cost.
  - Offsite facilities cost: $24,839 K.

- **Location factor:** Location determines climate (affects design & construction costs), local rules & taxes.
  - US Gulf coast refineries are relatively cheaper and have location factor of 1.0.
  - St. Louis has a factor of 1.4. Alaska North Slope has a factor of 3.0.

- **Contingencies:** 15% allowance for major loopholes and inaccuracies.

- **Cost of a midsize refinery in St. Louis in 1994 was about $174 million.**
  
  \[(82,976) \times (1.3) \times (1.4) \times (1.15) = 173,582\]

Take Inflation Factor into Account

- We have found the cost of a simple refinery to be $174 million in 1994. To bring it to 2010 use:

\[
\text{Cost in year (t)} = \left[ \text{Cost in year (s)} \right] \times \left[ \frac{\text{Index in year (t)}}{\text{Index in year (s)}} \right]
\]


- If this refinery were to be built in Alaska North Slope, the cost would be
  
  \[
  \text{Cost} = 301.36 \times \frac{\text{(Location factor in North Slope)}}{\text{(Location factor in St. Louise)}}
  \]
  
  \[
  = 301.36 \times \frac{3}{1.4}
  \]
  
  \[
  = $646 \text{ Million.}
  \]

Cost of **Capacity and Complexity**

- Cost of a $q = 30,000$ BPSD refinery in Alaska in 2010 has been found to be $646$ Million.
- The cost increases but does not double if we double the capacity. In particular,
  \[ \text{Cost of capacity } Q = \text{Cost of capacity } q \times (Q/q)^{0.6}. \]
- Doubling the capacity in Alaska, the cost of refinery increases to $646 \times 2^{0.6} = 979$ Million.
- A rough estimate of refinery cost is $15,000$ for each BPSD.
  - Using this, the cost of a $60,000$ BPSD refinery turns out to be $900$ Million, similar to the detailed estimate obtained for the same size refinery in Alaska.
  - However, this rough estimate becomes $450$ Million for a $30,000$ BPSD refinery whose detailed cost estimate is $646$ Million. The rough cost estimate can be inaccurate by about 50%.

- **Complexity** of a refinery can be defined in terms of complexity of its units.
  - Complexity of atmospheric distillation unit $← 1$. This unit gives the most output (BPCD) per $ invested.
  - If a 100,000 BPCD distillation unit costs $10$ Million, the cost per BPCD is $100$.
  - If a 20,000 BPCD catalytic reforming unit costs $10$ Million, the cost per BPCD is $500$.
  - Catalytic reforming is $500/100 = 5$ times more complex than atmospheric distillation.
  - Some examples of complexities: Catalytic Hydrocracking 6; Alkylation 10; Isomerisation 15; Lubricants 60.

- US Refinery complexity by company in 2003:
  - Valero 13.4; Exxon 12.8; ChevronTexaco 12.3; BP 11.6; Citgo 11.4; Shell 11; Marathon 10.6; ConocoPhillips 10.3; Premcor 9.4; Suncor 8.7; Tesoro 8.5.
  - “Higher complexity allows Valero to process cheaper higher sulfur crudes while maintaining a highly desirable product slate. Higher complexity usually means more energy input per barrel of crude.”
When to Invest?

An increase in uncertainty decreases the probability a refinery adjusts its capacity.

US Refining Capacity and Structure

- US refining capacity
  - was 19.4 million BPCD (Barrels per calendar day) in 1981.
  - is 17.7 million BPCD in 2011.
- This capacity number refers to the capacity of Atmospheric Oil Distillation column.
- Vacuum distillation capacity is 8.6 million BPCD. Thermal cracking capacity is 2.7 million BPCD. Catalytic hydro-cracking capacity is 1.9 million BPCD.
- Although the number of refineries significantly dropped from 324 in 1981 to 148 in 2011, the capacity did not.
  - Existing refineries expanded their capacities.
  - Expansion is more economic than a brand-new facility.
    » Economies of scale
    » Regulatory requirements are easier to overcome.
  - Top 3 US refineries process 36% of the crude oil; top 10 process 77%.
  - Concentrated ownership: There are fewer companies owning refineries now than before.
  - Diverse ownership: Vertically integrated major companies used to own most of refining capacity. Now midsize and independents are also involved in refining. Various ownership structures exist:
    » Holly Frontier (2828 N Harwood St, Dallas, TX 75201) is on its own and public.
    » Motiva enterprises (of Houston) 50-50 joint venture between Royal Dutch Shell and Saudi Refining.
    » Koch industries is privately owned.
    » ConocoPhillips is separating its production (upstream) from refining (downstream). Separation is expected to be completed in the second quarter of 2012. Downstream company will be called Phillips 66.
  - Regardless of ownership structure, refineries tend to be run as separate profit centers.
PADDs (Petroleum Administration for Defense Districts) were established during WW II.
- PADD I: East: CT, ME, MA, NH, RI, VT, DE, DC, MD, NJ, NY, PA, FL, GA, NC, SC, VA, WV
- PADD II: Midwest: IL, IN, IA, KS, KY, MI, MN, MO, NE, ND, SD, OH, OK, TN, WI
- PADD III: South: AL, AR, LA, MS, NM, TX
- PADD IV: Rockies: CO, ID, MT, UT, WY
- PADD V: West: AK, AZ, CA, HI, NV, OR, WA

US Capacities. PADD I 1.7; II 3.6; III 8.1; IV 0.6; V 3.2 million BPCD in 2005.

Global Capacities. Africa 3.2; Asia 22.2; Eastern Europe 10.2; Middle East 7.0; North America 20.6; South America 6.6; Western Europe 14.9 million BPCD in 2005.
Optimization of Refinery Operations

- Optimization of Refining Operations
  - Continuous processes $\rightarrow$ Continuous variables
- Optimization of Crude Oil Operations
  - Continuous crude inflow from a pipeline $\rightarrow$ Continuous variables
  - Discrete crude shipments as parcels $\rightarrow$ Discrete variables
A simple refinery has a contract to receive 20,000 barrels of crude A and 30,000 barrels of crude B. These crudes go through 4 processes: Distillation (light and middle), reforming, cracking (regular and coking) and blending.

- **Distillation** separates Crude A and B into light, medium, heavy naphta (cycloalkanes), light, heavy oil and residuum.

<table>
<thead>
<tr>
<th>Output/Input</th>
<th>Light Naphta</th>
<th>Medium Naphta</th>
<th>Heavy Naphta</th>
<th>Light Oil</th>
<th>Heavy Oil</th>
<th>Residuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude A</td>
<td>0.10</td>
<td>0.20</td>
<td>0.20</td>
<td>0.12</td>
<td>0.20</td>
<td>0.13</td>
</tr>
<tr>
<td>Crude B</td>
<td>0.15</td>
<td>0.25</td>
<td>0.18</td>
<td>0.08</td>
<td>0.19</td>
<td>0.12</td>
</tr>
</tbody>
</table>

- Light, medium and heavy naphtas have octane numbers 70, 80, 90. Light ignites faster.
- **Naphtas** can be blended to produce refined products or can go to reforming. Reforming’s output is reformed gasoline with octane number 115. Yield of each barrel of naphta is below.

<table>
<thead>
<tr>
<th>Light Naphta</th>
<th>Medium Naphta</th>
<th>Heavy Naphta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reformed gasoline</td>
<td>0.60 barrels</td>
<td>0.52 barrels</td>
</tr>
</tbody>
</table>

- **Oils** can be blended to produce jet fuel/fuel oil or can go to cracker. Cracker’s output is cracked oil and cracked gasoline with octane number 105. Yield of each barrel of oil is below.
  - E.g., 1 barrel of light oil yields 0.68 barrel of cracked oil and 0.28 barrel of cracked gasoline.

<table>
<thead>
<tr>
<th>Light oil</th>
<th>Heavy Oil</th>
<th>Used for blending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracked oil</td>
<td>0.68</td>
<td>0.75</td>
</tr>
<tr>
<td>Cracked gasoline</td>
<td>0.28</td>
<td>0.20</td>
</tr>
</tbody>
</table>


Processes Map and Yields Partial

Crude A
- Distillation
  - Light Naphtha
  - Medium Naphtha
  - Heavy Naphtha
  - Light Oil
  - Heavy Oil
  - Residuum

Crude B
- Distillation

Numbers not shown

Intermediate Products
- Refining
  - Reforming
    - 0.60
    - 0.52
    - Reformed Gasoline
  - Cracking
    - 0.28
    - 0.20
    - Cracked Gasoline
    - 0.68
    - Cracked Oil
  - Coking

Final Products
- Premium Gasoline
- Regular Gasoline
- Light Distillate Blending
- Middle Distillate Blending
- Jet Fuel
- Fuel oil
- Lube oil

1 barrel of heavy naphtha yields 0.45 barrel of reformed gasoline
1 barrel of heavy oil yields 0.20 barrel of cracked gasoline 0.75 barrel of cracked oil
Optimization of a Refinery

- **Residuum** can be used for producing lube oil or middle distillate blending in to jet fuel and fuel oil. Yield of each barrel of residuum is below.

<table>
<thead>
<tr>
<th></th>
<th>Residuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lube oil</td>
<td>0.50</td>
</tr>
</tbody>
</table>

- **Regular and premium** are two types of gasolines obtained by light distillate blending naphtas, reformed gasoline and cracked gasoline. Their octane numbers must be at least

<table>
<thead>
<tr>
<th></th>
<th>Regular gasoline</th>
<th>Premium gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octane number $\geq$</td>
<td>84</td>
<td>94</td>
</tr>
</tbody>
</table>

- **Jet fuel** is obtained by blending light, heavy, cracked oils and residuum. Its RVP (Reid Vapor Pressure) must be less than 1 kg/cm$^2$. The pressures of the inputs are as follows.

<table>
<thead>
<tr>
<th></th>
<th>Light oil</th>
<th>Heavy oil</th>
<th>Cracked oil</th>
<th>Residuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>RVP</td>
<td>1.0</td>
<td>0.6</td>
<td>1.5</td>
<td>0.05</td>
</tr>
</tbody>
</table>

- **Fuel oil** is obtained by blending cracked, light, heavy oil and residuum in the ratios of 3:10:4:1.
  - E.g., blending 3 barrels of cracked oil, 10 barrels of light oil, 4 barrels of heavy oil and 1 barrel of residuum results in 18 barrels of fuel oil.
Process Capacities, Limits and Prices

Capacities:
- Distillation Capacity 45,000 barrels per day.
- Reforming capacity is 10,000 BPD.
- Cracking capacity is 8,000 BPD.

Limits on the final products:
- Daily lube oil production must be between 500 and 1000 BPD.
- Premium gasoline production must be at least 40% of regular gasoline production.

Refined product prices in $/barrel

<table>
<thead>
<tr>
<th>Premium gasoline</th>
<th>Regular gasoline</th>
<th>Jet fuel</th>
<th>Fuel oil</th>
<th>Lube oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>120</td>
<td>80</td>
<td>70</td>
<td>30</td>
</tr>
</tbody>
</table>
Processes with Decision Variables

- Light Naphtha (LN) from Crude A (CA) and Crude B (CB)
- Medium Naphtha (MN)
- Heavy Naphtha (HN)
- Light Oil (LO)
- Heavy Oil (HO)
- Residuum (R)

Distillation:
- LN, MN, HN, LO, HO

Reforming:
- Reformed Gasoline (ReG)

Cracking:
- Cracked Gasoline (CG)
- Cracked Oil (CO)

Reformed Gasoline Blending:
- Premium Gasoline (PG) Octane ≥ 94
- Regular Gasoline (RG) Octane ≥ 84
- Jet Fuel (JF) RVP ≤ 1
- Fuel oil (FO)
- Lube oil (LuO)

Middle Distillate Blending:

Final Products:
- Premium Gasoline (PG)
- Regular Gasoline (RG)
- Jet Fuel (JF)
- Fuel oil (FO)
- Lube oil (LuO)

Intermediate Products:
- Light Naphtha (LN)
- Medium Naphtha (MN)
- Heavy Naphtha (HN)
- Light Oil (LO)
- Heavy Oil (HO)
- Residuum (R)
Constraints

- Contractual availability of crudes
  \[ CA \leq 20,000; \ CB \leq 30,000. \]

- Process capacities
  \[ CA + CB \leq 45,000 \text{ at distillation,} \]
  \[ LNR + MNR + HNR \leq 10,000 \text{ at reforming,} \]
  \[ LOC + HOC \leq 8,000 \text{ at cracking.} \]

- Daily lube oil production must be between 500 and 1000 BPD.
  \[ LuO \leq 1,000; \ LuO \geq 500. \]

- Premium gasoline production must be at least 40% of regular gasoline production.
  \[ PG \geq 0.4 \text{ RG.} \]
Distillation separates crudes into light, medium, heavy naphta, light, heavy oil and residuum.

<table>
<thead>
<tr>
<th></th>
<th>Light Naphta LN</th>
<th>Medium Naphta MN</th>
<th>Heavy Naphta HN</th>
<th>Light Oil LO</th>
<th>Heavy Oil HO</th>
<th>Residuum R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude A</td>
<td>CA</td>
<td>0.10</td>
<td>0.20</td>
<td>0.20</td>
<td>0.12</td>
<td>0.20</td>
</tr>
<tr>
<td>Crude B</td>
<td>CB</td>
<td>0.15</td>
<td>0.25</td>
<td>0.18</td>
<td>0.08</td>
<td>0.19</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\text{LN} &= 0.10 \text{CA} + 0.15 \text{CB}; \\
\text{MN} &= 0.20 \text{CA} + 0.25 \text{CB}, \\
\text{HN} &= 0.20 \text{CA} + 0.18 \text{CB}, \\
\text{LO} &= 0.12 \text{CA} + 0.08 \text{CB}, \\
\text{HO} &= 0.20 \text{CA} + 0.19 \text{CB}, \\
\text{R}  &= 0.13 \text{CA} + 0.12 \text{CB}.
\end{align*}
\]
Constraints: Naphta, Light, Heavy Oil, Residuum

- **Naphta** balance equation

  ![Diagram showing the balance equations for Naphta](diagram)

  - Light Naphtha \( LN \)
  - Medium Naphtha \( MN \)
  - Heavy Naphtha \( HN \)

  \[
  \begin{align*}
  LN &= LNPG + LNRG + LNR, \\
  MN &= MNPG + MNRG + MNR, \\
  HN &= HNPG + HNRG + HNR.
  \end{align*}
  \]

- **Light, Heavy Oil and Residuum** balance equations

  ![Diagram showing the balance equations for Light, Heavy Oil and Residuum](diagram)

  - Light Oil \( LO \)
  - Heavy Oil \( HO \)
  - Residuum \( R \)

  \[
  \begin{align*}
  LO &= LOC + LOB, \\
  HO &= HOC + HOB. \\
  R &= RC + RB.
  \end{align*}
  \]
Constraints: Process Balance Equations

- **Reforming** balance equations

  \[
  \text{ReG} = 0.60 \text{LNR} + 0.52 \text{MNR} + 0.45 \text{HNR}.
  \]

- **Cracking** balance equations

  \[
  \text{CG} = 0.28 \text{LOC} + 0.20 \text{HOC},
  \]
  \[
  \text{CO} = 0.68 \text{LOC} + 0.75 \text{HOC}.
  \]

- **Coking** balance equations

  \[
  \text{LuO} = 0.50 \text{RC}.
  \]
**Constraints:**

**Light Distillate Blending**

- **Reformed and Cracked Gasoline** balance equations

\[ \text{ReG} = \text{RGPG} + \text{RGRG}, \]
\[ \text{CG} = \text{CGPG} + \text{CGRG}. \]

- **Light Distillate Blending**

\[ \text{PG} = \text{LNPG} + \text{MNPG} + \text{HNPG} + \text{RGPG} + \text{CGPG}, \]
\[ \text{RG} = \text{LNRG} + \text{MNRG} + \text{HNRG} + \text{RGRG} + \text{CGRG}. \]
Constraints: Middle Distillate Blending
Recipe for Fuel Oil

- **Middle Distillate Blending**

  - To produce 180 barrels of FO, we blend 30 barrels of Cracked Oil, 100 barrels of Light Oil to Blending, 40 barrels of Heavy Oil to Blending, 10 barrels of Residuum to Blending.

  - If we have,
    - 70 barrels of CO, 40 barrels extra goes into JF,
    - 110 barrels of LOB, 10 barrels extra goes into JF,
    - 40 barrels of HOB, 0 barrels extra goes into JF,
    - 60 barrels of RB, 50 barrels extra goes into JF.

  - Eventually, we produce 180 barrels of FO and 100 barrels of JF.

\[
\text{CO} \geq \frac{3}{18} \text{FO}; \quad \text{LOB} \geq \frac{10}{18} \text{FO}; \quad \text{HOB} \geq \frac{4}{18} \text{FO}; \quad \text{RB} \geq \frac{1}{18} \text{FO},
\]

\[
\text{JF} = (\text{CO} - \frac{3}{18} \text{FO}) + (\text{LOB} - \frac{10}{18} \text{FO}) + (\text{HOB} - \frac{4}{18} \text{FO}) + (\text{RB} - \frac{1}{18} \text{FO}).
\]
Constraints: Octane and Vapor Pressure

**Octane numbers**

Light, medium and heavy naphtas have octane numbers 70, 80, 90. Reformed gasoline has octane number 115. Cracked gasoline has octane number 105.

<table>
<thead>
<tr>
<th>Octane number ≥</th>
<th>Regular gasoline</th>
<th>Premium gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>84</td>
<td>94</td>
<td></td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\text{LNGR} & \quad 70 + \frac{\text{MNNG}}{\text{RG}} 80 + \frac{\text{HNNG}}{\text{RG}} 90 + \frac{\text{RGNG}}{\text{RG}} 115 + \frac{\text{CGNG}}{\text{RG}} 105 \geq 84, \\
\text{PNPG} & \quad 70 + \frac{\text{MNPG}}{\text{PG}} 80 + \frac{\text{HNPG}}{\text{PG}} 90 + \frac{\text{RGPG}}{\text{PG}} 115 + \frac{\text{CGPG}}{\text{PG}} 105 \geq 94.
\end{align*}
\]

**Vapor pressure**

Jet fuel RVP must be less than 1 kg/cm².

<table>
<thead>
<tr>
<th></th>
<th>Light oil</th>
<th>Heavy oil</th>
<th>Cracked oil</th>
<th>Residuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>RVP</td>
<td>1.0</td>
<td>0.6</td>
<td>1.5</td>
<td>0.05</td>
</tr>
</tbody>
</table>

\[
\frac{\text{LOB} - (10/18)\text{FO}}{\text{JF}} 1 + \frac{\text{HOB} - (4/18)\text{FO}}{\text{JF}} 0.6 + \frac{\text{CO} - (3/18)\text{FO}}{\text{JF}} 1.5 + \frac{\text{RB} - (1/18)\text{FO}}{\text{JF}} 0.05 \leq 1.
\]
Objective

- Maximize the revenue from final products whose prices are $/barrel

<table>
<thead>
<tr>
<th>Premium gasoline</th>
<th>Regular gasoline</th>
<th>Jet fuel</th>
<th>Fuel oil</th>
<th>Lube oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>120</td>
<td>80</td>
<td>70</td>
<td>30</td>
</tr>
</tbody>
</table>

Maximize $140 \text{PG} + 120 \text{RG} + 80 \text{JF} + 70 \text{FO} + 30 \text{LuO}$.

- Inputs come through an existing contract. They are fixed and their costs are sunk.
Alteration Exercise: Modifying Middle Distillate Recipe for Jet Fuel in addition to Fuel Oil

- **Middle Distillate Blending**
  - Suppose that JF needs to be produced now by blending cracked, light, heavy oil and residuum in the ratios of 2:4:1:1. This modification is inspired by a question from Juan Vanegas Merit’14.
  - To produce 80 barrels of JF, we blend
    - 20 barrels of CO,
    - 40 barrels of LOB,
    - 10 barrels of HOB,
    - 10 barrels of RB.
  - If we want 80 barrels of JF and 180 barrels of FO, we need at least
    - 20 and 30 barrels of CO respectively for JF and FO,
    - 40 and 100 barrels of LOB respectively for JF and FO,
    - 10 and 40 barrels of HOB respectively for JF and FO,
    - 10 and 10 barrels of RB respectively for JF and FO.

Jet fuel RVP must be less than 1 kg/cm². When CO, LOB, HOB and RB are mixed at ratios of 2:4:1:1, the JF has RVP of \((2/8)1.5 + (4/8)1 + (1/8)0.6 + (1/8)0.05 = 7.65/8 < 1\). No RVP constraint is necessary!
Refinery Optimization in Practice

- Drop-down menu for a symbol
- Data entry by
  - typing numbers into tables
  - reading from Excel files
  - importing from database
- Inequalities often are in the background
- Check inequalities before solving

Refinery Operations Flowchart
Texas refinery obtains 3 intermediate products (components) C1, C2, C3 after distillation/conversion and plans to use these to produce 2 coatings: MightyPlate and Aluminum.

- The sales price of coatings are $1.15 / litre for MightyPlate and $1.30 / litre for Aluminum.
- Texas refinery has a contract to produce at least 10,000 liters of MightyPlate.
- The cost of producing 3 components (through purchasing crude, distillation, conversion) are $0.45 / litre for C1, $0.55 / litre for C2 and $0.75 / litre for C3.
- With current processes & input, the refinery can produce 4000 liters of C1, 7000 liters of C2 and 8000 liters of C3.
- There are technological constraints while blending components to make the coatings
  - MightyPlate can contain at most 55% C1 and at most 25% C3 and must contain at least 35% C2
  - Aluminum can contain at most 45% C2 and must contain at least 15% C1 and 25% C3.
- The processing (including treating and blending) costs are given as ¢ / litre by the table below

<table>
<thead>
<tr>
<th></th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>MightyPlate</td>
<td>12</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Aluminum</td>
<td>18</td>
<td>13</td>
<td>20</td>
</tr>
</tbody>
</table>
Texas Refinery Context Visualization

Technological constraints
- $M$ can contain $\leq 55\%$ $C_1$ and $\leq 25\%$ $C_3$ and must contain $\geq 35\%$ $C_2$.
- $A$ can contain $\leq 45\%$ $C_2$ and must contain $\geq 15\%$ $C_1$ and $\geq 25\%$ $C_3$. 

Crudes

1. Distillation

2. Conversion

Out of context

Context
Texas Refinery

Ingredients of a Formulation

To formulate: Define decision variables for each arrow:

\[ C1M, C2M, C3M, C1A, C2A, C3A \]

**Cost**

\[
\begin{align*}
\text{Cost } 0.45(\text{C1M} + \text{C1A}) \\
\text{C1M} + \text{C1A} \leq 4,000
\end{align*}
\]

\[
\begin{align*}
\text{Cost } 0.55(\text{C2M} + \text{C2A}) \\
\text{C2M} + \text{C2A} \leq 7,000
\end{align*}
\]

\[
\begin{align*}
\text{Cost } 0.75(\text{C3M} + \text{C3A}) \\
\text{C3M} + \text{C3A} \leq 8,000
\end{align*}
\]

**Revenue**

\[
\begin{align*}
\text{Revenue } 1.15(\text{C1M} + \text{C2M} + \text{C3M}) \\
\text{C1M} + \text{C2M} + \text{C3M} \geq 10,000
\end{align*}
\]

\[
\begin{align*}
\text{Revenue } 1.3(\text{C1A} + \text{C2A} + \text{C3A})
\end{align*}
\]

**Constraints**

- M can contain \( \leq 55\% \) C1
- M can contain \( \leq 25\% \) C3
- M must contain \( \geq 35\% \) C2
- A must contain \( \geq 15\% \) C1
- A must contain \( \geq 25\% \) C3
- A can contain \( \leq 45\% \) C2

\[
\begin{align*}
\text{C1M} & \leq 0.55(\text{C1M} + \text{C2M} + \text{C3M}) \\
\text{C3M} & \leq 0.25(\text{C1M} + \text{C2M} + \text{C3M}) \\
\text{C2M} & \geq 0.35(\text{C1M} + \text{C2M} + \text{C3M})
\end{align*}
\]

\[
\begin{align*}
\text{C1A} & \geq 0.15(\text{C1A} + \text{C2A} + \text{C3A}) \\
\text{C3A} & \geq 0.25(\text{C1A} + \text{C2A} + \text{C3A}) \\
\text{C2A} & \leq 0.45(\text{C1A} + \text{C2A} + \text{C3A})
\end{align*}
\]
Texas Refinery
Formulation: Objective Function and Constraints

Maximize \[ 1.15(C1M + C2M + C3M) + 1.3(C1A + C2A + C3A) \]
\[ -0.45(C1M + C1A) - 0.55(C2M + C2A) - 0.75(C3M + C3A) \]
\[ -0.12C1M - 0.15C2M - 0.10C3M - 0.18C1A - 0.13C2A - 0.20C3A \]

\[ C1M + C2M + C3M \geq 10,000 \]

MightyPlate Contract

\[ C1M + C1A \leq 4,000 \]
\[ C2M + C2A \leq 7,000 \]
\[ C3M + C3A \leq 8,000 \]

Component Availability

\[ C1M \leq 0.55(C1M + C2M + C3M) \]
\[ C3M \leq 0.25(C1M + C2M + C3M) \]
\[ C2M \geq 0.35(C1M + C2M + C3M) \]

MightyPlate Technology

\[ C1A \geq 0.15(C1A + C2A + C3A) \]
\[ C3A \geq 0.25(C1A + C2A + C3A) \]
\[ C2A \leq 0.45(C1A + C2A + C3A) \]

Aluminum Technology

All variables are nonnegative

For numerical solution see texasRefinery.xlsx
Summary

- Processes
- Markets
- Optimization

![Diagram showing characteristics of petroleum processing](image-url)
Optimization of Crude Oil Operations

- See [http://newton.cheme.cmu.edu/interfaces/crudeoil/main.html](http://newton.cheme.cmu.edu/interfaces/crudeoil/main.html)