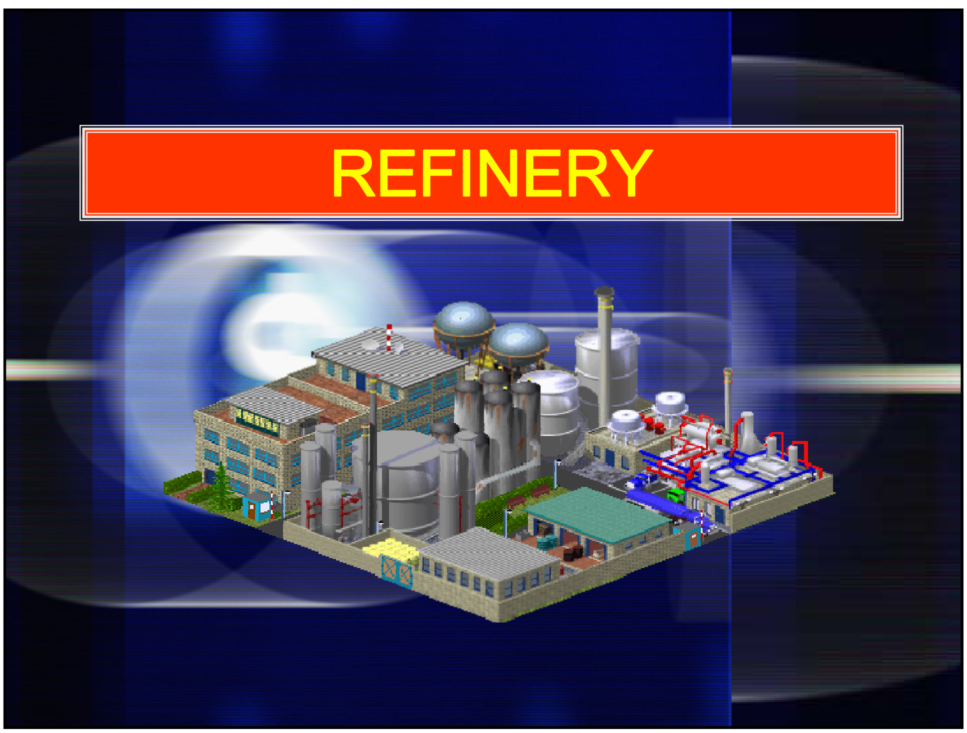
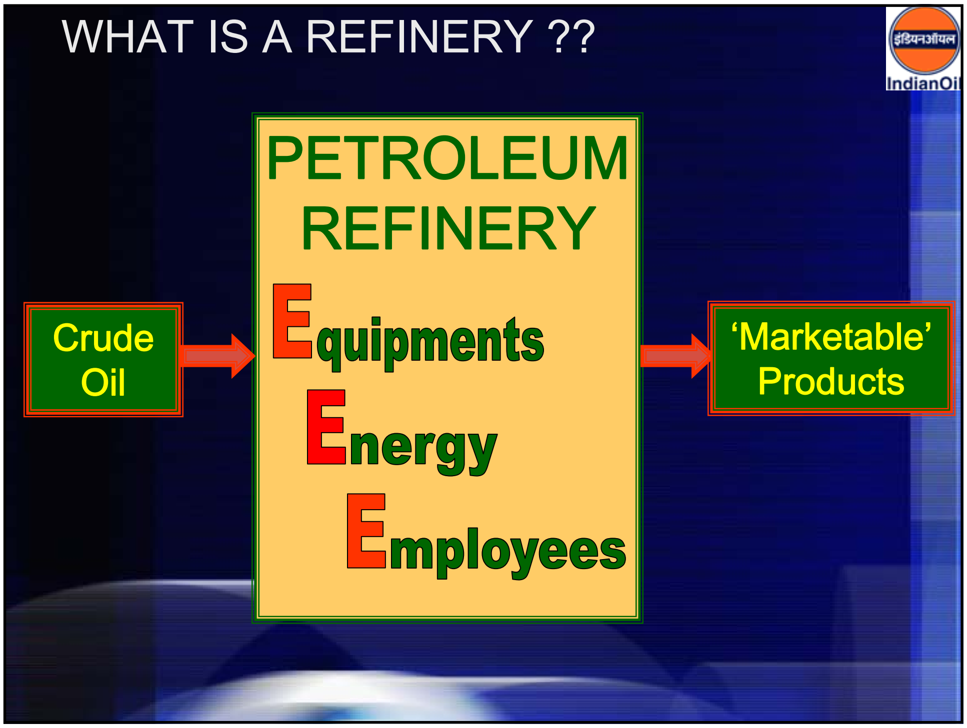
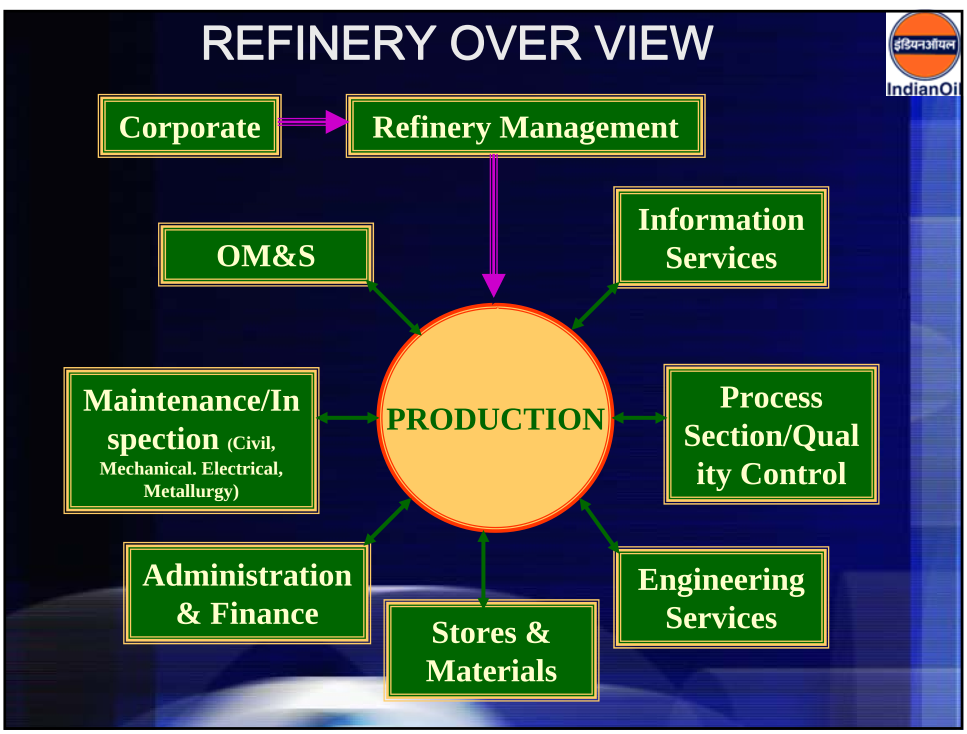
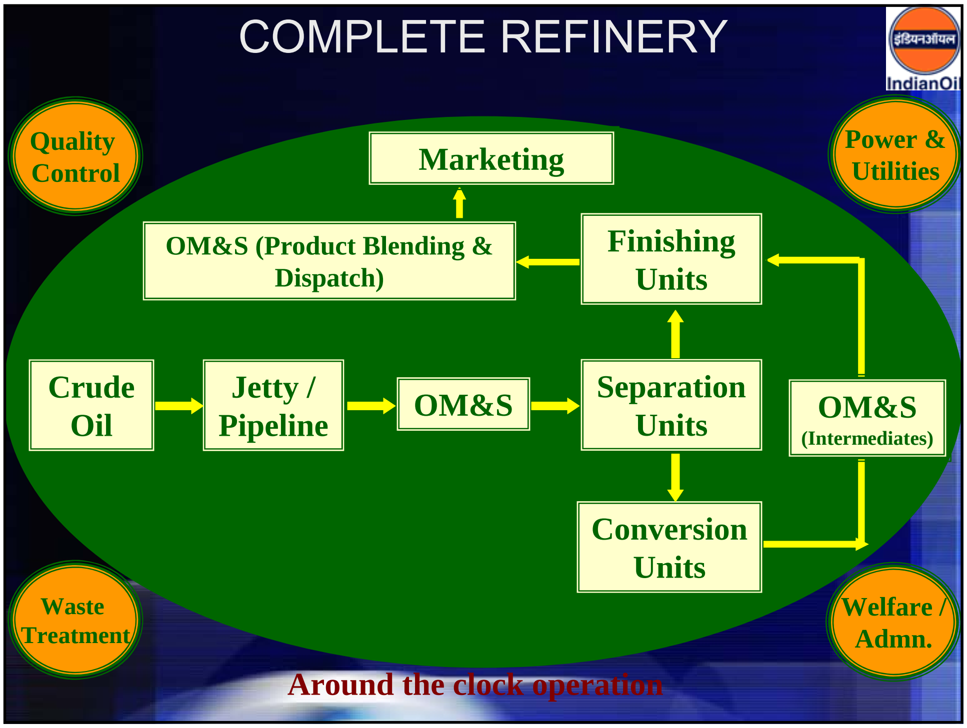
ESSENTIALS OF REFINERY PROCESSES

S K KALRA
INDIAN OIL CORPORATION LTD
PANIPAT REFINERY




WHAT IS A REFINERY ??
PETROLEUM REFINERY
Equipments
Energy
Employees
Crude Oil
'Marketable' Products
IndianOil


REFINERY OVER VIEW
Corporate
Refinery Management
OM&S
Information Services
Maintenance/Inspection (Civil, Mechanical. Electrical, Metallurgy)
PRODUCTION
Process Section/Quality Control
Administration & Finance
Stores & Materials
Engineering Services
IndianOil



Refinery Types

- Each refinery has its own unique processing scheme
  - » Product demand & specifications
  - » Individual economic considerations
- Simple
  - » Crude distillation, reforming, sulfur treating
  - » Range of products is limited
- Complex
  - » Simple + vacuum distillation, FCC, HC, alkylation, gas recovery
- Integrated
  - » Complex + recovery of material from VTB — coking
  - » Full range of products

Complexity of a Refinery

The combination of refining processes and operations employed (complexity) varies from one refinery to another.

Factors deciding the complexity of a refinery

- *Nature/source of crude oils to be processed*
- *Demand pattern in the markets to be covered*
- *Product quality – current / future*
- *Production of feed stocks for downstream units*
- *Inter-fuel substitution*
- *Environmental stipulations*

Crude Oil Characterization

By Gravity:

	°API	SG
Light	>35	<0.85
Medium	26-35	0.85-0.8984
Heavy	10-26	0.8984-1.00
Extra Heavy	<10	>1.00

By Sulphur (%wt.):

Sweet	<0.5
Medium sour	0.5-1.0
Sour	>1.0

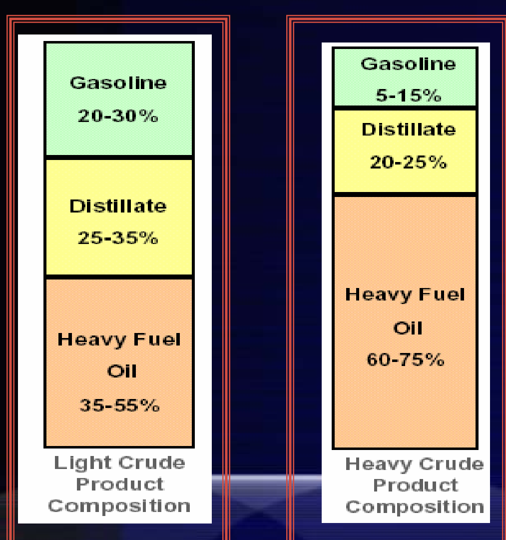
Crude Oil Characterization

- 4 types of crude oils available to refiners around the world:

	°API	Sulphur (% wt.)
Light Sweet	30-40	<0.5
Light Sour	30-40	0.5-1.5
Heavy Sour	15-30	1.5-3
Extra Heavy	<15	>3

- ***High Acid Crudes (HACs)***
  - → ***TAN (Total Acid Number) > 0.5mg KOH/gm Crude Oil***

PROFITABLE CRUDE



TYPE OF CRUDE TO BE USED

- Crude Availability
- Crude Cost
- Desired Product Yield
- Refinery Complexity
- Environmental Constraints

CRUDE OIL SELECTION & OPTIMISATION IN REFINERIES

Depends on :

- *Configuration of Refinery – what are the units present*
- *Metallurgy of refinery – particularly columns, piping to take care of acidic / corrosive crude*
- *Product demand in the region*
- *Netback/ GRM of a particular crude*
- *Availability of a particular crude at economic cost.*

Crude Oil Selection

- *Overall refinery economics depend on Crude cost + Processing Cost*
- *Lower the S, lower the SG*
  - *Higher is the crude price*
  - *Lower processing requirement*
- *HACs are normally cheaper*
  - *Higher neutralization cost*
  - *Refineries would like to handle crudes with TAN<0.5 & subsequent process streams containing TAN<1.5*

Crude Oil Selection

- *Crude availability shifting from*
  - *Light sweet → Heavy sour → Extra Heavy*
- *HACs are opportunity crudes*
- *New Refinery:*
  - *design to process Extra Heavy Crudes*
  - *design to process HACs in admixture*

MAJOR REFINERY PRODUCTS

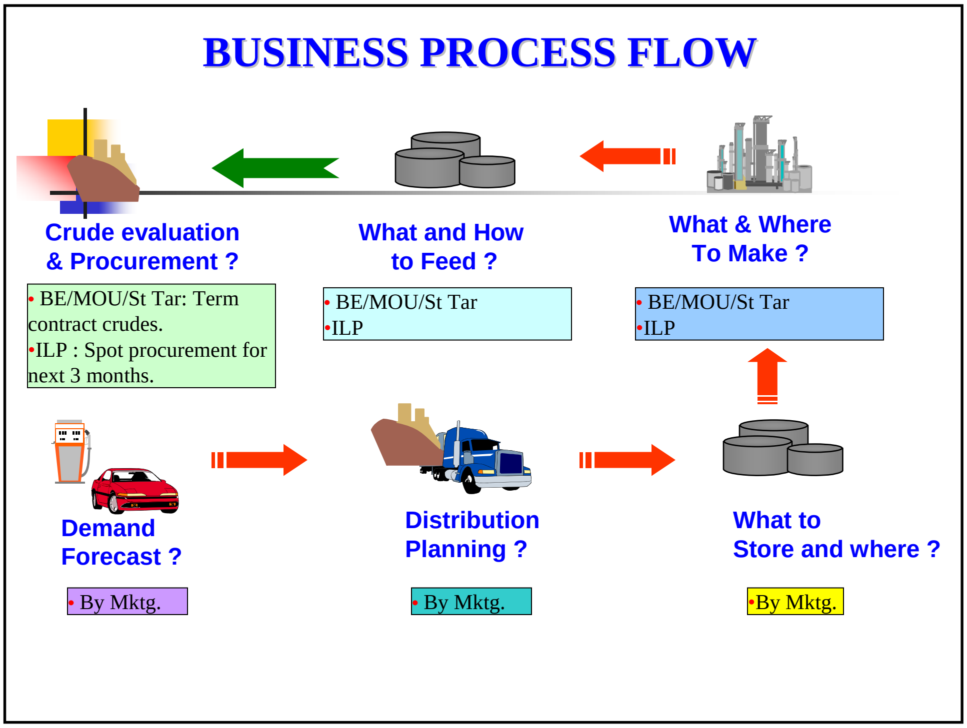
- *LPG (Propane/Butane)/Propylene*
- *MS/Naphtha/Solvents/Benzene/Toluene*
- *ATF/SKO/MTO/LABFS*
- *HSD/LDO*
- *FO/ LSHS /HPS/CBFS/PROCESS OILS*
- *Asphalts/Bitumen*
- *Lube Oil Base Stocks(GR-I & GR 2)*
- *RPC / CPC*
- *Slack Wax/ MCW/Paraffin Wax*

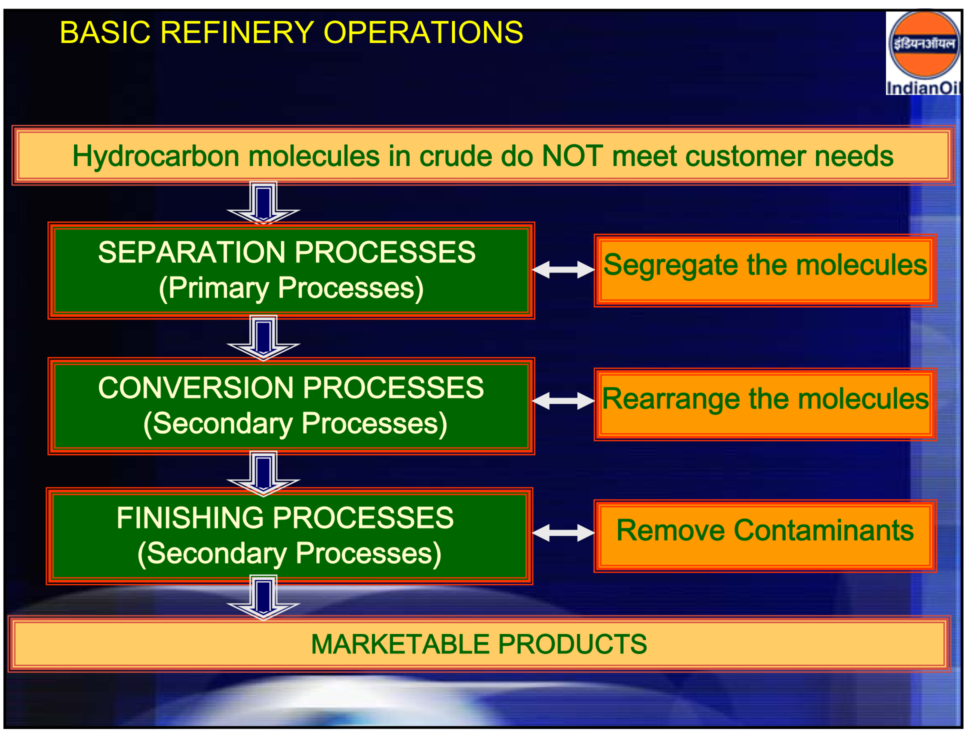
Critical Quality Parameters of Products

Sl.no	Product	Key Quality parameters
1.	LPG	Evaporation Temperature at 95 % Volume =2 deg C, Max Cu Corrosion =not worse than No.1 RVP =1050 KPa, Max
2.	Motor Spirit	Density =720-775 Kg/M3 RON =91 Min Sulphur =150 ppm, Max Benzene =1 Vol. %, Max
3.	ATF	Density =775-840 Kg/M3 Flash Point = 38 deg c, Min Sulphur =0.25 wt %,Max Smoke Point =20 mm, Min
4.	SKO	Density =790-820 Kg/M3 Flash Point =35 deg c, Min Sulphur = 0.25 wt %, Max Smoke point = 18 mm, Min

Critical Quality Parameters of Products

Sl.no	Product	Key Quality parameters
5.	Diesel	Density =820-845 Kg/M3 Sulphur = 350 ppm Cetane Number = 51 Min Recovery at 360 deg C =95 Min
6.	Fuel Oil	Kinematic Viscosity@ 50 deg c =125 , Max (Winter) =180 , Max (Summer) Sulphur = 4 wt %, Max Ash = 0.1 wt %, Max
7.	Bitumen	Penetration at 25 deg c =60 (1/10mm) , Min Flash Point =175 deg C,Min Softening Point =45-55 deg C


BUSINESS PROCESS FLOW
Crude evaluation & Procurement ?
• BE/MOU/St Tar: Term contract crudes.
•ILP : Spot procurement for next 3 months.
What and How to Feed ?
• BE/MOU/St Tar
•ILP
What & Where To Make ?
• BE/MOU/St Tar
•ILP
Demand Forecast ?
• By Mktg.
Distribution Planning ?
• By Mktg.
What to Store and where ?
•By Mktg.


BASIC REFINERY OPERATIONS
IndianOil
Hydrocarbon molecules in crude do NOT meet customer needs
SEPARATION PROCESSES (Primary Processes)
Segregate the molecules
CONVERSION PROCESSES (Secondary Processes)
Rearrange the molecules
FINISHING PROCESSES (Secondary Processes)
Remove Contaminants
MARKETABLE PRODUCTS

REFINERY SCHEME

Crude Pretreatment
- Desalting

Fractionation
- Atmospheric & Vacuum Distillation

Conversion
- Fluidized-bed Catalytic Cracking
- Hydrocracking
- Delayed Coking
- Visbreaking /Coking

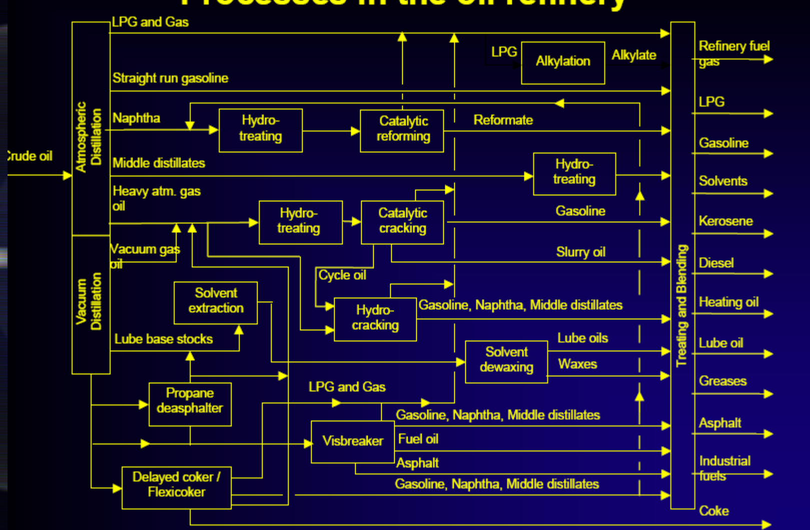
Treatment
- Diesel Hydrodesulphurization
- Diesel Hydrotreatment
- Solvent Extraction (e.g. FEU)
- Catalytic Reforming

Formulation & Blending

Other Refinery Processes

a. Sour Water Stripping b. Sulphur Recovery c. Cooling Water Treatment

Processes in the oil refinery



Processes in an Oil Refinery

Physical processes	Chemical processes: Thermal	Chemical processes: Catalytic
Distillation	Visbreaking	Hydrotreating
Solvent extraction	Delayed coking	Catalytic reforming
Propane deasphalting	Flexicoking	Catalytic cracking
Solvent dewaxing		Hydrocracking
Blending		Catalytic dewaxing
		Alkylation
		Polymerization
		Isomerization

Market Demands

- Clean products (no S, N, O, metals, etc.)
- More gasoline (high octane number)
- More diesel (high cetane number)
- Specific products (Aromatics, alkenes, etc.)
- Less residue

How to meet these demands?

- More sophisticated distillation
- Physical separation steps
- Chemical conversion steps

Refinery Operations

- PRIMARY PROCESSING UNITS
- SECONDARY PROCESSING UNITS

CONFIGURATION OF REFINERIES / REFINING PROCESSES

PRIMARY UNITS	CRUDE DISTILLATION UNIT (CDU)/ VACUUM DISTILLATION UNIT(VDU)
SECONDARY UNITS	FLUID CATALYTIC CRACKING UNIT (FCCU) , HYDRO-CRACKING UNIT (HCU) , DELAYED COKER UNIT (DCU) , VISBREAKER UNIT (VBU)
LUBE/WAX PRODUCING UNITS	FURFURAL EXTRACTION UNIT (FEU) / NMP EXTRACTION UNIT, SOLVENT DEWAXING UNIT (SDU) , CATALYTIC ISO-DEWAXING UNIT (CIDW) , WAX HYDROTREATING UNIT (WHU) , HYDRO-FINISHING UNIT (HFU)
TREATING UNITS	CATALYTIC REFORMING UNIT (CRU) DIESEL HYRDO-TREATING UNIT (DHDT), DIESEL HYDRO-DESULFURISATION UNIT (DHDS), MEROX UNIT, ETC...

PRIMARY PROCESSING UNIT

The purpose of Primary unit is to separate the crude in to different fractions by distillation.

Known as mother unit of the refinery, consist of

- CRUDE DISTILLATION UNIT (CDU)
- VACUUM DISTILLATION UNIT (VDU)

Commonly referred as Atmospheric and Vacuum Distillation unit (AVU)

Separation

Heavy at the bottom, light on the top

- *The separation of crude oil by atmospheric and vacuum distillation into groups of hydrocarbon compounds of different boiling point ranges (called "fractions" or "cuts")*
- *The first step in crude oil processing*
- *The process unit where the first separation takes place is called Crude Distillation Unit (CDU), Atmospheric Unit (AU) or Atmospheric & Vacuum Unit (AVU)*
- *This step is performed in all refineries : These units are called "Mother Units"*
- *Typical products from CDU are : Gas, LPG, naphtha, SKO/ATF, HSD and RCO.*
- *Vacuum Distillation of RCO produces VGO (or LOBS cuts) & VR*
- *All products need further treatment/processing.*

Atmospheric & Vacuum Distillation

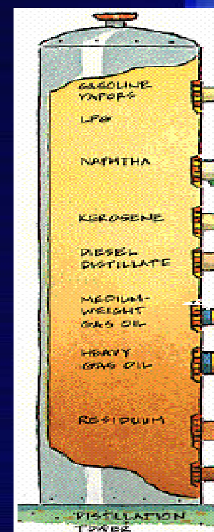
- Crude Stills
  - » Historically the oldest refining process
  - » Only the first step in crude oil processing
- Purpose
  - » To recover light materials
  - » Fractionate into sharp fractions
- Atmospheric
  - » Light gases
  - » Straight run gasoline
  - » Naphtha
  - » Distillates
  - » Atmospheric Gas Oil
  - » Atmospheric Residuum
- Vacuum
  - » Light & heavy vacuum gas oils
  - » Vacuum Residuum

Crude Oil Refining

Distillate fraction	Boiling point (°C)	C-atoms/ molecule	
Gases	<30	1-4	
Gasoline	30-210	5-12	
Naphtha	100-200	8-12	
Kerosine (jet fuel)	150-250	11-13	Middle Distillates
Diesel, Fuel oil	160-400	13-17	
Atmospheric Gasoil	220-345		
Heavy Fuel Oil	315-540	20-45	
Atmospheric Residue	>540	>30	
Vacuum Residue	>615	>60	

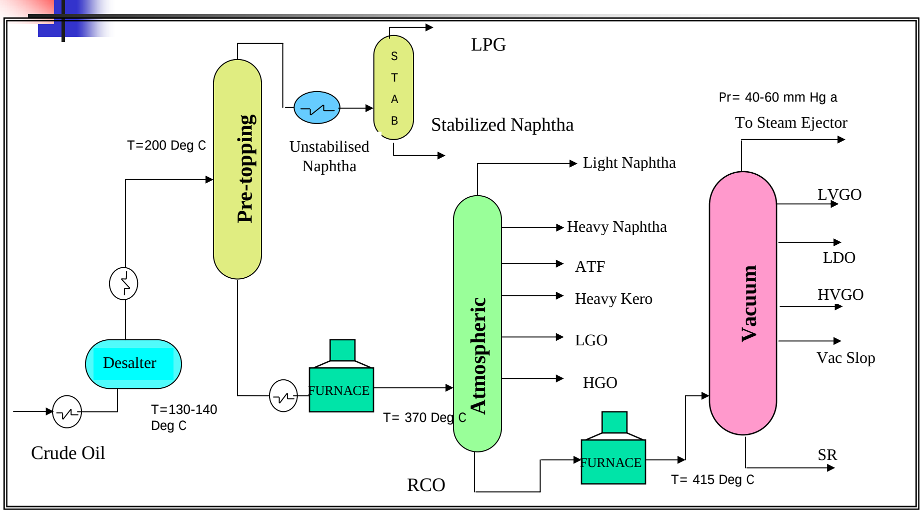
SEPARATION PROCESSES

Crude Oil

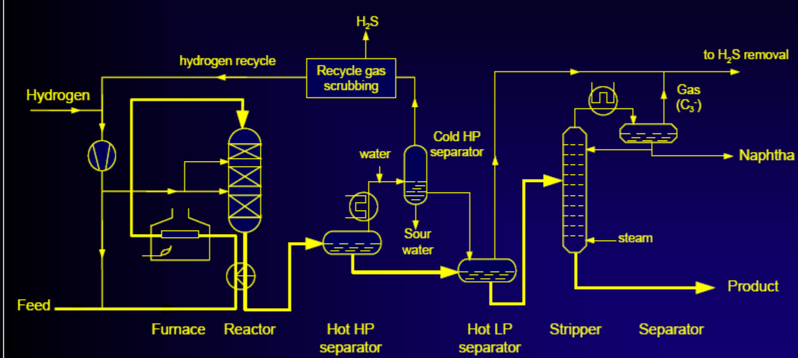


- **Fractions of crude boil at different temperatures**
- **Components are separated by distillation and drawn off as they condense**

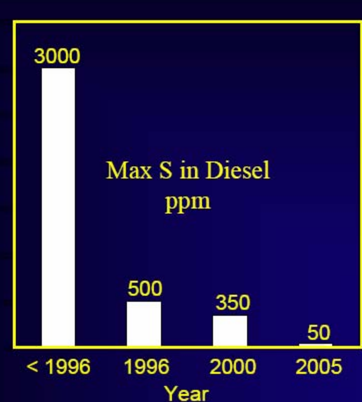
Atmospheric & Vacuum Distillation Unit Flow Diagram



Hydrotreating Process (trickle bed)



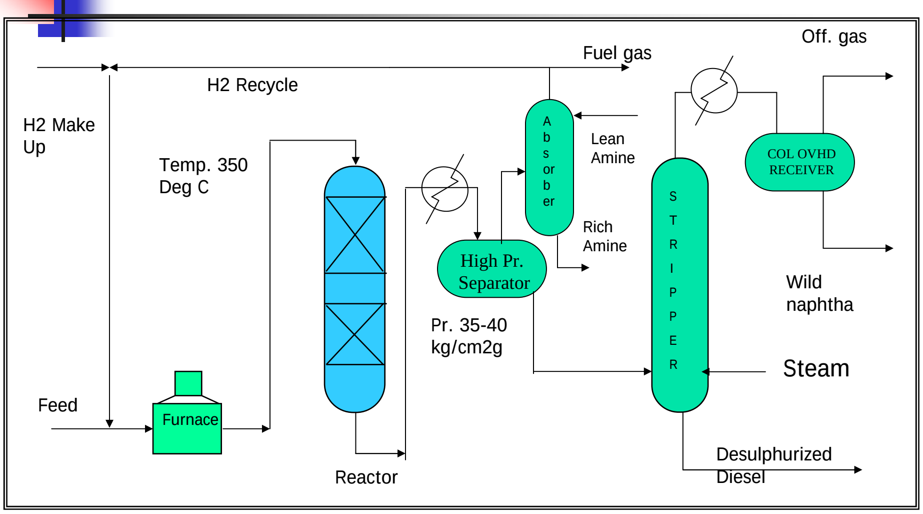
Development of maximum Sulfur Content in automotive Diesel in Europe



Diesel Hydro-Desulphurisation Unit (DHDS)

- **Objective : To meet the EURO-II diesel quality requirement (<500 ppm S)**
- **Feed : Straight run diesel / FCC diesel component/ Coker and Visbreaker diesel components.**
- **Catalyst : Ni-Mo oxides**

Diesel Hydro Desulphurisation Unit



DHDS Product Yields and Operating Conditions

1. Typical Product Yields

Sl.no.	Products	Wt%	End Users
1.	Off Gas	1.36	Refinery Fuel gas system after Amine Wash
2.	Wild Naphtha	1.04	To Naphtha Pool after stabilisation
3.	Diesel	97.1	To Euro II Diesel Pool

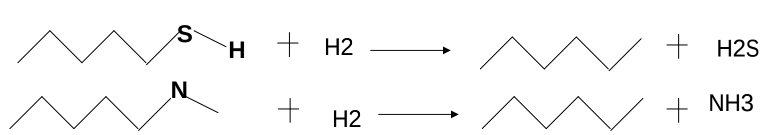
2. Operating Conditions :

Temperature range : 320-380 DEG C

System Pressure : 30-40 kg/cm2(g)

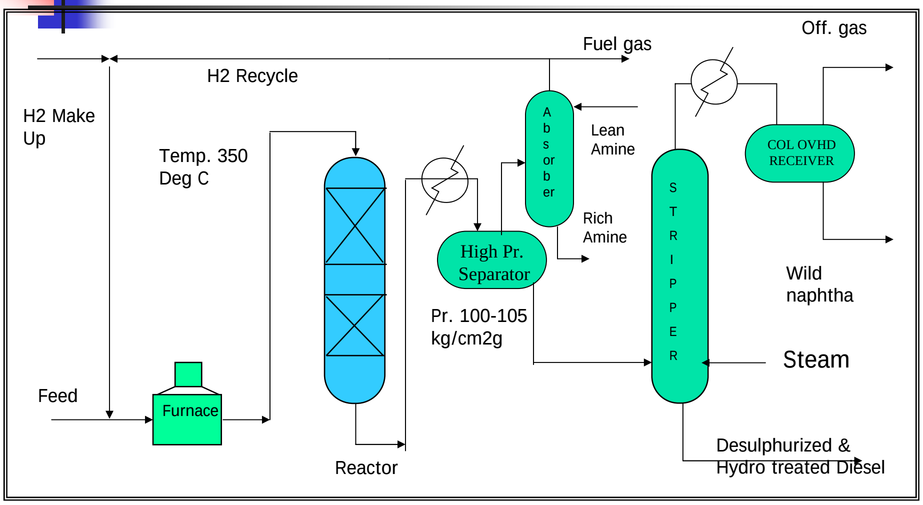
Diesel Hydrotreating Unit (DHDT)

- Objective : To meet the Euro –III/IV diesel quality requirement (350/50 ppm 'S' and Min. 51 Cetane No.)
- Feed : Straight run diesel / FCC diesel component/ Coker and Visbreaker diesel components.
- Catalyst : Ni-Mo oxides
- Chemical reactions: Desulphurisation and Denitrification



Aromatic compound + H2 --> Napthene Compound

Diesel Hydrotreator unit Flow Diagram



DHDT Product Yields and Operating Conditions

1. Typical Product Yields

Sl.no.	Products	Wt%	End Users
1.	Off Gas	2.65	Refinery Fuel gas system after Amine Wash
2.	Wild Naphtha	2.8	To Naphtha Pool after stabilisation
3.	Diesel	96.1	To Diesel Pool

2. Operating Conditions :

Temperature range : 320-380 DEG C

System Pressure : 100-105 kg/cm2(g)

Upgrading Gasoline Blend Stocks

	Reforming	Isomerization	Alkylation
Purpose	Create high octane gasoline blend stock		
Feedstock	Heavy Naphtha	Light Naphtha	C4s (Butylene & Isobutane)
Reactions	Dehydrogenation of Cycloparaffins	Isomerization of Straight Chain Paraffins	Combination of Smaller Molecules
Side Benefits	Make hydrogen for use elsewhere in the refinery		Use light olefins made in FCCU

Reforming

- Process to rearrange gasoline boiling range naphthenes & paraffins to aromatics & isoparaffins
  - » Goal to increase gasoline octane (anti-knock)
  - » Represents up to 50% gasoline pool
  - » Octane 90 - 102 RON (FCC: 90 - 92 RON)
  - » Hydrogen is a valuable side-product
- Heavy straight run naptha feedstocks (180 - 400°F)
  - » C7 through C10
  - » Lighter material does not give desired reactions
  - » Heavier material tends to coke (deactivates catalyst)
- Feeds need pretreating to remove poisons (S, N, metals, olefins)

Alkylation

- Makes gasoline components from materials that are too light to otherwise be in gasoline
- Alkylation
  - » Forms a highly branched isoparaffin by reacting an alkyl group (isobutane) with a light olefin (butylene)
  - » Produces high-octane gasoline with a low RVP
- Liquid catalysts at mild temperatures
  - » Sulfuric acid @ 45°F
  - » Hydrofluoric acid @ 95°F

Catalytic Reforming Unit (CRU)

- Objective : To Upgrade the Naphtha to High Octane MS Component (Reformate) .
- Feed : 85-160 Deg C cut Naphtha / Visbreaker Naphtha
- Catalyst : Ni-Mo Oxides for NHTU Reactor
Pt-Sn or Re for Reforming

Catalytic Reforming Unit

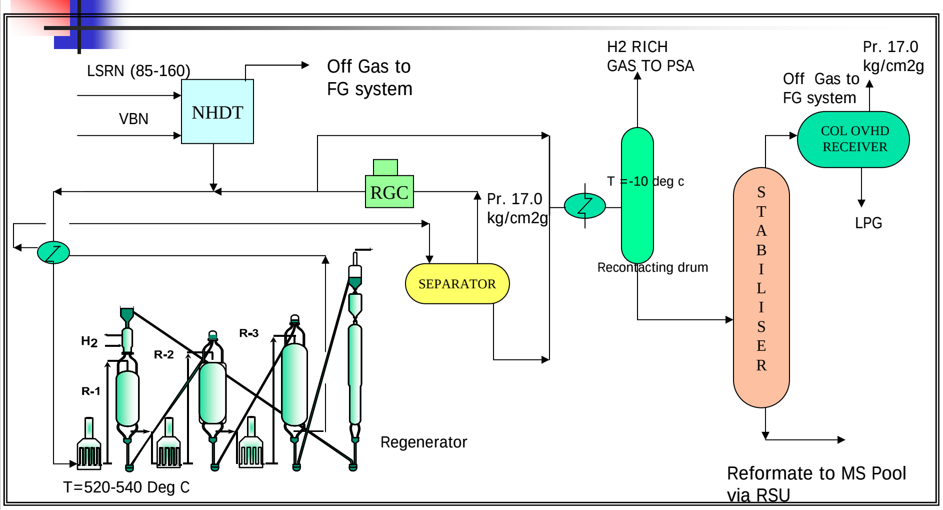
Main types of reformers are :

1. **Semi-regenerative (SR)**
   The reformer processes feedstock for a time and then shuts down for regeneration.

2. **Cyclic**
   Any reactor can be isolated for regeneration while the other reactors are in operation

3. **Moving bed or CCR**
   Catalyst is moved continuous through the reactors, withdrawn from the last reactor, regenerated in regeneration section and returned to the first reactor as fresh catalyst.

Continuous Catalytic Reforming Unit Flow Diagram



CRU Product Yield and Operating Conditions

1. Typical Product Yields

Sl.no.	Products	Wt%	Quality	End Users
1.	H2 Rich gas	6.5-8.0	94% H2 gas	PSA Unit to recover H2
2.	LPG	2.5-12	'S' free LPG	To MS Pool After catalytic Reforming
3.	Reformate	80-91	RON- 98, low 'S' , High Bz.	To MS POOL after Reformate Splitter

2. Operating Conditions :

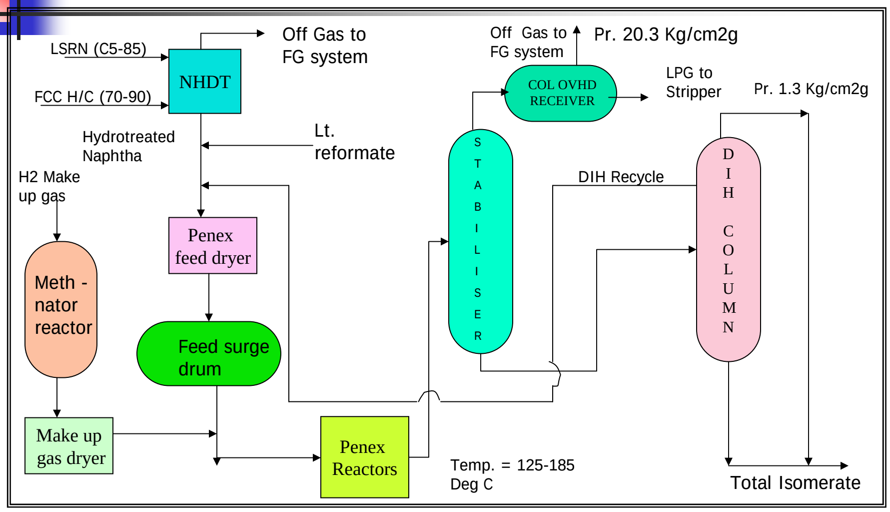
Temperature range : 490-540 DEG C

System Pressure : 2.0 - 30 kg/cm2(g)

Isomerisation Unit (PENEX-DIH)

- Objective : To Upgrade the Naphtha by increasing its Octane Number to Higher Octane/Low Benzene/Low Olefins MS Component (Isomerate) to Meet Euro III / IV MS Specifications.
- Feed : C5-85 Deg C cut Naphtha /FCC gasoline(70-90 deg C cut)/ Lt. Reformate
- Catalyst : Co-Mo for Hydrotreator Reactor
  Pt for Penex Reactor
  Ni Based for Methanation

Isomerisation Unit Flow Diagram



ISOM Product Yield and Operating Conditions

1. Typical Product Yields

Sl.no.	Products	Wt%	End Users
1.	Off gas	1.4	Refinery fuel gas System
2.	LPG	11.3	To LPG POOL
3.	Isomerate	87.3	To MS POOL

2. Operating Conditions :

Temperature range : 126- 145 DEG C

System Pressure : 33.5 kg/cm2(g)

Cracking process

- Fluidized Catalytic Cracking Unit
- Hydro Cracker Unit
- Visbreaker Unit
- Coking unit

TECHNOLOGICAL ASPECTS

FCCU / RFCCU	Heavier Hydro-Carbon molecules are cracked under severe operating conditions of Temp. (500 – 510 ºC) and pressure (1.4 - 2.2 kg/cm2) to get Lighter Hydro-Carbons like LPG , MS & HSD components. Strict operating conditions are maintained to get on-specs. products.
HCU / OHCU	Heavier Hydro-Carbon molecules are mixed with Hydrogen and the mixture is subjected to severe operating conditions of Temp. (380 - 400 ºC) and pressure (165 – 185 kg/cm2) to get Lighter Hydro-Carbons like LPG , MS & HSD components. Strict operating conditions are maintained to get on-specs. products. All products are of Superior quality w.r.t. Sulfur content.

Fluid Catalytic Cracking Unit (FCCU)

- **Objective : To convert Heavy Vacuum Gas Oil to valuable distillates like LPG, Gasoline, Diesel by catalytic cracking in fluidized bed.**
- **Feed : VGO/RCO/VR/HydroCracker Bottom.**
- **Catalyst : Silica & Alumina Zeolite Structure**

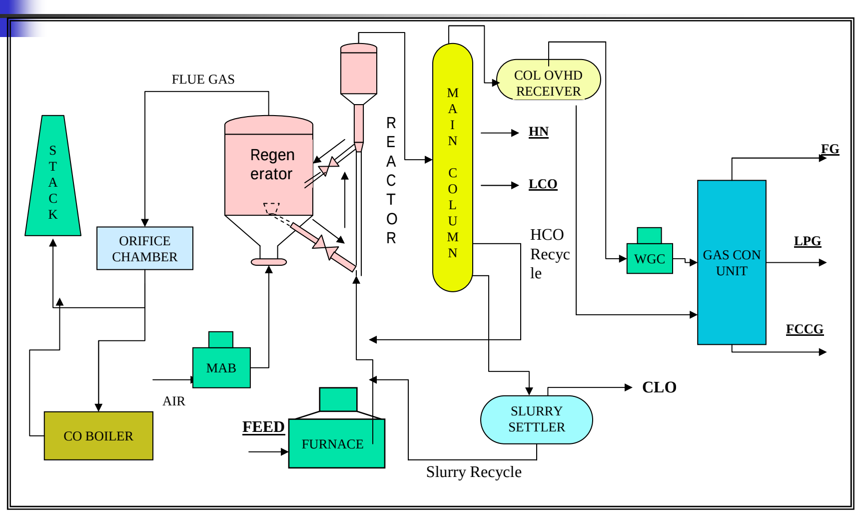
Fluidized Bed Catalytic Cracking

- Process gas oils using catalysts to crack the carbon-carbon bonds
  - » Cracking lowers the average molecular weight & produces higher yields of fuel products
- Attractive feed characteristics
  - » Small concentrations of contaminants
    - ✧Poison the catalyst
  - » Small concentrations of heavy aromatics
    - ✧Crack & deposit coke on catalyst
- Products may be further processed
  - » Further hydrocracked
  - » Alkylated to improve gasoline anti-knock properties

YIELD PATTERN OF VARIOUS FCC UNITS

	VGO FCC	RFCC	INDMAX	PETROFCC
FEED	VGO	VGO+VR	VGO+VR+EXTRACT	VGO
FEED QUALITY				
CCR, WT%	0.74	4.06	<10	0.74
S”, WT%	3.4	3.59		3.4
VR CONTENT, WT%	NIL	20 MAX	<44	NIL
PRODUCT, WT %				
GAS	1.47	3.00	10.44	8.80
LPG	8.68	8.79	16.80	21.00
PROPYLENE	3.04	3.71	11.20	22.00
GASOLINE	20.06	18.60	28.00	28.00
DIESEL (TCO)	52.64	46.45	10.10	9.50
FO	7.98	10.82	8.60	5.00
COKE	5.00	7.43	13.80	5.50
PRODUCT KEY PROPERTIES				
GASOLINE : RON	89	92.9	96	95
DIESEL CETANE INDEX	30.9	29.6	18	30

Fluid Catalytic Cracking Flow Diagram



FCCU Product Qualities & End Users

Sl.No	Product	Qualities	End Users
1.	Gas	H2S rich Off. Gas	Refinery Fuel gas System after Amine Wash
2.	LPG	H2S, Mercaptons, olefins like Propylene/Butylene	To LPG Pool/ Petrochemical feedstock
3.	Gasoline	High Octane No. and high Olefin contents	MS Pool
4.	Hy.Naphtha + LCO	Low Cetane no. High 'S' , Unsaturates	Diesel Pool After Hydrotreatment
5.	CLO	High Aromatics, Good Cutter Stock	Fuel Oil

Hydrocracker Unit

- **Objective : To convert Heavy Vacuum gas oil to valuable distillates like LPG, Naphtha, ATF, Kerosene and Diesel.**
- **Feed : VGO / Coker Products**
- **Catalyst : Ni/Mo oxides for Dematalisation & Hydrotreating**
  Ni/Mo/W(Tungsten) for Hydrocracking

Hydrocracking Process

- Feedstock : VGO
- Products & Yields:
  - Gas 2.5%
  - LPG 2.5%
  - Naphtha 8%
  - SKO/ATF 25%
  - HSD 22%
  - Unconverted 40%
- Good process for increasing distillates and producing finished products.
- Existing at Gujarat, Mathura, and Panipat refineries.

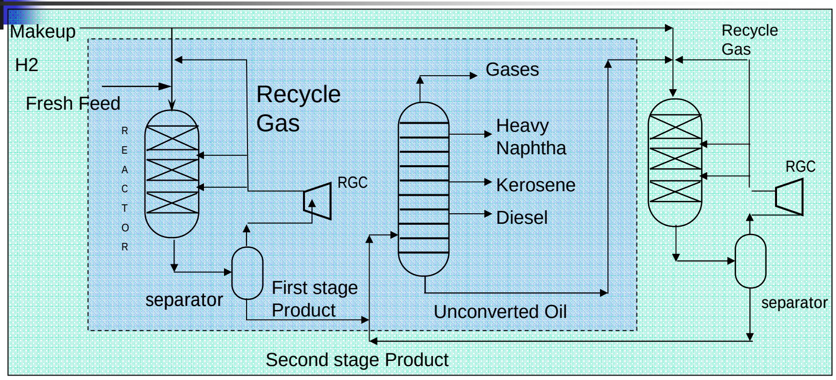
	HCU	OHCU
FEED	VGO	VGO
FEED QUALITY		
CCR, WT% MAX	1	1
S, WT%, MAX	2.8	2.8
N, PPM, MAX	800	800
Ni+V, PPM, MAX	1.25	1.25
SODIUM, PPM	1	1
PRODUCTS, WT %		
GAS	2.52	3.27
LPG	4.57	1.95
NAPHTHA	11.33	9.13
KEROSENE	39.58	12.00
DIESEL	41.81	50.65
BOTTOM	0.00	25.00

	HCU	OHCU
PRODUCT KEY PROPERTIES		
NAPHTHA:		
RON	72	72
S', PPM, MAX	10	10
KEROSENE :		
SMOKE POINT, MM	22-23	22-23
FREEZINFG POINT, ^{O}C	< 60	< 60
DIESEL :		
CETANE INDEX	62	56
S', PPM	< 10	< 10
POUT POINT, ^{O}C	- 12	- 12

Various configurations of Hydrocraker Units

1. Single stage Once through Hydrocraker unit (SSOT):
   a. Feed and Hydrogen is passed through reactors only once for 60 –80 % of partial conversion.
   b. Unconverted Oil is sent to FCCU.
2. Single stage recycle (SSRec) :
   a. Unconverted oil is recycled back to feed for 100% conversion.
3. Two stage Hydrocraker Unit:
   a. Unconverted Oil of SSOT is sent to another reactor for 100% conversion

Single stage Vs Two stage Hydrocraker unit



1) Single Stage in Blue

2) Two Stage is Blue and Green Combined

HCU Product Yields and Operating Conditions

1. Typical Product Yields

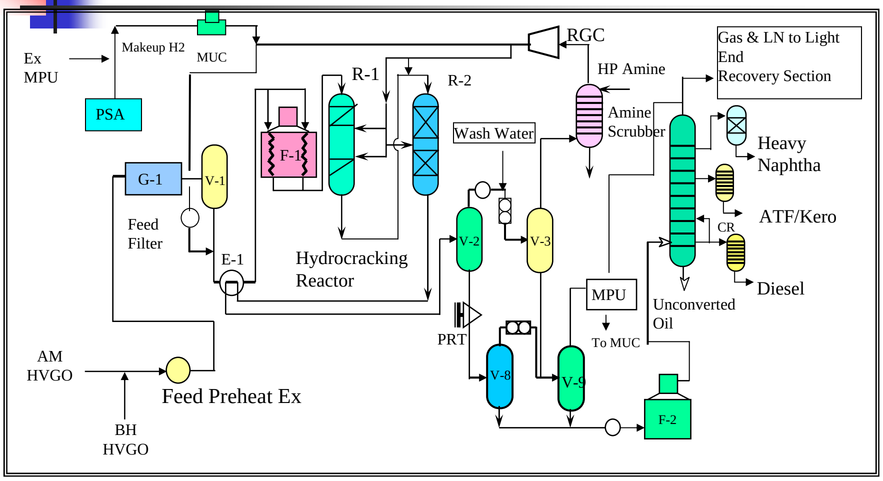
Sl.no.	Products	Wt%
1.	Off. Gas	2-4
2.	LPG	1.5-3
3.	Naphtha	6.5-10
4.	ATF/Kero	27-40
5.	Diesel	29-40
6.	Hydrocraker Bottom	5- 35

2. Operating Conditions :

Temperature range : 370-420 DEG C

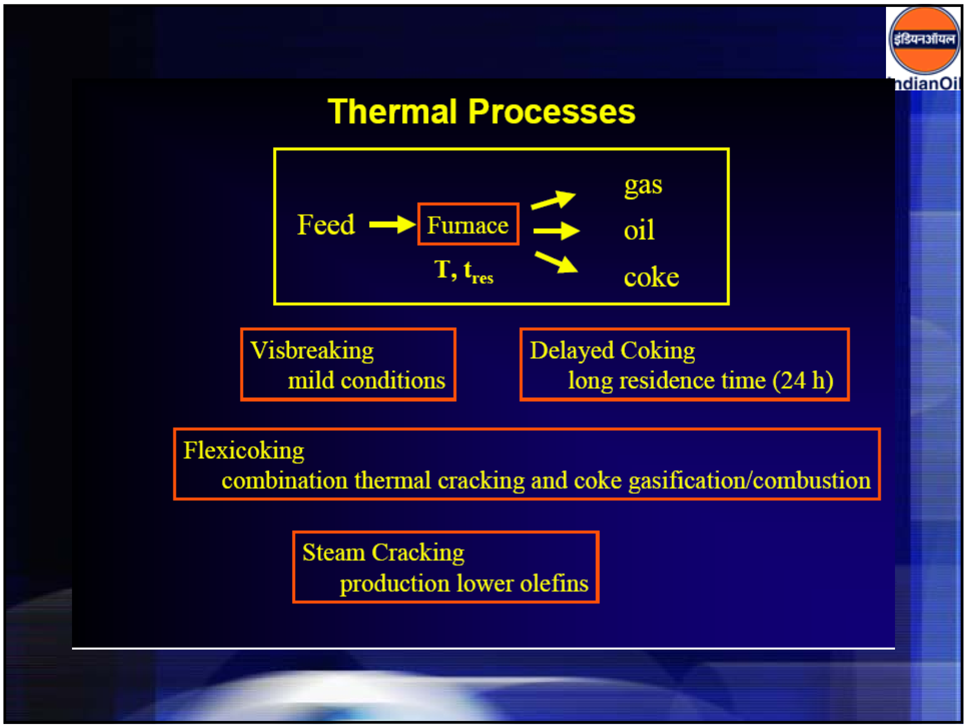
System Pressure : 160-170 kg/cm2(g)

Hydro Cracker Unit Flow Diagram



HCU Product Qualities & End Users

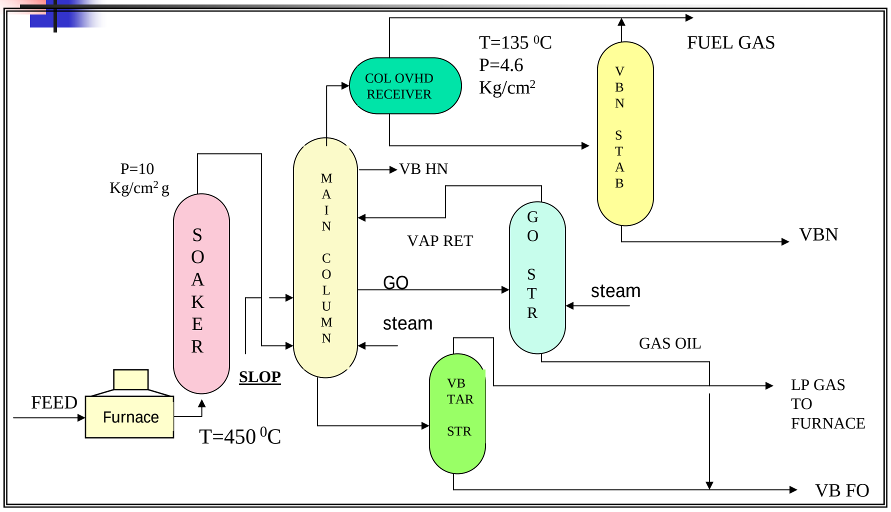
Sl.No	Product	Qualities	End Users
1.	Gas	H2S rich Off. Gas	Refinery Fuel gas System after Amine Wash
2.	LPG	H2S Contents	To LPG Pool after caustic wash
3.	Naphtha	low Octane No. and low ‘S’ contents	To Gasoline Pool / Hydrogen unit Feed
4.	ATF / Kero	Low ‘S’ and Low Aromatics	To ATF/ kero. Pool
5.	Diesel	Low ‘S’ and High Cetane	EURO – III Diesel
6.	Unconverted Oil	Low ‘S’, High Saturates	FCCU FEED



Visbreaker Unit (VBU)

- Objective : To reduce viscosity of Heavy Ends i.e. RCO/Vacuum residue by Thermal Cracking.
- Feed : RCO/Vacuum residue/Asphalts
- Typical Operating Conditions:
  - Temperature Range : 450-470 Deg C
  - Pressure : 9-14 kg/cm2(g)
- Viscosity of Feed : 500-3000 cst at 100 Deg C
- Viscosity of Product (VBtar) : 50 – 300 cst at 100 deg C

Visbreaker Unit Flow Diagram



Visbreaking Process

- Feedstock : Vacuum Residue
- Products & Yields:
  - Gas+loss 3%
  - Naphtha 2%
  - Gas oil 2%
  - FO 93%
- Good for FO production. Other products unstable and need further treatment
- Existing at Gujarat, Haldia, Mathura & Panipat refineries

VBU Product Yield/Qualities & End Users

Sl.No	Product	Yield	Qualities	End Users
1.	Gas	1.82	H_2S rich Off. Gas	Refinery Fuel gas System after Amine Wash
2.	VB Naphtha	3.12	H_2S, Mercaptons, high olefins	To FCCU or CRU
3.	VB Gas Oil	13.9	Low Cetane no, Highly unsaturated	To DHDS or Fuel Oil
4.	VB Tar	81.16	Lower Viscosity than feed	Fuel Oil

Delayed Coker

- **Objective : To produce valuable distillate from Heavy ends by thermal cracking.**
- **Feed : RCO/Vacuum Residue/other heavy ends or residues**
- **Typical Operating Conditions:**

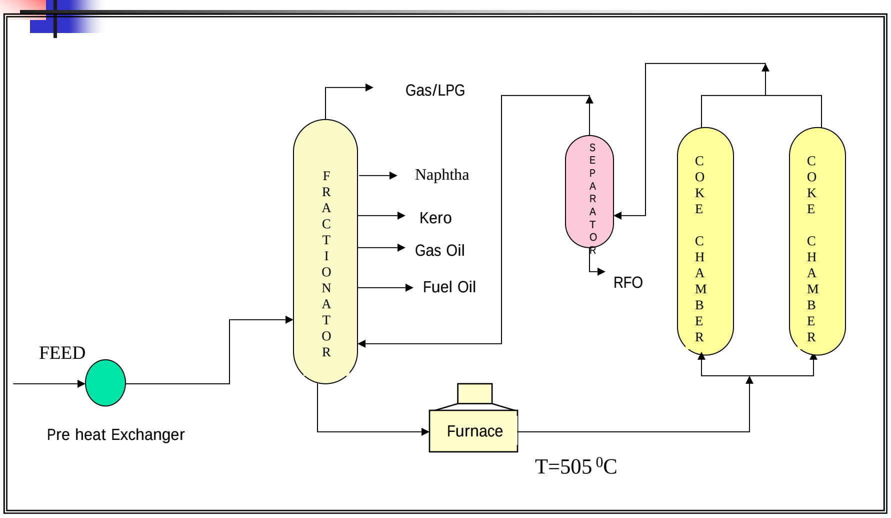
  Temperature Range : 495-505 Deg C

  Pressure : 2-3 kg/cm2(g)

Delayed Coking Process

- Feedstock : Vacuum Residue / VGO
- Products & Yields :
  - Gas+loss 10%
  - LPG 4%
  - Naphtha 5%
  - Gas oil 53%
  - FO 11%
  - RPC 17%
- Good process for increasing distillates and minimising black oil production.Gas oil & Naphtha need further treatment.
- Existing at Barauni, Guwahati & Digboi refineries and under commissioning at Panipat

Delayed Coker Unit Flow Diagram



Delayed Coker Product Yield/Qualities & End Users

Sl.No	Product	Qualities	End Users
1.	Gas	H2S rich Off. Gas	Refinery FG after Amine Wash
2.	LPG	Mercaptons, unsaturates	To LPG after Merox /Caustic wash
3.	Naphtha	Low Octane, High Olefins	To FCC or CRU
4.	Kerosene	High unsatuartes	To DHDT Feed
5.	Gas Oil	Low Cetane No. and high unsaturates	To DHDT & HCU feed
6.	Fuel Oil	Good cutter stock	Fuel Oil
7.	Coke	Low ash, High Sulphur	Gasification/Electrode Preparation/ cement ind.

Treating Process

- Caustic wash
- Merox Unit

Treating Process

1. **Caustic Washing** for removing H_2S and light Mercaptans and suitable for LPG and Naphtha

2. **Merox Process**
   a. Extractive Merox : Suitable for Lighter fractions
   b. Sweetening Merox: Suitable for boiling range upto 350 Deg C

Chemical Reaction:

$$2RSH + \frac{1}{2} O_2 \xrightarrow[\text{Iron group metal chelates}]{\text{Amb.Temp.}} RSSR + H_2O$$

After Treatment:
The treated stream is given water wash, followed by sand Bed Coalescer or salt drier for removing entrained water.

Production of Lubricating Oil Base Stock

Lube Base Oil Processing

- Crude Selection
- Multi-step manufacturing process

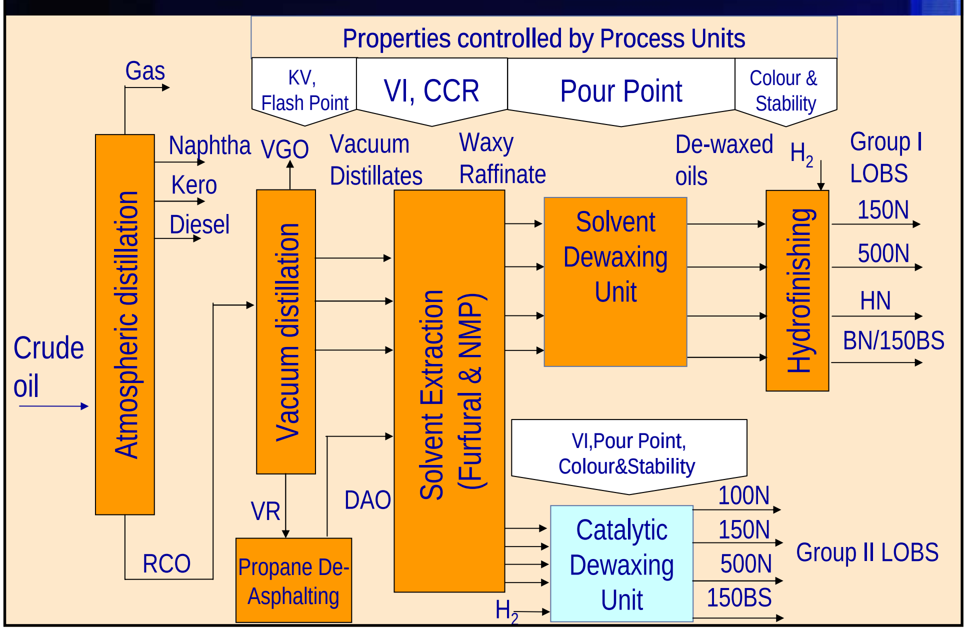
Lube Base Oils – Key Properties:

- Viscosity
- Viscosity Index
- Pour point
- Colour
- Flash point
- Volatility
- Oxidative & Thermal Stability

API Base Oil Characterization Groups

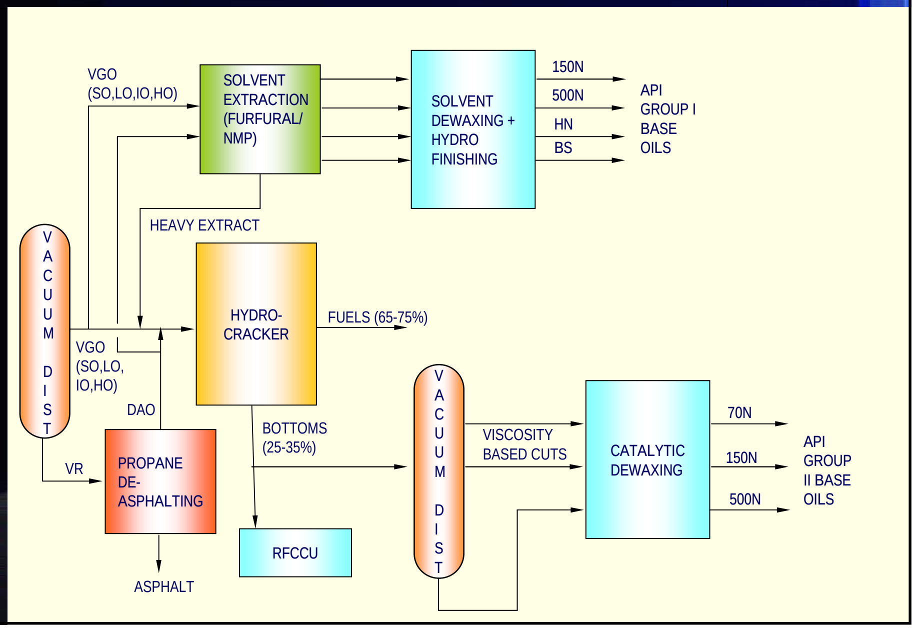
	Viscosity Index	Saturates % wt	Sulphur %wt
GROUP I	80-120	<90	>0.03
GROUP II	80-120	>90	<0.03
GROUP III	>120	>90	<0.03
GROUP IV	Poly Alpha Olefins(Synthetic Oils)		
GROUP V	All other base oils		

Lube Base Oil Processing Philosophy

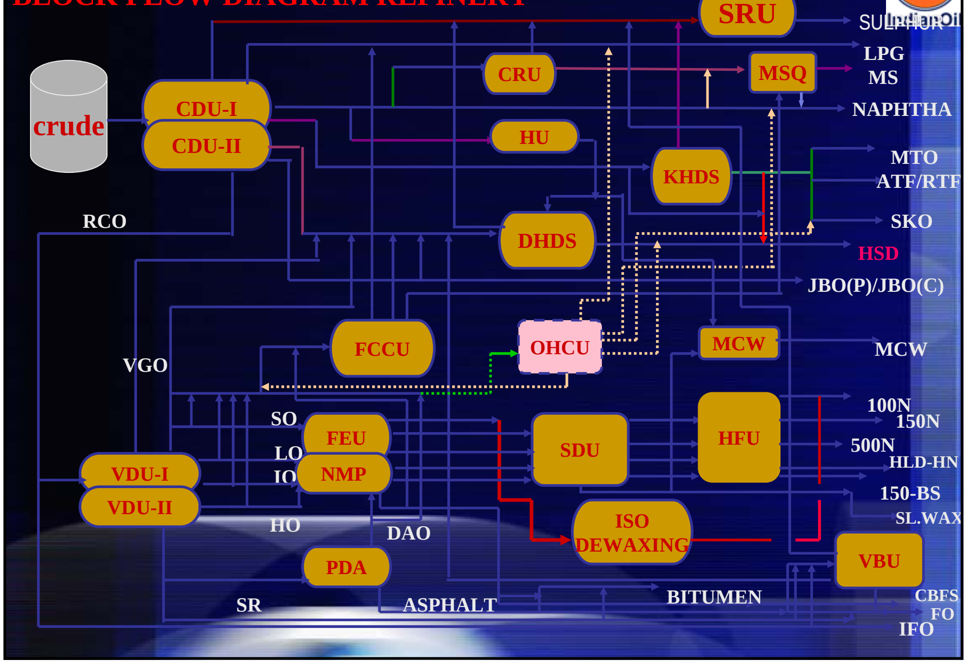


Haldia Refinery

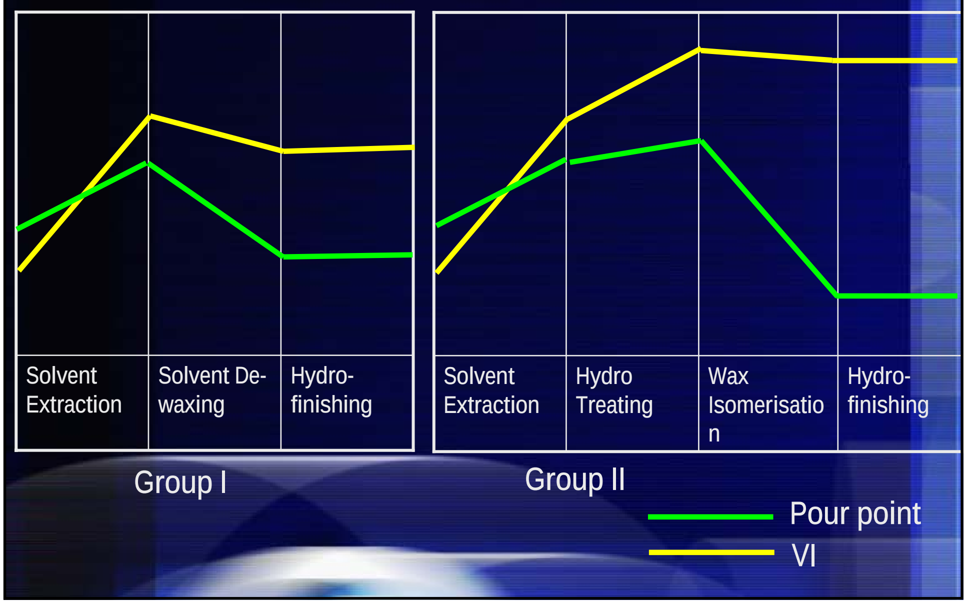
LOBS Production – Future Outlook



BLOCK FLOW DIAGRAM REFINERY



API Gr I and Gr II Processing Schemes



Other Process Units

- Hydrogen Generation Unit
- Bitumen Blowing Unit
- Sulphur Recovery Unit

Hydrogen Generation Unit (HGU)

- Objective : To Meet the Hydrogen requirement for DHDS/DHDT/OHCU/ISOM/Reforming Units and Other Hydrotreaters.
- Feed : Natural Gas / Naphtha
- Catalyst :

Catalyst :	Co-Mo	for Hydrotreater
	ZnO/K2Co3	for H2S and Chloride adsorber
	NiO	for Preformer
	Ni	for Reformer
	CuO	for HT/LT Shift reactors
	Adsorbents	for PSA Adsorbers

HGU Product Purity and Operating Conditions

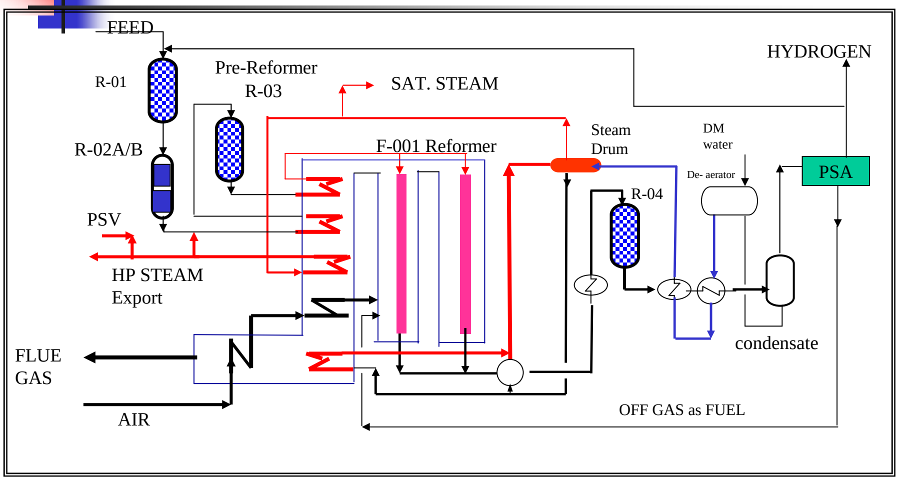
1. HGU Product is 99.99% Pure Hydrogen

2. Operating Conditions :

Temperature range : 860-870 Deg C

System Pressure : 23-26 kg/cm2(g)

Hydrogen Generation Unit Flow Diagram



Bitumen Blowing Unit

- Objective : To Produce different grades of Bitumen by air blowing of vacuum residue at high temperature.

  Bitumen is colloidal solution of asphaltenes and high molecular gums in the medium formed by oils and low molecular gums.

- Feed : Vacuum Residue

BBU yield /quality and Operating Conditions

1. Typical Product Quality

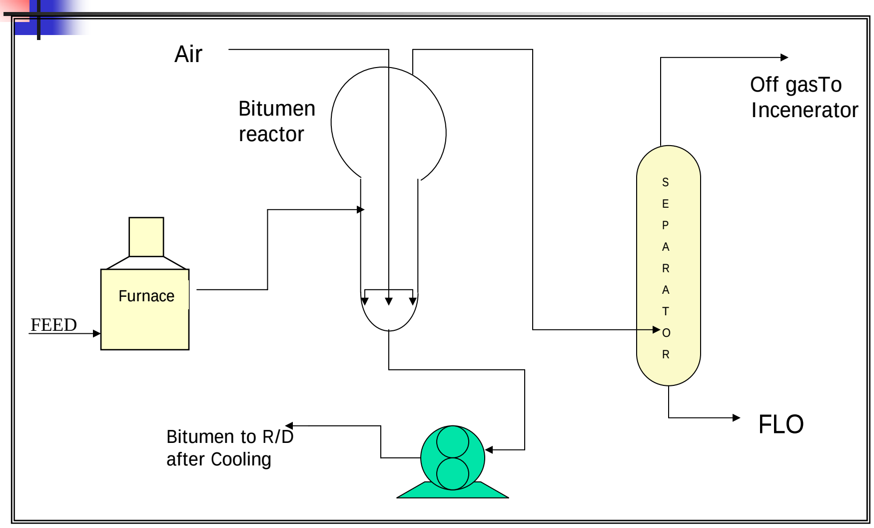
Sl.no.	Products	Wt%
1.	Off gas	0.86
2.	Recovered liquid cut (FLO)	0.26
3.	Finished Bitumen	98.88

2. Typical Operating Conditions of Bitumen Blowing Unit:

Temperature Range : 230-260 Deg C

Pressure : 0.5 kg/cm2(g)

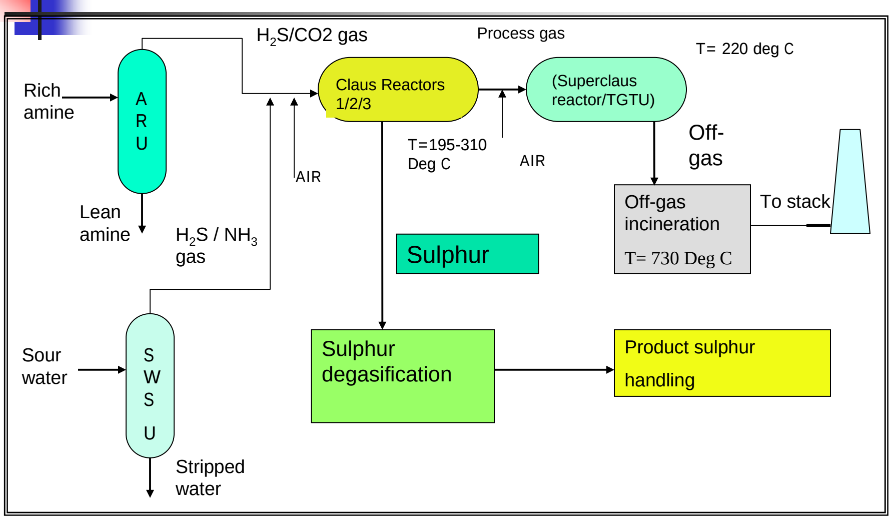
Bitumen Blowing Unit Flow Diagram



Sulphur Recovery Unit

- Objective : To Reduce the SO2 emission from the Refinery by recovering Sulphur from Amine Acid and Sour Gases produced during various Hydrotreating Process.
- Feed : Amine Acid gases and Sour acid gases

Sulphur Recovery Unit Flow Diagram



SRU Product Yield and Operating Conditions

1. Typical Product Yields

Sl.no.	Products	Wt%	End Users
1.	Off gas	0.1	To Stack after incineration
2.	Sulphur	99.9	Sulphur Yard for Dispatch

- Typical Operating Conditions:

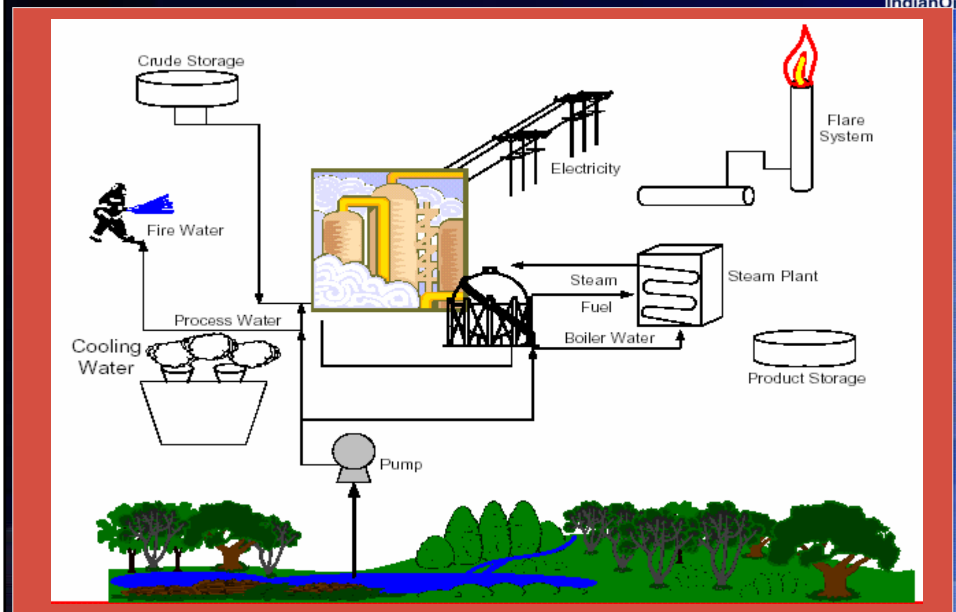
  Temperature Range : 195-320 Deg C

  Pressure : 0.56 kg/cm2(g)

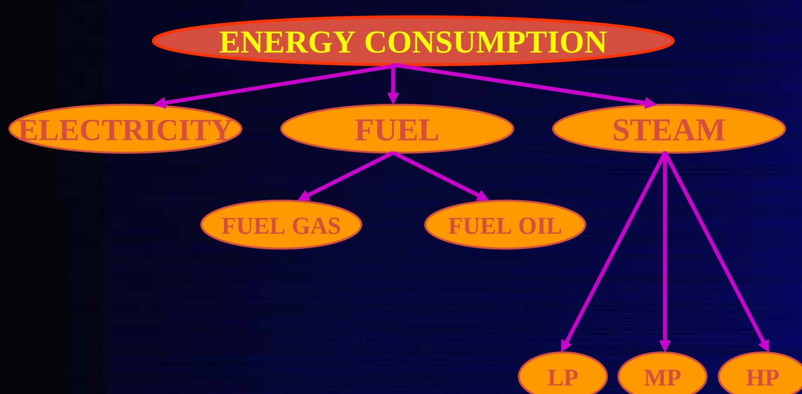
Other refinery Processes/operations

- ***Steam & Power generation***
- ***Process and DM water systems***
- ***Hydrogen,nitrogen and air systems***
- ***Flares and relief systems***
- ***Sulfur recovery system***
- ***Waste water treatment systems***
- ***Safety & fire fighting systems***
- ***Quality control, maintenance and administrative systems***

REFINERY- UTILITIES



ENERGY REQUIREMENT



Energy consumption differs in different refineries due to:

- **Refinery configuration / complexity**
- **Crude oil composition**
- **Technology / Equipments efficiency**

ENVIRONMENTAL CONCERNS

IndianOil

- SULPHUR in PRODUCTS
- BENZENE in PRODUCTS
- EFFLUENT WATER QUALITY
- SOx, NOx, H_2S, Toxic Gases
- OTHER WASTE

MINIMIZING POLLUTION

IndianOil

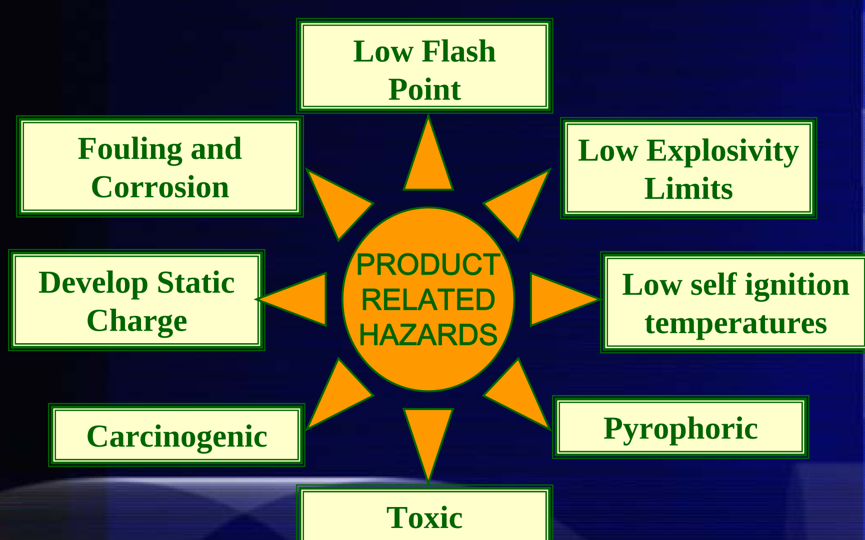
- Operate Furnaces Efficiently
- Unrecovered Light Ends burnt in flare Stack
- Avoid Spills & Accidental Releases
- Special Treatment of Sewer Water

MINIMIZING POLLUTION

FACILITIES TO BE IMPROVISED AT DESIGN STAGE

- Adequate Stack height for better dispersion of pollutants
- Desulphurisation of fuel gas
- Provision of a Sulphur recovery unit
- Provision of continuous SO2 analyzers in all stacks
- Providing Air monitoring stations
- Efficiently running Effluent Treatment Plants
- New Unit / Up-to-date technology for producing Ultra low Sulphur and benzene free fuels.

REFINERY OPERATIONS – HAZARDS



TECHNOLOGY ADOPTION IN REFINIERIES

- Desulfurization of fuel products for reduction in Sulfur- DHDS unit, Kero-HDS unit, DHDT
- Conversion processes for bottom of the barrel upgradation - FCC, Hydrocracker, DCU etc.
- Quality Improvement to meet environment norm- Cetane improvement in Diesel; Benzene, Olefin, Aromatics & Sulfur reduction in Motor Spirit.
- Adoption of catalytic-dewaxing technology for Quality Lube.

CHALLENGES TO OIL INDUSTRY

- Environmental pressure- key factor in development & acquisition of new technology
- Sophistication in equipment design- demands for high performance products.
- Adoption of Euro norms for environment friendly transport fuels production, viz.,Gasoline & Diesel.
- Demand for environment friendly, high quality LOBS- API class-II/ III.
- Cost Intensive Refining Technology

CONSTRAINTS TO MEET THE CHALLENGES

- *Crude oil sourcing - Indigenous production is only about 30% of the total requirement.*
- *Sharp fall in the availability of low Sulfur crude oil and even to the extent lighter crude oil.*
- *Hence refineries are forced to process wide variety of crude oil including high sulfur crude.*
- *Selection of suitable technology having enough flexibility.*

EMERGENCE OF COST INTENSIVE REFINING TECHNOLOGY

- *Switch over to Automation & Advance Controls*
- *Upgradation of the bottom of the barrel*
- *Efficiency Improvement thru' debottlenecking / low cost revamps etc.*
- *Environment friendly processes for pollution abatement*
- *Stringent quality products manufacture & QC.*

FUTURE CHALLENGES

- *TOTAL DEREGULATION*
- *COMPETITION FROM PRIVATE REFINING COMPANIES*
- *PRODUCT QUALITY – STRINGENT*
- *MARKET DYNAMICS*
- *MARGIN PRESSURE*
- *CUSTOMER FOCUS*

STRATEGIES

- *VALUE ADDITION*
- *CAPACITY SATURATION*
- *QUICK RESPONSE – QUALITY / QUANTITY*
- *COST REDUCTION*
- *EFFECTIVE MANNING*
- *INTEGRATION – FORWARD/BACKWARD/ LATERAL*

Refining Vision

- **Refinery Capacity**
- **Refinery Margins**
- **Product Quality**

INDIAN OIL CORPORATION LIMITED

ESSENTIALS OF REFINERY PROCESSESSES

Phase Equilibria in Refinery Processes

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Thermodynamic data needs in process simulation

Phase equilibria

Stream properties ;   enthalpy, entropy

Reaction equilibria ; Gibb's free energy of rxn, Eq. constt.

Basic Phase Equilibrium equation :

$$f_i^v = f_i^l \tag{1}$$

Where:

f_i^v = Fugacity of component i in the vapor phase

f_i^l = Fugacity of component i in the liquid phase

Applied thermodynamics provides two methods for representing the fugacities from the phase equilibrium relationship in terms of measurable state variables, the equation-of-state method and the activity coefficient method.

In the equation of state method:

$$f_i^v = \varphi_i^v y_i p \tag{2}$$

$$f_i^l = \varphi_i^l x_i p \tag{3}$$

With:

$$\ln \varphi_i^\alpha = -\frac{1}{RT}\int_\infty^{V\alpha}\left[\left(\frac{\partial p}{\partial n_i}\right)_{T,V,n_{i\neq j}} - \frac{RT}{V}\right]dV - \ln Z_m^\alpha \tag{4}$$

Hence,

$$\varphi_i^v y_i = \varphi_i^l x_i$$

Property Calculations :

- Fugacity coefficient:

$$f_i^v = \varphi_i^v y_i p \tag{13}$$

- Enthalpy departure:

$$\left(H_m - H_m^{ig}\right) = -\int_{\infty}^{V}\left(p - \frac{RT}{V}\right)dV - RT\ln\left(\frac{V}{V^{ig}}\right) + T\left(S_m - S_m^{ig}\right) + RT\left(Z_m - 1\right) \tag{14}$$

- Entropy departure:

$$\left(S_m - S_m^{ig}\right) = -\int_{\infty}^{V}\left[\left(\frac{\partial p}{\partial T}\right)_v - \frac{R}{V}\right]dV + R\ln\left(\frac{V}{V^{ig}}\right) \tag{15}$$

- Gibbs energy departure:

$$\left(G_m - G_m^{ig}\right) = -\int_{\infty}^{V}\left(p - \frac{RT}{V}\right)dV - RT\ln\left(\frac{V}{V^{ig}}\right) + RT\left(Z_m - 1\right) \tag{16}$$

- Molar volume:

Solve $p(T, V_m)$ for V_m.

Activity Coefficient method :

$$\varphi_i^v y_i p = x_i \gamma_i f_i^{*,l}$$

where

The liquid phase reference fugacity $f_i^{*,l}$ is computed as:

$$f_i^{*,l} = \varphi_i^{*,v}\left(T, p_i^{*,l}\right) p_i^{*,l} \theta_i^{*,l}$$

For non-condensing gaseous components :

$$\varphi_i^v y_i p = x_i \gamma_i^* H_i$$

Liquid property calculations :

Liquid phase: Liquid mixture enthalpy is computed as:

$$H_m^l = \sum_i x_i \left(H_i^{*,v} - \Delta_{vap} H_i^* \right) + H_m^{E,l} \tag{34}$$

Where:

$H_i^{*,v}$	=	Pure component vapor enthalpy at T and vapor pressure
$\Delta_{vap} H_i^*$	=	Component vaporization enthalpy
$H_m^{E,l}$	=	Excess liquid enthalpy

Excess liquid enthalpy $H_m^{E,l}$ is related to the activity coefficient through the expression:

$$H_m^{E,l} = -RT^2 \sum_i x_i \frac{\partial \ln \gamma_i}{\partial T} \tag{35}$$

Liquid mixture Gibbs free energy and entropy are computed as:

$$S_m^l = \frac{1}{T} \left(H_m^l - G_m^l \right) \tag{36}$$

$$G_m^l = G_m^v - RT \sum_i \ln \varphi_i^{*,l} + G_m^{E,l} \tag{37}$$

Where:

$$G_m^{E,l} = RT \sum_i x_i \ln \gamma_i \tag{38}$$

Liquid density is computed using an empirical correlation.

Equations of State :

Cubic EOS :

Redlich-Kwong(-Soave) based	Peng-Robinson based
Redlich-Kwong	Standard Peng-Robinson
Standard Redlich-Kwong-Soave	Peng-Robinson
Redlich-Kwong-Soave	Peng-Robinson-MHV2
Redlich-Kwong-ASPEN	Peng-Robinson-WS
Schwartzentruber-Renon	
Redlich-Kwong-Soave-MHV2	
Predictive SRK	
Redlich-Kwong-Soave-WS	

An example of this class of equations is the Soave-Redlich-Kwong equation of state (Soave, 1972):

$$p = \frac{RT}{(V_m - b)} - \frac{a(T)}{V_m(V_m + b)} \qquad (45)$$

$$a = \sum_i \sum_j x_i x_j (a_i a_j)^{1/2} (1 - k_{a,ij})$$

$$b = \sum_i x_i b_i = \sum_i \sum_j x_i x_j \left(\frac{b_i + b_j}{2} \right)$$

Activity Coefficient Models :

Van Laar

Scatchard-Hildebrand

Margules

Redlich Kister

Wilson

NRTL

UNIQUAC

UNIFAC

- Non Random Two Liquid (NRTL) Model:
  - applicable to partially miscible as well as completely miscible systems
  - The NRTL equation for the excess Gibbs energy

$$\frac{g^E}{RT} = \sum_i x_i \frac{\sum_j x_j G_{ji} \tau_{ji}}{\sum_k x_k G_{ki}}$$

  - Activity coefficient in its **generalized form** is given by

$$\ln \gamma_i = \left[\frac{\partial (nG^E / RT)}{\partial n_i} \right]_{P,T,n_j}$$

$$\ln \gamma_i = \frac{\sum_j \tau_{ji} G_{ji} x_i}{\sum_k G_{ki} x_k} + \sum_j \frac{x_j G_{ij}}{\sum_k G_{kj} x_k} \left(\tau_{ij} - \frac{\sum_k x_k \tau_{kj} G_{kj}}{\sum_k G_{kj} x_k} \right)$$

- contd…

  - where: *i, j, k = 1, 2,…c ;*

$$\tau_{ij} = \frac{(g_{ji} - g_{ii})}{RT} \;;$$

$$G_{ji} = \exp\left(-\alpha_{ji} \tau_{ji}\right) \;;$$

  - τ_{ij}'s & α_{ij} *are NRTL model parameters*
    - *where*

$\tau_{ij} \neq \tau_{ji}$

$\alpha_{ij} = \alpha_{ji} = 0.2$ …for liquid – liquid system

- UNIFAC (Universal Functional Activity Coefficient) method
  - estimates activity coefficients based on the group contribution concept
  - Excess Gibbs energy (and logarithm of the activity coefficient) as a combination of 2 effects-
    1. combinatorial term
    2. residual term

$$\ln\gamma_i = \ln\gamma_i^{\,C} + \ln\gamma_i^{\,R}$$

$$\ln\gamma_i^C = \ln\left(\frac{\varphi_i}{x_i}\right) + \frac{z}{2} q_i \ln\left(\frac{\theta_i}{\varphi_i}\right) + l_i - \frac{\varphi_i}{x_i}\sum_{j=1}^{NOG} x_j l_j$$

where

$$\varphi_i = \frac{x_i r_i}{\sum_{j=1}^{c} x_j r_j}\ ;\ \theta_i = \frac{x_i q_i}{\sum_{j=1}^{c} x_j q_j}\ ;\ l_i = \frac{\bar{z}}{2}(r_i - q_i) - (r_i - 1)$$

$$r_i = \sum_{k=1}^{NOG} v_k^i R_k\ ;\ q_i = \sum_{k=1}^{NOG} v_k^i Q_k$$

- contd…

$$\ln\gamma_i^R = \sum_{k}^{NOG} v_i^k (\ln\Gamma_k - \ln\Gamma_k^i)$$

- where
  - Γ_k = residual activity coefficient of group k in the mixture
  - Γ_k^i = residual activity coefficient of group k in a reference solution containing **only** molecules of type i.
- The parameters Γ_k and Γ_k^i are defined by:

$$\ln\Gamma_k = Q_k\left(1 - \ln\sum_{m}^{NOG}\theta_m\tau_{mk} - \sum_{m}^{NOG}\frac{\theta_m\tau_{km}}{\sum_{n}^{NOG}\theta_n\tau_{nm}}\right)$$

$$\theta_k = \frac{X_k Q_k}{\sum_{m}^{NOG} X_m Q_m}\quad ;\quad \tau_{mn} = e^{-b_{mn}/T}$$

X_k is the group mole fraction of group k in the liquid:

$$X_k = \frac{\sum_{j}^{c} v_{kj} x_j}{\sum_{j}^{c}\sum_{m}^{NOG} v_{mj} x_j}$$

Property methods for Petroleum mixtures :

Liquid Fugacity and K-Value Models

Property Method Name	Models
BK10	Braun K10 K-value model
CHAO-SEA	Chao-Seader liquid fugacity, Scatchard-Hildebrand activity coefficient
GRAYSON/GRAYSON2	Grayson-Streed liquid fugacity, Scatchard-Hildebrand activity coefficient
MXBONNEL	Maxwell-Bonnell liquid fugacity

Petroleum-Tuned Equations of State

Property Method Name	Models
PENG-ROB	Peng-Robinson
RK-SOAVE	Redlich-Kwong-Soave
SRK	Soave-Redlich-Kwong

Eqn of State property methods for hydrocarbons at high pressure:

Property Method Name	Models
BWR-LS	BWR-Lee-Starling
BWRS	Benedict-Webb-Rubin-Starling
LK-PLOCK	Lee-Kesler-Plöcker
PR-BM	Peng-Robinson-Boston-Mathias
RKS-BM	Redlich-Kwong-Soave-Boston-Mathias

- Peng-Robinson (PR)
    - Most enhanced model in Aspen HYSYS
    - Largest applicability range in terms of T and P
    - Special treatments for some key components
    - Largest binary interaction parameter database
- PRSV
    - Modified PR model
    - Better representation of vapor pressure of pure components and mixtures
    - Extends applicability of the original PR model to moderately non-ideal systems
- SRK
    - Modified RK model
    - Can provide comparable results to PR in many cases, but with a lot less enhancement in Aspen HYSYS
- PR-Twu
- SRK-Twu
- Twu-Sim-Tassone (TST)
    - Modified equations of state models for hydrocarbon systems-non ideal systems (used for glycol package)
- Generalized Cubic Equation of State (GCEOS)
    - Provides a framework which allows users to define and implement their own generalized cubic equation of state including mixing rules and volume translation
- MBWR
    - Modified BWR model
    - Having 32 parameters, this model works extremely well with a number of pure components within specified T and P ranges
- Lee-Kesler-Plöcker
    - Also a modified BWR model for non-polar substances and mixtures
- BWRS
    - Modified BWR to handle multi components
    - Requires experimental data

- Zudkevitch Joffee
  - Modified RK model with better prediction of VLE for hydrocarbon systems, and systems containing hydrogen

- Kabadi-Danner
  - Modified SRK model with the enhancement to improve the VLE calculations for H_2O-hydrocarbon systems, particularly in dilute regions

- Sour PR/Sour SRK
  - Used for sour water systems containing H_2S, CO_2, and NH_3 at low to moderate pressures

Semi-empirical Models :

- Chao-Seader model
  - Applicable to hydrocarbon systems in the range of T=0-500C, and P<10,000 kPa

- Grayson-Streed model
  - An extension to the Chao-Seader model with special emphasis on H_2
  - Recommended for heavy hydrocarbon systems with high H_2 content, such as hydrotreating units

- **Hydrocarbon systems up to distillate range hypo components**
  - **– PR, SRK or any other EOS***
- **Vacuum columns – GS, PR or BK10**
- **Sour gas sweetening with Amines**
- **Sour water treatment process – Sour PR/SRK**
- **Clean fuels for sulfur components and hydrocarbons**
- **High H2 content systems – GS, PR**
- **Utility systems using H2O – Steam Table**

Refinery Processes :

Application	Recommended Property Method
Low pressure applications(up to several atm) Vacuum tower Atmospheric crude tower	Petroleum fugacity and K-value correlations (and assay data analysis)
Medium pressure applications (up to several tens of atm) Coker main fractionator FCC main fractionator	Petroleum fugacity and K-value correlations Petroleum-tuned equations of state (and assay data analysis)
Hydrogen-rich applications Reformer Hydrofiner	Selected petroleum fugacity correlations Petroleum-tuned equations of state (and assay data analysis)
Lube oil unit De-asphalting unit	Petroleum-tuned equations of state (and assay data analysis)

Gas Processing

Application	Recommended Property Method
Hydrocarbon separations Demethanizer C3-splitter	Equations of state for high pressure hydrocarbon applications (with kij)
Cryogenic gas processing Air separation	Equations of state for high pressure hydrocarbon applications Flexible and predictive equations of state
Gas dehydration with glycols	Flexible and predictive equations of state
Acid gas absorption with Methanol (rectisol) NMP (purisol)	Flexible and predictive equations of state
Acid gas absorption with Water Ammonia Amines Amines + methanol (amisol) Caustic Lime Hot carbonate	Electrolyte activity coefficients
Claus process	Flexible and predictive equations of state

Scope of Optimization

in

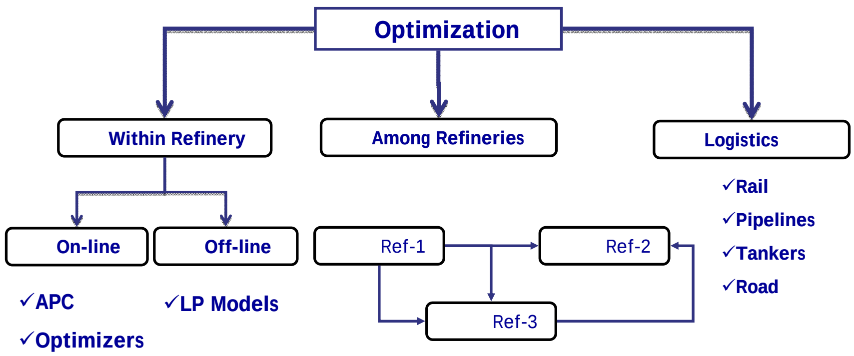
Refining Operation

The Presentation Structure

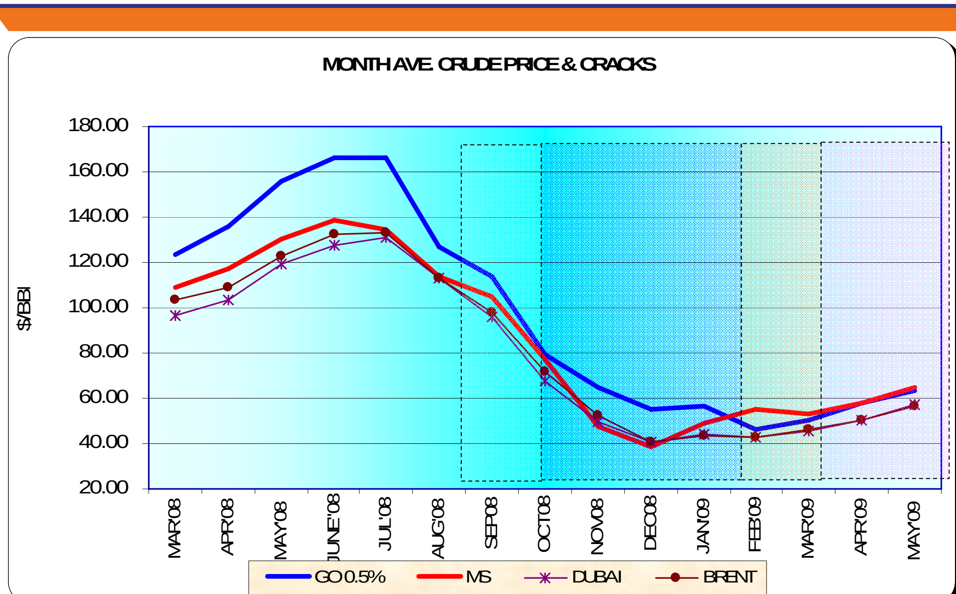
- ✓ Basics of Optimization
- ✓ Optimization within Refinery
- ✓ Optimization among Refineries
- ✓ Petroleum Supply Chain Optimization

Basics of Optimization

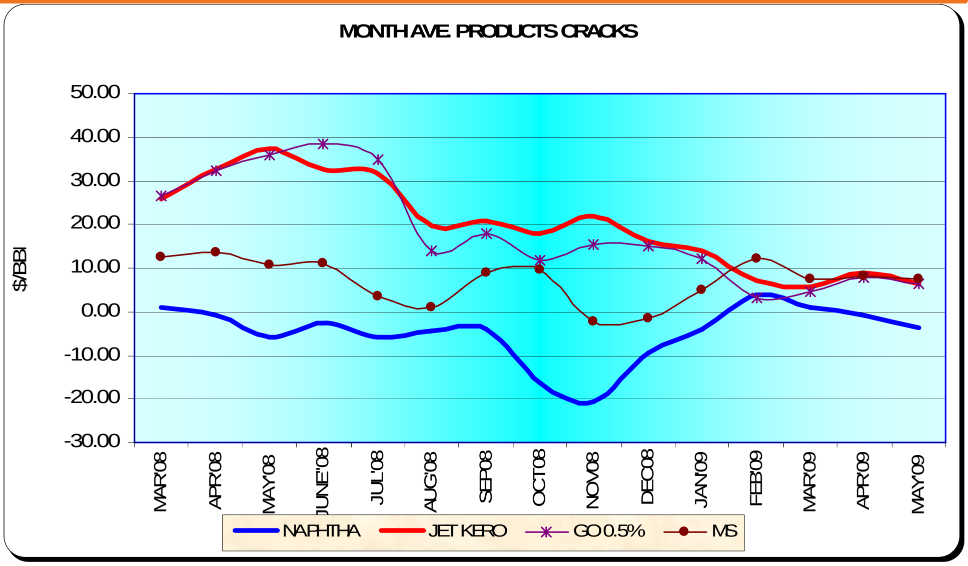
- A process to achieve best solution / performance within defined constraints
  - Profit Maximization
  - Throughput maximization within hardware constraints
  - Maximize equipment life through optimum usage



Basics of Optimization



Basics of Optimization



Basics of Optimization

- Optimization
  - Profit Maximization
  - Throughput maximization within hardware constrainits
  - Maximize equipment life through optimum usage

- Ref. Profit =Prod. Realization – Input Cost – Operating cost
  = Sum(Qi*Pi) - Sum(Ci*pi) – Sum (Fi*Ui) – Losses

Qi (Prod. qty) = f (Type of crude, Process Configuration, Demand Pattern)
=> Under Control

Pi (Prod. Price) = f (Demand -> domestic, International)
=> Little control

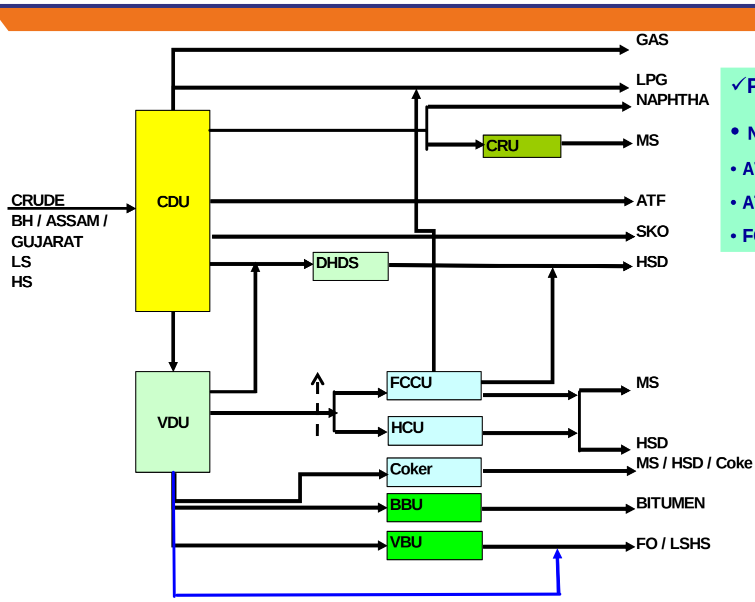
pi (Crude Cost) = f (Global demand (Premium/Disc), Location of Ref. & Crude source)
=> No control

Ci (Crude Type) = f (Production rate, Global demand, Political scenario)
=> Under control

Basics of Optimization

✓ Optimization within Refinery

Optimization within Refinery



✓Product Mix Optimization

- Naphtha/ MS / Pet-chem
- ATF / SKO
- ATF / SKO / HSD
- FO / Bitumen

Optimization within Refinery

Functional Objective

- Maximize Gross Refinery Margin
  - Input cost reduction
  - Maximize capacity utilization to reduce operating cost
  - Maximize value added products
    - Swing Operation in FCCU
    - Optimum utilization of VBU / BBU
  - Minimize low value products irrespective of demand
- Operational Efficiency improvement
  - Fuel & Loss, R&M cost, Quality give-away etc.

Net Margin = Products sold * Transfer Price - Crude process * Crude cost at Refinery - Operating Cost

Optimization within Refinery

Margins

- Function of
  - Demand pattern
  - Products Prices
  - Product pattern of refinery & Its flexibility / Optimization
  - Refinery configuration
  - Logistic Infrastructure availability
- Optimization
  - LPG Vs Propylene (PRU)
  - Naphtha Vs MS (CCRU, FCCU, Isom, Crude type)
  - SKO Vs ATF
  - SK Vs HSD
  - FO / LSHS Vs HSD
  - FO Vs Bitumen

Optimization within Refinery

IndianOil

On-line Optimization

- Advanced Process Control
  - CDU Pressure minimization subject to constraints
  - CDU COT maximization subject to constraints
  - FCC Severity maximization / optimization
  - Value added product maximization subject to property constraints
    - Inferential properties prediction
    - Constraint controller
    - Multi-variable predictive control
    - On-line Optimizer
  - Offsite blend optimization

Optimization within Refinery- Offline

IndianOil

Product pattern Optimization

- Secondary units availability
  - FCC / RFCC
  - HCU / OHCU
  - Coker / VBU / BBU
  - Naphtha cracker
- Type of crude processing
  - LS / HS / Hy. crude
    - Refinery operating cost
- Flexibility of swinging product pattern
  - Demand pattern
    - Seasonal demand (Naphtha, ATF, Bitumen)
    - Prod. Price difference (FO / HSD, LDO/ HSD, Naphtha vs Nat. Gas)
  - RTPs of products

Optimization within Refinery

Product Pattern Optimization

- **Secondary Units- FCC / RFCC**
  - MS / LPG maximization
  - Suitable for higher UOP K VGO feed
  - Medium investment
  - Medium Op. cost
    - CCR limitation
    - Metal limitation
    - Lower Cetane of TCO
- **Secondary Units- HCU / OHCU**
  - SK / ATF / HSD maximization without any treatment
  - Lower UOP K VGO feed can be processed
  - High investment
  - High Op. cost
    - Nitrogen limitation

Optimization within Refinery

Product pattern Optimization

- **Secondary Units- Coker**
  - Residue up-gradation
  - Facilitates Hy. Crude processing
  - Relatively low investment
  - Relatively low Op. cost
    - Around 30% coke generation
    - HPS vs Coke price deciding factor
    - Cracked products needs treatment
    - HCGO needs reprocessing in HCU / FCCU

Optimization within Refinery

IndianOil

Product Pattern Optimization

- **Secondary Units- VBU**
  - Viscosity breaking to produce FO
  - Lower cutter stock requirement
  - Low investment
  - Low Op. cost
  - Dubai vs Brent, FO vs HSD deciding factor

- **Secondary Units- BBU**
  - Suitable for VR having high Asphaltenes
  - Releases cutter stock for value added products
  - Seasonal and reagion specific demand
  - No import facility
  - Dubai vs Brent, FO vs HSD deciding factor

Optimization within Refinery

IndianOil

Input cost Optimization

Input Cost = f (Type of crude. Logistic cost, other inputs)

- **Crude Type**
  - LS Crude (Low S, High API, High Dist.)
    - Lower Operating cost
    - Higher FOB and logistic cost
  - HS Crude (High S, Medium API, Medium Dist.)
    - High Operating cost
    - Medium FOB and Lower Logistic cost
  - Hy. Crude (High / Low S, Low API, Low Dist.)
    - High Operating cost
    - High viscosity affecting PL capacity
    - High Acid no., Metal content
    - Cheaper crude
  - The capability of type of crude processing will depend on Refinery configuration

Refinery LP Model

Input
Available Crude Basket
Crude and Product Prices
at refinery gate
Product demand
Shutdown Slate
Change in product specs.

Model

- Crude Assays
- Process unit configuration
- Feed Blends
- Product Blends
- Product Specs

Objective : Profit Maximization

Output
Crude Mix and Qty.
Product pattern
Sec Unit capacity utilisation.
Sec Units feed
and Product Blends

- Refinery Production Planning
- Crude evaluation
- Blend Optimization
- Investment Analysis
- Inventory Management
- Back casting

Provision for 24 Multi-periods

Basics of Optimization

Optimization within Refinery

✓ Optimization among Refineries

Refineries configuration

	IOCL REFINERIES							ASSOCIATES REFINERIES		
Units	J	P	M	B	H	G	D	BRPL	CPCL	CBR
CAP.,MMTPA	13.70	12.00	8.00	6.00	6.00	1.00	0.65	2.35	9.50	1.00
CDU	☺	☺	☺	☺	☺	☺	☺	☺	☺	☺
VDU	☺	☺	☺	☺	☺	☺	☺	☺	☺	
RFCC/FCC	☺	☺	☺	☺	☺	☺			☺	
HCU/OHCU	☺	☺	☺						☺	
VBU	☺	☺	☺		☺				☺	
BBU	☺	☺	☺		☺		☺		☺	
COKER		☺		☺		☺	☺	☺		
LOBS					☺		☺			
P/CHEMICAL	☺	☺								

J; KOYALI, P:PANIPAT,M:MATHURA,B:BARAUNI, H:HALDIA, G:GUWAHATI, D;DIGBOI

Optimization Between Refineries

Synergy among multi-refinery operation to maximize over all profit

- Intermediate stream sharing
  - Refinery configuration
  - Planned shutdown schedule
  - Capacity constraint in One refinery and availability in other Refinery

- SRGO (J-> P/M, BGR->G/B) : HS crude & prod. Optimization
- Reformat (J/B/D -> G) : Optimization between Naphtha & MS
- PXN (M- > P) : HS crude maximization
- IFO (J- > P) : HS crude maximization
- PNCP Feed (J/M - > P) : Naphtha export minimization

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- Basics of Optimization
- Optimization within Refinery
- Optimization among Refineries
- ✓ Petroleum Supply Chain Optimization

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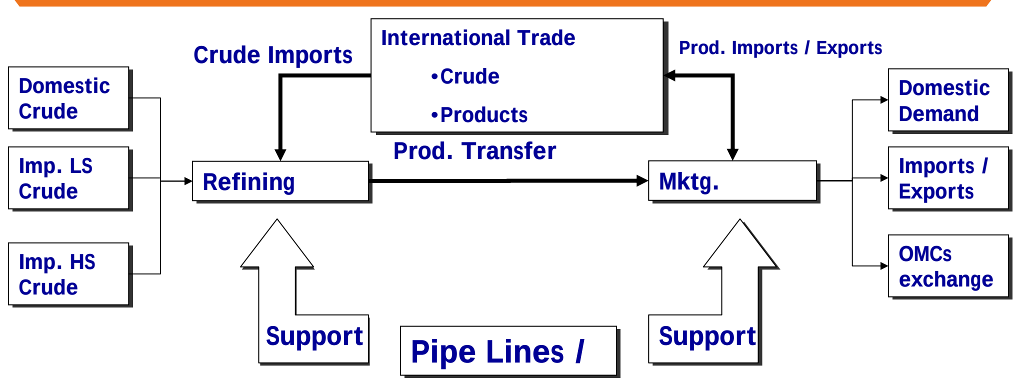
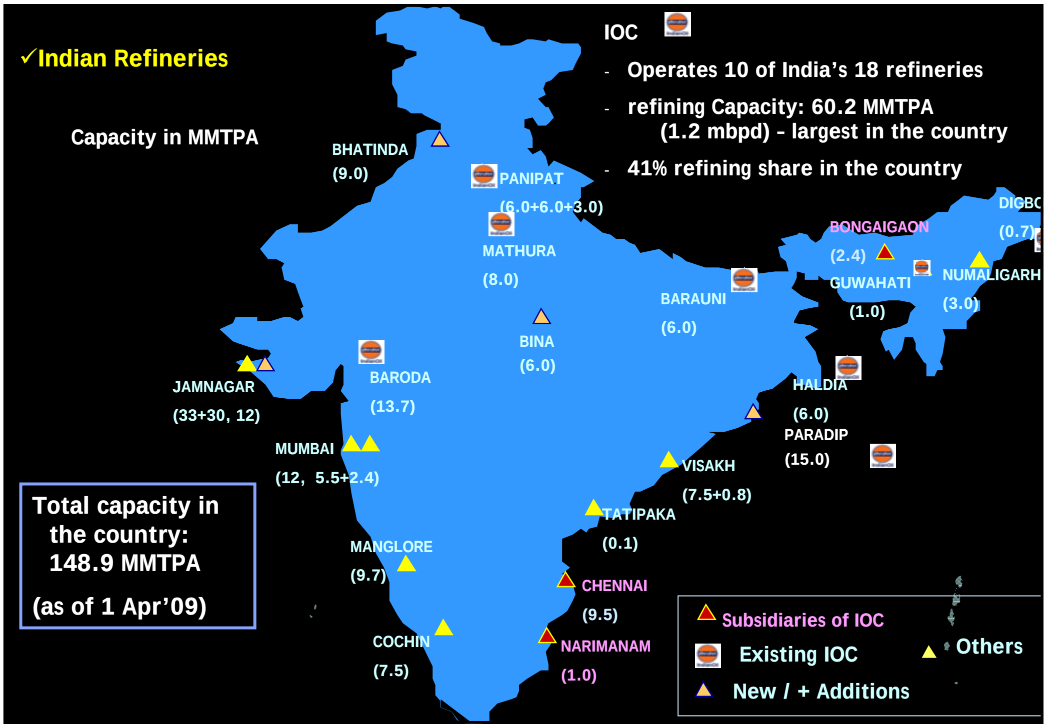
Corporate Supply Chain



Up-Stream

(High Lead time)

Down-Stream



Infrastructure

IndianOil

- **Crude**
  - Vadinar / Mundra port (VLCC) for North-West Refineries
    - SMPL for Gujarat, Panipat & Mathura
    - Mundra for Panipat
  - Haldia Port for East coast Refineries
    - Lower Draft and port congestion
  - HBCPL for Barauni Refinery
  - Commissioning of Paradeep- Haldia crude pipeline
- **Product**
  - Demand growth in North West Sector
  - Euro-III products & ATF demand in Metro cities
  - Product movement from East to North-West
  - Limited export facility at Haldia port
  - Dahej / Kandla for Naphtha Export
  - No Import / Export facility for ATF and Bitumen

Complexity in Indian Oil Supply Chain

IndianOil

- 40 Crudes in basket from S. America to S.E.Asia
- 10 Refineries
- Large distribution network
  - 10 major products
  - 200 Depots (excluding LPG network)
  - 40 Terminals
  - 17 Pipelines
  - 4 Transportation modes
- One crude pipeline catering to 3 refineries
- Crude procurement 3 months in advance

Down stream Oil Industry: Overview

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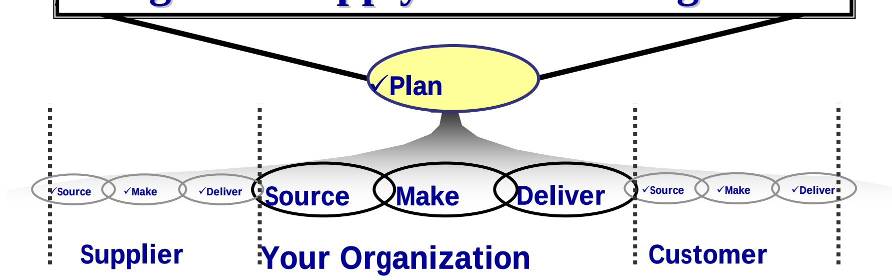
Integrated Supply Chain Management



Up-stream time Mgmt

M+4 Months

SCOR model

Source: The Supply Chain Council

Down-stream time Mgmt.

IOCL,BPCL,HPCL

Crude evaluation / purchase

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- Line up crude term contract for 50-60 % of requirement
- Spot / short term purchase for balance quantity
- Buy crude giving maximum Supply chain margin
- Based on landed crude price & domestic products pricing
- Crude purchase at Vadinar & Paradeep port

  - **Synergy between already purchased crude**
  - **Crude matching with demand**
  - **Domestic market discounts**
  - **Products sale at domestic demand location price**
  - **Excess product for export based on economics**
  - **Variable operating cost (Fuel & Loss)**
  - **Emission norms consideration**

Supply Chain Objectives

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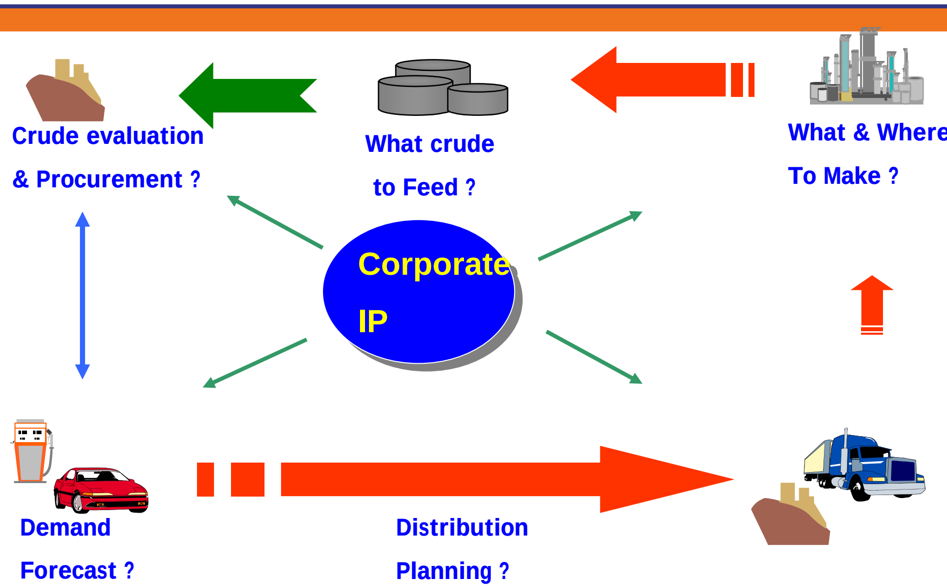
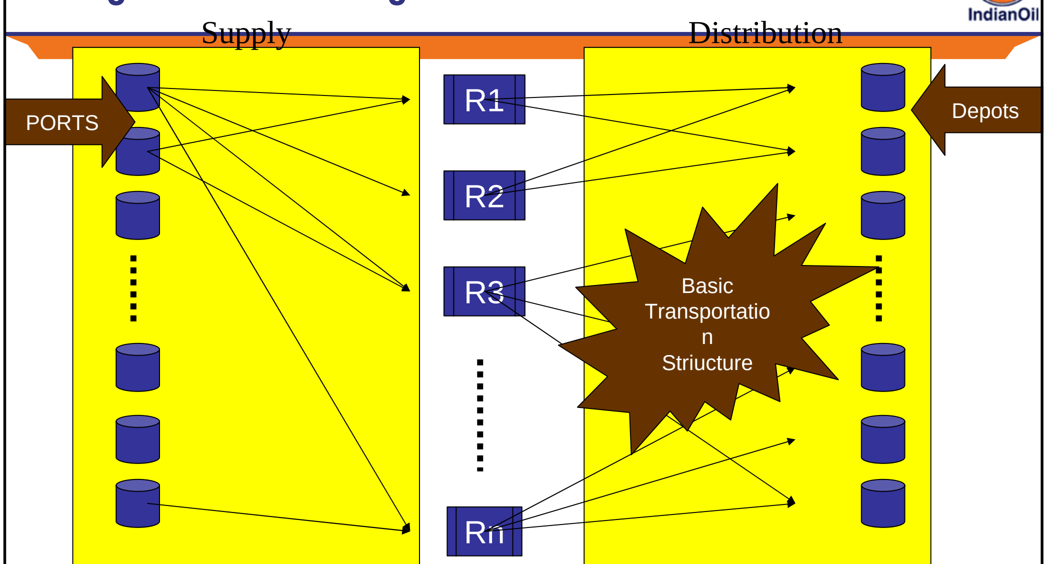
- Maximize Corporate Profits
  - Profit Refinery + Profit Mktg. = Profit Corporate?
- Optimize the following
  - Raw material
  - Operating cost of refinery
  - Products Logistics Cost ensuring minimal under recovery
  - Inventory cost
  - synchronized & optimized business process operation
- Supply chain Visibility with their interdependency
- Quick response / Corrective actions to address internal / external contingencies

SCM: Integrated Approach



Integrated Planning Model



Integrated Planning (IP) Model

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Input	Output
- Crude Availability at Ports	- Refinery wise T'put & Crude Alocation
- Location level Demand	- Crude requirement for future period
- Desired Inventory build up / depletion	- Refinery wise Product Pattern
- Committed Exports, Imports	- Detailed Distribution Plan
- Exchangeswith OMCs	Product wise, mode wise
- Planned Shutdown schedule	- Purchases, Exchanges
- Changes in product specs.	- Gross Margin
- Crude Prices / Purchase Cost	
- Product Prices	

Objective : Profit Maximisation

Provision of Multi-period planning

Model Sizes

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Models	Constraints (No of Rows)	Variables (No of Columns)
Refinery Planning, RPMS	**2500 - 5500**	**6000 - 14500**
Distribution Planning, SAND	**2500 - 5500**	**8500 - 19000**
Integrated Planning	**23000**	**63000**

Benefits

- Optimizes the whole supply chain giving **higher margins** and **increased profitability**
- Crude selection and allocation which takes into account product demands, refinery capabilities and effect of crudes already procured
- Optimal refinery production planning considering crude assay, unit capacities, product specs and demand pattern
- Optimal distribution planning considering transportation costs, taxes and duties and transportation constraints

THANK YOU

Overview of Industrial Practices in Planning & Scheduling

-Dayanand Deshpande,
12 Jun 2009
Honeywell

Agenda

- Supply Chain Management & Structure of Advanced Planning Systems (APS)
- Planning
  - Demand Planning & Forecasting
  - Advanced Planning and Optimisation
  - Distribution Planning
- Scheduling
  - Production Scheduling
  - Distribution Scheduling (Rail/ Road/ Ship and Pipeline Scheduling)
- Implementation of APS – A case study
- Conclusions & Outlook

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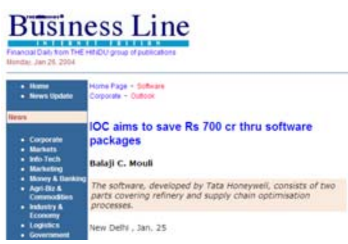
SCM- Another Short-lived Management philosophy???

- "The task of integrating organisational units along a supply chain and coordinating material, information and financial flows in order to fulfil (ultimate) customer demands with the aim of improving competitiveness of a supply chain as a whole"



Benefit Area	Sample Value
Reduction in Inventories • Adjust safety stock **Improved Forecasting** • Statistics can reduce error 10% • Collaboration can reduce error 30% **Lower Supply Chain Costs** • Reduction in premium freight costs **Improved Customer Satisfaction**	Specialty manufacturer reduced inventory $15M in first year • Reduction in working inventory • Reduction in premium freight • Customer service increase from 85% to 95% across 5000+ railcar fleet • 40% reduction in forecast error by manufacturer with over 15,000 sku's Production efficiencies generated additional revenues of $4M / year • Estimated shift in cycle lengths of 2-8 days / line
Improved Efficiency / Capacity • Reduce process variability • Improved quality • Increased throughput	Non Linear Control implementation for polymers manufacturer saved millions of dollars per year • Capacity increase of 8% • Transition time reduction of 30% • Quality variability reduction of 50%
Asset Utilization / Reliability • 3-8% Improvement	Loop scout contributed to refrigeration production increase valued at $1.7M / year at Honeywell Multi Products plant in Geismar, LA

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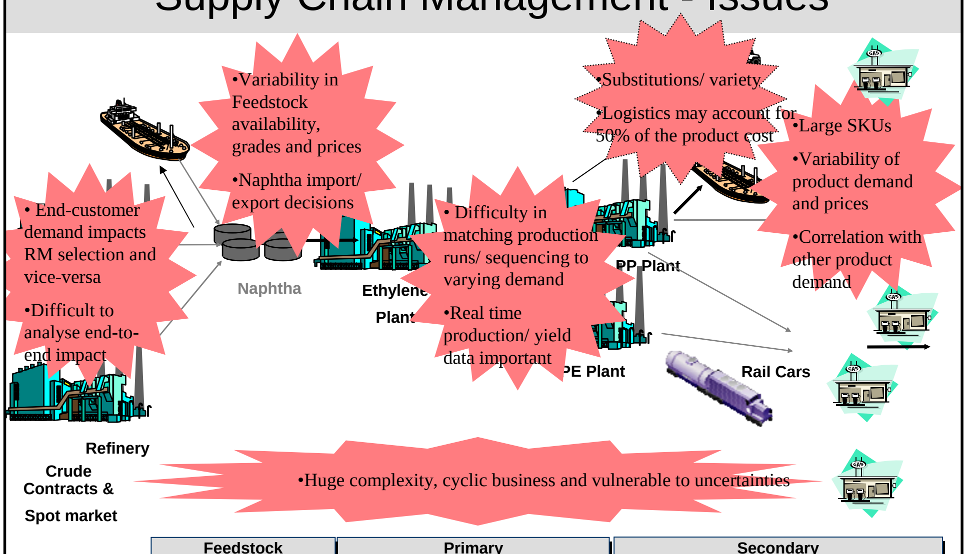
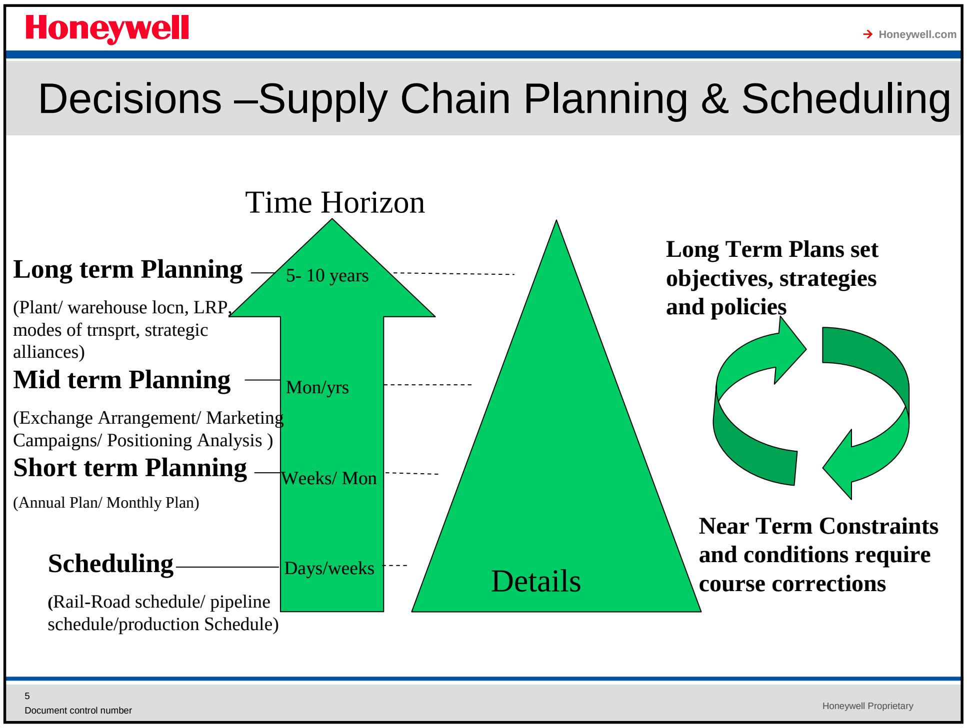
Supply Chain Management - Issues

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Decisions –Supply Chain Planning & Scheduling
Time Horizon
Long term Planning
(Plant/ warehouse locn, LRP, modes of trnsprt, strategic alliances)
5- 10 years
Mid term Planning
(Exchange Arrangement/ Marketing Campaigns/ Positioning Analysis)
Mon/yrs
Short term Planning
(Annual Plan/ Monthly Plan)
Weeks/ Mon
Scheduling
(Rail-Road schedule/ pipeline schedule/production Schedule)
Days/weeks
Details
Long Term Plans set objectives, strategies and policies
Near Term Constraints and conditions require course corrections
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Document control number
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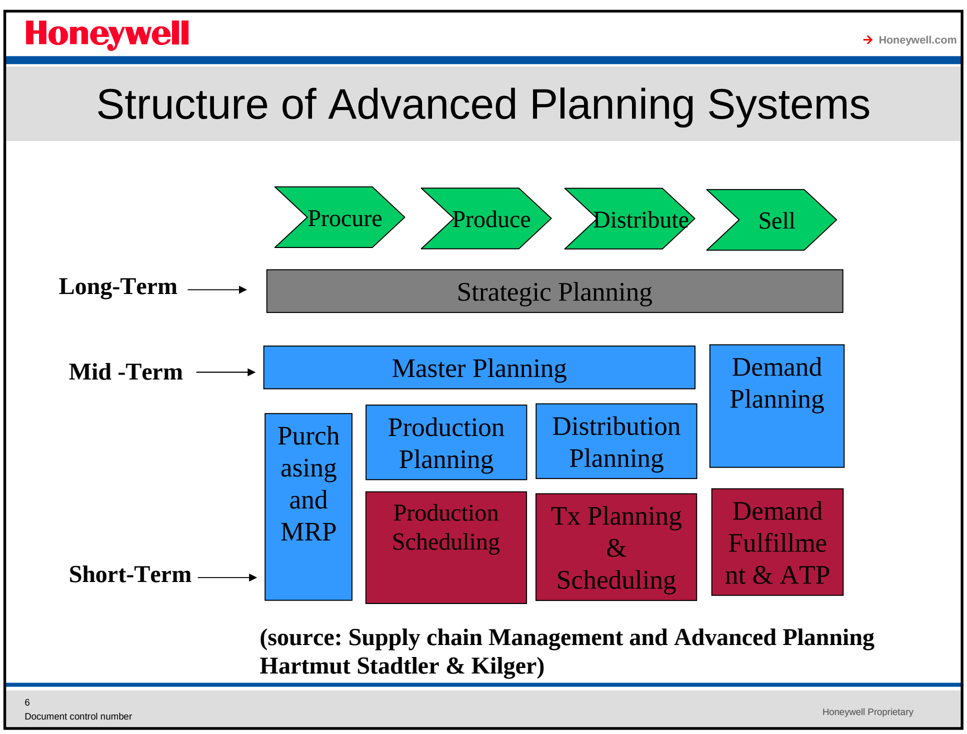
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Structure of Advanced Planning Systems
Procure
Produce
Distribute
Sell
Long-Term
Strategic Planning
Mid -Term
Master Planning
Demand Planning
Purchasing and MRP
Production Planning
Distribution Planning
Production Scheduling
Tx Planning & Scheduling
Demand Fulfillment & ATP
Short-Term
(source: Supply chain Management and Advanced Planning Hartmut Stadtler & Kilger)
6
Document control number
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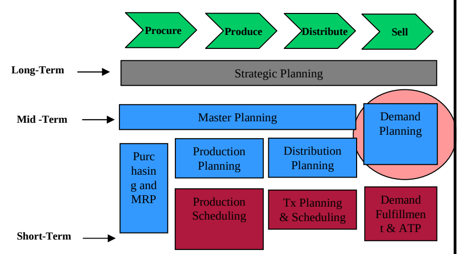
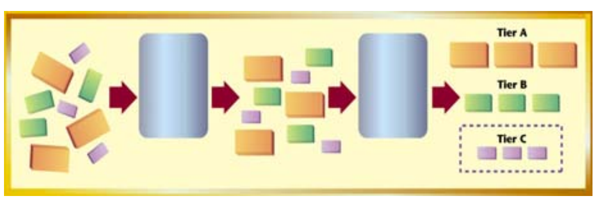
Demand Planning

- Starting point of supply chain planning
- Three stages of Demand Planning
  - Statistical Forecasting
  - Judgemental (user) inputs
  - Collaboration
- Enablers – Advanced Forecasting Techniques
  - **Moving Average**
  - →SMP(3)
  - **Exponential Smoothing**
  - →9 methods including Holt and Winters
  - **Box-Jenkins**
  - →(ARIMA)
  - **Dynamic Regression**
  - **Discrete Distributions**
  - →Poison & Negative Binomial



Demand Forecasting Process

1. Gather sales history



4. Pass onto Statistical Forecasting

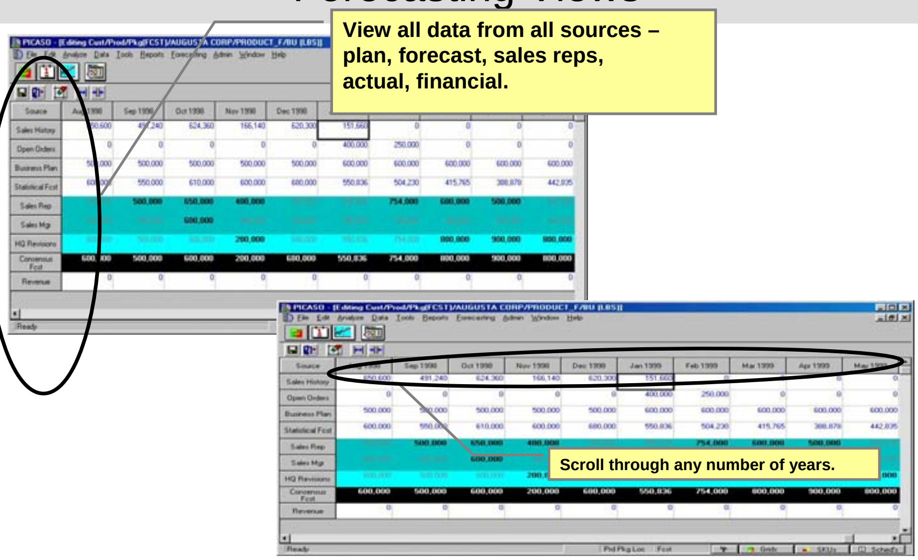
2. Clean data

- **Fix product/name changes**
- **Fix non-optimal shipment history**

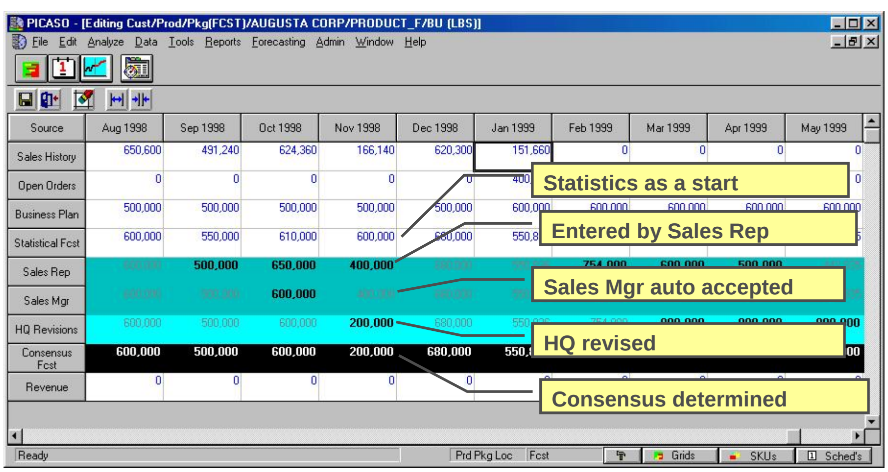
3. Prioritize customers

- **Identify ABC criteria**
- **Consolidate Tier C customers**

Forecasting Views



Collaborative Forecasting



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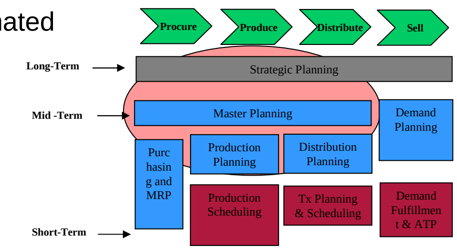
Master Planning and Optimisation – Why Now?

- Shareholders demand higher profits
- Customers/Competitors force service improvements
- M&A's yield more complex supply chains
  - More plants, distribution locations, and products
- eBusiness requires accurate, automated collaboration
- Enablers:
  - Better data (ERP, SCP)
  - Improved supply chain models
  - Improved LP solvers – ILOG/ xpress
  - Faster CPU's



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Supply Chain Optimiser

- Determines most profitable customer and product mix
- Considers customer demands and margins, production capacity, and production/distribution costs

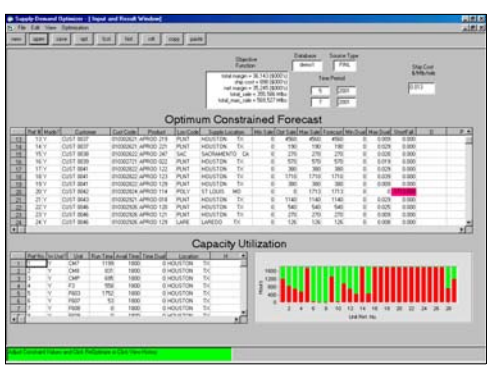
INPUTS

Customer Demand

Production Capability

Prices and Costs

Production & Distribution Costs



OUTPUTS

Optimized Sales Plan

Optimized Production Plan

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Typical Uses of SCO

- Optimize & balance the supply-demands
- Evaluate customer trade-offs
- Examine equipment capacity changes
- Identify profit opportunities

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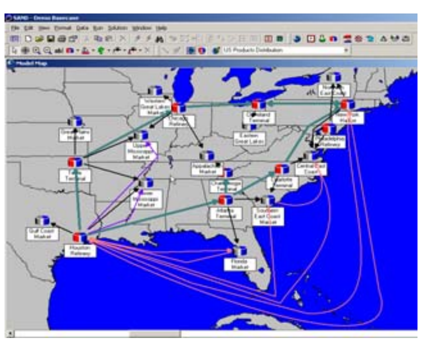
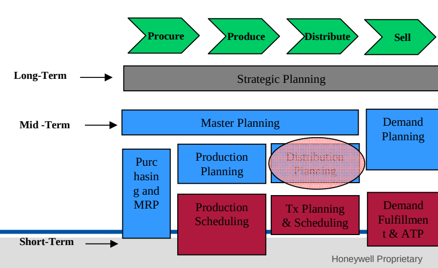
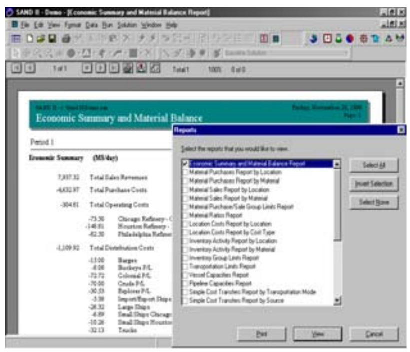
Distribution Planning - Highlights



- Use of LP and MIP for optimising the profitability (Max sales – dist. Cost)
- Multiplant, multiwarehouse problem
- construct a distribution network directly on a map
- Manipulating the Map Interface



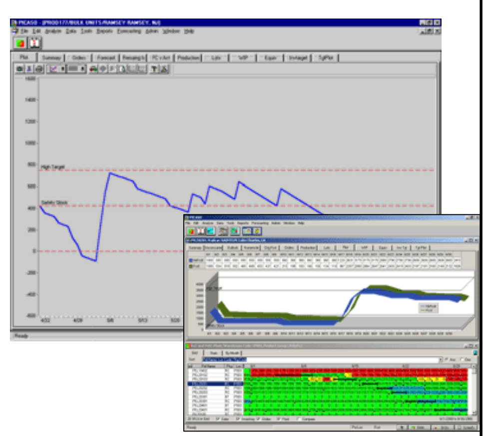
Distribution Planning



- Multi-Period Capabilities
- “what if” analysis
- Solution Reporting
- Capabilities
- Customized Reports

Distribution Replenishment Planning

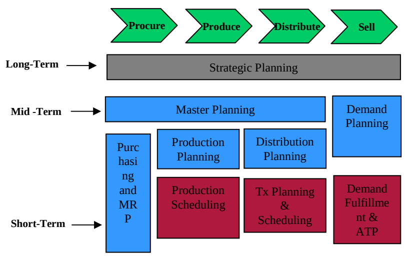
- Predicts material needs at plants, supply points and vendor managed inventory locations
- Generates replenishment schedules to meet unsatisfied material demands
- Adjusts replenishment plans as supplies and demands vary
- Considers lead times, lot sizes, production schedules, policies & constraints

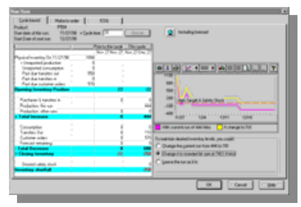


Demo

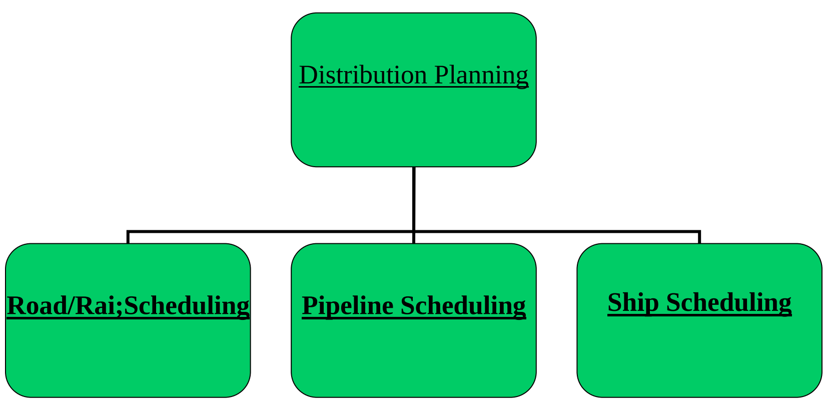
Production Scheduling

- Wide range of processes
  - Continuous, semi-continuous, batch…
  - MTO – MTS – mixed mode
- Supports decision support & what-if analysis
  - Tied to and financial model
- Includes embedded optimization algorithms
- Open architecture for unique optimization plug-ins





Distribution Planning and Scheduling



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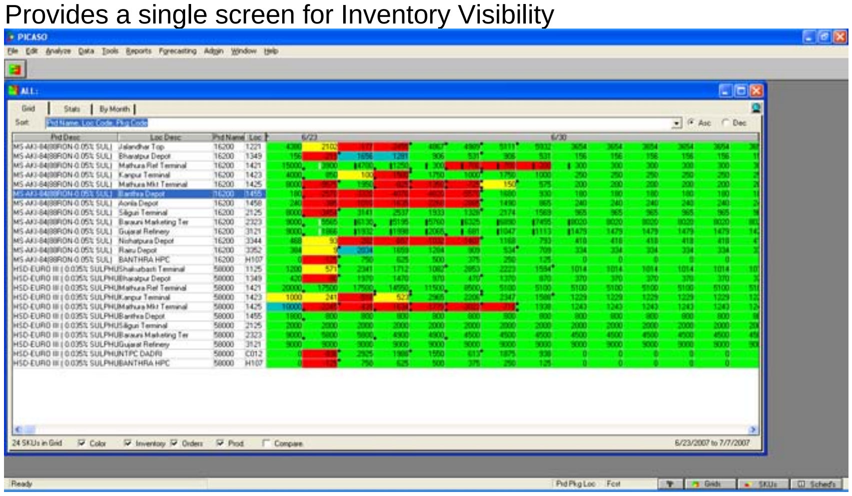
Rail Road Scheduling

Provides a single screen for Inventory Visibility



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Highlights

Complex Technical Integration
(Includes interfaces from diverse sources)

- ERP for Shipped Sales and Open Orders
- Inventory
- In-transit and Stock Transfers
- Inputs from Demand Planning Solution
- Inputs from Monthly Distribution Plan (integration with SAND)
- Inputs from customized GUIs

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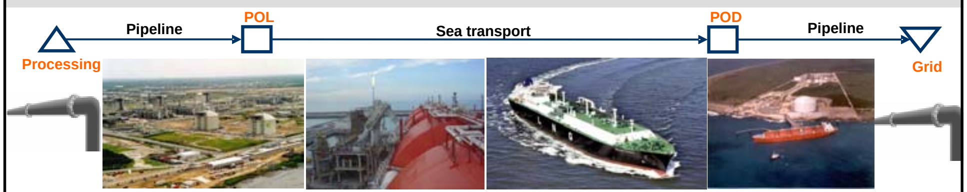
Fleet Scheduling and Management System



System for Fleet Scheduling & Optimization

- Fleet management
- LNG and other refined products
- Contract management
- Update Schedule and Annual Delivery Program (ADP)
- Replenishment
- Operational Decision Support and Re-planning of Operations

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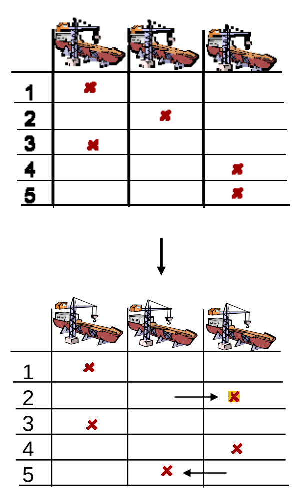
The Fleet Scheduling Problem

- Assign cargoes to ships
- Decide optimal visiting sequences for each ship
- A complex combinatorial problem
  - 3 vessels and 5 cargoes ⇒ 243 alternatives
  - 10 vessels and 20 cargoes ⇒ 100,000,000,000,000,000,000
- Constraints:
  - Capacity
  - Time windows (multiple)
  - Compatibility
  - Etc...
- Rescheduling often needed



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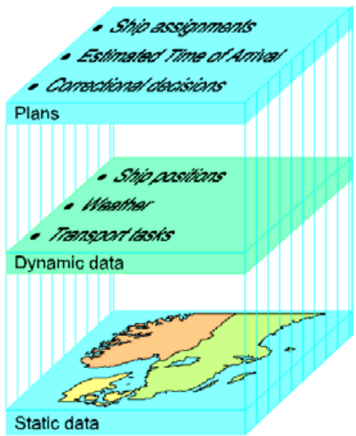
Main Components (1)



- Electronic charts
- Information of ships, cargoes, ports etc
- Automatic calculation of distances
- Graphical user interface
- Ship positions reports by satellite
- Optimization tool for fleet scheduling
- Calculation for manual planning
- Automatic update of ETA

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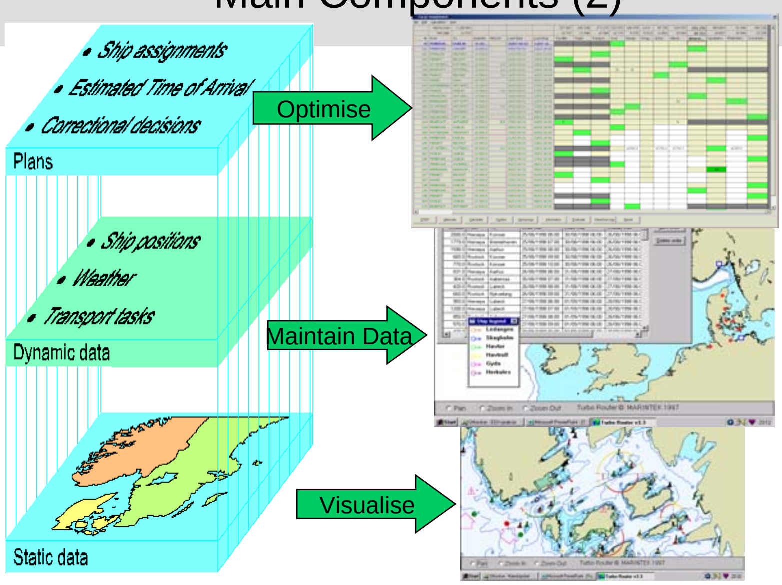
Main Components (2)



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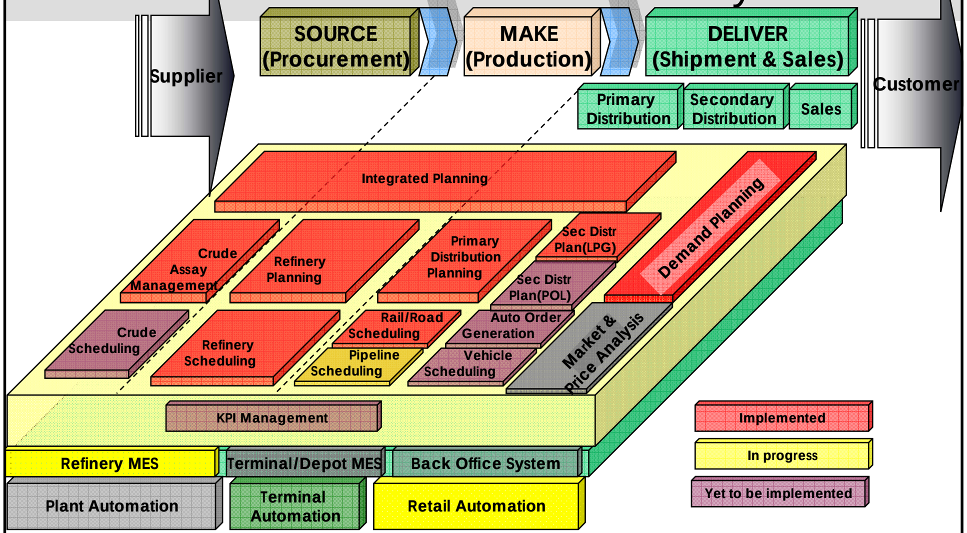
APS Solutions – Case Study



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Conclusions & Outlook

- APS Solutions deliver tangible/ intangible benefits
- Challenges remain in terms of
  - Integration among different modules
  - Change Management
- Technologies such as RFID, SOA would be helpful in APS going forward

Mathematical Programming for Scheduling of Process Operations

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Basic Definitions & Applications

Scheduling: Efficient management of resources over a set of units to perform a group of activities in an optimal fashion

Planning: What? Where? How much?

Scheduling: How?

Applications:

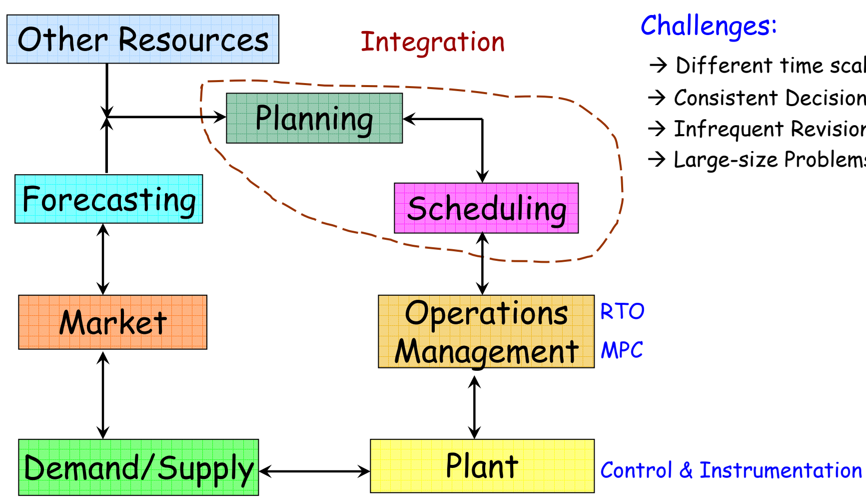
- Operations Research Community:
  - Flowshops & Jobshops
  - Scheduling of Personnel, Vehicles etc.
- Chemical Engineering:
  - Batch plants: Food, Pharmaceuticals, Paper products & Specialty Chemicals
  - Continuous/Semi-continuous: Petrochemical & Refinery operations

People & Places

Chemical engineers have made significant contributions in Operations Scheduling in the past two decades

- ♣ Shah, Pantelides et al → Imperial College, London
- ♣ Grossmann et al → CMU
- ♣ Floudas et al → Princeton Univ.
- ♣ Karimi et al → NUS
- ♣ Reklaitis, Pekny et al → Purdue
- ♣ Pinto et al → RPI
- ♣ Ierapetritou et al → Rutgers Univ.

Supply Chain of an Enterprise



Challenges:

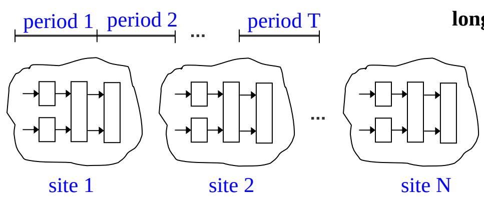
→ Different time scales
→ Consistent Decisions
→ Infrequent Revision
→ Large-size Problems

Vertical Integration in an Enterprise is Desirable

Planning and Scheduling

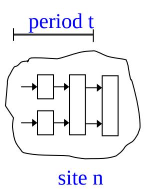
Multi-site Production Planning:

Time Horizon is longer



Medium-term & Short-term Scheduling:

Relatively Short Time Horizons



Typical Time Horizons:

Planning → 3 months to 1 year
Medium-term → week or month
Short-term → hour or day

Problem Statement

Given:

- Set of products along with their demands and due dates
- Set of manufacturing locations
- Process flow sheet at each plant
- Equipment and storage capacities
- Batch processing time for each product in all stages
- Transition times (sequence dependent)
- Production, transportation, inventory or earliness, and tardiness costs

For Planning determine:

- Order allocation across plants
- Amounts of products to be produced
- Length of short-term horizon

For Scheduling determine:

- Optimal sequencing at each plant
- Start and finish times of different tasks on each unit
- Optimal inventory levels
- Optimal dispatch schedule

Classification of Scheduling Problems

- Batch Plants
- Continuous/Semi-continuous
- Mixed production lines

- Serial units
- Parallel lines
- Hybrid flowshops

- Medium-term Scheduling
- Short-term scheduling
- Cyclic scheduling
- Robust scheduling
- Reactive scheduling

- Discrete time
- Continuous-time formulation
  - Slot-based
  - Global-event based
  - Unit-specific-event based
  - Precedence based

Classification of Scheduling Problems

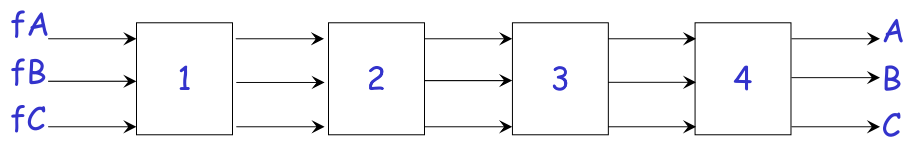
- Max Profit
- Min Make Span
- Min Tardiness/Earliness

- Multi-product plants (job shops)
- Multi-purpose plants (flow shops)

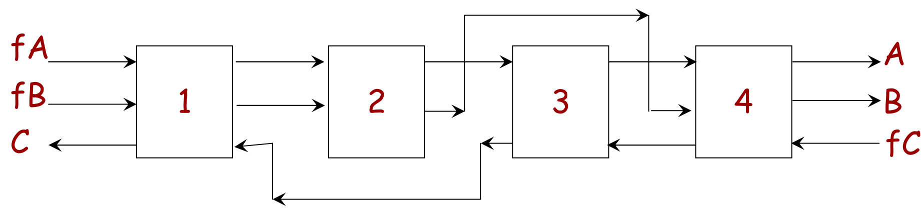
- Without Resources
- With Resources (Utilities)

- Unlimited Storage
- No Storage / Zero-wait
- Finite-Intermediate Storage
  - Dedicated Storage
  - Flexible Storage

Classification of Scheduling Problems



Multi-product plants (flow shop)

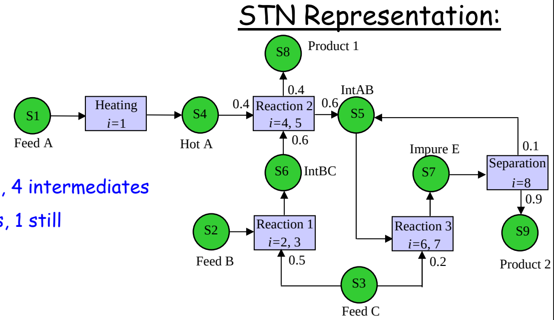


Multi-purpose plants (job shop)

Process Representation

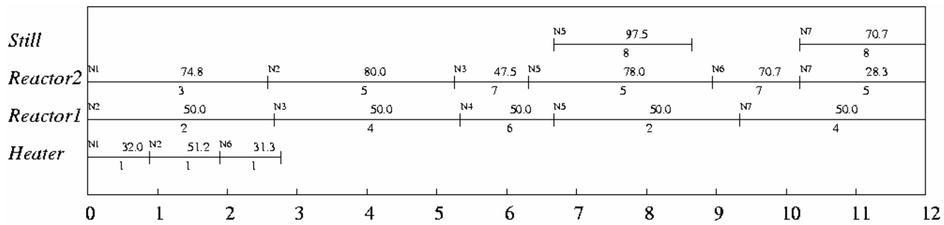
- State-Task Network (STN)
- Resource-Task Network (RTN)
- Recipe diagrams

STN Representation:



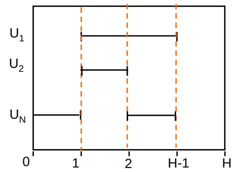
- 2 products, 3 feeds, 4 intermediates
- 1 heater, 2 reactors, 1 still
- 9 states, 8 tasks

Gantt Chart Schedule:



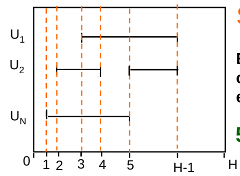
Different Time Representations

- Discrete Time Representation



Time intervals of equal length common to all units

- Continuous Time Representation I



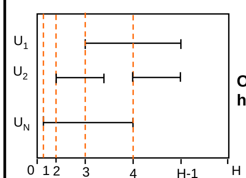
Slot based

Both start and end times of tasks have to be at an event

5 slots or 6 events

Time intervals of unequal and unknown length common to all units

- Continuous Time Representation II



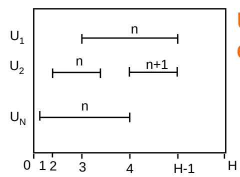
Global event based

Only the start times of tasks have to be at an event

4 events

Events common to all units

- Continuous Time Representation III



Unit Specific event based

Only 2 events

Events different for each unit

Scheduling Characteristics

Performance criteria
- Profit maximization
- Make-span minimization
- Mean-flow time minimization
- Average tardiness minimization

Transfer policies
- UIS (Unlimited Intermediate Storage)
- NIS (No Intermediate Storage)
- FIS (Finite Intermediate Storage)
- ZW (Zero-Wait Policy)
- MIS (Mixed Intermediate Storage)

Mathematical Model

Max Profit or Min Makespan

s.t. Allocation constraints
Material balance constraints
Capacity constraints
Storage constraints
Duration constraints
Sequence constraints
Demand constraints
Due date constraint
Time horizon constraints

⇓

Mixed-Integer Linear/Nonlinear Optimization Problem

Solution of the Scheduling Model

- Broadly Two approaches for solution:
  - → Deterministic Methods
  - → Stochastic Methods

Commercial Software:

Modeling Languages

- ♣ GAMS
- ♣ ILOG OPL Studio
- ♣ MOSEL from XPRESSMP
- ♣ AMPL, LINGO etc.

Solvers

- ♣ LP/MILP → CPLEX
- ♣ MINLP → SBB, DICOPT, BARON
- ♣ NLP → SNOPT, MINOS, CONOPT
- ♣ DAEs → MINOPT

Short-Term Scheduling: Batch Plants

Shaik & Floudas (2008)

RTN representation has not been explored in literature for unit-specific event-based models

– Unit-Specific Event-based Continuous-time formulation for Short-Term Scheduling of Batch Plants without Resources (such as utilities)

–The work is extension of STN model of Ierapetritou & Floudas (1998)

– Improved Sequencing Constraints (for handling sequence-dependent changeovers)

– Alternate approach for handling dedicated finite-intermediate storage without the need for considering storage as a separate task

– Additional tightening constraint

– Limitation: Does not allow tasks to take place over multiple events

Short-Term Scheduling Model

Nomenclature

Sets

I	tasks
I_r	tasks related to resource *r*
R	resources
R^J	equipment resources
R^S	material resources
R^{FIS}	material resources with finite dedicated storage
N	event points within the time horizon

Parameters

H	scheduling horizon
P_r	price of resource *r*
D_r	demand for resource *r*
τ_r	sequence independent clean up time
$\tau_{ii'}$	sequence-dependent clean up time required between tasks *i* and *i'*
E_r^{min}	lower bound on the availability of resource *r*
E_r^{max}	upper bound on the availability of resource *r*
μ_{ri}^p , μ_{ri}^c	proportion of equipment resource produced, consumed in task *i*, $\mu_{ri}^p \geq 0$, $\mu_{ri}^c \leq 0$
ρ_{ri}^p , ρ_{ri}^c	proportion of material resource produced, consumed in task *i*, $\rho_{ri}^p \geq 0$, $\rho_{ri}^c \leq 0$

Short-Term Scheduling Model

Nomenclature

Binary variables

w(i,n) Assign the beginning of task *i* at event *n*

Positive variables

b(i,n) Amount of material processed by task *i* in event *n*

$E_0(r)$ initial amount of resource *r* available or required from external sources

$E(r,n)$ excess amount of resource *r* available at event *n*

$T^s(i,n)$ time at which task *i* starts at event *n*

Capacity Constraints

$$w(i,n)B_i^{\min} \le b(i,n) \le w(i,n)B_i^{\max} \qquad \forall i \in I, n \in N \qquad (1)$$

$$E_r^{\min} \le E(r,n) \le E_r^{\max} \qquad \forall r \in R, n \in N \qquad (2)$$

Short-Term Scheduling Model

Excess Resource Balances

The amount of a resource *r* produced or consumed by task *i* is represented as: $\mu_{ri} w(i,n) + \rho_{ri} b(i,n)$

$$E(r,n) = E(r,n-1) + \sum_{i \in I_r} \left(\mu_{ri}^p w(i,n-1) + \rho_{ri}^p b(i,n-1) \right) + \sum_{i \in I_r} \left(\mu_{ri}^c w(i,n) + \rho_{ri}^c b(i,n) \right)$$

$$\forall r \in R, n \in N, n > 1 \qquad (3a)$$

$$E(r,n) = E_0(r) + \sum_{i \in I_r} \left(\mu_{ri}^c w(i,n) + \rho_{ri}^c b(i,n) \right) \qquad \forall r \in R, n \in N, n = 1 \qquad (3b)$$

The excess resource balances are more generic compared to their counterpart (material balances) in STN based models

Analysis for Equipment Resources: (keeps track of the status of a unit)

$$E(r,n) = E(r,n-1) + \sum_{i \in I_r} \mu_{ri}^p w(i,n-1) + \sum_{i \in I_r} \mu_{ri}^c w(i,n) \qquad \forall r \in R^J, n \in N, n > 1$$

$$E(r,n) = E_0(r) + \sum_{i \in I_r} \mu_{ri}^c w(i,n) \qquad \forall r \in R^J, n \in N, n = 1$$

A separate task is assumed for each task suitable in multiple equipment resources

Implicitly represents the allocation constraint (No need to write separately)

Analysis for Material Resources: (Reduces to the material balances in STN)

Short-Term Scheduling Model

Sequencing Constraints

(i) Same task in the same unit

$$T^s(i,n+1) \ge T^s(i,n) + \alpha_i w(i,n) + \beta_i b(i,n) \qquad \forall i \in I, n \in N, n < N \qquad (4)$$

(ii) Different tasks in the same unit:

(a) No changeovers or cleanup times:

$$T^s(i,n+1) \ge T^s(i',n) + \alpha_{i'} w(i',n) + \beta_{i'} b(i',n) \qquad \forall r \in R^J, i \in I_r, i' \in I_r, n \in N, n < N \qquad (5a)$$

(b) Sequence-independent cleanup times:

$$T^s(i,n+1) \ge T^s(i',n) + \alpha_{i'} w(i',n) + \beta_{i'} b(i',n) + \tau_r w(i',n) \quad \forall r \in R^J, i \in I_r, i' \in I_r, i \ne i', n \in N, n < N \qquad (5b)$$

(c) Sequence-dependent changeovers:

$$T^s(i,n) \ge T^s(i',n') + \alpha_{i'} w(i',n') + \beta_{i'} b(i',n') + \tau_{i'i} w(i,n) - H(1 - w(i',n')) - H \sum_{i'' \in I_r} \sum_{n' < n'' < n} w(i'',n'')$$

$$\forall r \in R^J, i \in I_r, i' \in I_r, i \ne i', n \in N, n' \in N, n > n' \qquad (5c)$$

Short-Term Scheduling Model

Sequencing Constraints

(iii) Different tasks in different units:

$$T^s(i,n+1) \ge T^s(i',n) + \alpha_{i'} w(i',n) + \beta_{i'} b(i',n) - H(1 - w(i',n))$$

$$\forall r \in R^S, i' \in I_r, i \in I_r, i \ne i', \rho^p_{ri'} > 0, \rho^c_{ri} < 0, n \in N, n < N \qquad (6)$$

Time Bounding Constraints

$$T^s(i,n) \le H \qquad \forall i \in I, n \in N \qquad (7a)$$

$$T^s(i,N) + \alpha_i w(i,N) + \beta_i b(i,N) \le H \qquad \forall i \in I \qquad (7b)$$

Tightening Constraint

$$\sum_{n \in N} \sum_{i \in I_r} (\alpha_i w(i,n) + \beta_i b(i,n)) \le H \qquad \forall r \in R^J \qquad (8)$$

The tightening constraint provides a better LP relaxation

Objective Function

Maximization of Profit

$$\text{Max Profit } = \sum_{r\in R^S} P_r \left(E(r,N) + \sum_{i\in I_r} \left(\mu_{ri}^p w(i,N) + \rho_{ri}^p b(i,N) \right) \right) \qquad (9)$$

Minimization of MakeSpan (MS)

Demand Constraints

$$E(r,N) + \sum_{i\in I_r} \left(\mu_{ri}^p w(i,N) + \rho_{ri}^p b(i,N) \right) \geq D_r \qquad \forall r \in R^S \qquad (10)$$

Time Bounding Constraints

$$T^s(i,N) + \alpha_i w(i,N) + \beta_i b(i,N) \leq MS \qquad \forall i \in I \qquad (11)$$

Modified Tightening Constraint

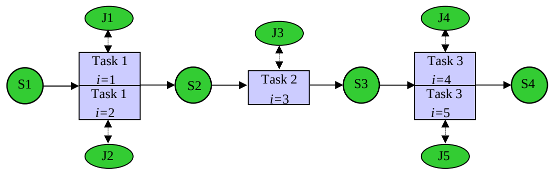
$$\sum_{n\in N} \sum_{i\in I_r} (\alpha_i w(i,n) + \beta_i b(i,n)) \leq MS \qquad \forall r \in R^J \qquad (12)$$

This is the model for Unlimited Intermediate storage (UIS)

Benchmark Examples

Example 1

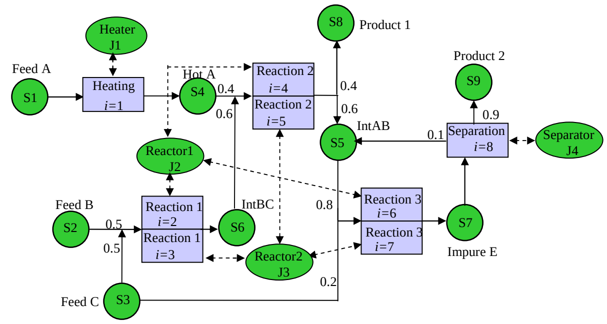
Sundaramoorthy & Karimi (2005), and Shaik, Janak, Floudas (2006)



- Problem involves 5 units, 3 processing tasks, and 4 states (1 feed, 2 int, 1 product)
- Variable batch sizes and processing times
- Finite intermediate storage (FIS) for intermediates S2 and S3
- Consider two objective functions:
  - Maximization of Profit for 3 cases of different time horizons:
    - Case 1a: H=8 hr
    - Case 1b: H=12 hr
    - Case 1c: H=16 hr
  - Minimization of Makespan for 2 cases of different demands:
    - Case 1a: D_4 =2000 mu
    - Case 1b: D_4 =4000 mu

Benchmark Examples

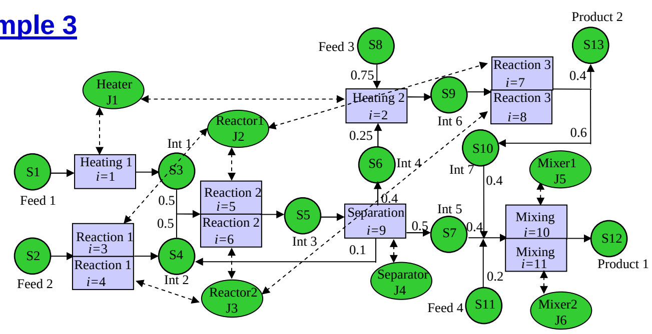
Example 2



- Problem involves 4 units, 8 processing tasks, 9 states (3 feed, 4 int, 2 product)
- Variable batch sizes and processing times
- Finite intermediate storage (FIS) for intermediates S4,S5,S6 and S7
- Consider two objective functions:
  - Maximization of Profit for 3 cases of different time horizons:
    - Case 2a: H=8 hr
    - Case 2b: H=12 hr
  - Minimization of Makespan for the following demands:
    - D_8 =200 mu
    - D_9 =200 mu

Benchmark Examples

Example 3



- Problem involves 6 units, 11 processing tasks, 13 states (4 feed, 7 int, 2 product)
- Variable batch sizes and processing times
- Finite intermediate storage (FIS) for all intermediates S3 –S7, S9 and S10
- Consider two objective functions:
  - Maximization of Profit for 2 cases of different time horizons:
    - Case 3a: H=8 hr
    - Case 3b: H=12 hr
  - Minimization of Makespan for 2 cases of different demands:
    - Case 3a: D_{12} =100 mu, D_{13} =200 mu
    - Case 3b: D_{12} = D_{13} =250 mu

Benchmark Examples

Data of coefficients of processing times of tasks, limits on batch sizes of units

	Task i		Unit j	α_{ij}	β_{ij}	B_{ij}^{min} (mu)	B_{ij}^{max} (mu)
Example 1	Task1	(*i*=1)	Unit1	1.333	0.01333	---	100
		(*i*=2)	Unit2	1.333	0.01333	---	150
	Task2	(*i*=3)	Unit3	1.000	0.00500	---	200
	Task3	(*i*=4)	Unit4	0.667	0.00445	---	150
		(*i*=5)	Unit5	0.667	0.00445	---	150
Example 2	Heating	(*i*=1)	Heater	0.667	0.00667	---	100
	Reaction1	(i=2)	Reactor1	1.334	0.02664	---	50
		(i=3)	Reactor2	1.334	0.01665	---	80
	Reaction2	(i=4)	Reactor1	1.334	0.02664	---	50
		(i=5)	Reactor2	1.334	0.01665	---	80
	Reaction3	(i=6)	Reactor1	0.667	0.01332	---	50
		(i=7)	Reactor2	0.667	0.008325	---	80
	Separation	(*i*=8)	Separator	1.3342	0.00666	---	200
Example 3	Heating1	(*i*=1)	Heater	0.667	0.00667	---	100
	Heating2	(*i*=2)	Heater	1.000	0.01000	---	100
	Reaction1	(i=3)	Reactor1	1.333	0.01333	---	100
		(i=4)	Reactor2	1.333	0.00889	---	150
	Reaction2	(i=5)	Reactor1	0.667	0.00667	---	100
		(i=6)	Reactor2	0.667	0.00445	---	150
	Reaction3	(i=7)	Reactor1	1.333	0.01330	---	100
		(i=8)	Reactor2	1.333	0.00889	---	150
	Separation	(*i*=9)	Separator	2.000	0.00667	---	300
	Mixing	(*i*=10)	Mixer1	1.333	0.00667	20	200
		(i=11)	Mixer2	1.333	0.00667	20	200

Sundaramoorthy & Karimi (2005), and Shaik, Janak, Floudas (2006)

Benchmark Examples

Data of storage capacities, initial stock levels and prices of various resources

	Example 1			Example 2			Example 3		
Resource	Storage capacity (mu)	Initial stock (mu)	Price ($/mu)	Storage capacity (mu)	Initial stock (mu)	Price ($/mu)	Storage capacity (mu)	Initial stock (mu)	Price ($/mu)
S1	UL	AA	0	UL	AA	0	UL	AA	0
S2	200	0	0	UL	AA	0	UL	AA	0
S3	250	0	0	UL	AA	0	100	0	0
S4	UL	0	5	100	0	0	100	0	0
S5	--	--	--	200	0	0	300	0	0
S6	--	--	--	150	0	0	150	50	0
S7	--	--	--	200	0	0	150	50	0
S8	--	--	--	UL	0	10	UL	AA	0
S9	--	--	--	UL	0	10	150	0	0
S10	--	--	--	--	--	--	150	0	0
S11	--	--	--	--	--	--	UL	AA	0
S12	--	--	--	--	--	--	UL	0	5
S13	--	--	--	--	--	--	UL	0	5

UL – Unlimited storage capacity
AA – Available as and when required

Sundaramoorthy & Karimi (2005), and Shaik, Janak, Floudas (2006)

Other models used in Comparative Study

Comparison based on our own implementation & same software and hardware

Reference	Abbreviation used
STN:	
Ierapetritou, M. G.; Floudas, C. A. Effective continuous-time formulation for short-term scheduling: 1. Multipurpose batch processes. *Ind. Eng. Chem. Res.* **1998**, *37*, 4341. **UIS**	**I&F**
Lin, X.; Floudas, C. A. Design, synthesis and scheduling of multipurpose batch plants via an effective continuous-time formulation. *Comput. Chem. Eng.* **2001**, *25*, 665. **FIS**	**L&F**
RTN:	
Castro, P. M.; Barbosa-Povoa, A. P.; Matos, H. A.; Novais, A. Q. Simple continuous-time formulation for short-term scheduling of batch and continuous processes. *Ind. Eng. Chem. Res.* **2004**, *43*, 105.	**CBMN**
Shaik, M. A.; Floudas, C. A. Unit-specific event-based continuous-time approach for short-term scheduling of batch plants using RTN framework. *Comput. Chem. Eng.* **2008**, *32*, 260.	**S&F**
Recipe Diagrams:	
Sundaramoorthy, A.; Karimi, I. A. A simpler better slot-based continuous-time formulation for short-term scheduling in multipurpose batch plants. *Chem. Eng. Sci.* **2005**, *60*, 2679.	**S&K**

Computational Results (UIS)

Example 1 — Maximization of Profit

Model	Events	CPU time (s)	Nodes	RMILP ($)	MILP ($)	Binary variables	Continuous variables	Constraints	Nonzeros
Example 1a (H=8)									
S&K	5	0.05	13	2000.0	1840.2	40	215	192	642
CBMN(Δt=1)	5	0.01	0	2000.0	1840.2	20	70	86	274
(Δt=2)	5	0.02	7	2000.0	1840.2	35	85	116	414
I&F	4	0.01	1	2000.0	1840.2	10	48	69	176
S&F	4	0.01	1	2000.0	1840.2	10	68	84	239
Example 1b (H=12)									
S&K	9	26.83	27176	4481.0	3463.6	80	415	408	1358
CBMN(Δt=1)	9	0.23	606	4419.9	3301.6[a]	40	130	162	546
(Δt=2)	9	10.32	21874	5237.6	3463.6	75	165	232	886
I&F	6	0.03	24	4000.0	3463.6	20	76	115	314
	7	0.19	589	4857.6	3463.6	25	90	138	383
S&F	6	0.02	28	4000.0	3463.6	20	106	130	427
	7	0.23	720	4701.8	3463.6	25	125	153	521
Example 1c (H=16)									
S&K	12	5328.22	3408476	6312.6	5038.1	110	565	570	1895
	13	>67000[b]	36297619	6381.9	5038.1	120	615	624	2074
CBMN(Δt=2)	12	1086.08	1642027	7737.6	5000.0[a]	105	225	319	1240
(Δt=3)	12	3911.14	4087336	7737.6	5038.1	150	270	409	1680
(Δt=3)	13	40466.83	44252075	8237.6	5038.1	165	295	448	1848
I&F	9	1.76	6596	6601.5	5038.1	35	118	184	521
	10	20.60	89748	6601.5	5038.1	40	132	207	590
S&F	9	1.46	5487	6600.9	5038.1	35	163	199	709
	10	21.76	91080	6601.7	5038.1	40	182	222	803

[a] Suboptimal solution. Relative Gap: 1.24 %[b]

Computational Results (UIS)

Example 2

Maximization of Profit

Model	Events	CPU time (s)	Nodes	RMILP ($)	MILP ($)	Binary variables	Continuous variables	Constraints	Nonzeros
Example 2a (H=8)									
S&K	5	0.07	4	1730.9	1498.6	48	235	249	859
CBMN(Δt=1)	5	0.01	4	1730.9	1498.6	32	104	114	439
I&F	4	0.03	13	1812.1	1498.6	18	90	165	485
	5	0.28	883	2305.3	1498.6	26	115	216	672
S&F	4	0.03	10	1730.9	1498.6	18	106	173	564
	5	0.23	681	2123.3	1498.6	26	135	224	783
Example 2b (H=10)									
S&K	8	105.5	88679	2690.6	1962.7	84	433	456	1615
CBMN(Δt=1)	8	1.82	6449	2690.6	1860.7[a]	56	170	189	760
(Δt=2)	8	81.95	194968	3136.3	1959[a]	104	218	261	1238
(Δt=3)	8	207.43	366226	3136.3	1962.7	144	258	321	1635
I&F	6	2.16	6713	3078.4	1943.2[a]	34	140	267	859
	7	43.73	101415	3551.8	1943.2[a]	42	165	318	1046
S&F	6	1.79	5180	2730.7	1943.2[a]	34	164	275	1002
	7	36.28	89069	2780.2	1943.2[a]	42	193	326	1221
Example 2c (H=12)									
S&K	9	561.58	288574	3265.2	2646.8	96	499	525	1867
	10	10889.61	3438353	3315.8	2646.8	108	565	594	2119
	11	>67000[b]	17270000	3343.4	2646.8[a]	120	631	663	2371
CBMN(Δt=2)	9	331.72	593182	3730.5	2646.8	120	248	298	1426
	10	4366.09	6018234	4070.0	2646.8	136	278	335	1614
	11	>67000[c]	80602289	4409.5	2646.8[a]	152	308	372	1802
I&F	7	6.19	14962	3788.3	2658.5	42	165	318	1046
	8	105.64	211617	4297.9	2658.5	50	190	369	1233
S&F	7	5.29	12006	3301.0	2658.5	42	193	326	1221
	8	85.67	167306	3350.5	2658.5	50	222	377	1440

[a] Suboptimal solution; Relative Gap: 1.59 %[b], 2.58%[c]

Limitation: Does not allow tasks to occur over multiple events (motivation for the Unified Model)

Computational Results (UIS)

Example 3

Maximization of Profit

Model	Events	CPU time (s)	Nodes	RMILP ($)	MILP ($)	Binary variables	Continuous variables	Constraints	Nonzeros
Example 3a (H=8)									
S&K	7	184.46	145888	2513.8	1583.4	102	597	584	2061
CBMN(Δt=2)	7	6.90	10361	2606.5	1583.4	121	264	343	1495
I&F	5	0.38	1176	2100.0	1583.4	30	155	303	875
	6	25.92	57346	2847.8	1583.4	41	190	377	1139
S&F	5	0.40	1074	2100.0	1583.4	30	185	317	1015
	6	23.25	50566	2751	1583.4	41	226	391	1324
Example 3b (H=12)									
S&K	9	372.92	94640	3867.3	3041.3	136	783	792	2789
CBMN(Δt=2)	9	107.97	47798	3864.3	3041.3	165	348	457	2031
I&F	7	18.33	15871	3465.6	3041.3	52	225	451	1403
S&F	7	0.73	579	3465.6	3041.3	52	267	465	1633

[a] Suboptimal solution

Scheduling of Refinery Operations

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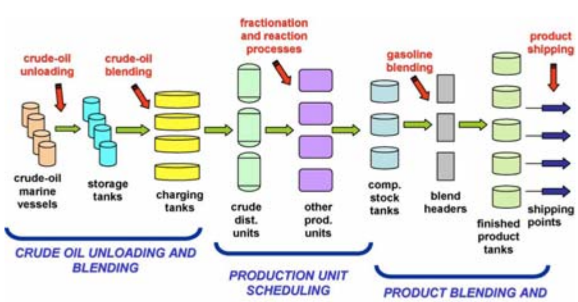
A Typical Oil Refinery

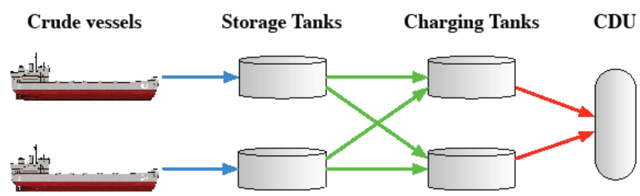
- Crude-oil refining into useful petroleum products:
  - LPG, gasoline, diesel fuel, kerosene, heating oil, …
- 3 parts:
  - Crude-oil unloading and blending
  - Fractionation and reaction processes
  - Product blending and shipping



(Mendez et al., 2006)

Crude-oil scheduling problem (Lee et al., 1996)

- Scheduling horizon [0,*H*]
- 4 types of resources:
  - Crude-oil marine vessels
  - Storage tanks
  - Charging tanks
  - Crude Distillation Units (CDUs)
- 3 types of operations:
  - Unloading: Vessel unloading to storage tanks
  - Transfer: Transfer from storage tanks to charging tanks
  - Distillation: Distillation of charging tanks



(Mendez et al., 2006)

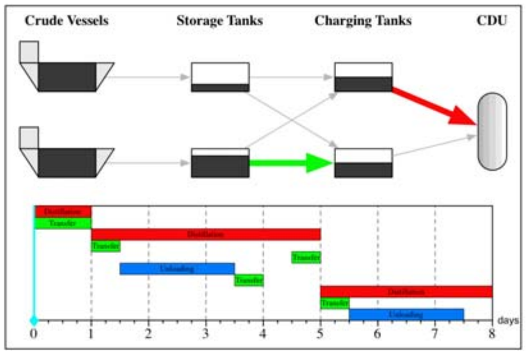
Crude-oil Scheduling problem

- Given
  - Refinery configuration
  - Logistics constraints
  - Initial tanks inventory and composition
  - Vessels arrival time, inventory level and composition
  - Distillation specifications and demands (planning decisions)
- Determine
  - Required operations
  - Timing decisions
  - Transfer volumes
- Minimize
  - Cost of distilled crude-oil mixtures

(Mendez et al., 2006)

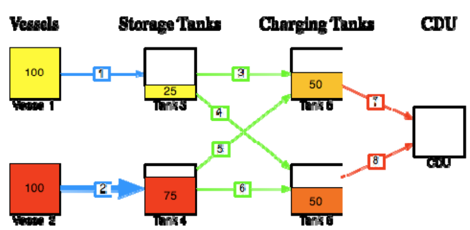
Crude-oil Scheduling problem: Example

- Common logistics constraints:
  - Only one docking station available for vessel unloadings
  - No simultaneous inlet and outlet operations on tanks
  - Crude distillation units can only be charged by one tank
  - Continuous distillation

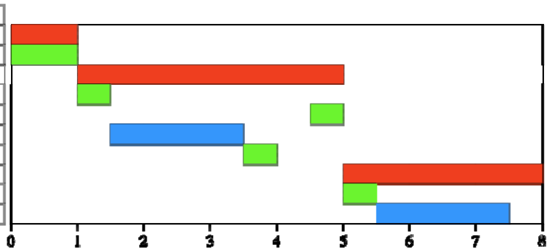


(Mendez et al., 2006)

Crude-oil Scheduling problem: Example



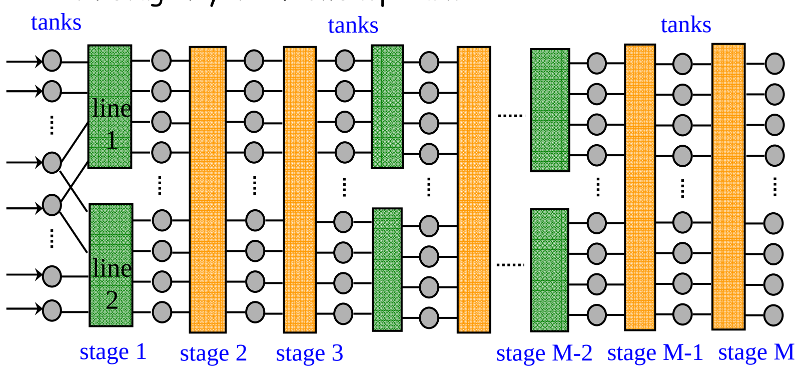
Task	Operation	Volume
1	Distillation 7	5
2	Transfer 6	50
3	Distillation 8	100
4	Transfer 3	25
5	Transfer 5	19,5
6	Unloading 1	100
7	Transfer 3	5,5
8	Distillation 7	95
9	Transfer 6	5,5
10	Unloading 2	100



(Mendez et al., 2006)

Hybrid Flowshop Facility*

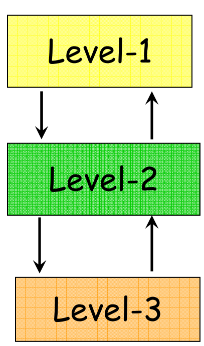
Consider Integration of Planning and Scheduling for an M-stage Hybrid Flowshop Plant



Multi-level Decomposition of the Overall Problem of Integration of Planning and Scheduling

* Munawar et al., Ind. Eng. Che. Res., 2003, 2005

Proposed Multi-level Structure for Lube-oil scheduling



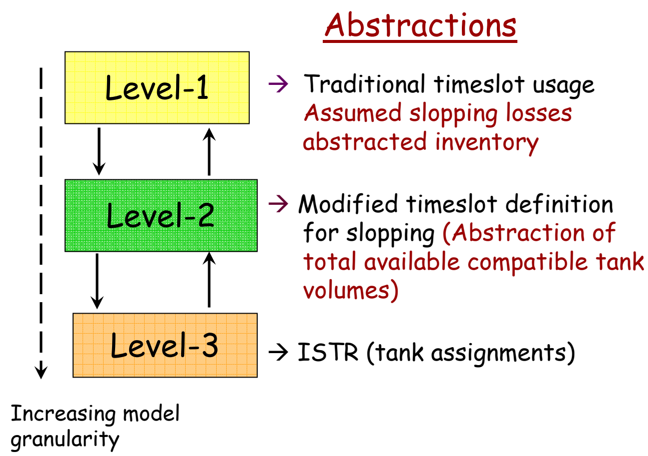
→ Planning over a multi-period horizon: Order Redistribution

→ Detailed scheduling in each period: Meeting Production Targets

→ Operator level inventory scheduling : ISTR (Individual Tank Assignments)

Embedding proactive/contingency measures

Multi-level Structure for Lube-oil scheduling

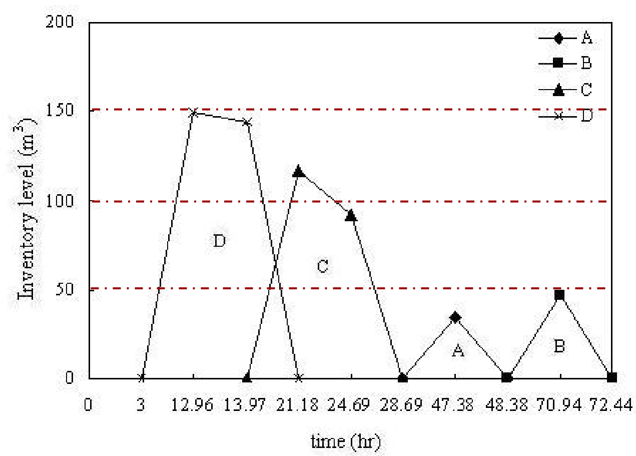


Level-2: Extensions to Large problems

Performance indices	4P3S	5P3S	6P3S	8P3S	10P3S
Discrete variables	48	66	98	154	252
Continuous variables	476	717	1112	1848	3436
No. of equations	606	855	1231	1621	2609
CPU time (sec)	13.2	19.4	68.3	372.3	648.1
Non linear N-Z	1135	1609	2388	3667	6251

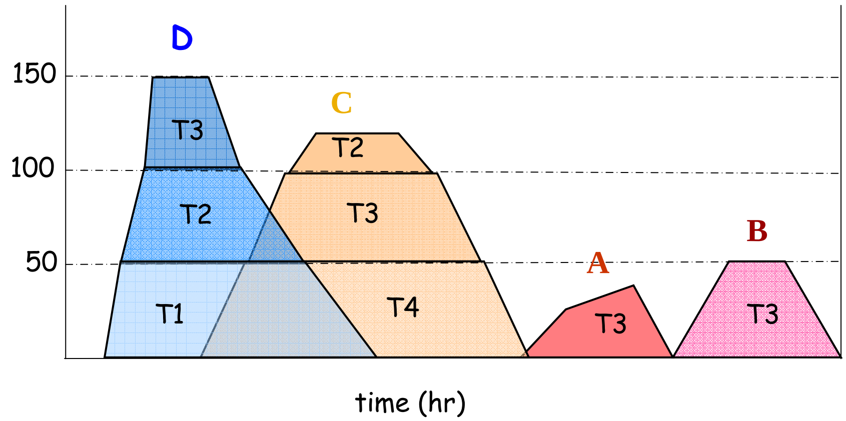
Level-3: Tank assignments

Suppose: Tanks each 50 m^3 capacity

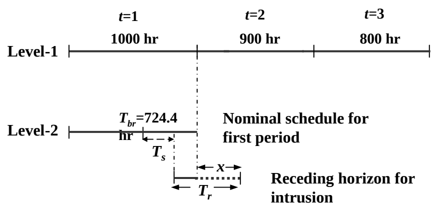


Level-3: ISTR algorithm

- Sub-profile generation
- Non-overlapping zones
- Reuse of tanks



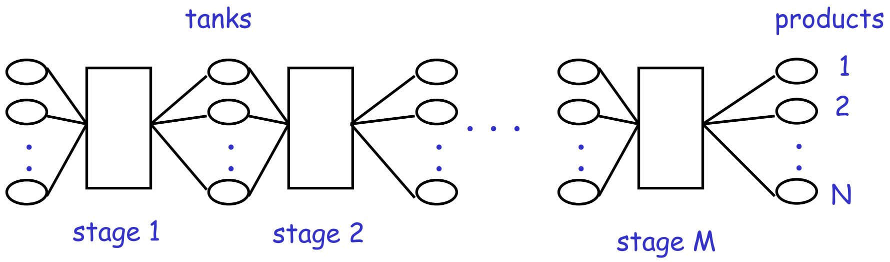
Reactive scheduling between first two levels



T_s (hr)	x (hr)	ε (m^3)
0	0	0
1	8.678	0
10	87.8	0
25	222.13	0
50	447.59	0
75	673.89	0
90	809.88	0
99	891.52	0
99.9	899.66	0
100	900	0.795
101	900	12.98

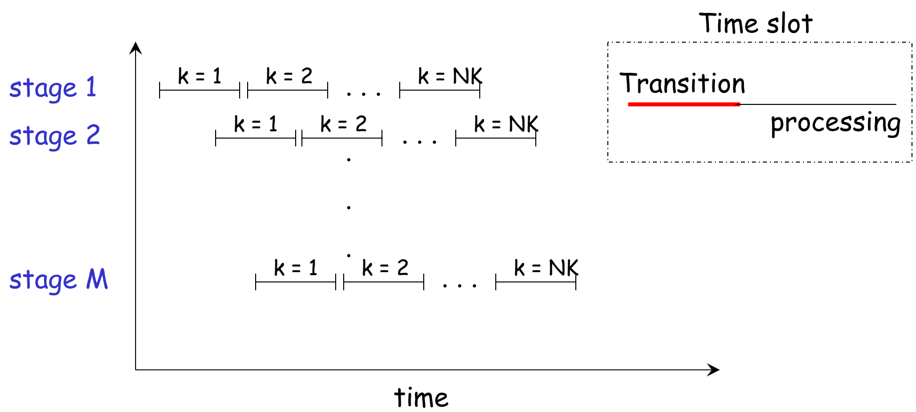
Local disturbances are attenuated locally

Cyclic Scheduling Problem



Multistage Multiproduct Continuous Plant
(Pinto & Grossmann, 1994)

Mathematical Formulation



Time slot representation

MINLP model for Cyclic Scheduling

Maximize

Profit = $$\sum_i p_i \frac{Wp_{Mi}}{T_c} - \sum_i \sum_m Cinv_{im} \frac{\mathrm{Im}_{im}}{T_c} - \sum_i \sum_j \sum_k \sum_m Ctr_{ij} \frac{Z_{ijkm}}{T_c}$$

$$-\frac{1}{2} \sum_i \sum_k Cinvf_i \ \alpha_{iM} Rp_{iM} \left(1 - \frac{Tpp_{ikM}}{T_c}\right) Tpp_{ikM} \qquad (1)$$

subject to

$$\sum_k y_{ikm} = 1 \qquad \forall\, \mathbf{i} \quad \forall\, \mathbf{m} \qquad (2a)$$

$$\sum_i y_{ikm} = 1 \qquad \forall\, \mathbf{k} \quad \forall\, \mathbf{m} \qquad (2b)$$

$$\sum_j z_{ijkm} = y_{ikm} \qquad \forall\, \mathbf{j} \quad \forall\, \mathbf{k} \quad \forall\, \mathbf{m} \qquad (3a)$$

$$\sum_i z_{ijkm} = y_{jk--1m} \qquad \forall\, \mathbf{i} \quad \forall\, \mathbf{k} \quad \forall\, \mathbf{m} \qquad (3b)$$

MINLP model for Cyclic Scheduling

$$Tsp_{ikm} - U^{T}_{im}\, y_{ikm} \le 0 \qquad \forall \mathbf{i} \quad \forall \mathbf{k} \quad \forall \mathbf{m} \qquad (4a)$$

$$Tep_{ikm} - U^{T}_{im}\, y_{ikm} \le 0 \qquad \forall \mathbf{i} \quad \forall \mathbf{k} \quad \forall \mathbf{m} \qquad (4b)$$

$$Tpp_{ikm} - U^{T}_{im}\, y_{ikm} \le 0 \qquad \forall \mathbf{i} \quad \forall \mathbf{k} \quad \forall \mathbf{m} \qquad (4c)$$

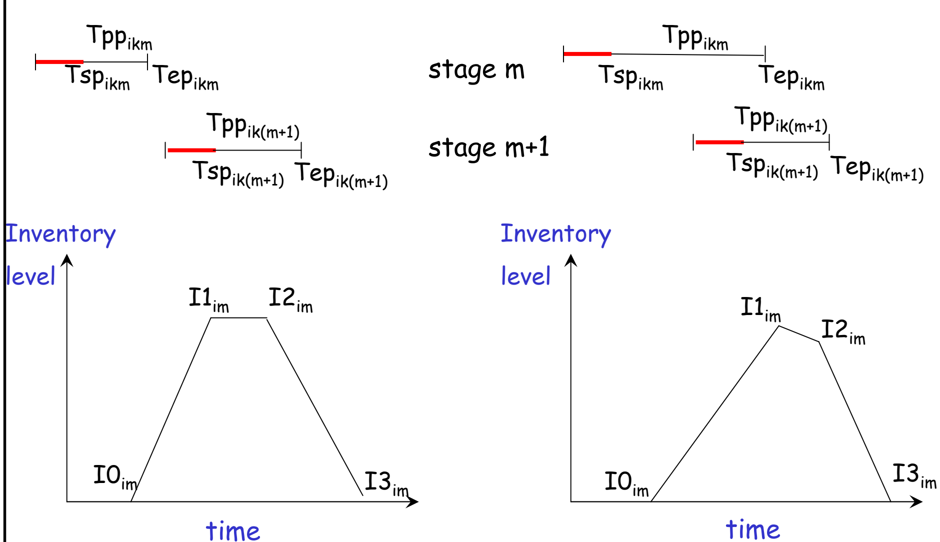
$$Tpp_{ikm} = Tep_{ikm} - Tsp_{ikm} \qquad \forall \mathbf{i} \quad \forall \mathbf{k} \quad \forall \mathbf{m} \qquad (4d)$$

$$\sum_i Tsp_{i1m} = \sum_i \sum_j \tau_{ijm}\, z_{ij1m} \qquad \forall \mathrm{m} \qquad (5a)$$

$$\sum_i Tsp_{i(k+1)m} = \sum_i Tep_{ikm} + \sum_i \sum_j \tau_{ijm}\, z_{ij(k+1)m} \qquad \forall\, \mathbf{k} < \mathbf{NK} \quad \forall \mathbf{m} \qquad (5b)$$

$$T_c \ge \sum_k \left(\sum_i Tpp_{ikm} + \sum_i \sum_j \tau_{ijm} Z_{ijkm} \right) \qquad (5c)$$

Inventory Breakpoints



Inventory Breakpoints

$$I1_{im} = I0_{im} + \alpha_{im} Rp_{im} \min\left\{\sum_k Tsp_{ik(m+1)} - \sum_k Tsp_{ikm}, \sum_k Tpp_{ikm}\right\}$$

$$I2_{im} = I1_{im} + \left(\alpha_{im} Rp_{im} - Rp_{i(m+1)}\right)\max\left\{0, \sum_k Tep_{ikm} - \sum_k Tsp_{ik(m+1)}\right\}$$

$$I3_{im} = I2_{im} - Rp_{i(m+1)} \min\left\{\sum_k Tpp_{ik(m+1)}, \sum_k Tep_{ik(m+1)} - \sum_k Tep_{ikm}\right\}$$

$$0 \le I1_{im} \le \mathrm{Im}_{im}$$

$$0 \le I2_{im} \le \mathrm{Im}_{im}$$

$$0 \le I3_{im} \le \mathrm{Im}_{im}$$

$$\mathrm{Im}_{im} \le U^{I}_{im}$$

$$I3_{im} = I0_{im} \qquad \forall i \ \ \forall m \qquad (6)$$

$$Wp_{Mi} = \alpha_{iM} Rp_{iM} \sum_k Tpp_{ikM} \qquad \forall\, i \qquad (7a)$$

$$Wp_{Mi} \ge D_i T_c \qquad \forall\, i \qquad (7b)$$

Mathematical model

Variables:

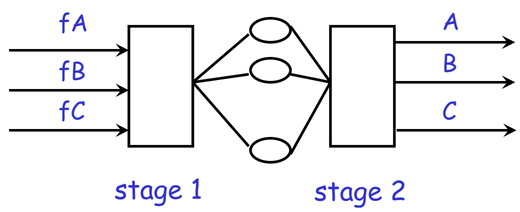
$$y_{ikm} \in \{0,1\}$$

$$0 \le z_{ijkm} \le 1$$

$$Tsp_{ikm}, Tep_{ikm}, Tpp_{ikm}, Wp_{Mi}, T_c, \mathrm{Im}_{im}, I0_{im}, I1_{im}, I2_{im}, I3_{im} \ge 0$$

Most of the Scheduling problems in Chemical Engineering result in MILP/MINLP models with large number of binary and continuous variables.

3P2S Scheduling Problem



Product	sale price ($/ton)	demand (kg/h)
A	150	50
B	400	100
C	650	250

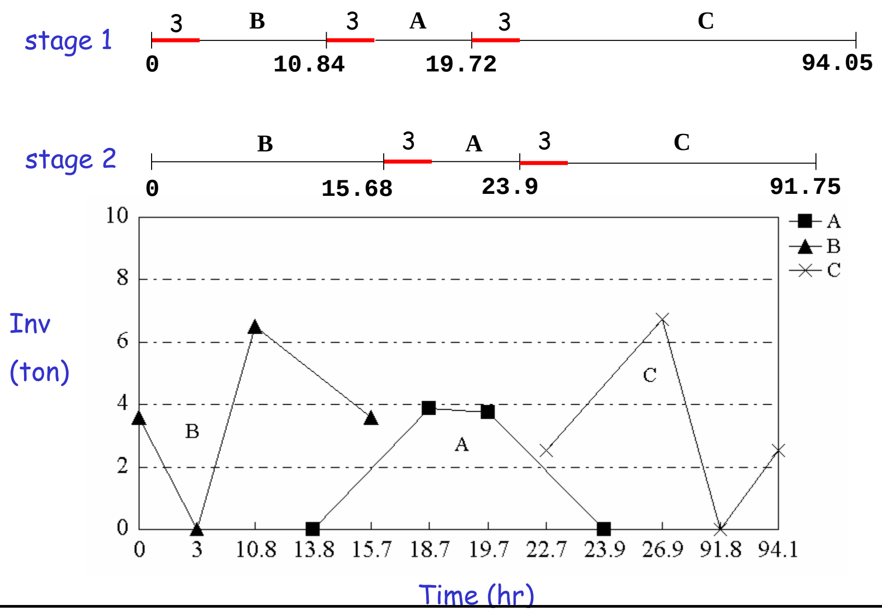
3P2S Problem data

product	stage 1 processing rate (kg/h)	stage 1 intermediate storage ($/ton)	stage 2 processing rate (kg/h)	stage 2 final inventory ($/ton.h)
A	800	140.6	900	4.06
B	1200	140.6	600	4.06
C	1000	140.6	1100	4.06

Transition times (sequence dependent)

product	stage 1 A	stage 1 B	stage 1 C	stage 2 A	stage 2 B	stage 2 C
A	-	10	3	-	7	3
B	3	-	6	3	-	10
C	8	3	-	4	0	-

3P2S Solution



3P2S Solution

Profit = $ 442.53 / hr

Cycle time = 94.05 hr

Variables = 146 (18 bin)

Constraints = 162

CPU time = 12.43 sec

Product	demand (kg/hr)	production (kg/h)
A	50	50
B	100	100
C	250	758