PASI 2005

Pan American Advanced Studies Institute Program on Process Systems Engineering

Part 3

Process and Supply Chain Operations

Supply chain optimization

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Outline

I. Strategic Framework to the Analysis of Supply Chain Networks
II. Design of Supply Chain Networks
III. Planning of Supply Chains
IV. Planning, Scheduling and Supply Chain Management for Operations in Oil Refineries

Appendices

- I. Demand Forecast
- II. Transportation Issues
- III. The Role of Inventory

Supply Chain

- Scope: a supply chain covers the flow of materials, information and cash across the entire enterprise
- Supply chain management: process of integrating, planning, sourcing, making and delivering product, from raw material to end customer, and measuring the results globally
- To satisfy customers and make a profit
- Why a ‘supply chain’?

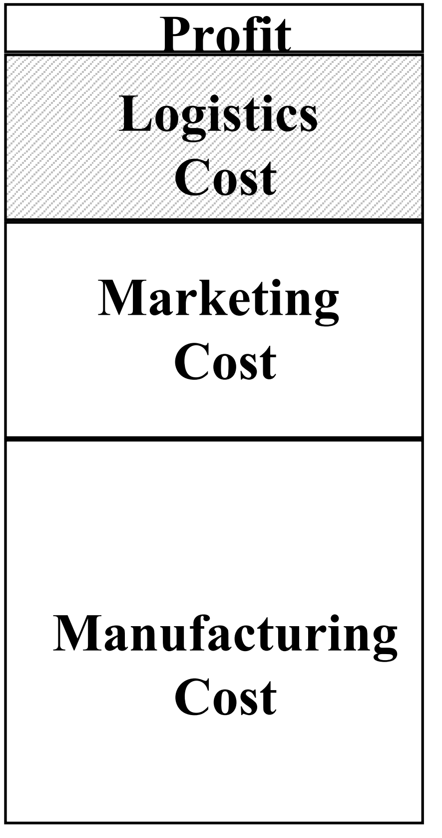
Traditional View: Logistics in the Economy

	1990	1996
■ Freight transportation	$352	$455 billion
■ Inventory expense	$221	$311 billion
■ Administrative expense	$ 27	$ 31 billion
■ Logistics related activity	11%	10.5% GNP

Source: Cass Logistics

Traditional View: Logistics in the Manufacturing Firm

- Profit: 4%
- Logistics cost : 21%
- Marketing cost: 27%
- Manufacturing cost : 48%



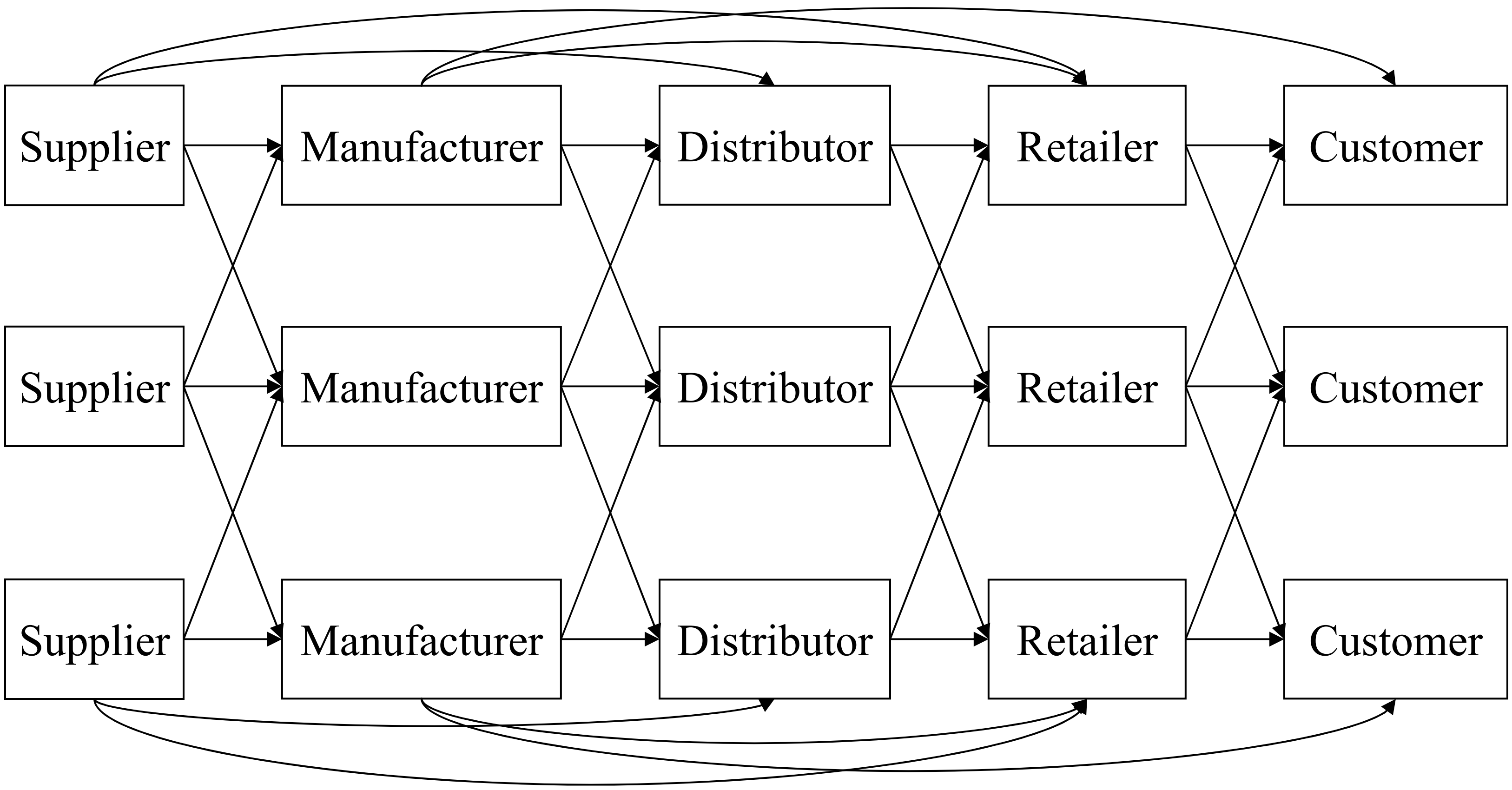
Supply Chain Management: The Magnitude in the Traditional View

- The grocery industry could save $30 billion (10% of operating cost by using effective logistics and supply chain strategies
  - A typical box of cereal spends 104 days from factory to sale
  - A typical car spends 15 days from factory to dealership
- Compaq estimates it lost $0.5 billion to $1 billion in sales in 1995 because laptops were not available when and where needed
- P&G estimates it saved retail customers $65 million by collaboration resulting in a better match of supply and demand
- Laura Ashley turns its inventory 10 times a year, five times faster than 3 years ago

Objectives of a Supply Chain

- Maximize overall value generated
  - Satisfying customer needs at a profit
  - Value strongly correlated to profitability
  - Source of revenue – customer
  - Cost generated within supply chain by flows of information, product and cash
  - Flows occur across all stages – customer, retailer, wholesaler, distributor, manufacturer and supplier
  - Management of flows key to supply chain success

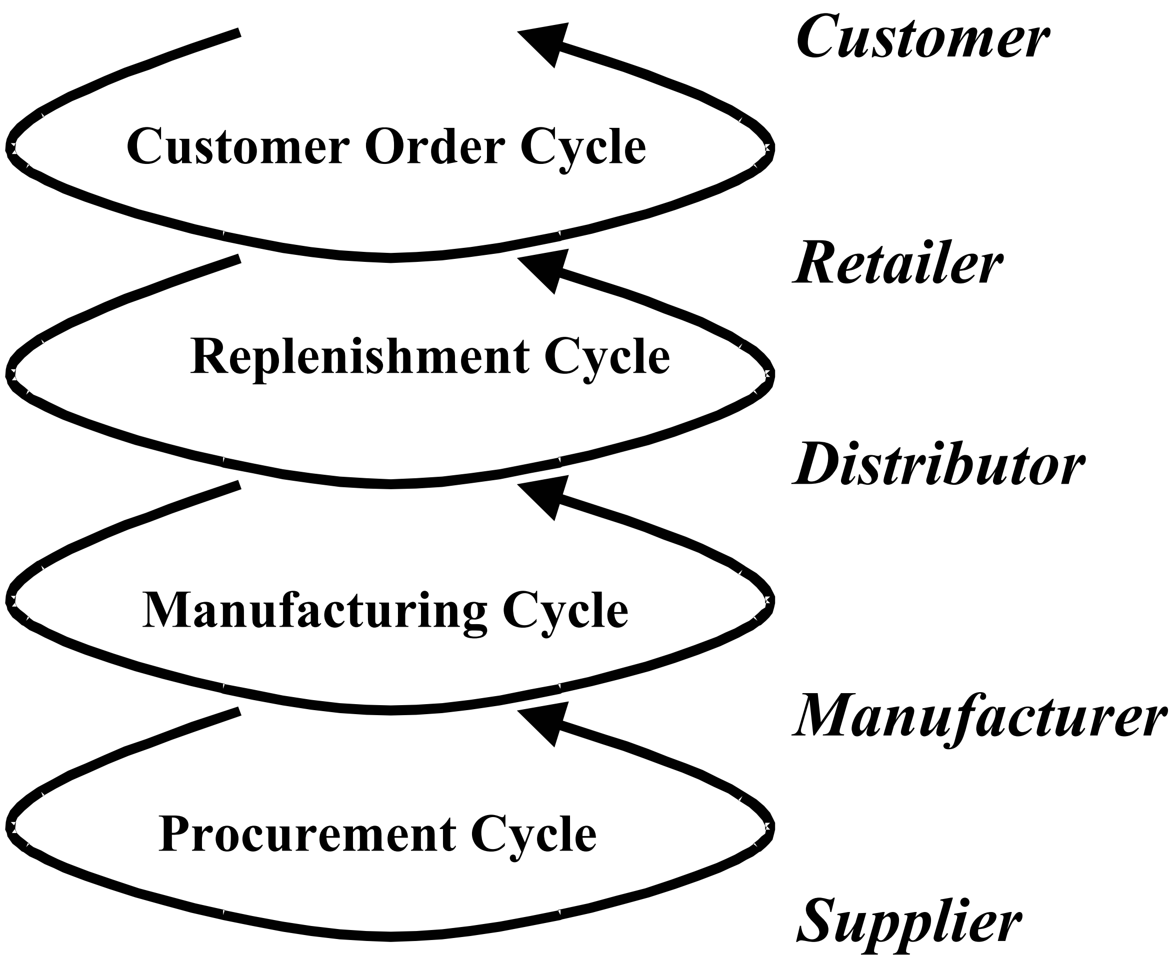
Supply Chain Stages



Decision phases in a supply chain

- Supply chain strategy or design
  - Location and capacity of production and warehouse facilities?
  - Products to be manufactured, purchased or stored by location?
  - Modes of transportation?
  - Information systems to be used?
  - Configuration must support overall strategy
- Supply chain planning
  - Operating policies – markets served, inventory held, subcontracting, promotions, …?
- Supply chain operation
  - Decisions and execution of orders?

Cycle View of Supply Chains



Process view of a supply chain

- Customer order cycle
  - Trigger: maximize conversion of customer arrivals to customer orders
  - Entry: ensure order quickly and accurately communicated to all supply chain processes
  - Fulfillment: get correct and complete orders to customers by promised due dates at lowest cost
  - Receiving: customer gets order

Process view of a supply chain

- Replenishment cycle
  - Replenish inventories at retailer at minimum cost while providing necessary product availability to customer
  - Retail order:
    - Trigger – replenishment point – balance service and inventory
    - Entry – accurate and quick to all supply chain
    - Fulfillment – by distributor or mfg. – On time
    - Receiving – by retailer, update records

Process view of a supply chain

- Manufacturing cycle
  - Includes all processes involved in replenishing distributor (retailer) inventory, on time @ optimum cost
  - Order arrival
  - Production scheduling
  - Manufacturing and shipping
  - Receiving

Process view of a supply chain

- Procurement cycle
  - Several tiers of suppliers
  - Includes all processes involved in ensuring material available when required

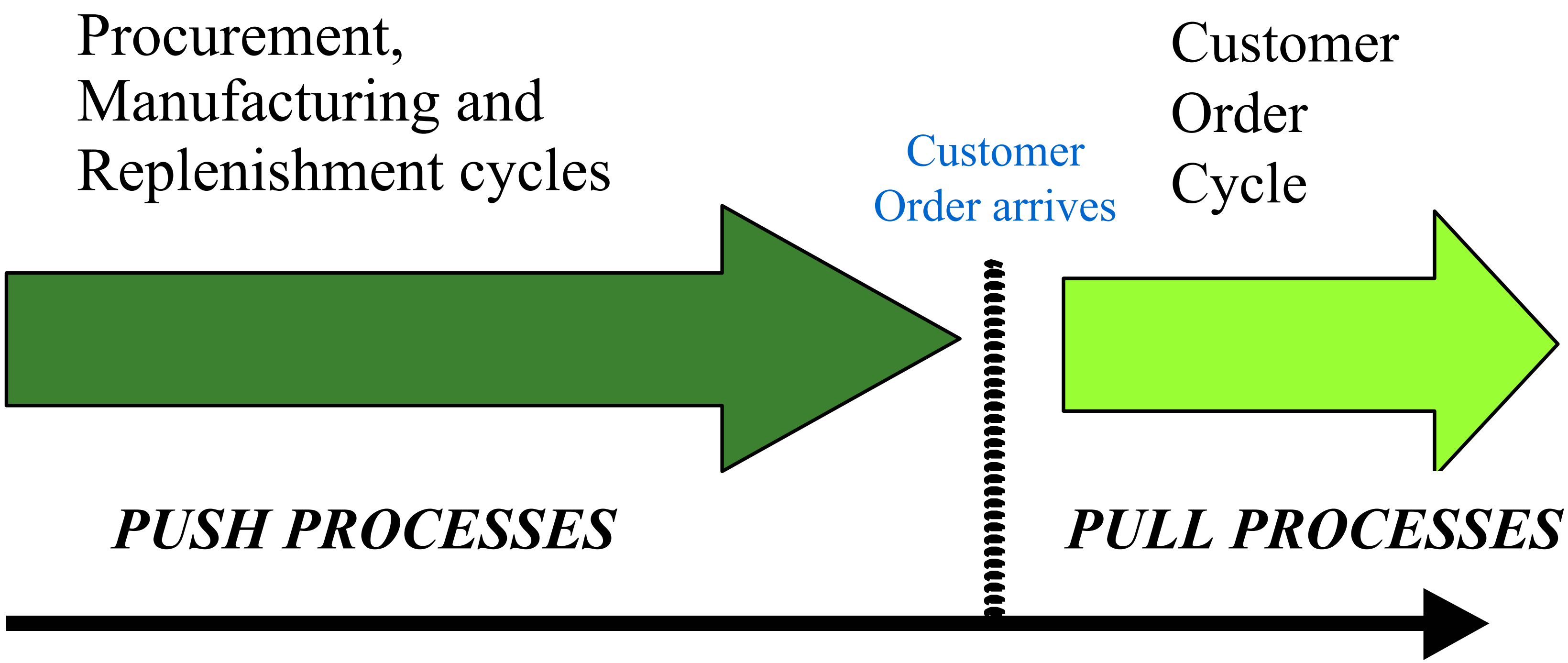
Supply chain macro processes

- CRM (Customer Relationship Management) – all processes focusing on interface between firm and customers
- ISCM (Internal Supply Chain Management) – processes internal to firm
- SRM (Supplier Relationship Management) – all processes focusing on interface between firm and suppliers

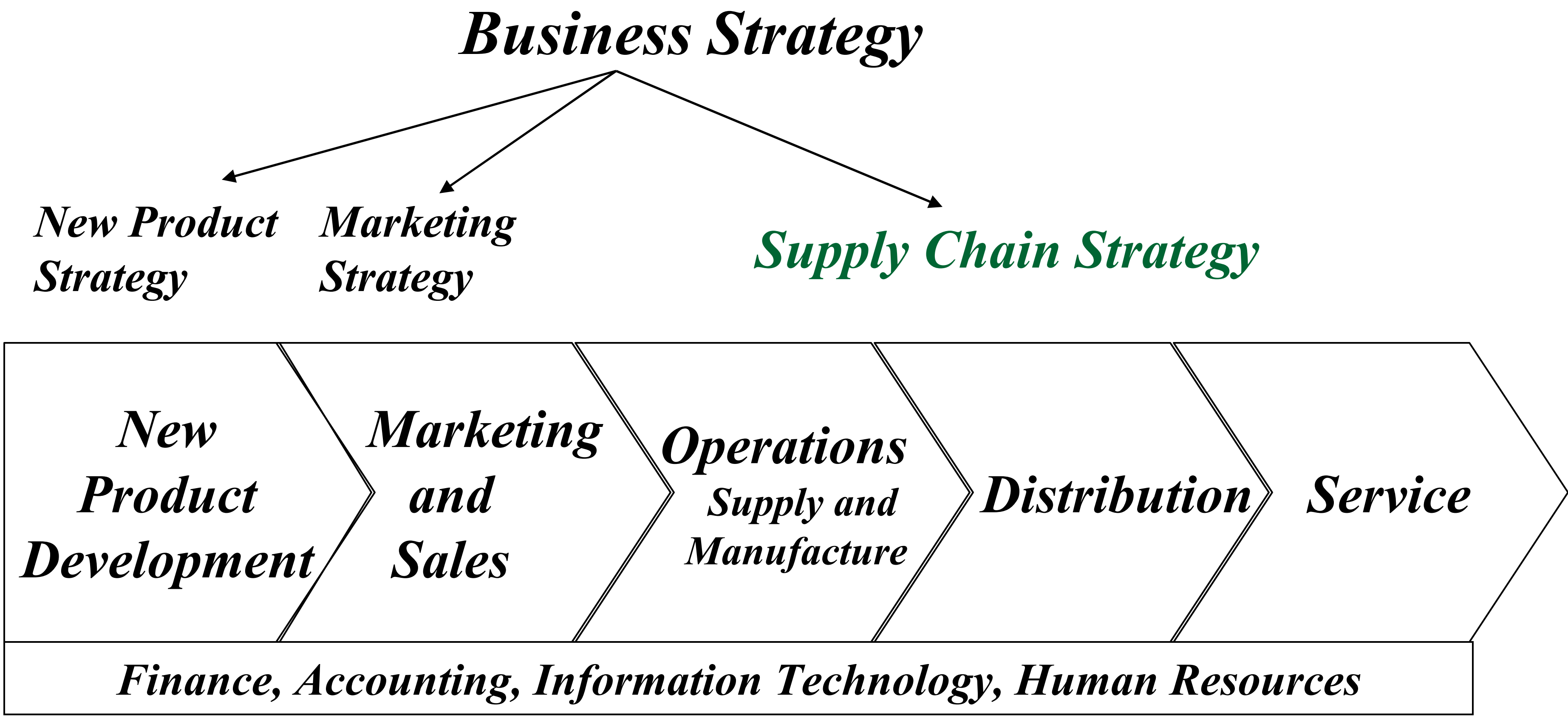
Push/Pull View of Supply Chains

Pull – processes in response to a customer order

Push – processes in anticipation of a customer order



Supply chain performance – Strategic fit and scope



Achieving strategic fit

- Understanding the Customer and Demand Uncertainty
  - Quantity - lot size
  - Response time
  - Product variety
  - Service level
  - Price
  - Innovation

Implied Demand Uncertainty

Regular Demand Uncertainty due to customers demand **and Implied Demand Uncertainty** due to uncertainty in Supply Chain

Levels of Implied Demand Uncertainty

Detergent	High Fashion
Long lead time steel	Emergency steel

Price — Customer Need — ***Responsiveness***

Low ⟷ ***High***

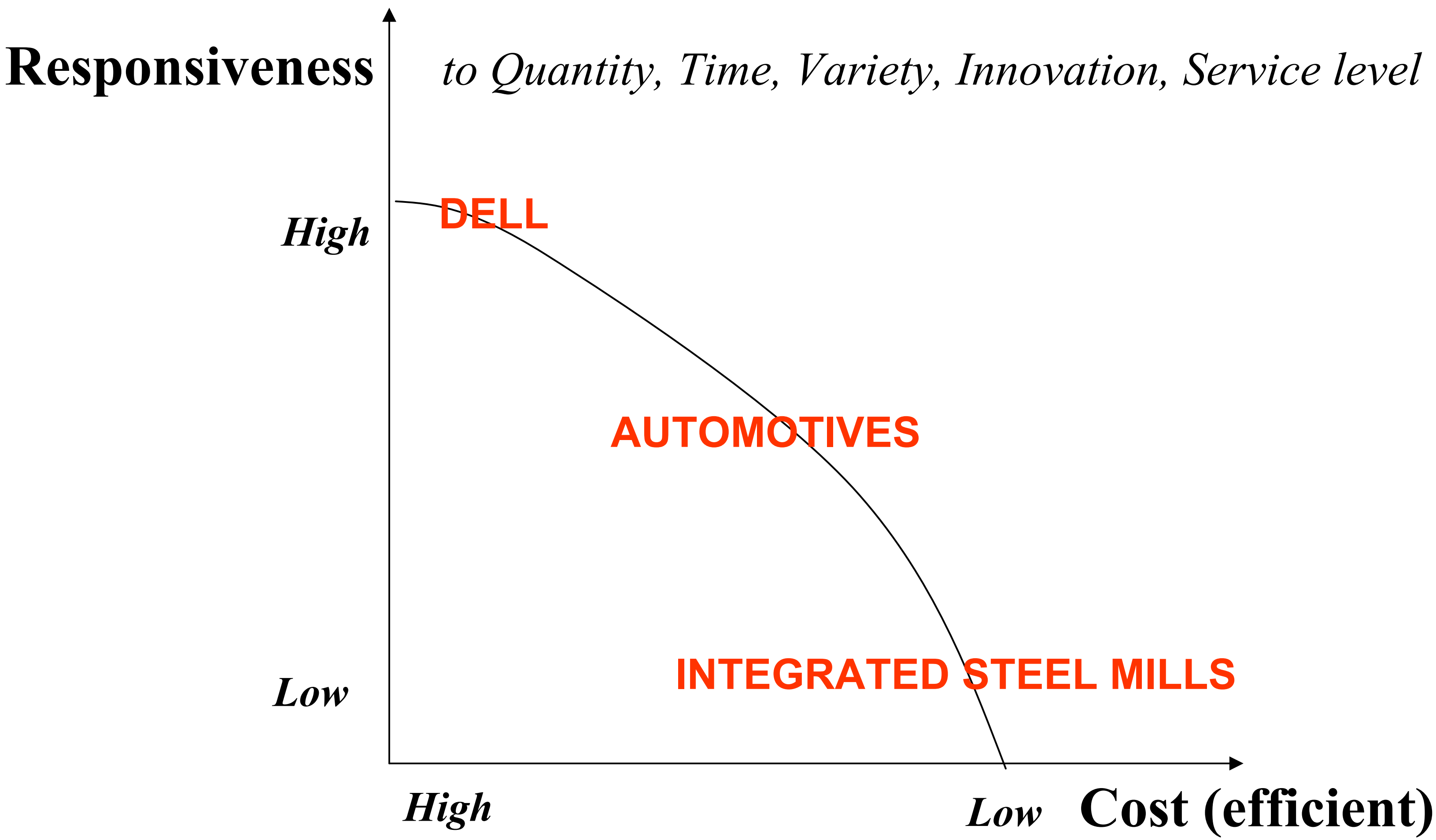
Implied Demand Uncertainty	Low	High
Product Margin	Low	High
Average Forecast Error	10%	40-100%
Average Stockout rate	1-2%	10-40%
Average markdown	0%	10-25%

Fischer (1997) Harvard Bus. Rev, March-April, 83

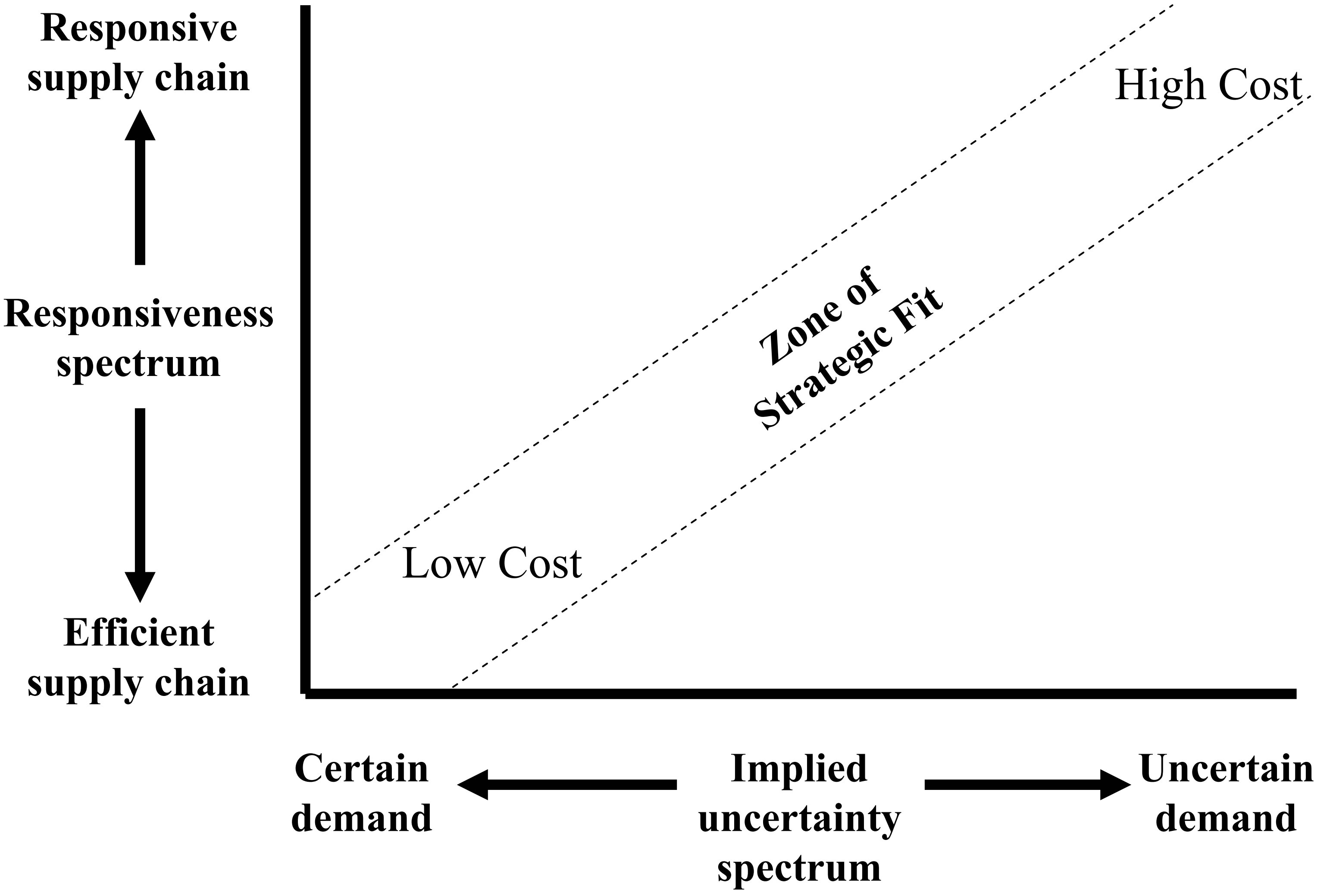
Supply source uncertainty

- Supply uncertainty increases with...
  - Frequent breakdowns
  - Unpredictable and/or low yields
  - Poor quality
  - Limited supplier capacity
  - Inflexible supply capacity
  - Evolving production processes
- Life cycle position of product
  - New products high uncertainty
  - salt *vs* existing automobile model *vs* new communication device

Understanding the Supply Chain



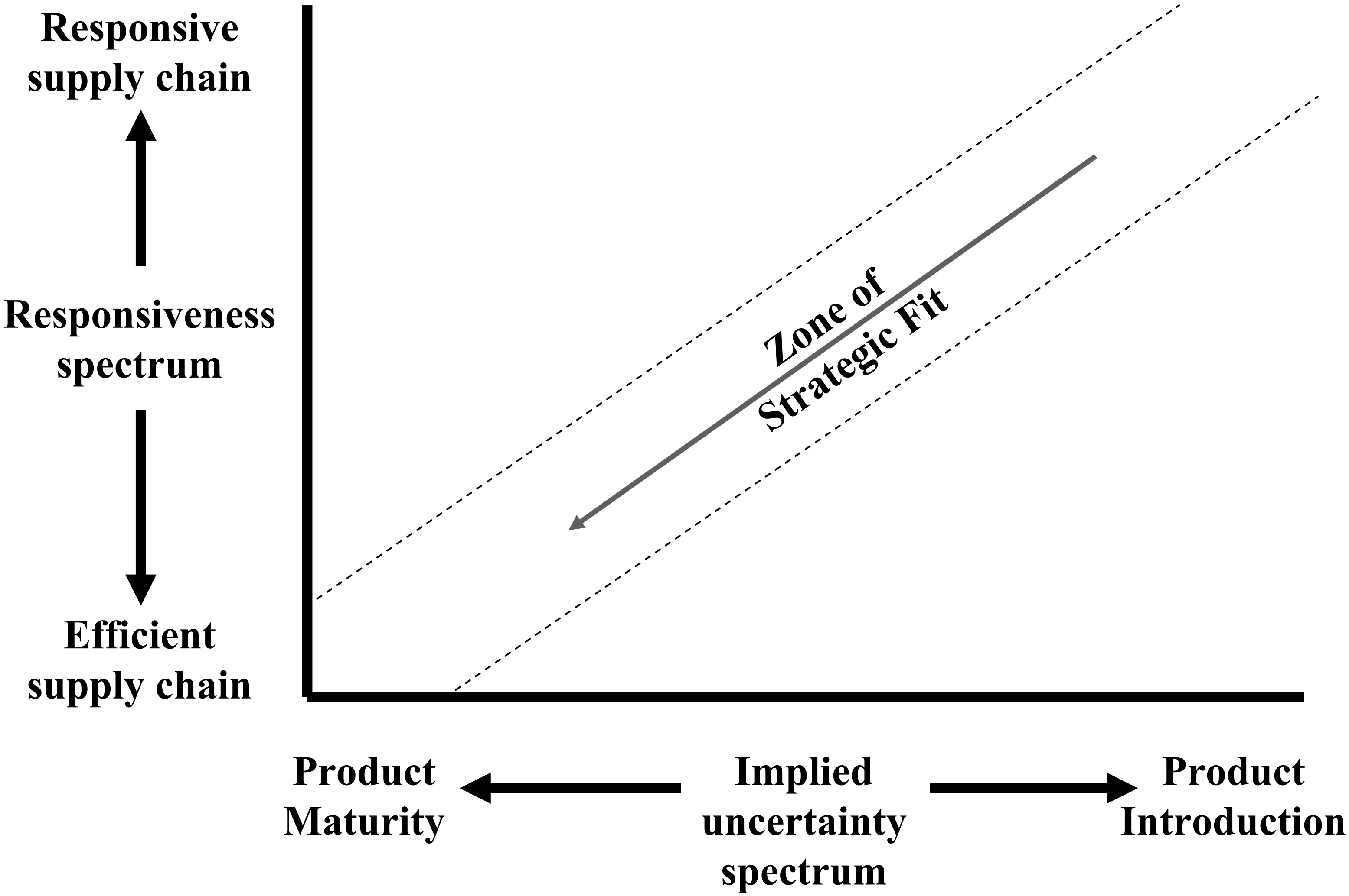
Achieving Strategic Fit



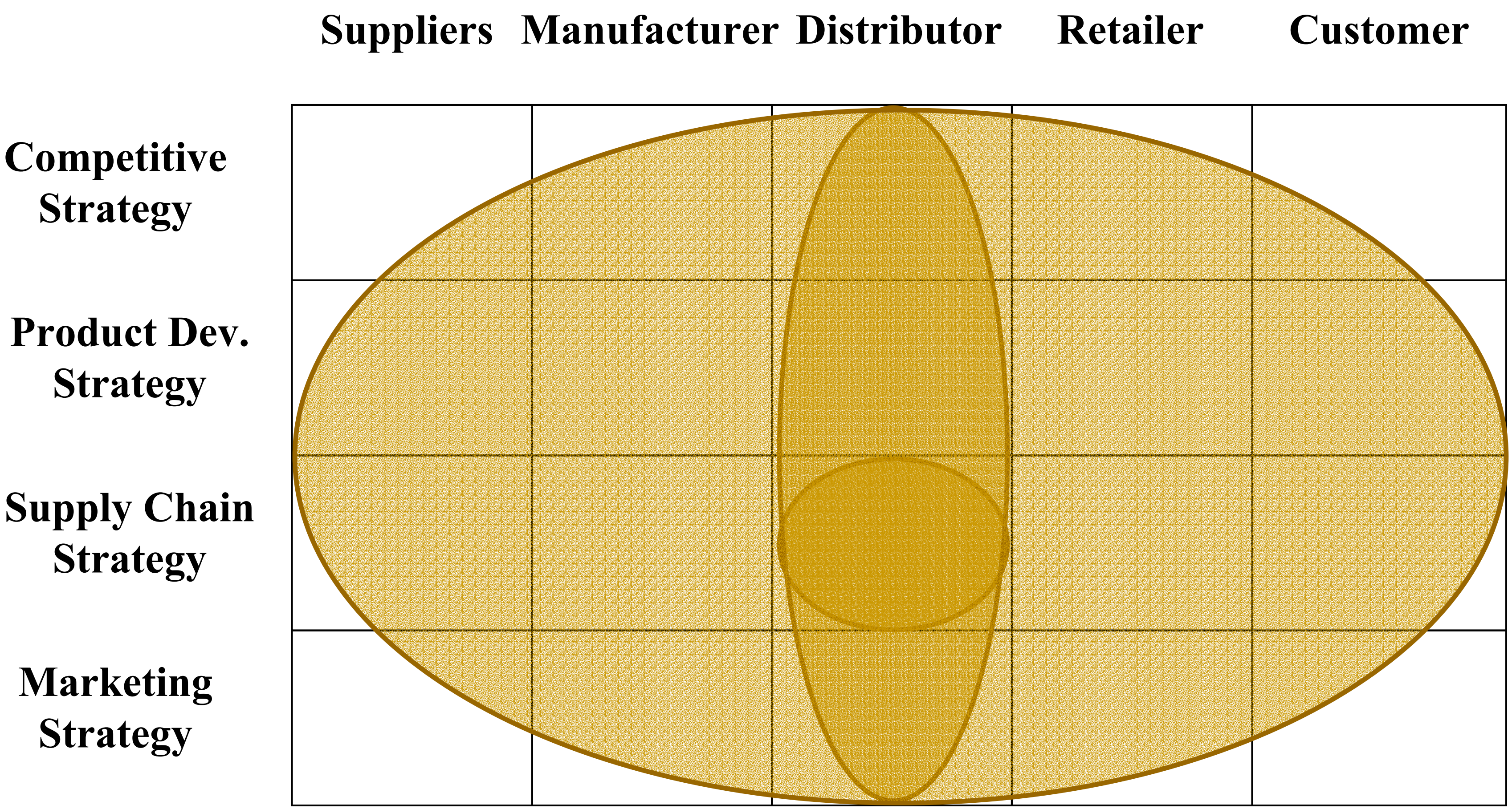
Responsive and Efficient Supply Chains

	Efficient	Responsive
Primary goal	demand at lowest cost	respond quickly
Product design strategy	maximize performance at minimum cost	create modularity
Pricing strategy	Lower margins	higher margins
Manufacturing strategy	lower costs (high utilization)	maintain flexibility
Inventory strategy	minimize to lower cost	maintain buffer inventory
Lead time strategy	reduce but not at expense of costs	aggressively reduce
Supplier strategy	select based on cost and strategy	select based on speed, flexibility, reliability and quality

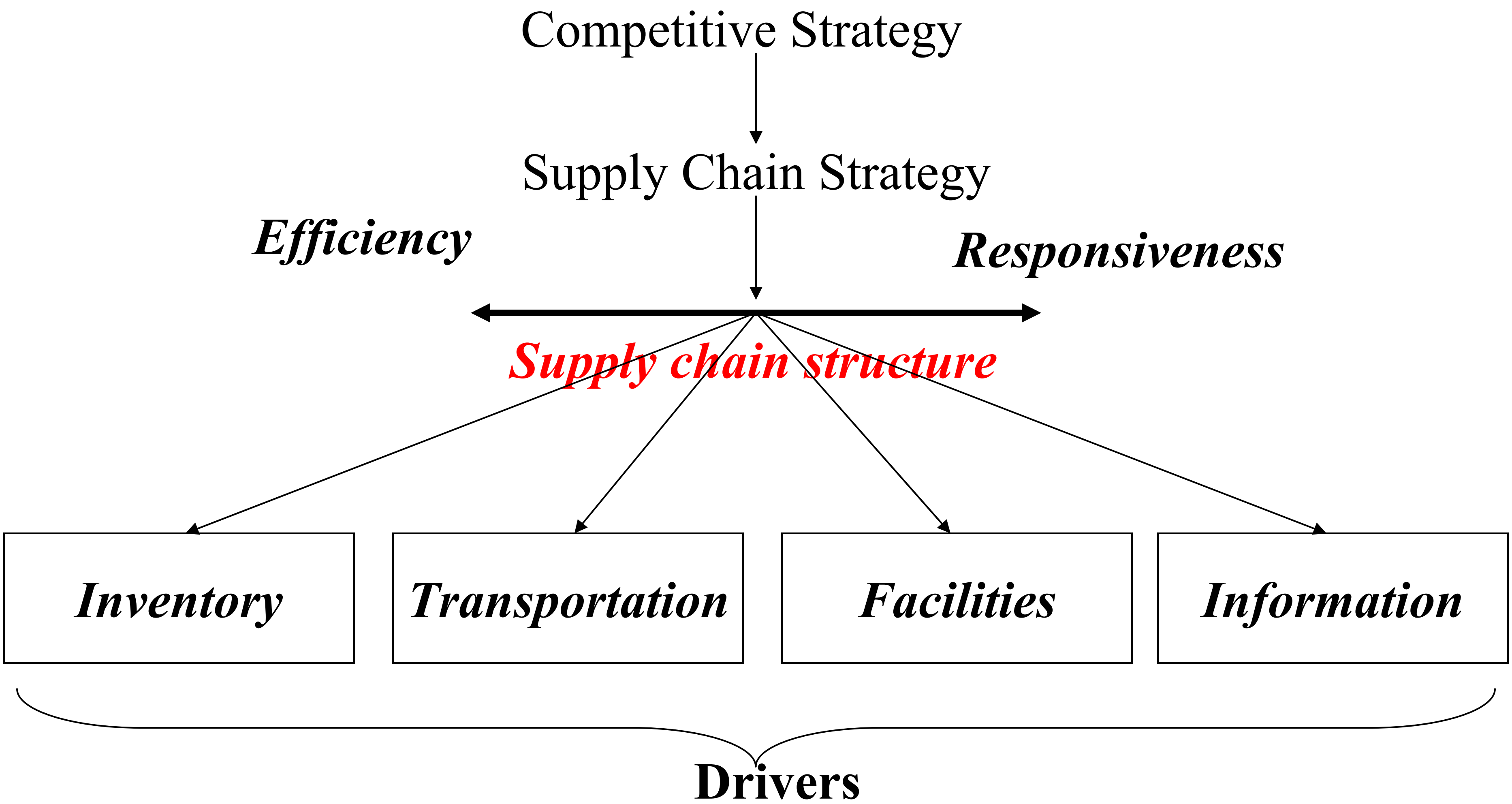
Product life cycle



Strategic Scope



Drivers of Supply Chain Performance



TRADE OFF FOR EACH DRIVER

Inventory

- ‘What’ of supply chain
- Mismatch between supply and demand
- Major source of cost
- Huge impact on responsiveness
- Material flow time
  - i = d t (i – inventory, d – throughput, t – flow time)
- Role in competitive strategy
- Components
  - Cycle inventory – average inventory between replenishments
  - Safety inventory - to cover demand and supply uncertainty
  - Seasonal inventory – counters predictable variation
- Overall trade off: responsiveness vs. efficiency

Transportation

- ‘How’ of supply chain
- Large impact on responsiveness and efficiency
- Role in competitive strategy
- Components
  - Mode – air, truck, rail, ship, pipeline, electronic
  - Route selection
  - In house or outsource
- Overall trade off: responsiveness vs efficiency

Facilities

- ‘Where’ of supply chain
- Transformed (factory) or stored (warehouse)
- Role in competitive strategy
- Components
  - Location - central or decentral
  - Capacity – flexibility vs. efficiency
  - Manufacturing methodology – product or process focus
  - Warehousing methodology – storage – sku, job lot, crossdocking
- Overall trade off: responsiveness vs. efficiency

Information

- Affects every part of supply chain
  - Connects all stages
  - Essential to operation of all stages
- Role in competitive strategy
  - Substitute for inventory
- Components
  - Push vs. pull
  - Coordination and information sharing
  - Forecasting and aggregate planning
  - Enabling technologies
    - EDI, Internet, ERP, SCM
- Overall trade off: responsiveness vs. efficiency

Considerations for Supply Chain Drivers

Driver	***Efficiency***	***Responsiveness***
Inventory	Cost of holding	Availability
Transportation	Consolidation	Speed
Facilities	Consolidation / Dedicated	Proximity / Flexibility
Information	What information is best suited for each objective	

Obstacles to achieving strategic fit

- Increasing variety of products
- Decreasing product life cycles
- Increasingly demanding customers
- Fragmentation of supply chain ownership
- Globalization
- Difficulty executing new strategies
- All increase uncertainty

Major obstacles to achieving fit

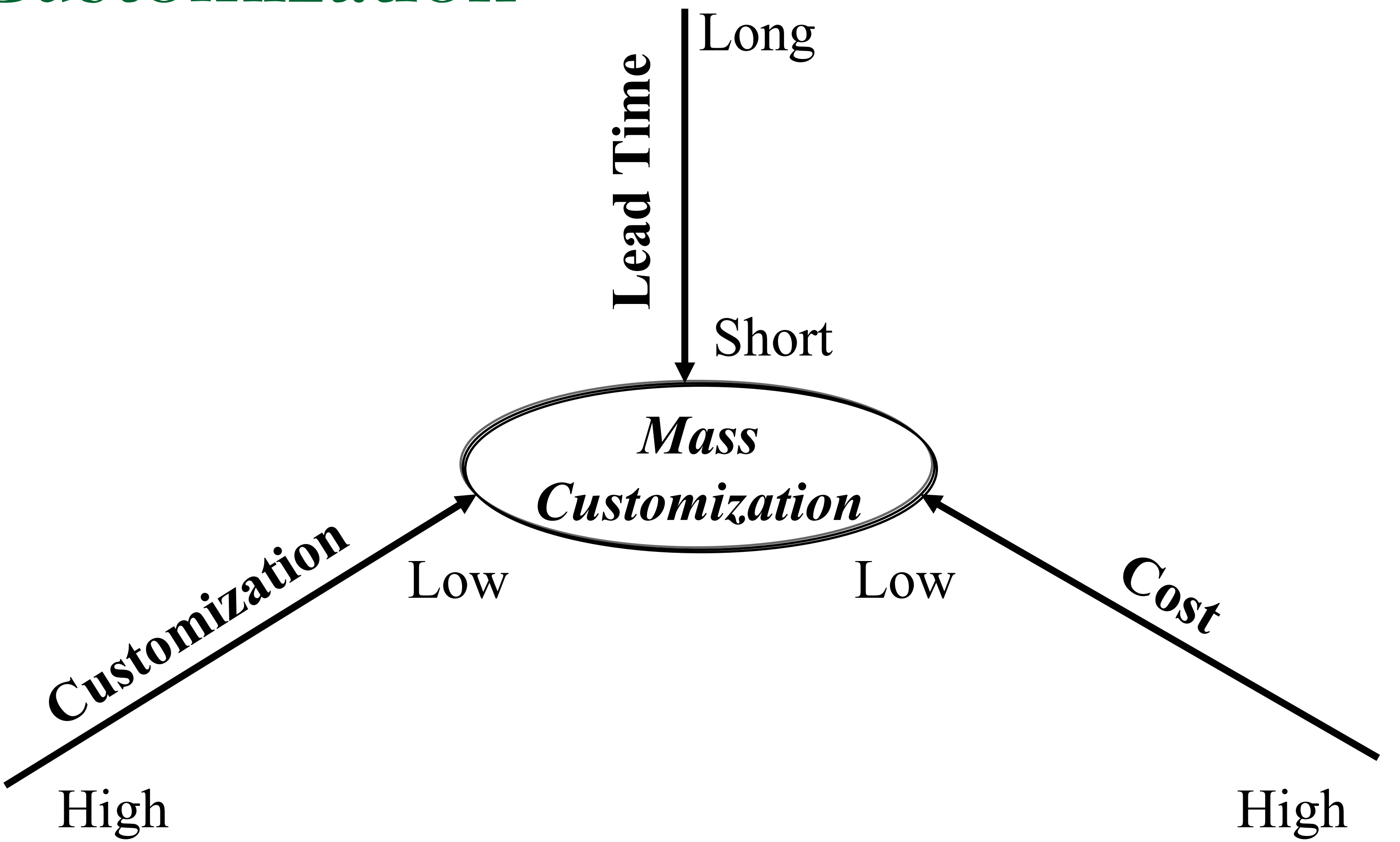
- Multiple global owners / incentives in a supply chain
  - Information Coordination & Contractual Coordination

Local optimization and lack of global fit

- Increasing product variety / shrinking life cycles / demanding customers/customer fragmentation

Increasing demand and supply uncertainty

Dealing with Product Variety: Mass Customization



Fragmentation of Markets and Product Variety

- Are the requirements of all market segments served identical?
- Are the characteristics of all products identical?
- Can a single supply chain structure be used for all products / customers?
- No! A single supply chain will fail different customers on efficiency or responsiveness or both.

II.
Designing the supply chain network

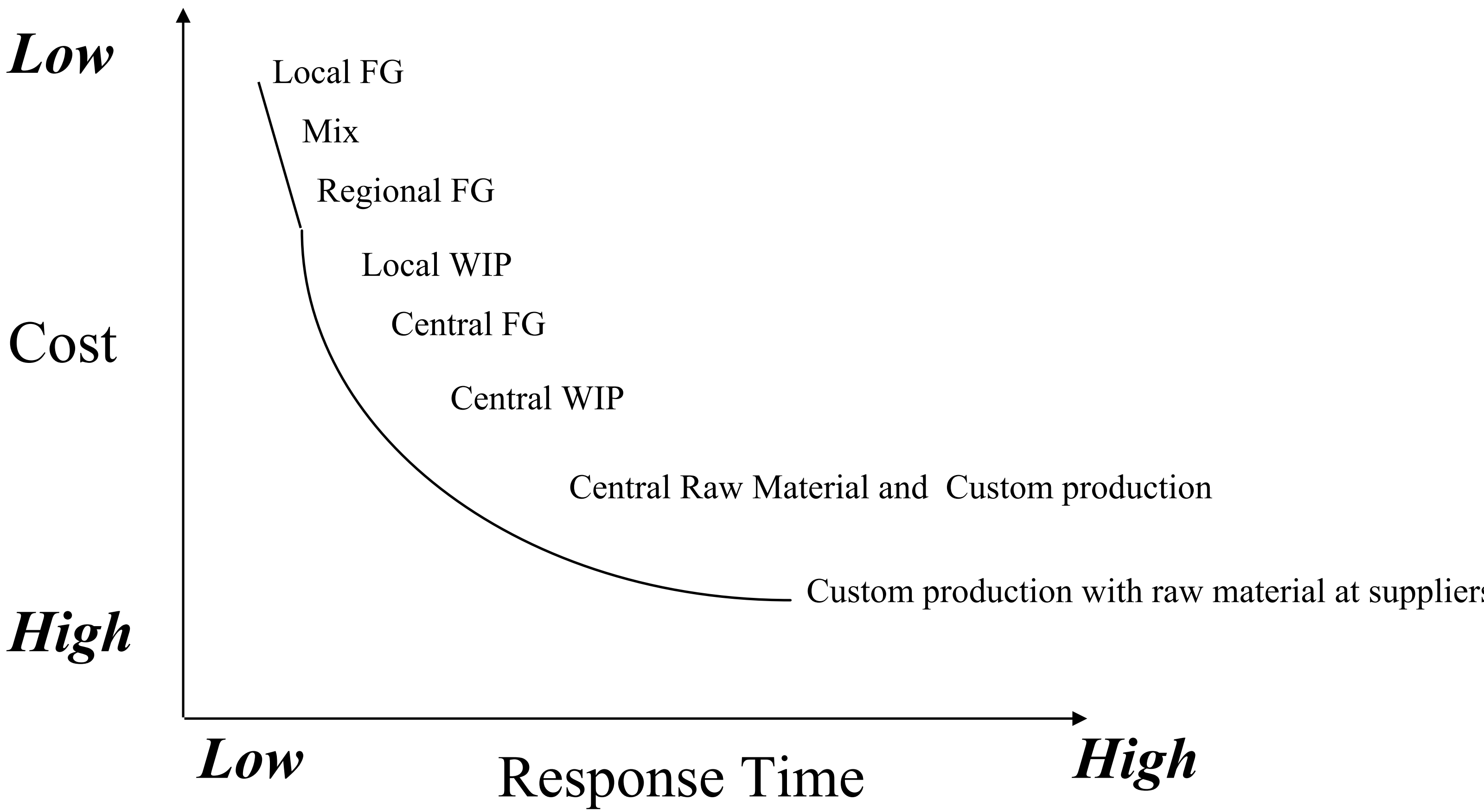
FACILITY DECISIONS:
Network Design Decisions

- Facility role
  - What processes are performed
- Facility location
  - Where should facilities be located
- Capacity allocation
  - How much capacity should be allocated to each facility
- Market & supply allocation
  - What markets should each facility serve
  - What supply sources should feed each facility

Factors Influencing Network Design Decisions

- Strategic
  - Cost or Responsiveness focus
- Technological
  - Fixed costs and flexibility determine consolidation
- Macroeconomic
  - Tariffs and Tax incentives. Stability of currency
- Political stability - clear commerce & legal rules
- Infrastructure
  - sites, labor, transportation, highways, congestion, utilities
- Competition
- Logistics and facility costs

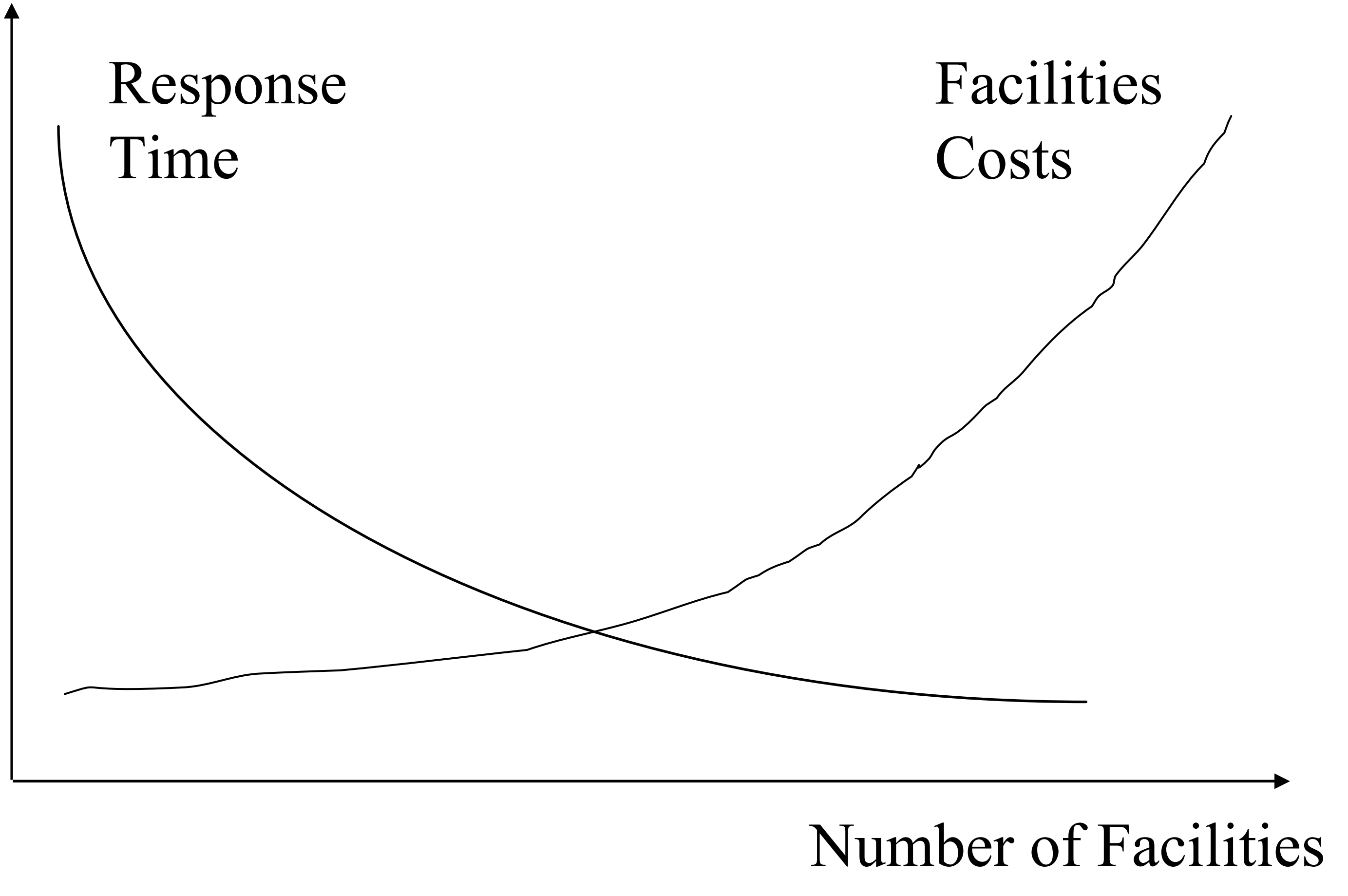
The Cost-Response Time Frontier



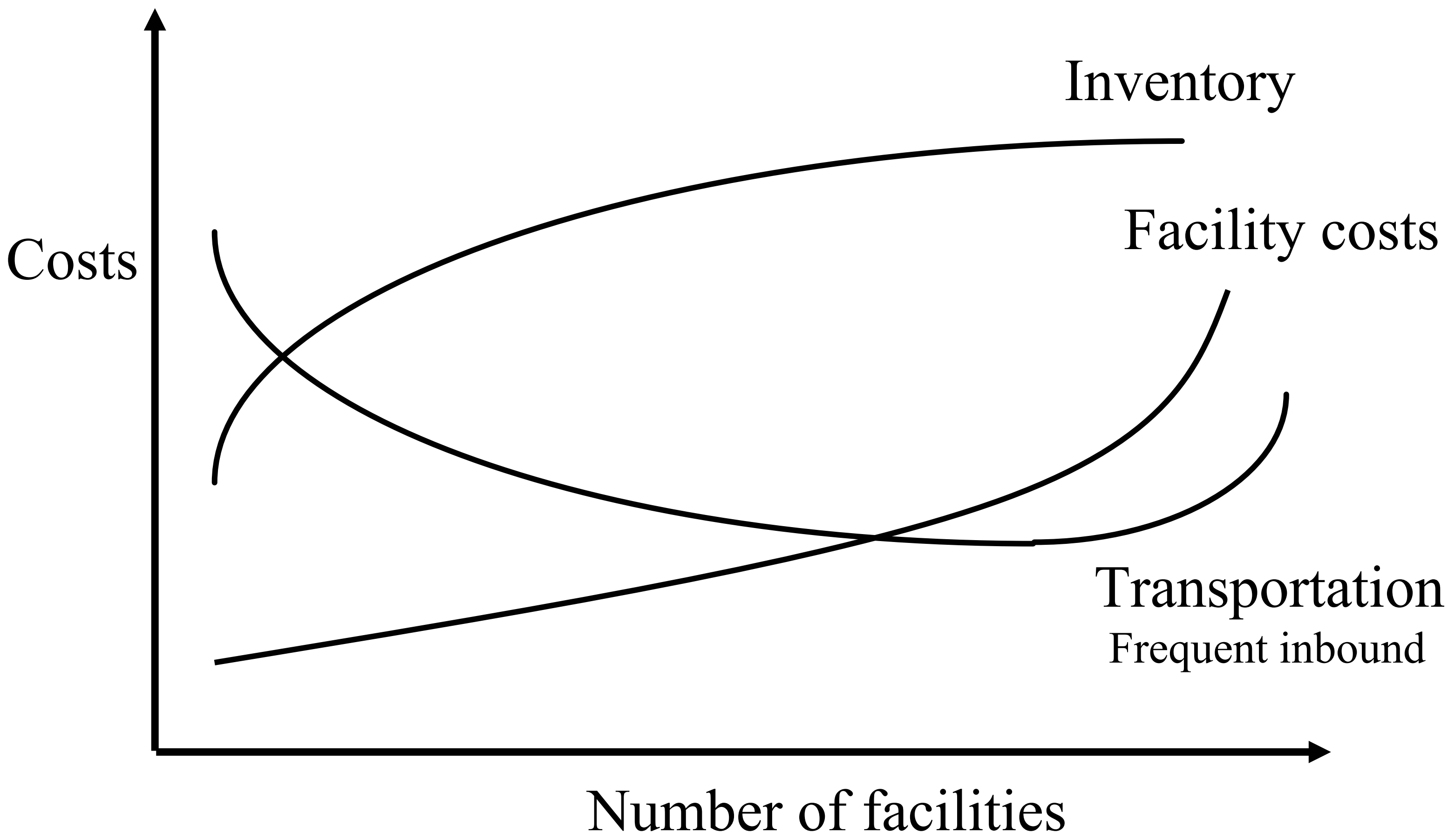
Logistics and facilities costs

- Inventory costs
- Transportation costs
  - Inbound and outbound
- Facility (setup and operating) costs
- Total logistics costs

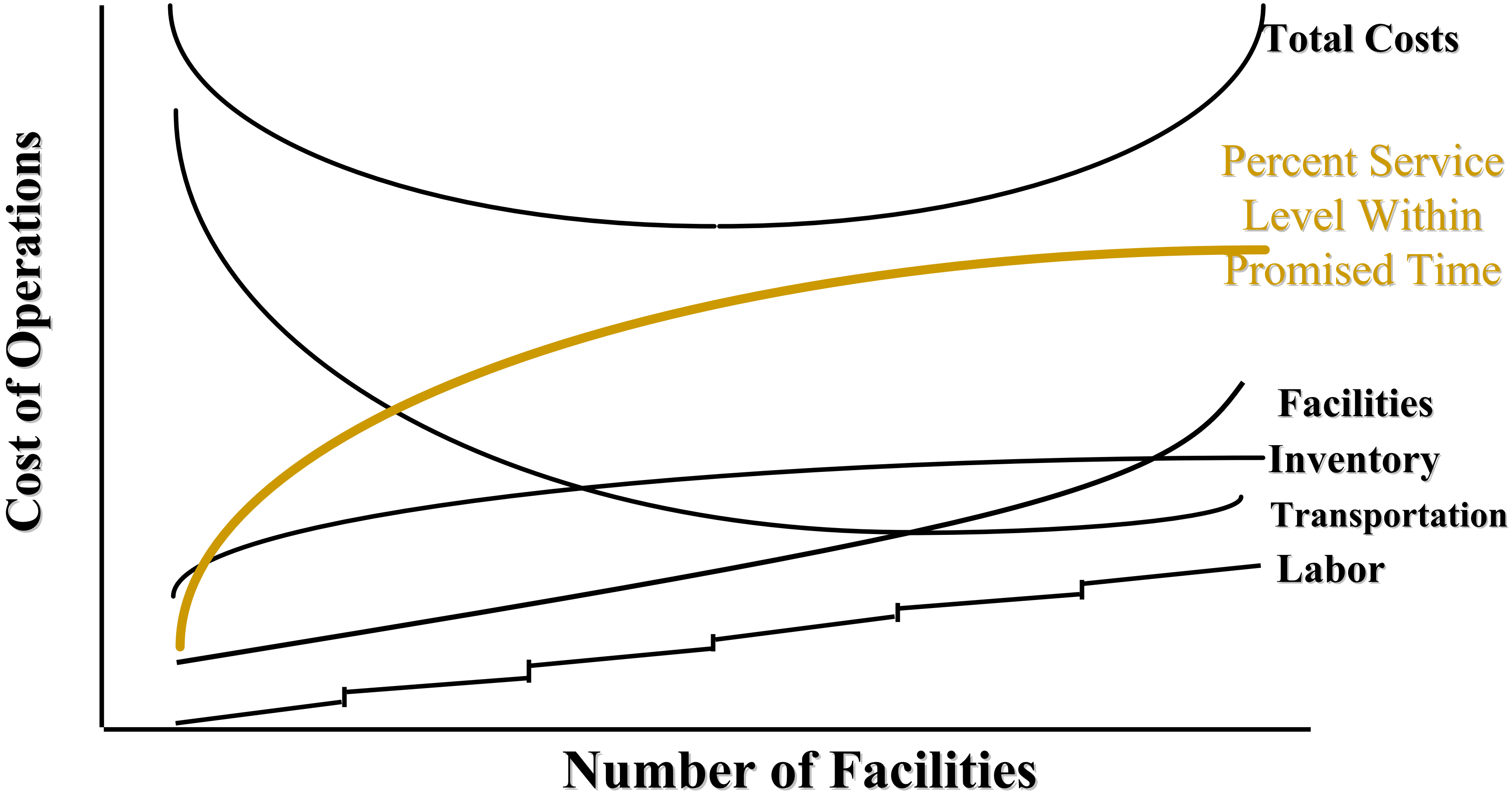
Service and Number of Facilities



Costs and Number of Facilities



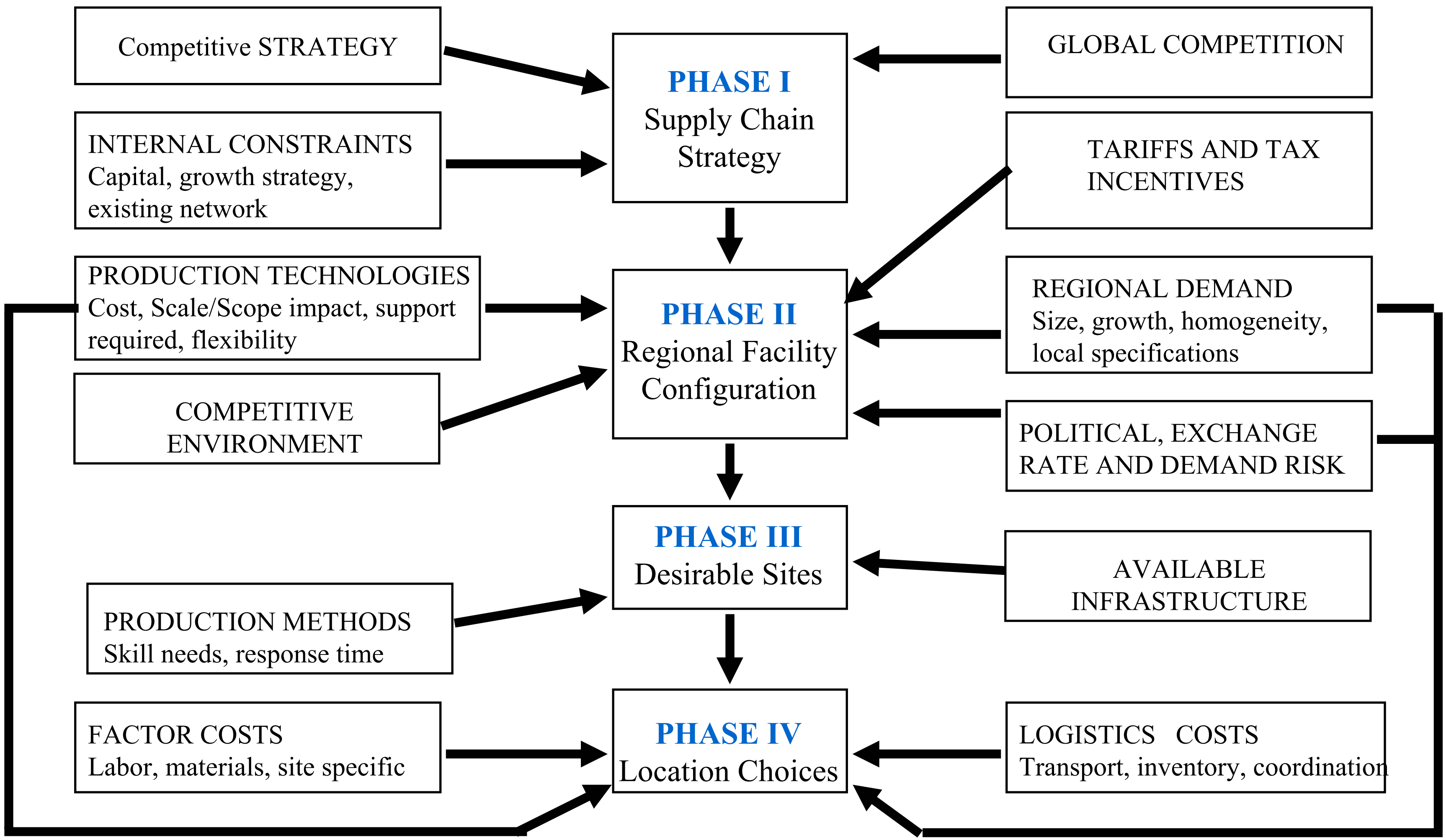
Cost Build-up as a function of facilities



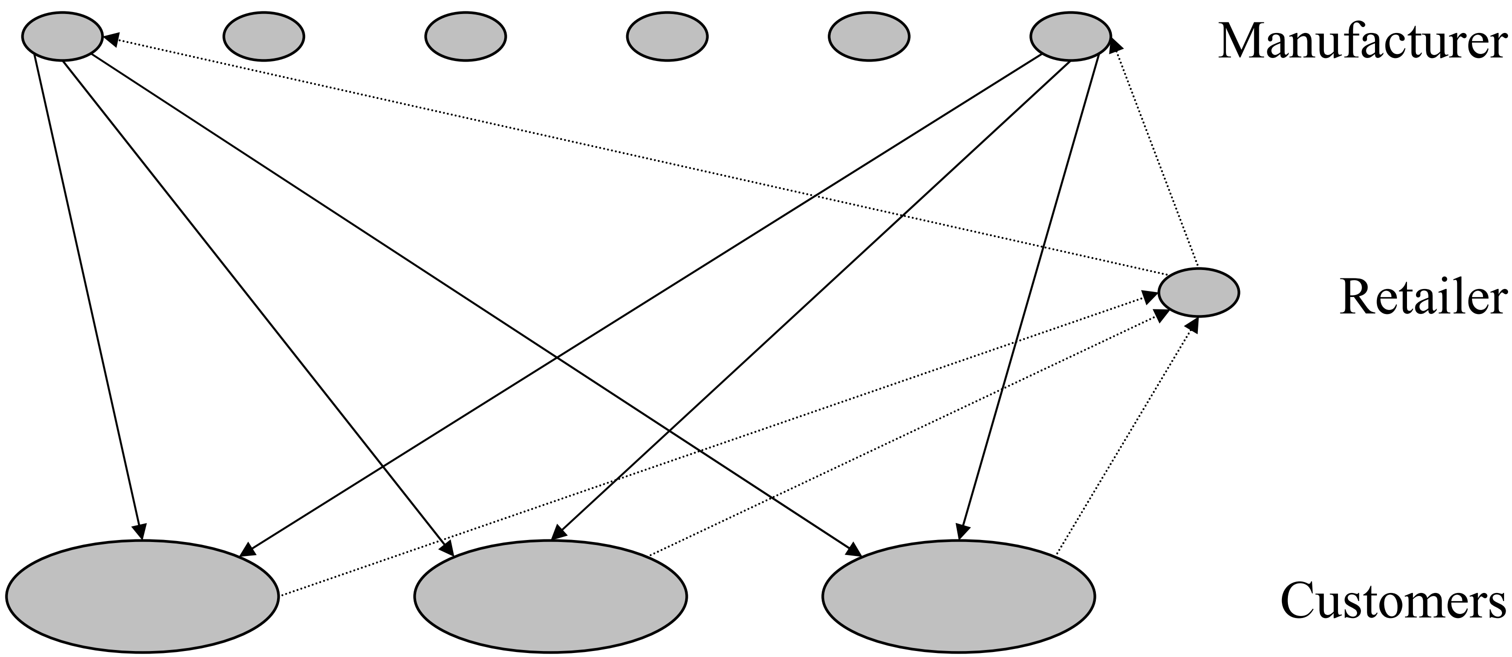
Framework for network design decisions

- Define a supply chain strategy
  - COMPETITIVE strategy
- Define a regional facility strategy
  - Location, roles and capacity
- Select desirable sites
  - Hard infrastructure – transport, utilities, suppliers, warehouses
  - Soft infrastructure – skilled workforce, community
- Choose location
  - Price location and capacity allocation

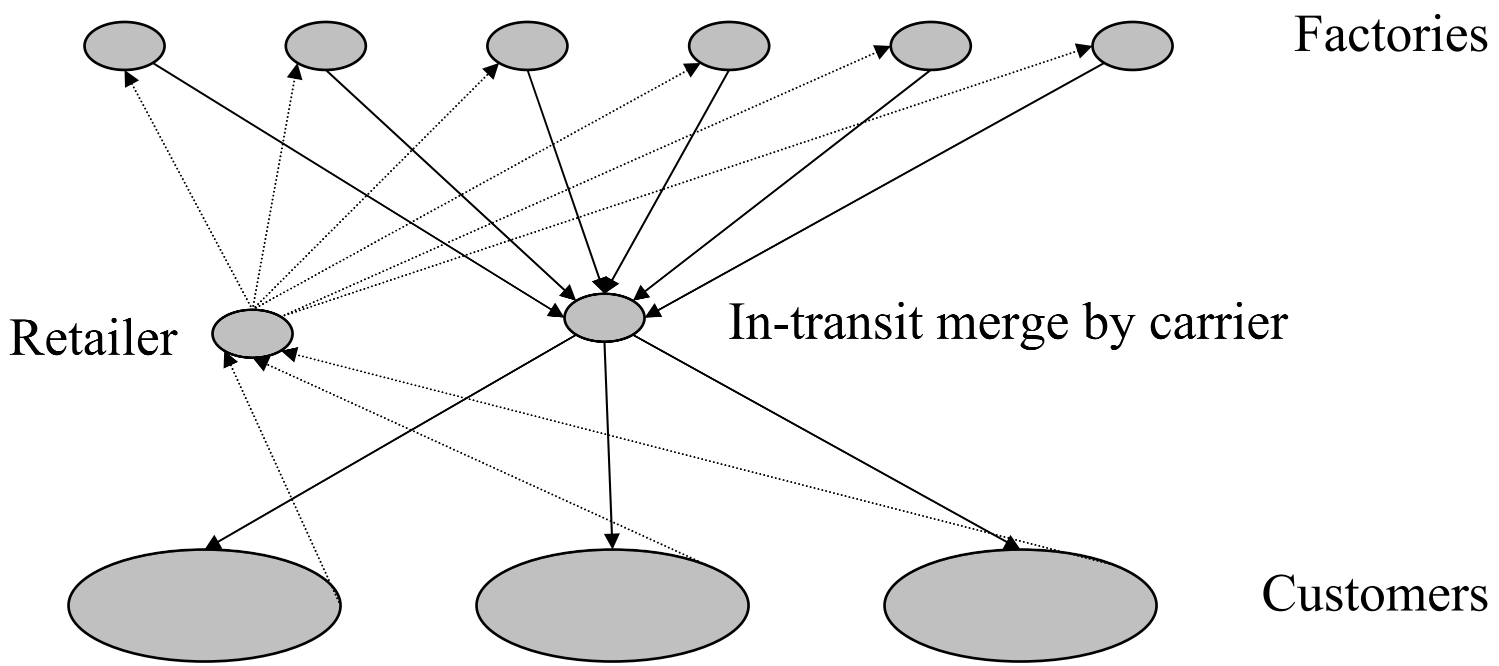
A Framework for Global Site Location



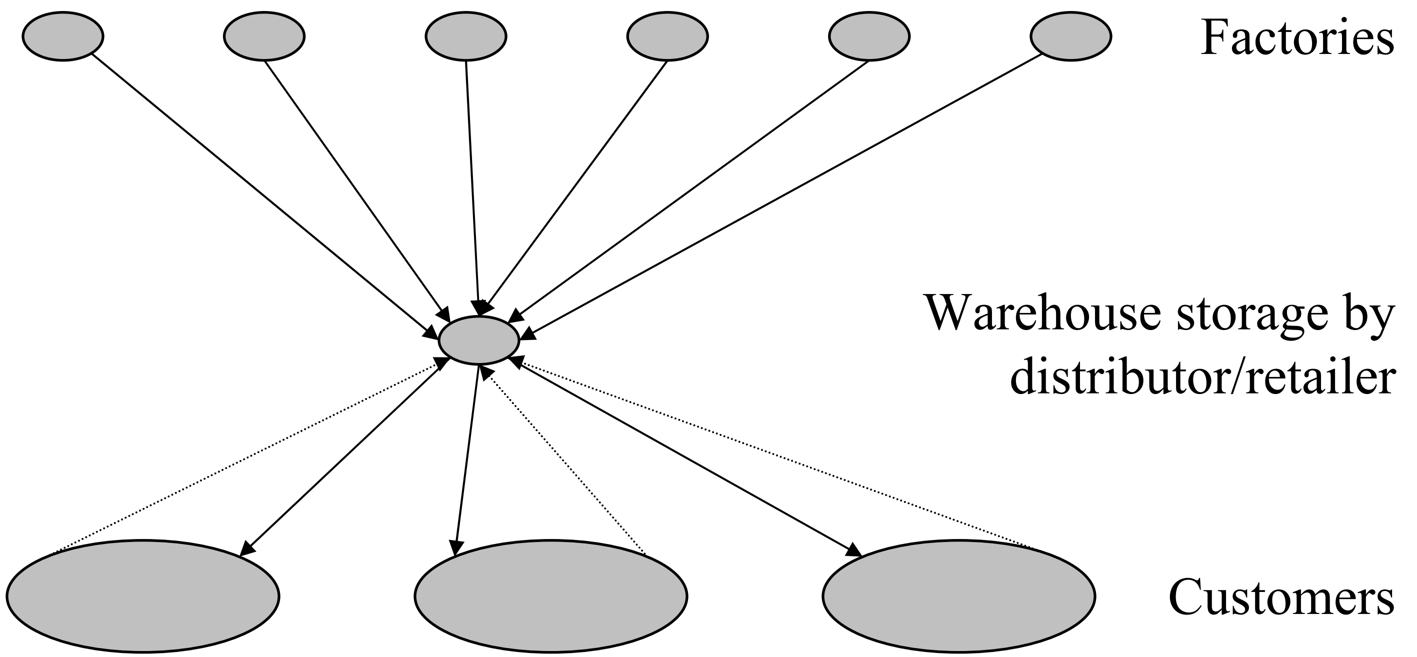
Manufacturer Storage with Direct Shipping



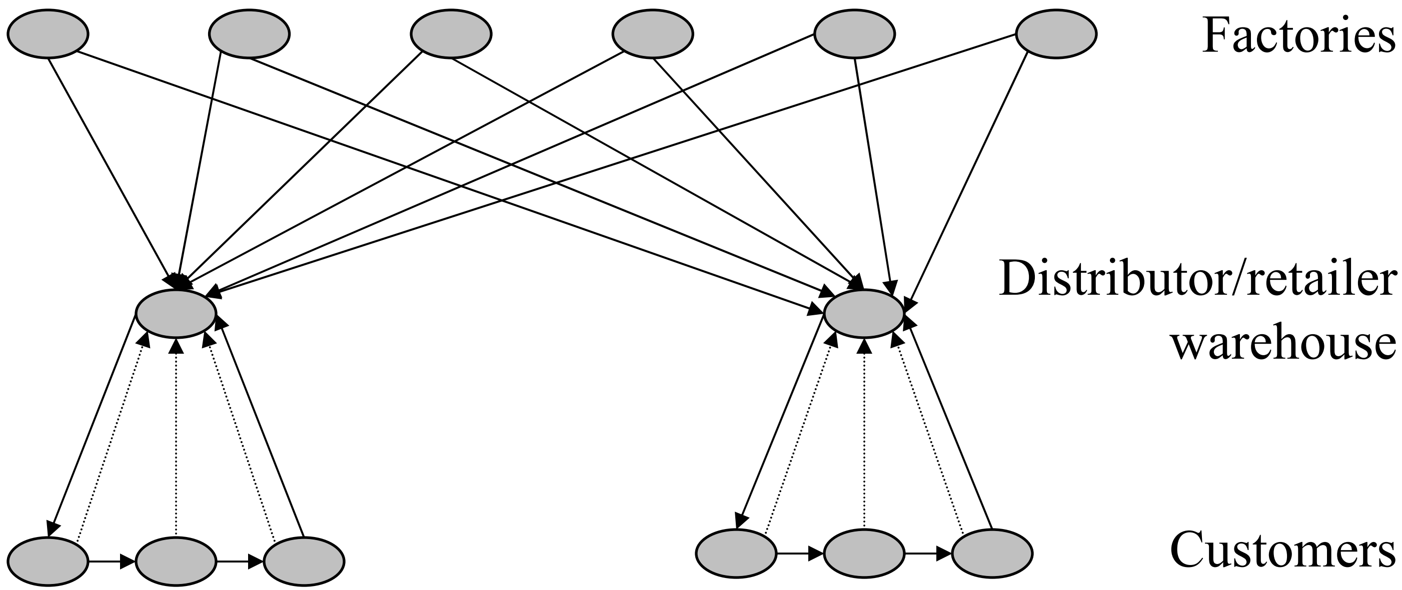
In-Transit Merge Network



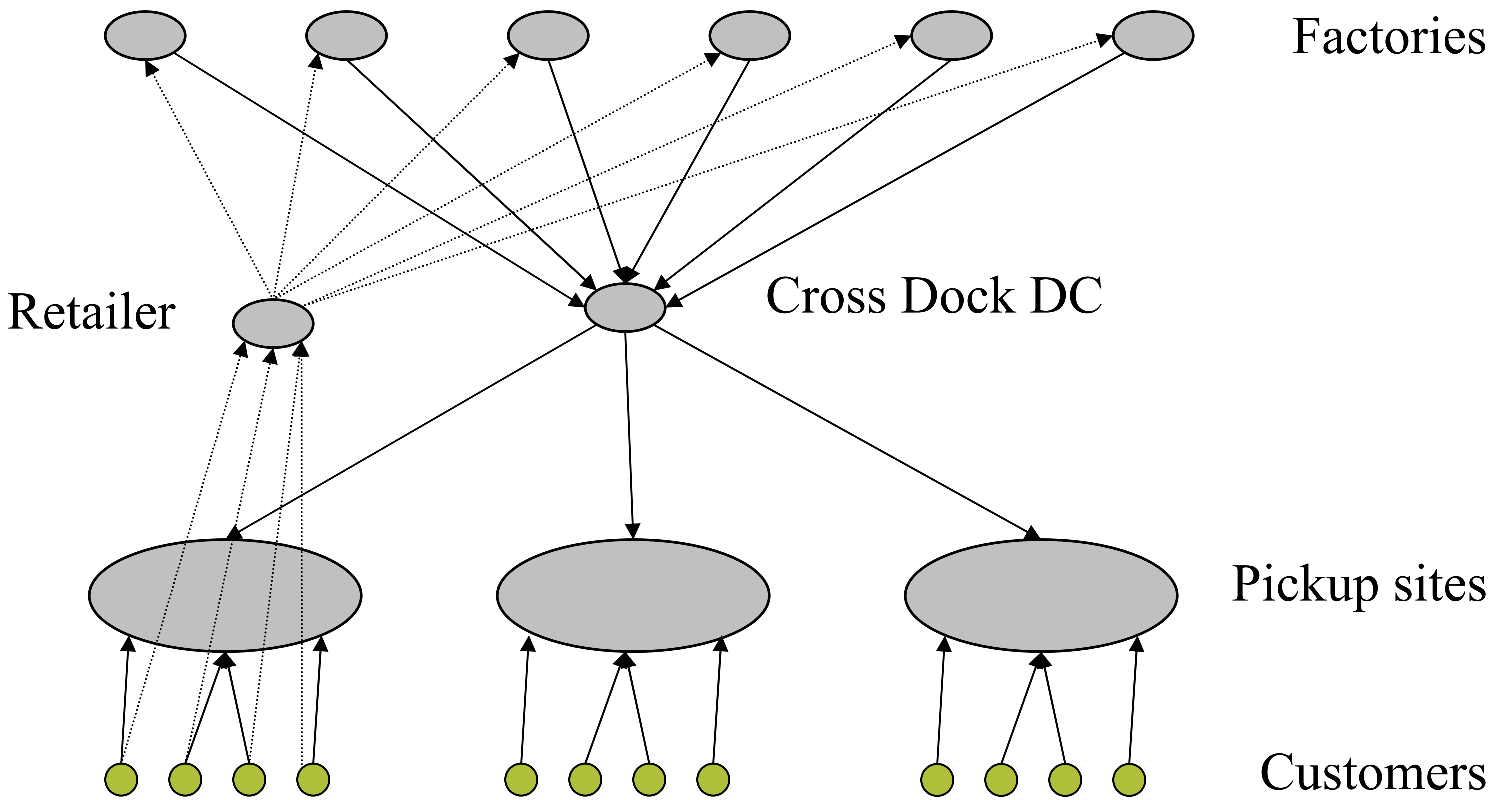
Distributor Storage with Carrier Delivery



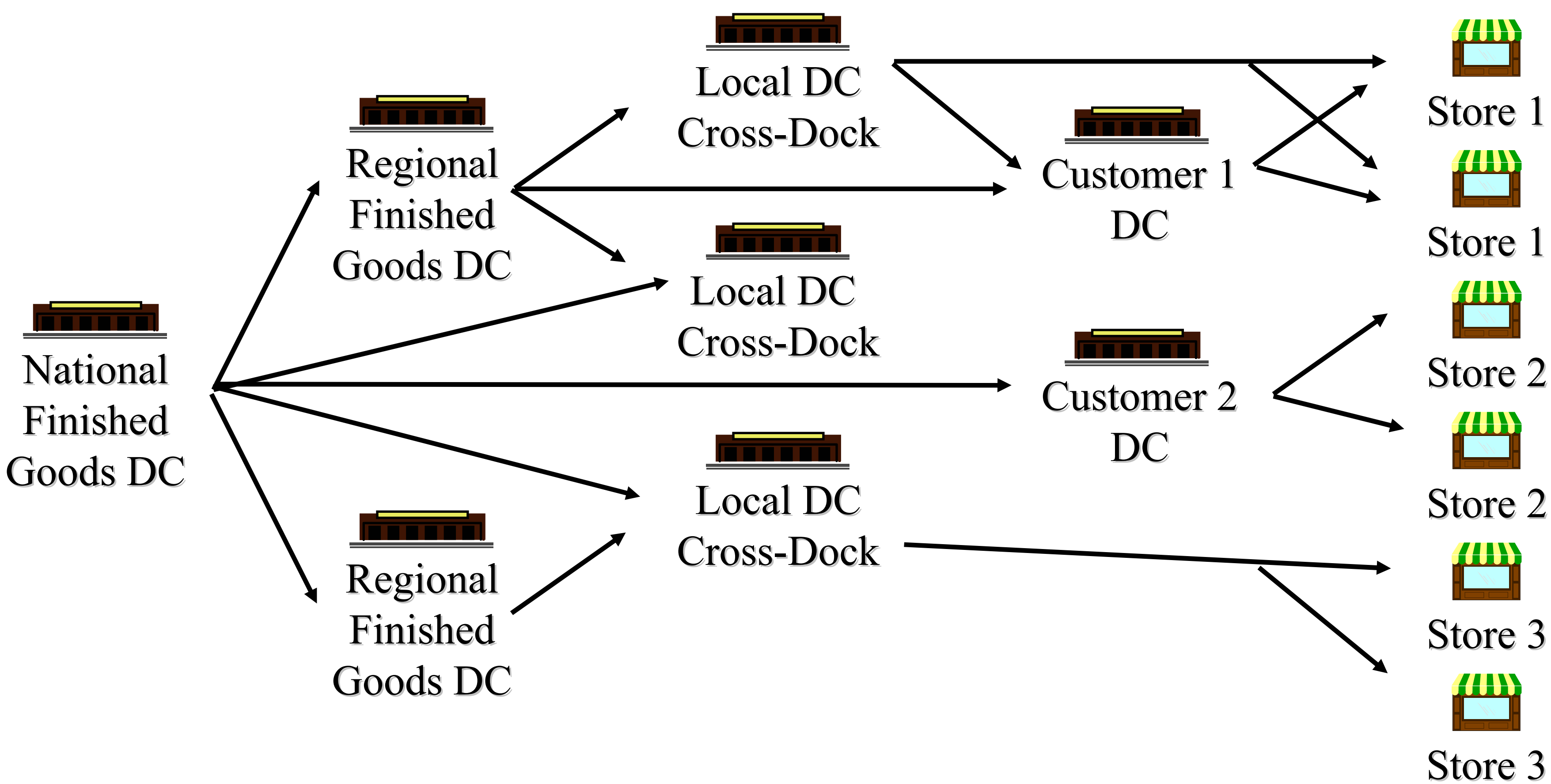
Distributor Storage with “Last Mile” Delivery



Manufacturer or Distributor Warehouse with Consumer Pickup



Tailored Network: Multi - Echelon Finished Goods Network



Network Optimization Models

- Allocating demand to production facilities
- Locating facilities and allocating capacity
  - Speculative Strategy
    - Single sourcing
  - Hedging Strategy
    - Match revenue and cost exposure
  - Flexible Strategy
    - Excess total capacity in multiple plants
    - Flexible technologies

Key Costs:
Fixed facility cost
Transportation cost
Production cost
Inventory cost
Coordination cost

Which plants to establish? How to configure the network?

Capacitated Plant Location Models

Decisions

y_i	1 if plant i is open; 0 otherwise
x_{ij}	quantity shipped from plant i to market j

n	number of potential plant locations
m	number of markets
f_i	annualized fixed cost of keeping plant i open
c_{ij}	cost of producing and shipping from i to j

$$Max \quad Profit = \sum_{i=1}^{n} f_i \cdot y_i + \sum_{i=1}^{n} \sum_{j=1}^{m} c_{i,j} \cdot x_{i,j}$$

D_j	annual demand from market j

$$\sum_{i=1}^{n} x_{i,j} = D_j \qquad j = 1, \ldots m$$

K_i	potential capacity of plant i

$$\sum_{j=1}^{m} x_{i,j} \le K_i \cdot y_i \qquad i = 1, \ldots n$$

$$y_i \in \{0,1\} \qquad i = 1, \ldots n$$

Gravity Location Models

ASSUMPTION: TRANSPORT COSTS GROW LINEARLY WITH SHIPMENTS

$$Min \quad \text{Total Cost} \quad TC = \sum_{n=1}^{k} D_n \cdot d_n \cdot f_n$$

$$d_n = \sqrt{(x - x_n)^2 + (y - y_n)^2}$$

x, y	Warehouse Coordinates
x_n, y_n	Coordinates of delivery location n
d_n	Distance to delivery location n
f_n	Cost per ton mile to delivery location n
D_n	Quantity to be shipped

Demand Allocation Model

- Which market is served by which plant?
- Which supply sources are used by a plant?

$$Min\, C = \sum_{i=1}^{n}\sum_{j=1}^{m} c_{i,j} x_{i,j}$$

$s.t.$

All mkt demand satisfied

$$\sum_{i=1}^{n} x_{i,j} = D_j \qquad j = 1,\ldots m$$

No factory capacity exceed

$$\sum_{j=1}^{m} x_{i,j} \le K_i \qquad i = 1,\ldots n$$

$$x_{i,j} \ge 0 \qquad i = 1,\ldots n;\ j = 1,\ldots m$$

x_{ij}	*quantity shipped from plant site i to customer j*
C_{ij}	*cost to produce & ship one unit from factory i to market j*
n	*no. of factory locations*
m	*no. of markets*
D_j	*annual demand from market j*
K_i	*annual capacity of factory i*

Warehouse and Plant Location Model

- Plant and warehouse locations?
- Quantities shipped between various points?

$$Min\, C = \underbrace{\sum_{i=1}^{n} f_i y_i + \sum_{e=1}^{t} f_e y_e}_{} + \underbrace{\sum_{h=1}^{l}\sum_{i=1}^{n} c_{h,i} x_{h,i} + \sum_{i=1}^{n}\sum_{e=1}^{t} c_{i,e} x_{i,e} + \sum_{e=1}^{t}\sum_{j=1}^{m} c_{e,j} x_{e,j}}_{}$$

Fixed costs
plants
warehouse

Shipping costs
Supply source to plant
Plant to warehouse
Warehouse to market

Warehouse and Plant Location Model

- Supplier capacity $$\sum_{i=1}^{n} x_{h,i} \leq S_h \qquad h = 1,\ldots l$$
- Balance supply-plant $$\sum_{h=1}^{l} x_{h,i} - \sum_{e=1}^{t} x_{i,e} \geq 0 \qquad i = 1,\ldots n$$
- Supplier capacity $$\sum_{e=1}^{t} x_{i,e} \leq K_i y_i \qquad i = 1,\ldots n$$
- Balance plant-warehouse $$\sum_{i=1}^{n} x_{i,e} - \sum_{j=1}^{m} x_{e,j} \geq 0 \qquad e = 1,\ldots t$$
- Warehouse capacity $$\sum_{j=1}^{m} x_{e,j} \leq W_e y_e \qquad e = 1,\ldots t$$
- Demand satisfaction $$\sum_{e=1}^{t} x_{e,j} = D_j \qquad j = 1,\ldots m$$

Network design decisions in practice

- Do not underestimate the life span of plants
  - Long life hence long term consequences
  - Anticipate effect future demands, costs and technology change
  - Storage facilities easier to chance than production facilities
- Do not gloss over cultural implications
  - Location – urban, rural, proximity to others
- Do not ignore quality of life issues
  - Workforce availability and morale
- Focus on tariffs & tax incentives when locating facilities
  - Particularly in international locations

III.
Supply chain management of flexible process networks - Lagrangean-based decomposition techniques

Peter Chen
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Content

- Motivation
- Decomposition techniques considered
  - Lagrangean and Lagrangean/surrogate relaxation
  - Subgradient and Modified subgradient optimization
- Problem Statement
- CPFN Model
  - Structure
  - Objective and constraints
- Observation
- Decomposition Applied
  - Lagrangean relaxation
  - Lagrangean/surrogate relaxation
- Strategies Proposed
- Results
- Conclusion
- Future Work

Motivation

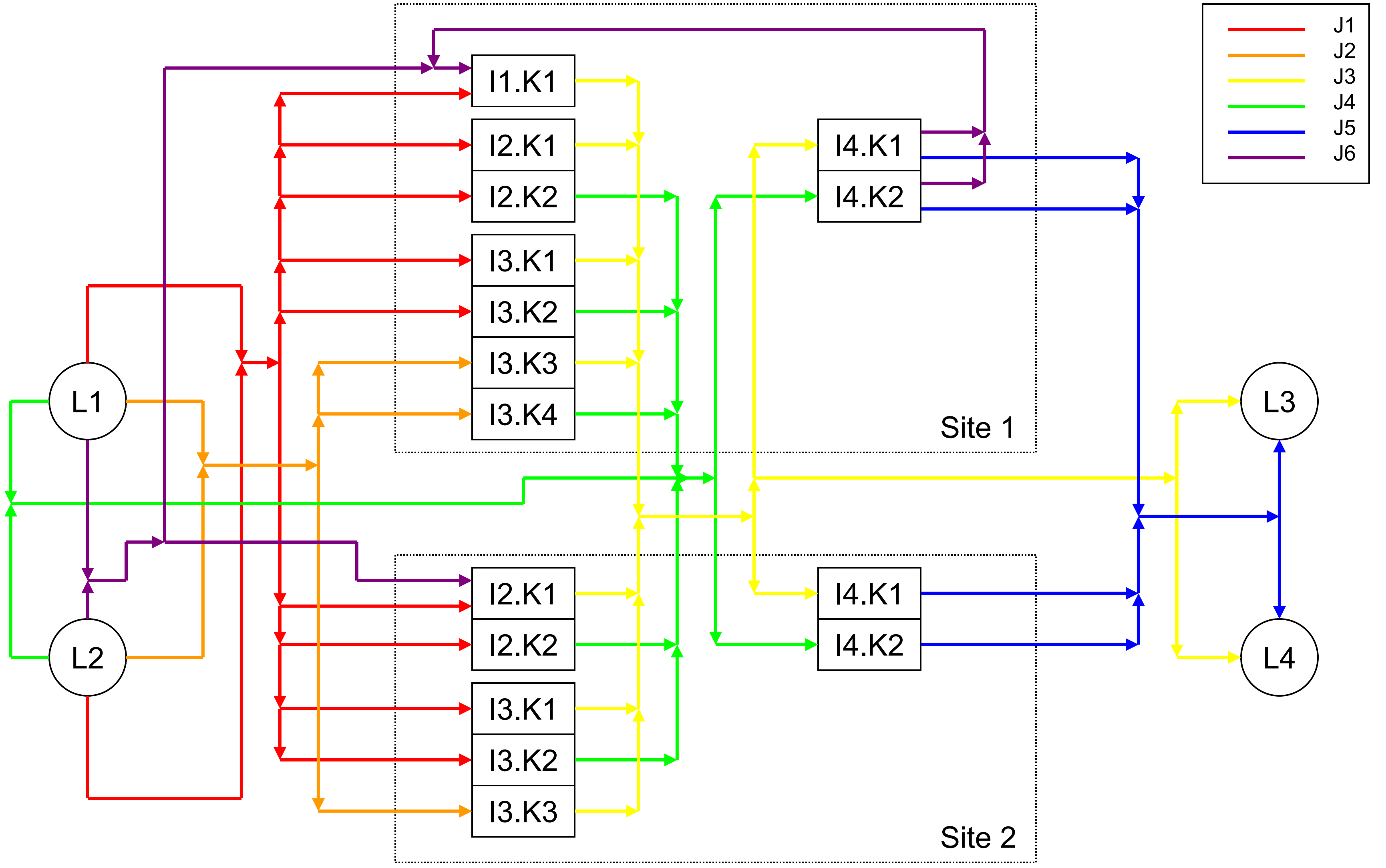
- Difficulties faced by most chemical companies
  - Increasing number of competitors
  - Increasing product variety from customer demand
  - Larger and more complicated process network
  - More efficient management is needed to survive and stay competitive
- Why decomposition techniques are needed
  - The optimization of process networks are very difficult to solve using standard (full-scale) method.
    - Large computational effort
    - Technological barriers
- Comparison of techniques are necessary
  - Various decomposition techniques exist
  - The effectiveness of the techniques is not standardized

Problem Statement

- A process network interconnects in a finite number of ways.
  - Processes I1~I4
    - I1 is dedicated
    - I2, I3, and I4 are flexible
  - Chemicals J1~J6
    - J1 and J2 are purchased
    - J3 is consumed or sold as product
    - J4 and J6 are purchased or produced
    - J5 is sold as product
  - Sites C1 & C2
    - C1: consists of all the processes and production schemes, contains byproduct J6.
    - C2: doesn’t have I1, I3 contains only 3 schemes, and J6 is not produced.
  - Markets L1~L4
    - L1 and L2 sells raw materials
    - L3 and L4 buys products

Bok et al. (2000) Ind. Eng. Chem. Res. 39, 1279-1290.

CFPN Structure



CFPN Model – Objective Function

- Objective – Maximize the operating profit of the network

$$Max\ Z_{CPFN} = \sum_{j\in J}\sum_{l\in L}\sum_{c\in C}\sum_{t\in T}\gamma_{jlt}S_{jlct}$$

Amount chemical sold

$$-\sum_{j\in J}\sum_{l\in L}\sum_{c\in C}\sum_{t\in T}\varphi_{jlt}P_{jlct}$$

Amount chemical bought

$$-\sum_{i\in I}\ \sum_{j\in JM_{ik}}\ \sum_{k\in K_i}\sum_{c\in C}\sum_{t\in T}\delta_{ikct}W_{ijkct}$$

Process operation cost

$$-\sum_{j\in J}\sum_{c\in C}\sum_{t\in T}\xi_{jc}V_{jct}$$

Inventory cost

$$-\sum_{i\in I}\sum_{k\in K_i}\sum_{k'\in K_i}\sum_{c\in C}\sum_{t\in T}\zeta_{ikk'c}Z_{ikk'ct}$$

Changeover cost

$$-\sum_{j\in J}\sum_{c\in C}\sum_{t\in T}\theta_{jlt}SF_{jlt}$$

Shortfall penalty cost

$$-\sum_{d\in D}\sum_{l\in L}\sum_{c\in C}\sum_{t\in T}\omega_{dlct}YP_{dlct}$$

Raw material delivery cost

$$-\sum_{j\in J}\sum_{l\in L}\sum_{t\in T}\phi_{jct}F_{jct}$$

Transportation cost

List of Assumptions

- Assumptions
  - Mass balance of raw materials and byproducts are proportional to the main product of the process and respective production scheme.
  - The operating cost of a process is proportional to the amount of main product produced.
  - Changeover only implies in cost and the overall time spent is negligible.
  - Only one delivery of chemicals from one market over τ_c time interval is allowed.
  - Demand is given by a range of values, having an upper and a lower bounds

CFPN Model – Constraints

- Ratio of input chemicals to the main product

$$W_{ijkct} = \mu_{ijkc} W_{ij'kct} \qquad i \in I_j, j \in JI_{ikc}, j' \in JM_{ik}, k \in K_i, c \in C, t \in T$$

- Ratio of output chemicals to the main product

$$W_{ijkct} = \mu_{ijkc} W_{ij'kct} \qquad i \in I_j, j \in JO_{ikc}, j' \in JM_{ik}, k \in K_i, c \in C, t \in T$$

- Limits production under available capacity

$$W_{ijkct} \le \rho_{ijck} Q_{ic} \qquad i \in I_j, j \in JM_{ik}, k \in K_i, c \in C, t \in T$$

- Indicates when changeover occurred ($Z_{ikk'ct} = 1$)

$$Y_{ikct} + Y_{ik'ct+1} - 1 \le Z_{ikk'ct} \qquad i \in I_j, k \in K_i, k' \in K_i, c \in C, t \in T$$

- Allows only one production scheme per time period

$$\sum_{k \in K_i} Y_{ikct} = 1 \qquad i \in I_j, k \in K_i, c \in C, t \in T$$

CFPN Model – Constraints (Cont'd)

- Mass balance of chemicals in the network

$$V_{jc,t-1} + \sum_{i \in O_j} \sum_{k \in K_i} W_{ijkct} + \sum_{l \in L} P_{jlct} + F_{jct} = V_{jct} + \sum_{l \in L} S_{jlct} + \sum_{i \in I_j} \sum_{k \in K_i} W_{ijkct} + \sum_{c' \in C - \{c\}} F_{jc't} \qquad j \in J, c \in C, t \in T$$

- Delivery of raw materials

$$P_{jlct} \le \sum_{d \in D} YP_{dlct} P^U_{jlct} \qquad j \in J, l \in L, c \in C, t \in T$$

- Limits one delivery of chemicals over a τ_c time interval.

$$YP_{dlc,t-2} + YP_{dlc,t-1} + YP_{dlct} \le 1 \qquad d \in D, l \in L, c \in C, t \in T$$

- Prevents the purchase of raw material from exceeding the available amount

$$\sum_{c \in C} P_{jlct} \le a^U_{jlt} \qquad j \in J, l \in L, t \in T$$

CFPN Model – Constraints (Cont'd)

- Limits the product sales below the maximum allowable demand

$$\sum_{c \in C} S_{jlct} \le d_{jlt}^{U} \qquad j \in J, l \in L, t \in T$$

- Shortfall penalty if the minimum demand is not met

$$SF_{jlt} \ge SF_{jl,t-1} + d_{jlt}^{L} - \sum_{c \in C} S_{jlct} \qquad j \in J, l \in L, t \in T$$

- Bounds

$$V_{jct} \le V_{jct}^{U}$$

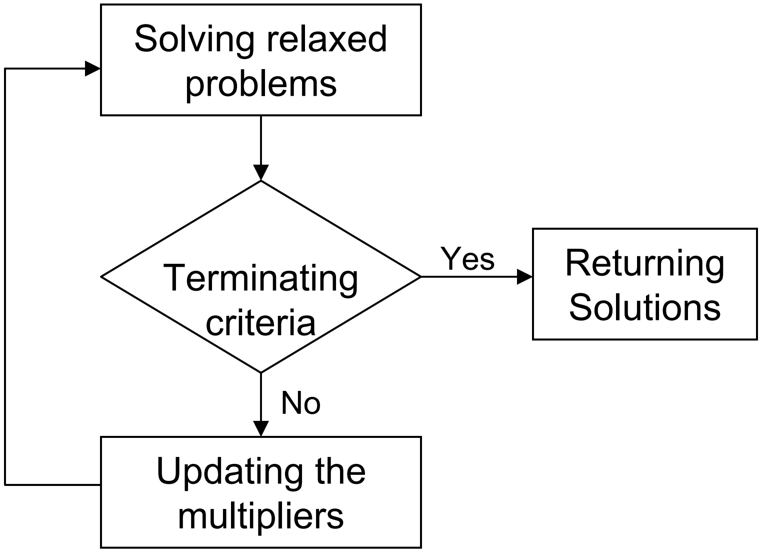
$$Z_{ikk'ct} \le 1$$

$$F_{jct}, P_{jlct}, S_{jlct}, SF_{jlt}, V_{jct}, W_{ijkct}, Z_{ikk'ct} \ge 0$$

$$Y_{ikct}, YP_{dlct} \in \{0,1\}$$

Decomposition techniques considered

- Relaxation
  - Lagrangean relaxation
    - Easier to solve
      - Relaxing the right constraint
      - Obtaining a good multiplier
  - Lagrangean/surrogate relaxation
    - Reduction in the oscillating behavior
- Updating multipliers
  - Subgradient optimization
    - Simple algorithm structure
  - Modified subgradient optimization
    - Accelerating convergence
      - A more suitable step size
      - Improved search direction



Lagrangean and Lagrangean/surrogate relaxation

- General MIP

$$Z = \max\ cx + dy$$
$$Ax + By \le b$$
$$Cx + Dy \le e$$
$$x \ge 0^m$$
$$y \in \{0,1\}^n$$

- Lagrangean relaxation

$$Z(u) = \max\ cx + u\big(b - (Ax + By)\big)$$
$$Cx + Dy \le e$$
$$x \ge 0^m$$
$$y \in \{0,1\}^n$$

- Lagrangean/surrogate relaxation

$$Z_u(t) = \max\ cx + t \cdot u\big(b - (Ax + By)\big)$$
$$Cx + Dy \le e$$
$$x \ge 0^m$$
$$y \in \{0,1\}^n.$$

Narciso and Lorena, *EJOR* **1999**, *114,* 165

Subgradient and modified subgradient optimization

- Subgradient optimization

$$u^{k+1} = u^k + t_k g^k \qquad t_k = \frac{l_k\left(w - L\left(u^k\right)\right)}{\left\|g^k\right\|^2} \qquad \varepsilon_1 \le l_k \le 2 - \varepsilon_2 \; \left(\varepsilon_1, \varepsilon_2 > 0\right)$$

- Modified subgradient optimization

$$u^{k+1} = u^k + t_k d^k \qquad t_k = \left(\frac{1}{\beta_k}\right)\left[\frac{\overline{L} - L(u^k)}{\left\|d^k\right\|^2}\right] \qquad \alpha_r = \begin{cases} \varepsilon_0 & if\;\; r \ge r_2 \\ e^{-0.6933(r/r_1)^{3.26}} & otherwise \end{cases}$$

$$d^k = g^k + \xi_k d^{k-1};$$

$$\xi_k = \begin{cases} -\gamma \dfrac{d^{k-1} g^k}{\left\|d^{k-1}\right\|^2} & If\;\; d^{k-1} g^k \ge 0, \\ 0 & Otherwise \end{cases}$$

$$\overline{L} = \alpha_r L^0 + (1 - \alpha_r) L^c;$$

Fumero, *Comp. & Oper. Res.* **2001**, *28*, 33-52.

Observation

- Constraints that link variables at different time period

$$Y_{ikct} + Y_{ik'ct+1} - 1 \le Z_{ikk'ct} \qquad i \in I_j, k \in K_i, k' \in K_i, c \in C, t \in T$$

$$V_{jc,t-1} + \sum_{i \in O_j} \sum_{k \in K_i} W_{ijkct} + \sum_{l \in L} P_{jlct} + F_{jct} = V_{jct} + \sum_{l \in L} S_{jlct} + \sum_{i \in I_j} \sum_{k \in K_i} W_{ijkct} + \sum_{c' \in C - \{c\}} F_{jc't} \qquad j \in J, c \in C, t \in T$$

$$YP_{dlc,t-2} + YP_{dlc,t-1} + YP_{dlct} \le 1 \qquad d \in D, l \in L, c \in C, t \in T$$

$$SF_{jlt} \ge SF_{jl,t-1} + d^L_{jlt} - \sum_{c \in C} S_{jlct} \qquad j \in J, l \in L, t \in T$$

- The model can be decomposed into |T| separate problems if the variables at different time periods in these constraints are treated as different variables.

Decomposition applied

- Following equations are declared and converted to the equivalent inequality form

$$V^B_{jct} = V^C_{jct} \quad \rightarrow \quad V^B_{jct} \geq V^C_{jct} \quad and \quad V^B_{jct} \leq V^C_{jct}$$

$$SF^B_{jlt} = SF^C_{jlt} \quad \rightarrow \quad SF^B_{jlt} \geq SF^C_{jlt} \quad and \quad SF^B_{jlt} \leq SF^C_{jlt}$$

$$Y^A_{ikct} = Y^B_{ikct} \quad \rightarrow \quad Y^A_{ikct} \geq Y^B_{ikct} \quad and \quad Y^A_{ikct} \leq Y^B_{ikct}$$

$$YP^A_{dlct} = YP^B_{dlct} \quad \rightarrow \quad YP^A_{dlct} \geq YP^B_{dlct} \quad and \quad YP^A_{dlct} \leq YP^B_{dlct}$$

$$YP^B_{dlct} = YP^C_{dlct} \quad \rightarrow \quad YP^B_{dlct} \geq YP^C_{dlct} \quad and \quad YP^B_{dlct} \leq YP^C_{dlct}$$

- Following variable replacement are done

$$V_{jct} \rightarrow V^B_{jct}, \quad V_{jc,t-1} \rightarrow V^C_{jc,t-1}$$

$$SF_{jlt} \rightarrow SF^B_{jlt}, \quad SF_{jl,t-1} \rightarrow SF^C_{jl,t-1}$$

$$Y_{ikc,t+1} \rightarrow Y^A_{ikc,t+1}, \quad Y_{ikct} \rightarrow Y^B_{ikct}$$

$$YP_{dlct} \rightarrow YP^A_{dlct}, \quad YP_{dlc,t-1} \rightarrow YP^B_{dlc,t-1}, \quad YP_{dlc,t-2} \rightarrow YP^C_{dlc,t-2}$$

- The model is decomposed into |T| sub-problems through relaxation

Lagrangean relaxation

- Relaxing the following inequalities into objective

$$V_{jct}^{B} \le V_{jct}^{C},\quad SF_{jlt}^{B} \le SF_{jlt}^{C},\quad Y_{ikct}^{A} \ge Y_{ikct}^{B},\quad YP_{dlct}^{A} \le YP_{dlct}^{B},\quad Yp_{dlct}^{B} \ge YP_{dlct}^{C}$$

- Adding the remaining inequalities as constraints

$$V_{jct}^{B} \ge V_{jct}^{C},\quad SF_{jlt}^{B} \ge SF_{jlt}^{C},\quad Y_{ikct}^{A} \le Y_{ikct}^{B},\quad YP_{dlct}^{A} \ge YP_{dlct}^{B},\quad Yp_{dlct}^{B} \le YP_{dlct}^{C}$$

- Resulting objective function

$$\begin{aligned}
Max\ Z_{CFPN-LR} = & \sum_{t\in T}\left(\sum_{j\in J}\sum_{l\in L}\sum_{c\in C}\gamma_{jlt}S_{jlct}\right) - \sum_{t\in T}\left(\sum_{j\in J}\sum_{l\in L}\sum_{c\in C}\varphi_{jlt}P_{jlct}\right) - \sum_{t\in T}\left(\sum_{i\in I}\sum_{j\in JM_{ik}}\sum_{k\in K_i}\sum_{c\in C}\delta_{ikct}W_{ijkct}\right) \\
& - \sum_{t\in T}\left(\sum_{j\in J}\sum_{c\in C}\xi_{jc}V_{jct}^{B}\right) - \sum_{t\in T}\left(\sum_{i\in I}\sum_{k\in K_i}\sum_{k'\in K_i}\sum_{c\in C}\zeta_{ikk'c}Z_{ikk'ct}\right) - \sum_{t\in T}\left(\sum_{j\in J}\sum_{c\in C}\theta_{jlt}SF_{jlt}^{B}\right) - \sum_{t\in T}\left(\sum_{d\in D}\sum_{l\in L}\sum_{c\in C}\omega_{dlct}YP_{dlct}^{A}\right) \\
& - \sum_{t\in T}\left(\sum_{j\in J}\sum_{l\in L}\phi_{jct}F_{jct}\right) + \sum_{t\in T}\left(\sum_{j\in J}\sum_{c\in C}u_{jct}^{V}(V_{jct}^{C} - V_{jct}^{B})\right) + \sum_{t\in T}\left(\sum_{i\in I}\sum_{k\in K_i}\sum_{c\in C}u_{ikct}^{Y}(Y_{ikct}^{A} - Y_{ikct}^{B})\right) \\
& + \sum_{t\in T}\left(\sum_{j\in J}\sum_{l\in L}u_{jlt}^{SF}(SF_{jlt}^{C} - SF_{jlt}^{B})\right) + \sum_{t\in T}\left(\sum_{d\in D}\sum_{l\in L}\sum_{c\in C}u_{dlct}^{YP1}(YP_{dlct}^{B} - YP_{dlct}^{A})\right) + \sum_{t\in T}\left(\sum_{d\in D}\sum_{l\in L}\sum_{c\in C}u_{dlct}^{YP2}(YP_{dlct}^{B} - YP_{dlct}^{C})\right)
\end{aligned}$$

Lagrangean relaxation (Cont'd)

- Resulting objective function at time period *t*

$$Max\ Z^t_{CFPN-LR} = \sum_{j\in J}\sum_{l\in L}\sum_{c\in C}\gamma_{jlt}S_{jlct} - \sum_{j\in J}\sum_{l\in L}\sum_{c\in C}\varphi_{jlt}P_{jlct} - \sum_{i\in I}\sum_{j\in JM_{ik}}\sum_{k\in K_i}\sum_{c\in C}\delta_{ikct}W_{ijkct} - \sum_{j\in J}\sum_{c\in C}\xi_{jc}V^B_{jct}$$
$$- \sum_{i\in I}\sum_{k\in K_i}\sum_{k'\in K_i}\sum_{c\in C}\zeta_{ikk'c}Z_{ikk'ct} - \sum_{j\in J}\sum_{c\in C}\theta_{jlt}SF^B_{jlt} - \sum_{d\in D}\sum_{l\in L}\sum_{c\in C}\omega_{dlct}YP^A_{dlct} - \sum_{j\in J}\sum_{l\in L}\phi_{jct}F_{jct}$$
$$+ \sum_{j\in J}\sum_{c\in C}u^V_{jct}(V^C_{jct} - V^B_{jct}) + \sum_{i\in I}\sum_{k\in K_i}\sum_{c\in C}u^Y_{ikct}(Y^A_{ikct} - Y^B_{ikct}) + \sum_{j\in J}\sum_{l\in L}u^{SF}_{jlt}(SF^C_{jlt} - SF^B_{jlt})$$
$$+ \sum_{d\in D}\sum_{l\in L}\sum_{c\in C}u^{YP1}_{dlct}(YP^B_{dlct} - YP^A_{dlct}) + \sum_{d\in D}\sum_{l\in L}\sum_{c\in C}u^{YP2}_{dlct}(YP^B_{dlct} - YP^C_{dlct})$$

- The total profit is equal to the summation over the time periods

$$Z_{CFPN-LR} = \sum_{t\in T} Z^t_{CFPN-LR}$$

Lagrangean relaxation - Constraints

- List of constraints

$$W_{ijkct} = \mu_{ijkc} W_{ij'kct} \qquad i \in I_j, j \in JI_{ikc}, j' \in JM_{ik}, k \in K_i, c \in C$$

$$W_{ijkct} = \mu_{ijkc} W_{ij'kct} \qquad i \in I_j, j \in JO_{ikc}, j' \in JM_{ik}, k \in K_i, c \in C$$

$$W_{ijkct} \leq \rho_{ijck} Q_{ic} \qquad i \in I_j, j \in JM_{ik}, k \in K_i, c \in C$$

$$Y_{ikct}^{B} + Y_{ik'c,t+1}^{C} - 1 \leq Z_{ikk'ct} \qquad i \in I_j, k \in K_i, k' \in K_i, c \in C$$

$$\sum_{k \in K_i} Y_{ikct}^{B} = 1 \qquad i \in I_j, k \in K_i, c \in C$$

$$V_{jc,t-1}^{C} + \sum_{i \in O_j} \sum_{k \in K_i} W_{ijkct} + \sum_{l \in L} P_{jlct} + F_{jct} = V_{jct}^{B} + \sum_{l \in L} S_{jlct} + \sum_{i \in I_j} \sum_{k \in K_i} W_{ijkct} + \sum_{c' \in C - \{c\}} F_{jc't} \qquad j \in J, c \in C$$

$$P_{jlct} \leq \sum_{d \in D} YP_{dlct}^{C} P_{jlct}^{U} \qquad j \in J, l \in L, c \in C$$

$$YP_{dlc,t-2}^{C} + YP_{dlc,t-1}^{B} + YP_{dlct}^{A} \leq 1 \qquad d \in D, l \in L, c \in C$$

Lagrangean relaxation – Constraints (Cont'd)

$$\sum_{c \in C} P_{jlct} \le a^U_{jlt} \qquad j \in J, l \in L$$

$$\sum_{c \in C} S_{jlct} \le d^U_{jlt} \qquad j \in J, l \in L$$

$$SF^B_{jlt} \ge SF^C_{jl,t-1} + d^L_{jlt} - \sum_{c \in C} S_{jlct} \qquad j \in J, l \in L$$

$$V^B_{jct} \le V^U_{jct}, \quad V^C_{jct} \le V^U_{jct}, \quad Z_{ikk'ct} \le 1$$

$$F_{jct}, P_{jlct}, S_{jlct}, SF^B_{jlt}, SF^C_{jlt}, V^B_{jct}, V^C_{jct}, W_{ijkct}, Z_{ikk'ct} \ge 0$$

$$Y^A_{ikct}, Y^B_{ikct}, YP^A_{dlct}, YP^B_{dlct}, YP^C_{dlct} \in \{0,1\}$$

$$V^B_{jct} \ge V^C_{jct}, \quad SF^B_{jlt} \ge SF^C_{jlt}, \quad Y^A_{ikct} \le Y^B_{ikct}, \quad YP^A_{dlct} \ge YP^B_{dlct}, \quad Yp^B_{dlct} \le YP^C_{dlct}$$

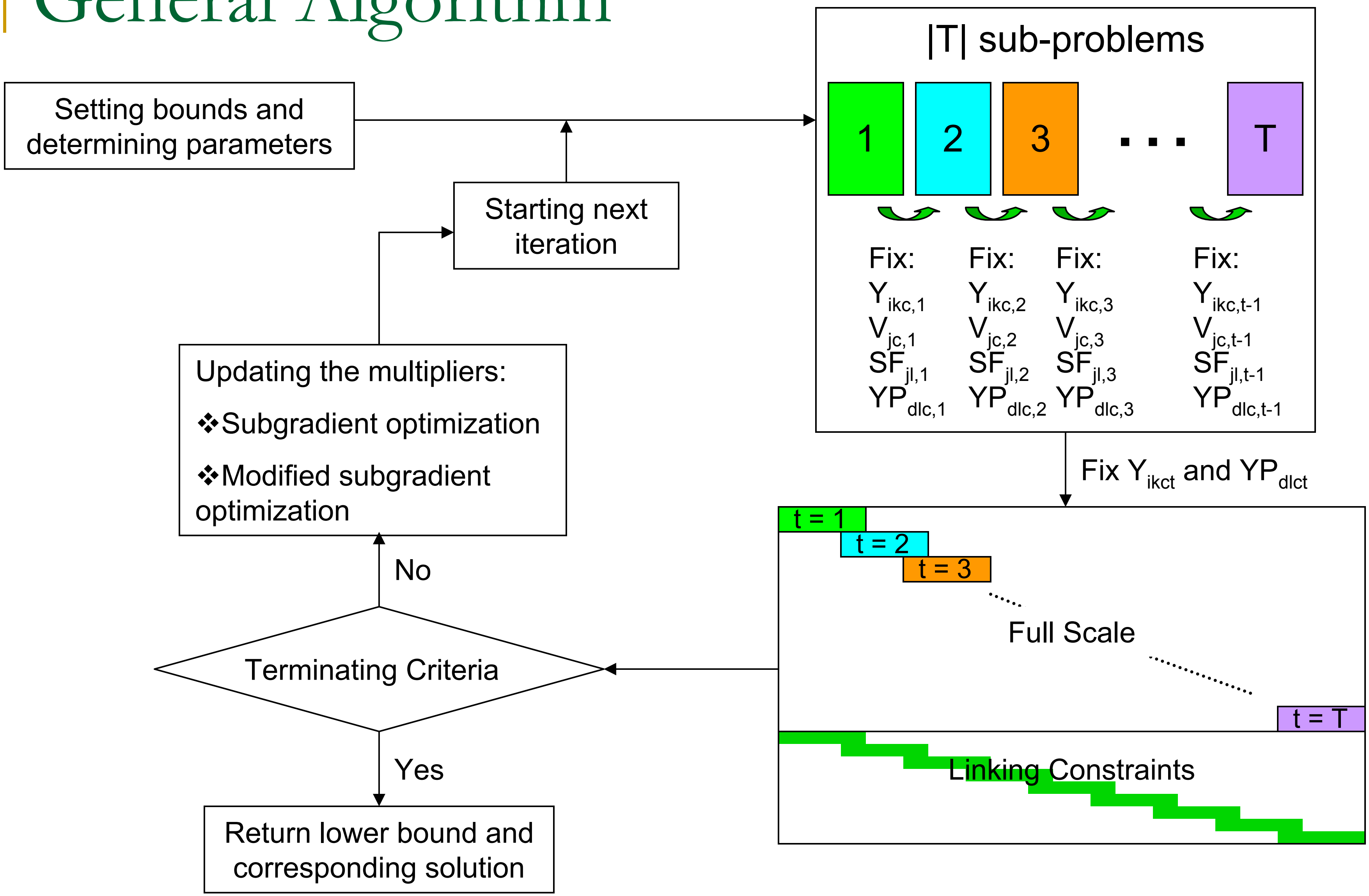
Lagrangean/surrogate relaxation

- Lagrangean/surrogate relaxation is done in a similar fashion like the Lagrangean relaxation
- Resulting objective function at each time period *t*

$$
\begin{aligned}
Max\ Z^t_{CFPN-LS} = & \sum_{j\in J}\sum_{l\in L}\sum_{c\in C}\gamma_{jlt}S_{jlct} - \sum_{j\in J}\sum_{l\in L}\sum_{c\in C}\varphi_{jlt}P_{jlct} - \sum_{i\in I}\sum_{j\in JM_{ik}}\sum_{k\in K_i}\sum_{c\in C}\delta_{ikct}W_{ijkct} - \sum_{j\in J}\sum_{c\in C}\xi_{jc}V^B_{jct} \\
& - \sum_{i\in I}\sum_{k\in K_i}\sum_{k'\in K_i}\sum_{c\in C}\zeta_{ikk'c}Z_{ikk'ct} - \sum_{j\in J}\sum_{c\in C}\theta_{jlt}SF^B_{jlt} - \sum_{d\in D}\sum_{l\in L}\sum_{c\in C}\omega_{dlct}YP^A_{dlct} - \sum_{j\in J}\sum_{l\in L}\phi_{jct}F_{jct} \\
& + t\times\Bigg(\sum_{j\in J}\sum_{c\in C}u^V_{jct}(V^C_{jct}-V^B_{jct}) + \sum_{i\in I}\sum_{k\in K_i}\sum_{c\in C}u^Y_{ikct}(Y^A_{ikct}-Y^B_{ikct}) + \sum_{j\in J}\sum_{l\in L}u^{SF}_{jlt}(SF^C_{jlt}-SF^B_{jlt}) \\
& + \sum_{d\in D}\sum_{l\in L}\sum_{c\in C}u^{YP1}_{dlct}(YP^B_{dlct}-YP^A_{dlct}) + \sum_{d\in D}\sum_{l\in L}\sum_{c\in C}u^{YP2}_{dlct}(YP^B_{dlct}-YP^C_{dlct})\Bigg)
\end{aligned}
$$

- Subject to the same constraints as the Lagrangean relaxation
- Total Profit: $Z_{CFPN-LS} = \sum_{t\in T} Z^t_{CFPN-LS}$

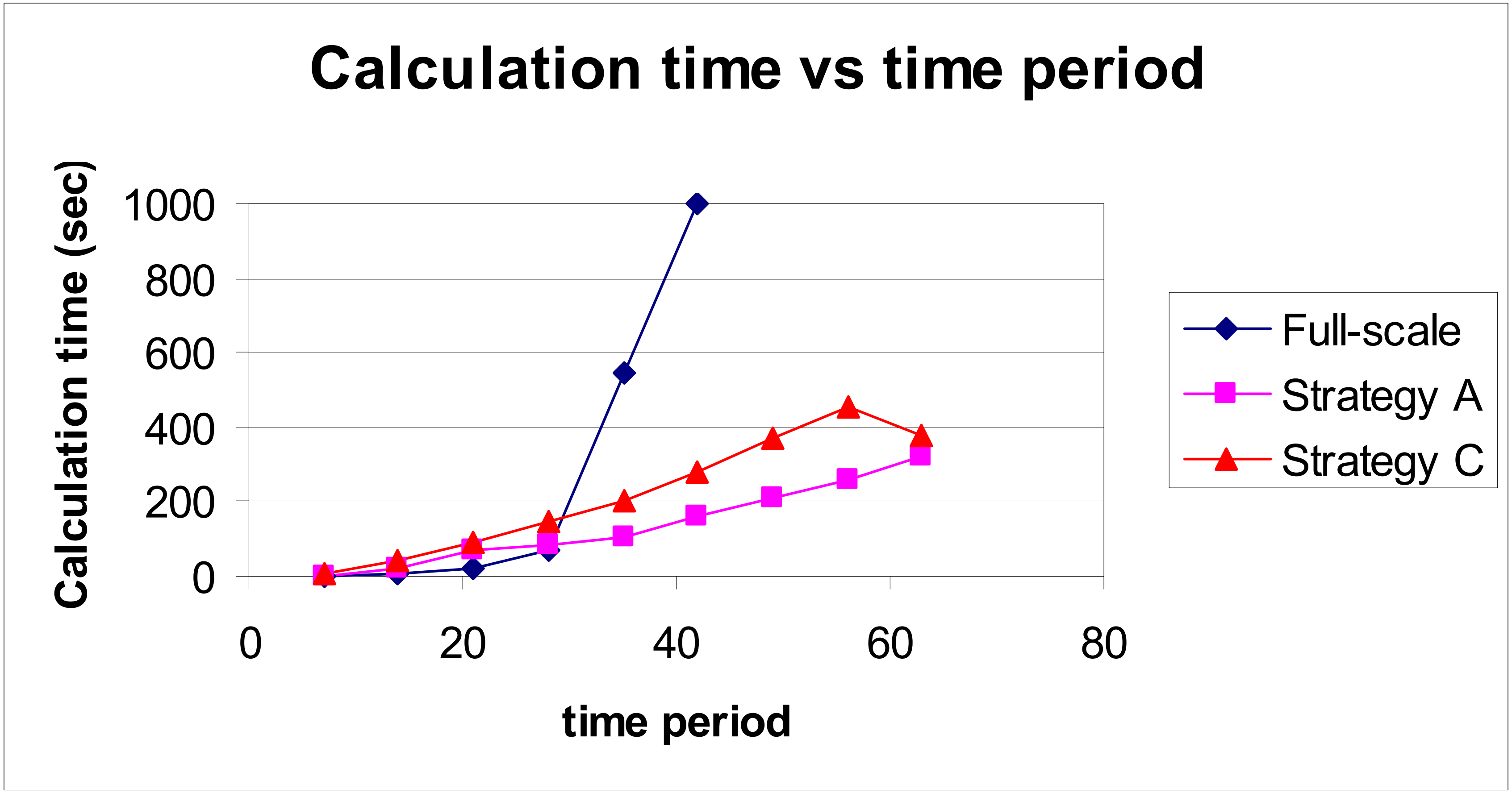
General Algorithm



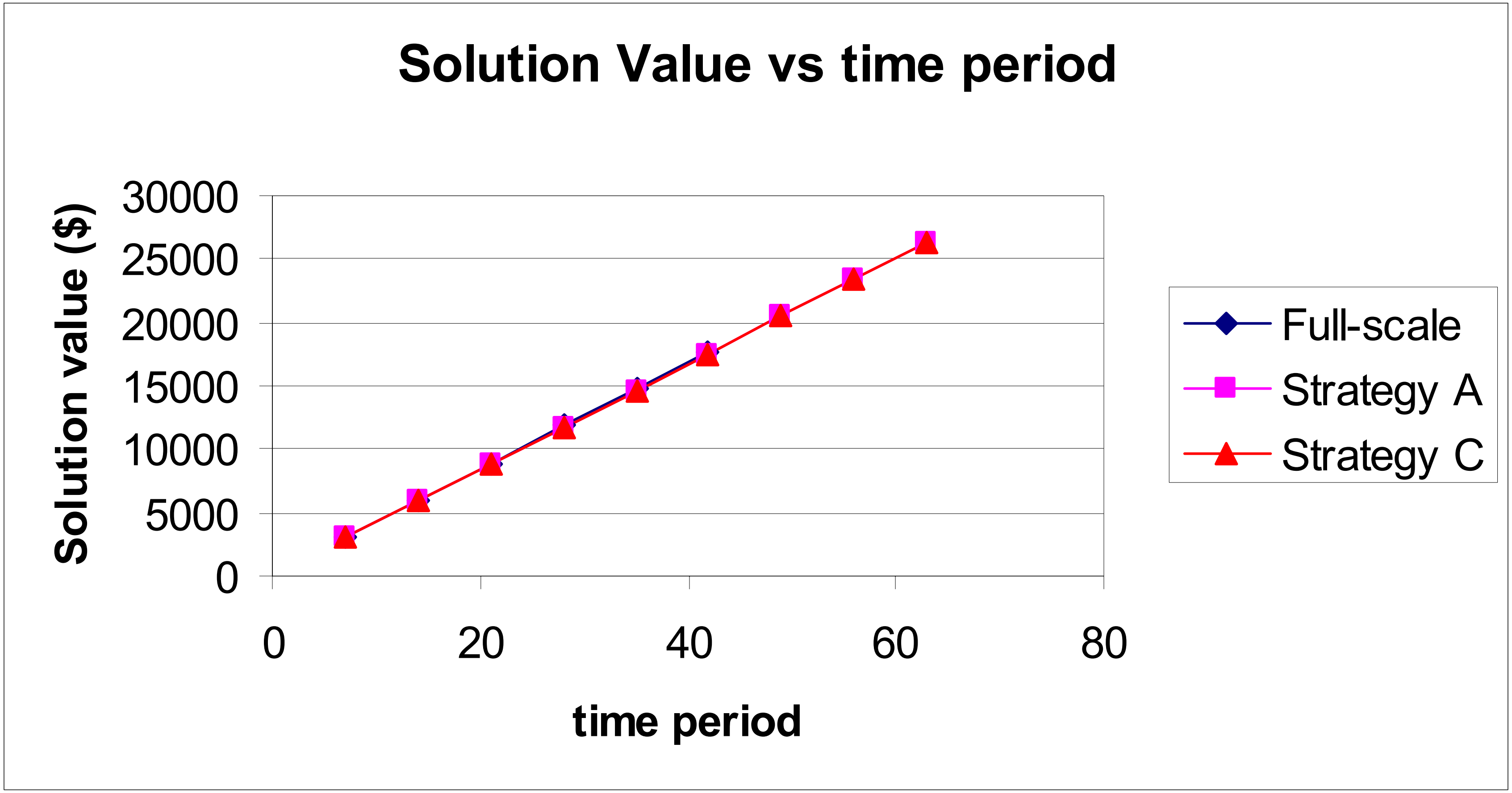
Proposed strategy

- Strategy A
  - Lagrangean relaxation with subgradient optimization
- Strategy B
  - Lagrangean relaxation with modified subgradient optimization
- Strategy C
  - Lagrangean/surrogate relaxation with subgradient optimization
- Strategy D
  - Lagrangean/surrogate relaxation with modified subgradient optimization

Results – Calculation time



Results – Solution value



Results – Percent difference from the optimum

time period	Strategy A	Strategy C
7	0.000	0.000
14	0.554	0.536
21	1.195	1.723
28	0.829	0.826
35	0.833	0.824
42	1.317	1.313

Conclusion

- Calculation time
  - Time spent is much less than the full scale method
- Solution value
  - The percentage deviation from the optimum is below 2%
- Lagrangean vs. Lagrangean/surrogate relaxation
  - Lagrangean/surrogate always used equal or more iterations
  - Lagrangean/surrogate spent slightly more time
  - For same number of iterations, Lagrangean relaxation gave equal or better solution value

Alternative approaches

- Decentralized approach
  - Model predictive control strategies
    - Multiproduct, multiechelon distribution networks with multiproduct batch plants
    - (Perea, Ydstie and Grossmann, 2003)
  - Comparison with integrated approach
    - Poorer coordination of the supply chain decisions
    - Smaller computational time

Future work

- Implementing modified subgradient optimization
- Testing strategies B and D and compare them with A and C
- Search for new strategies
  - Other decomposition methods
  - Applying *search_t** algorithm for each set of multiplier values

IV.
Planning, Scheduling and Supply Chain Management for Operations in Oil Refineries

JOSÉ M. PINTO

OUTLINE

- *Introduction*
- *Planning Models*
  - *refinery diesel production*
- *Scheduling models*
  - *crude oil scheduling*
  - *fuel oil / asphalt area*
- *Logistics*
  - *oil supply model*
- *Petroleum Supply Chain*
- *Conclusions*

MOTIVATION

Refinery Targets

- Profitability Maximization
  (Pelham and Pharris, 1996; Ramage, 1998)
- Minimization of Operational Costs
  (Bodington and Shobrys, 1996)

Beginning of Computational Applications for *Planning/Scheduling*:

- Petrochemical Industry: **1950s** (Linear Programming)
  (Symonds, 1955; Bodington, 1992) (Dantzig, 1963)
- CPI in general: **1970s**
  (Reklaitis, 1991; Kudva and Pekny; 1993)

ADVANCES

- Availability of more powerful and less expensive computers;
- Mathematical Developments:
    - Time representation;
      (Moro and Pinto, 1998)
    - Combinatorics in MIP;
      (Raman and Grossmann, 1994)
    - Non-convexities in MINLP;
      (Viswanathan and Grossmann, 1990)

Consequences for the Petroleum Industry:
(Ramage, 1998)

Unit Level *Optimization (FCC, Crude Unit, etc..)*	*Large Portions of the Plant or* ***Plant-wide*** *Optimization*
1980's	**1990's**

OPTIMIZATION IN REFINERY OPERATIONS

LPs in crude blending and product pooling (50´s)	*(Symonds, 1955)*
Advanced control : MPC	*(Cutler, DMCC,1983)*
Planning models	*(Coxhead, Moro et al, 1998.)*
crude selection, crude allocation for multi refinery	
partnership models for raw material supply	
OVM Refinery, Austria (**LP**)	*(Steinschorn and Hofferl, 1997)*
In-house simulation models for scheduling	*(Magalhaes et al., 1998)*
Scheduling optimization models	
gasoline blending	*(Bodington, 1993)*
gasoline production, *TEXACO*(**NLP**)	*(Rigby et al., 1995)*
crude oil unloading	*(Lee et al., Shah, 1996)*

OUTLINE

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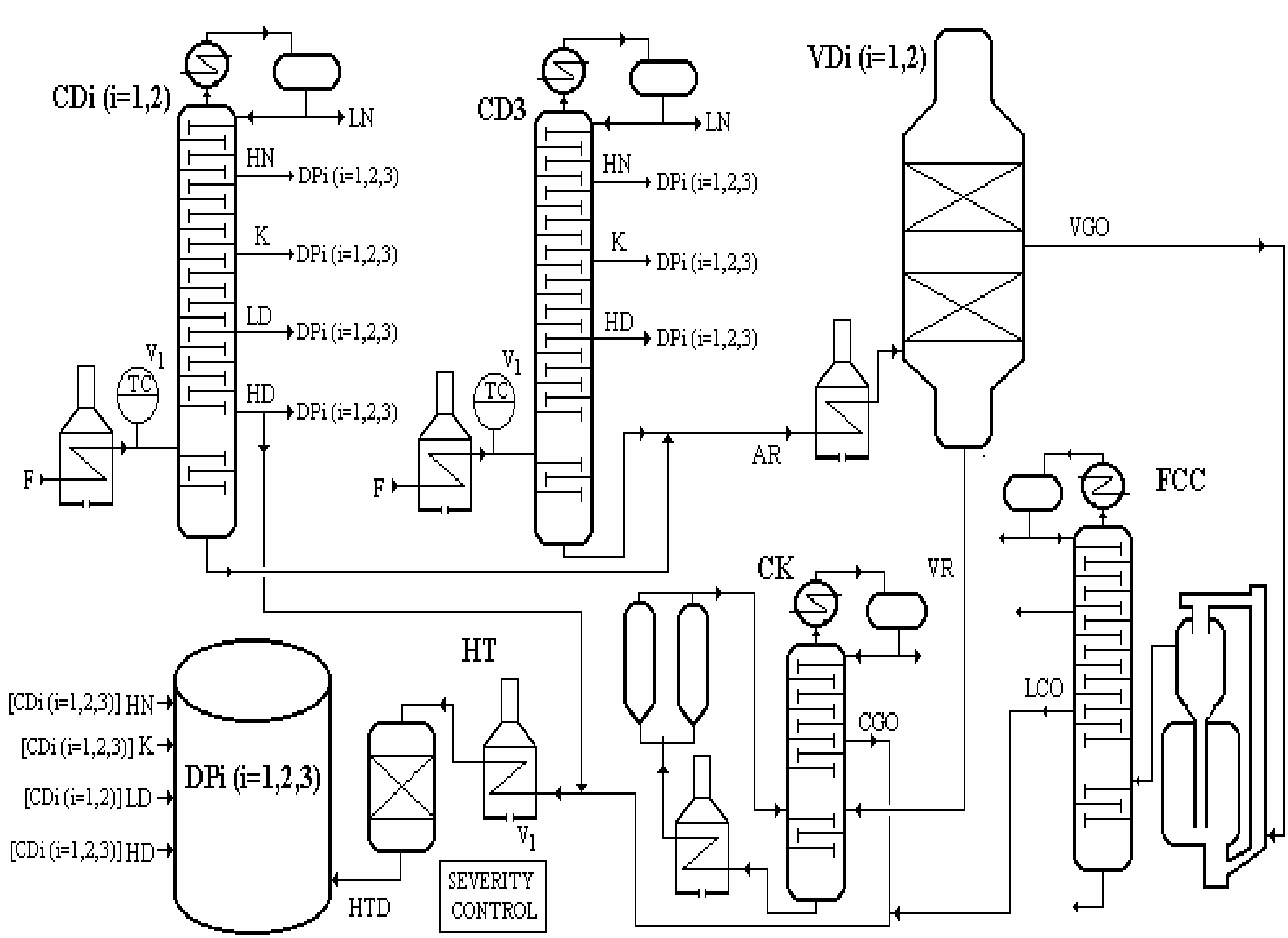
- *Conclusions*

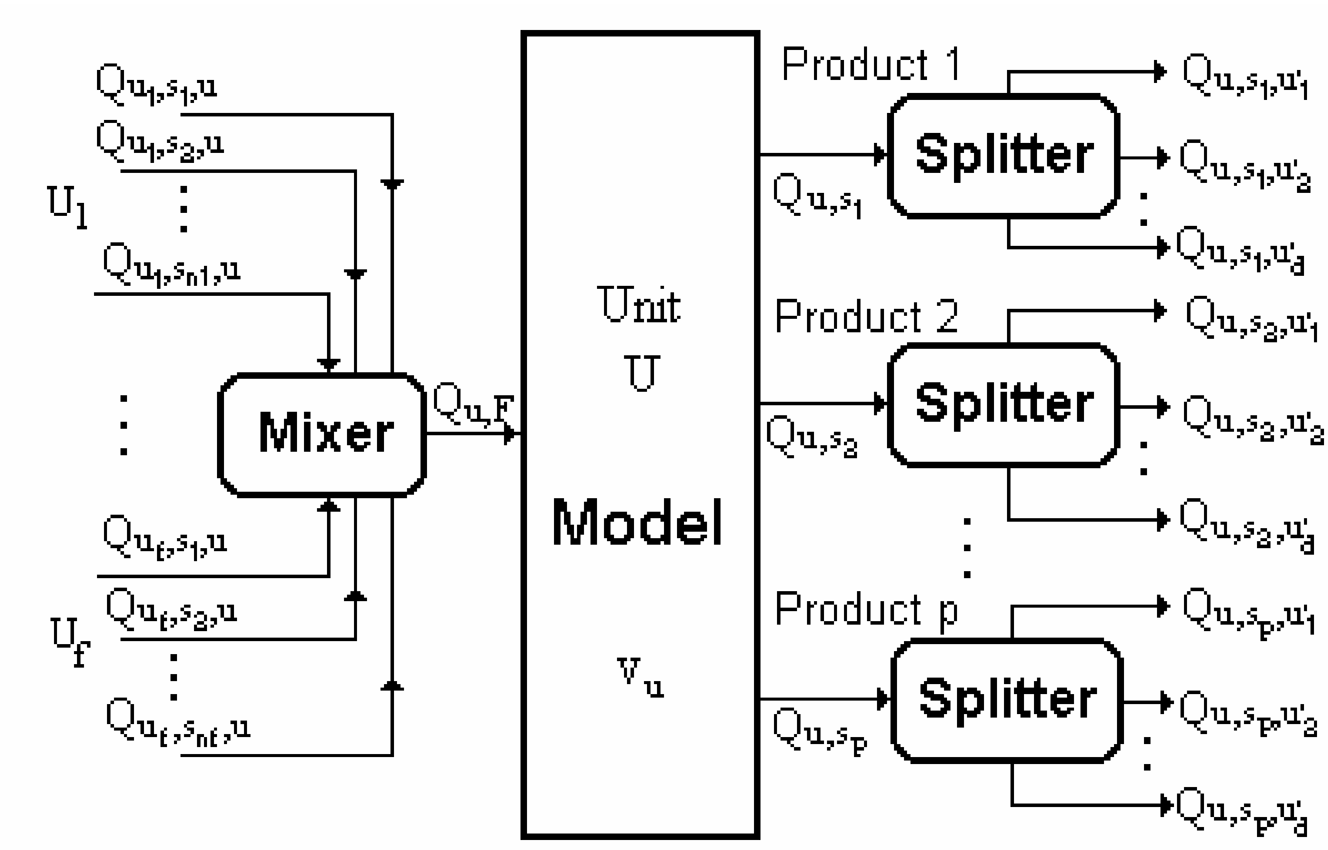
PLANNING MODEL FOR REFINERIES

Objectives

- To develop a general representation for refinery units
  - streams with multiple inputs and destinations
  - nonlinear mixing and process equations
  - bounds on unit variables
- To apply to the production planning of a real world refinery
  - diesel production
  - to satisfy multiple specifications


CDi (i=1,2)
LN
HN
DPi (i=1,2,3)
K
DPi (i=1,2,3)
LD
DPi (i=1,2,3)
HD
DPi (i=1,2,3)
V_1
TC
F
CD3
LN
HN
DPi (i=1,2,3)
K
DPi (i=1,2,3)
HD
DPi (i=1,2,3)
V_1
TC
F
VDi (i=1,2)
VGO
AR
FCC
CK
VR
LCO
CGO
HT
[CDi (i=1,2,3)] HN
[CDi (i=1,2,3)] K
[CDi (i=1,2)] LD
[CDi (i=1,2,3)] HD
DPi (i=1,2,3)
HTD
SEVERITY CONTROL
V_1

TYPICAL PROCESS UNIT



UNIT EQUATIONS

- Feed flowrate:

$$Q_{u,F} = \sum_{u' \in U_u} \sum_{s \in S_{u',u}} Q_{u',s,u}$$

- Feed Properties:

$$P_{u,F,j} = f_j\,(Q_{u',s,u} \,,\, Pu',s,j\,) \qquad u' \in U_u,\ s \in S_{u',u},\ j \in J_s$$

- Total flowrate of each product stream:

$$Q_{u,s} = f\,(Q_{u,F} \,,\, P_{u,F,j} \,,\, V_u\,) \qquad j \in J_F,\ s \in S_U$$

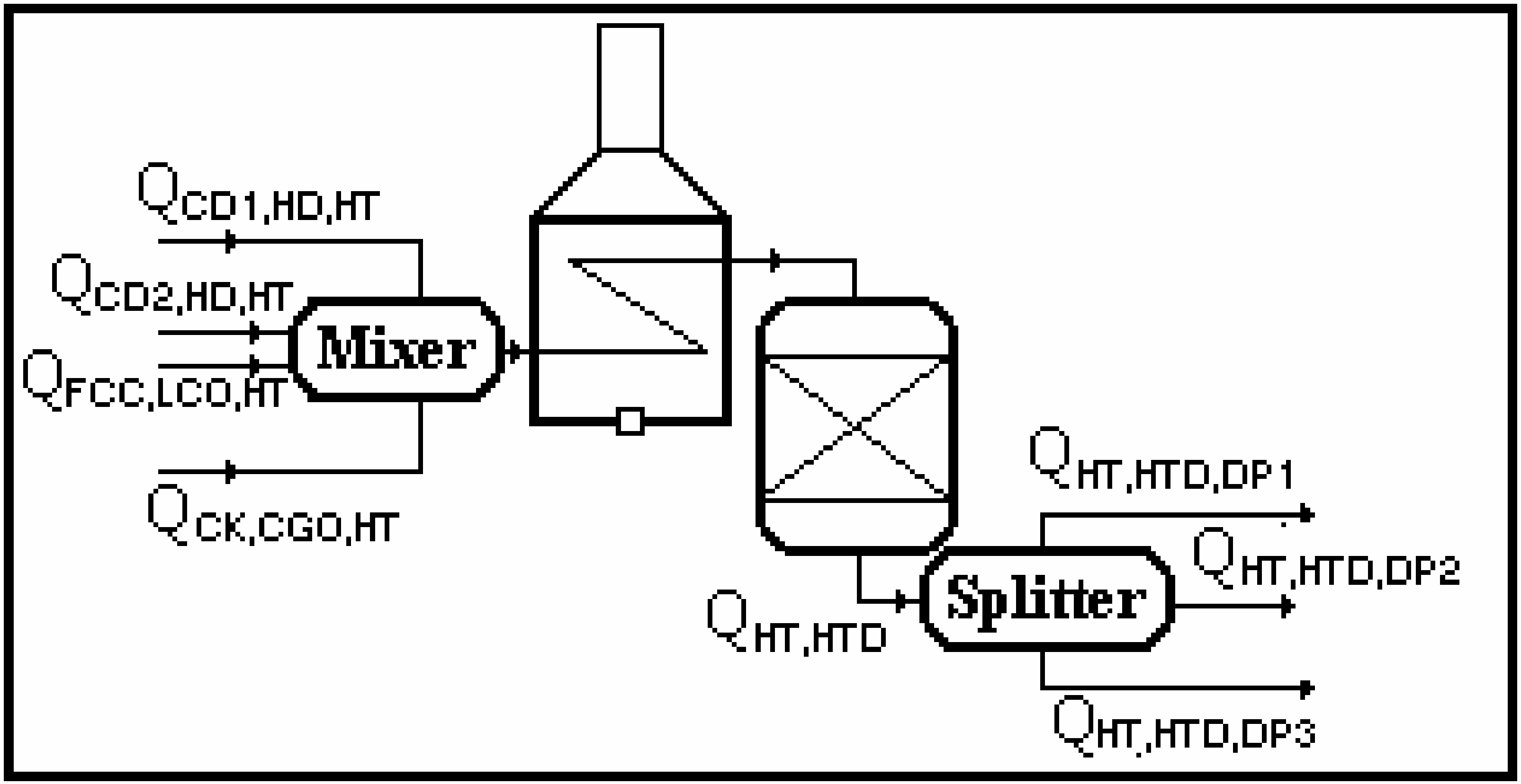
- Unit product stream properties:

$$P_{u,s,j} = f_j\,(P_{u,F,j} \,,\, V_u\,) \qquad j \in J_s,\ s \in S_U$$

- Product streams flowrates (splitter):

$$Q_{u,s} = \sum_{u' \in U_{s,u}} Q_{u,s,u'} \qquad s \in S_U$$

HYDROTREATING UNIT (HT)



HT MODEL

Feed flowrate:

$$Q_{HT,F}=Q_{CD1,HD,HT}+Q_{CD2,HD,HT}+Q_{FCC,LCO,HT}+Q_{CK,CGO,HD}$$

Feed properties:

$$P_{HT,F,j} = f_j\,(Q_{u',s,HT}\,,\,P_{u',s,j}) \qquad \in \qquad u' \in U_{HT}\,,\ s \in S_{u',HT},\ j \quad J_{HT}$$

Example - Flash Point (FP)

$$P_{HT,F,FP} = 0.55\left[\frac{10006.1}{ln(\alpha)+14.0922} - 415\right] \qquad \alpha = \frac{\sum_{u \in U_{HT}} Q_{u,HD,HT} I_{u,HD,FP}}{\sum_{u \in U_{HT}} Q_{u,HD,HT}}$$

$$I_{u,HD,FP} = \exp[10006.1/(1.8\,P_{u,HD,FP}+415) - 14.0922] \qquad u \in U_{HT}$$

REAL-WORLD APPLICATION

Planning of diesel production

Petrobras RPBC refinery in Cubatão (SP, Brazil).

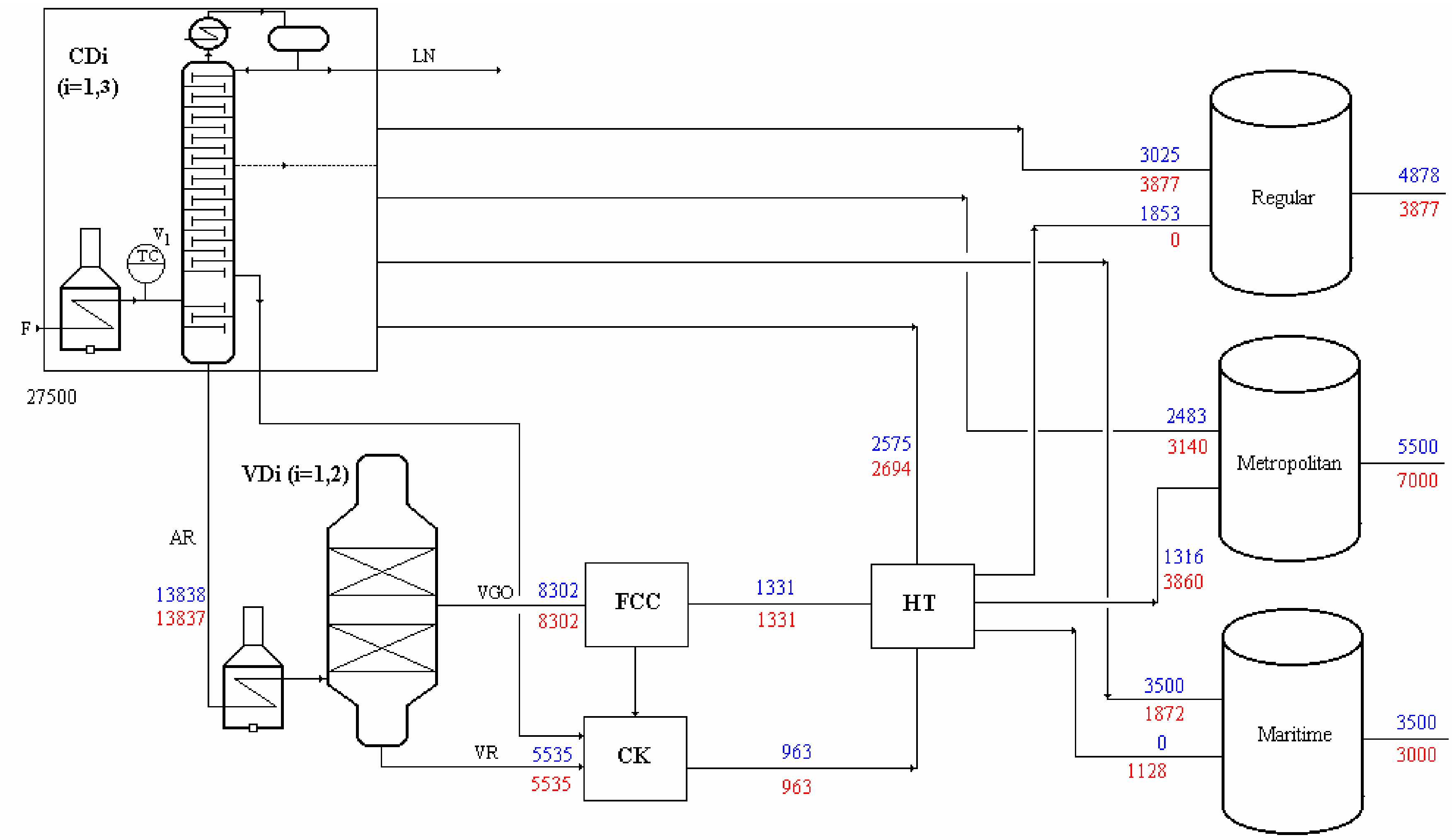
Three types of diesel oil:

Metropolitan Diesel.	Low sulfur levels metropolitan areas
Regular Diesel.	Higher sulfur levels other regions of the country
Maritime Diesel.	High flashing point.

DIESEL SPECIFICATIONS

Property	DIESEL		
	REGULAR	METROPOLITAN	MARITIME
DENSITY min / max	0.82/ 0.88	0.82/ 0.88	0.82/ 0.88
FLASH POINT min (°C)	-	-	60.0
ASTM 50% min / max (°C)	245.0/ 310.0	245.0/ 310.0	245.0/ 310.0
ASTM 85% max (°C)	370.0	360.0	370.0
CETANE NUMBER min	40.0	42.0	40.0
SULFUR CONTENT max (% WEIGHT)	0.5	0.2	1.0

MAIN RESULTS



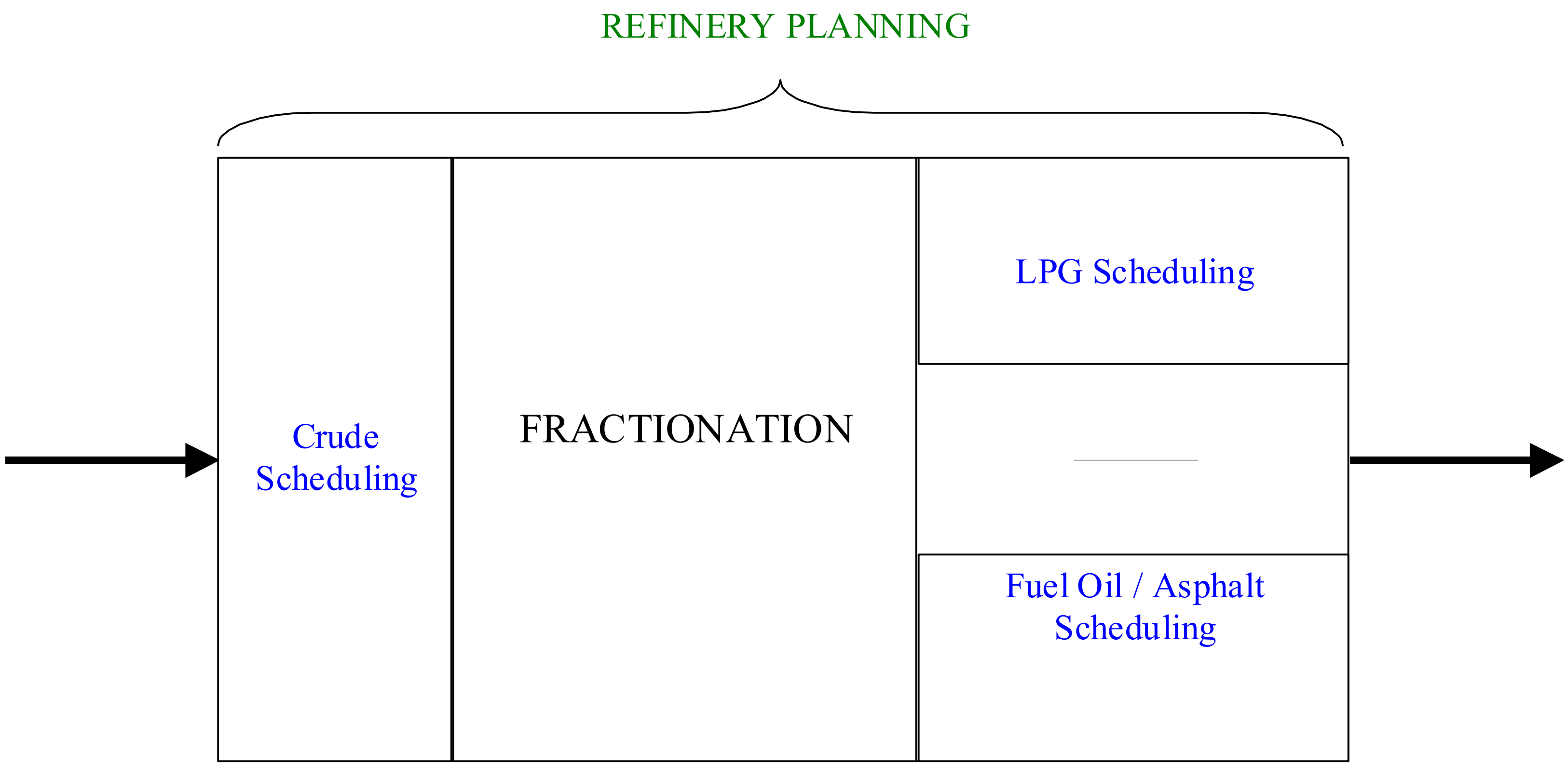
Potential Improvement US$ 23,000 / day or US$ 8,000,000 / yr

Implemented with on-line data acquisition

OUTLINE

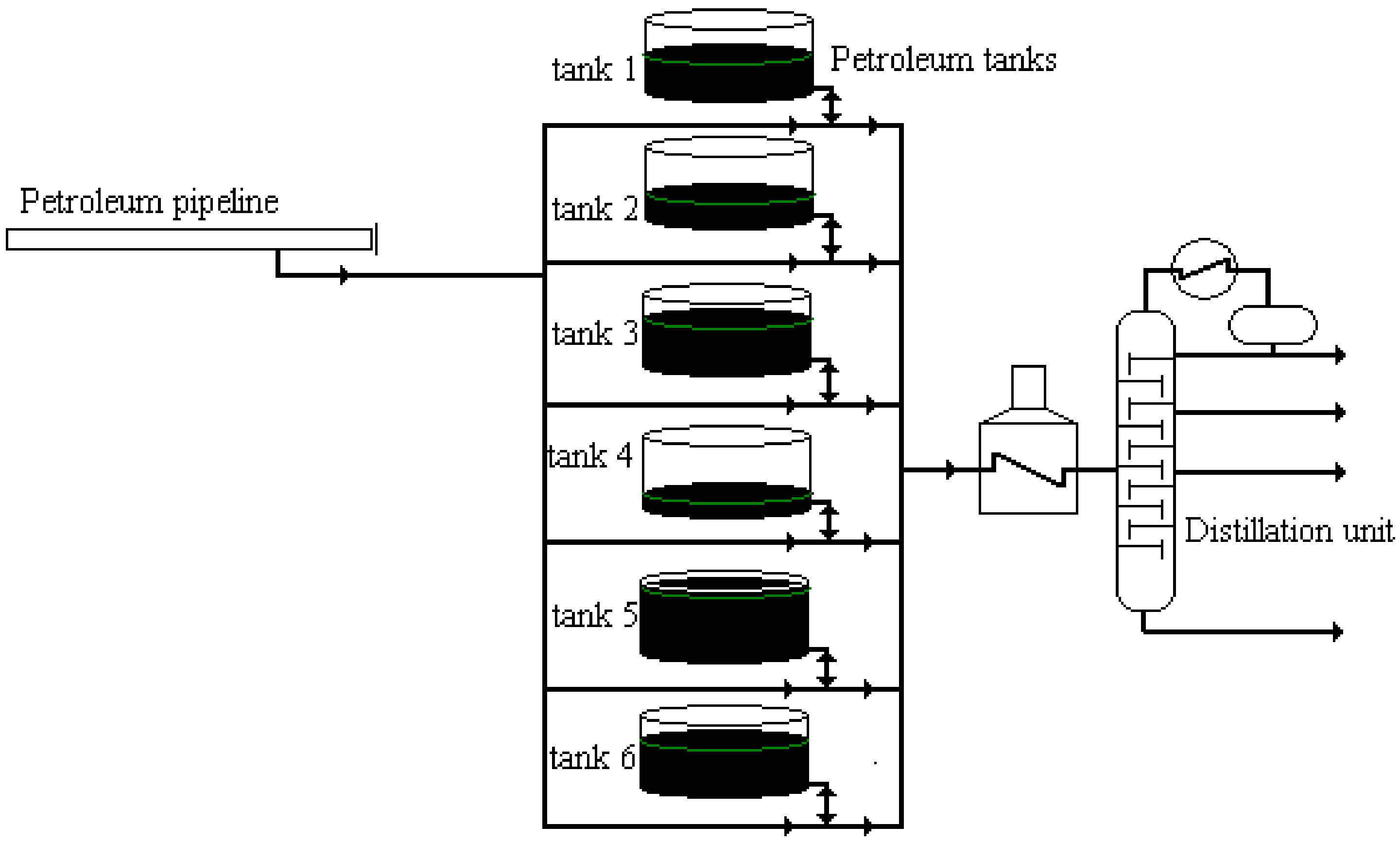
- *Introduction*
- *Planning Models*
  - *refinery diesel production*
- *Scheduling models*
  - *crude oil scheduling*
  - *fuel oil / asphalt area*
- *Logistics*
  - *oil supply model*
- *Conclusions*

PROPOSED APPROACH FOR PLANNING AND SCHEDULING



SHORT TERM CRUDE OIL SCHEDULING

Crude Oil System



OBJECTIVES

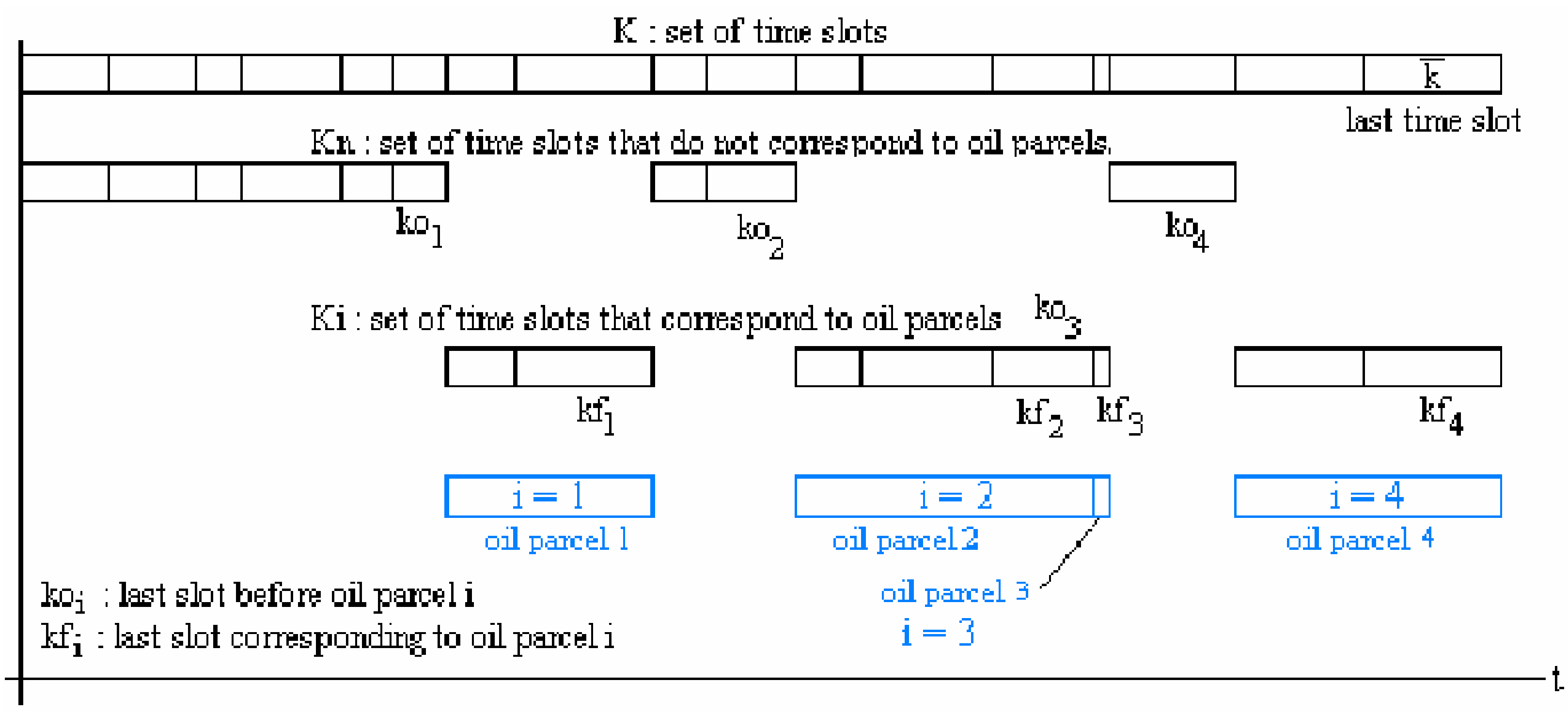
maximize total operating profit

- revenue provided by oil processing
- cost of operating the tanks

generate a schedule for crude oil operations

- receiving oil from pipeline
- waiting for brine settling
- feeding the distillation units

TIME SLOT REPRESENTATION



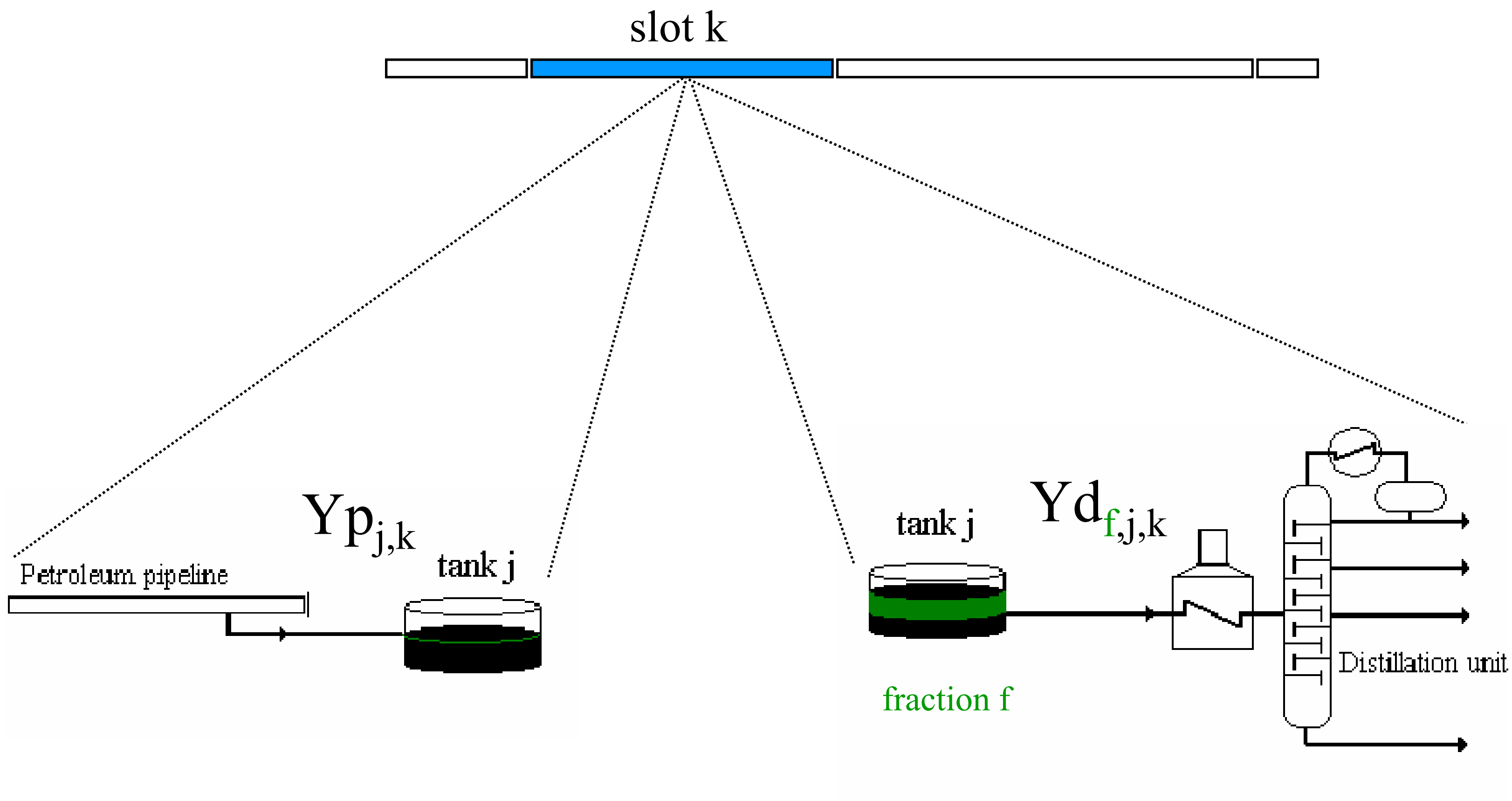
MILP OPTIMIZATION MODEL

Max total operating profit

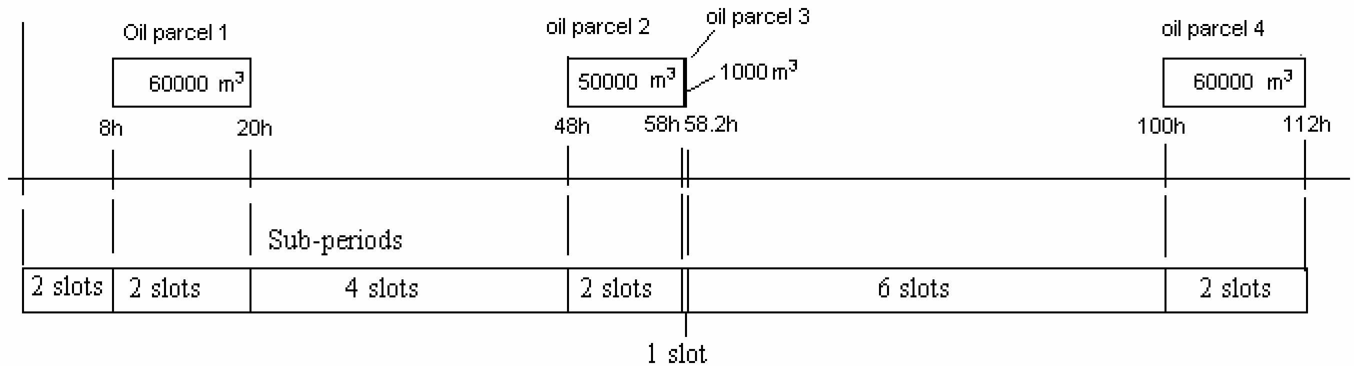
subject to:

- Timing constraints
- Pipeline material balance equations
- Pipeline operating rules
  - Pipeline always connected to a tank
- Material balance equations for the tanks
  - Volumetric equations
  - Component volumetric balance
- Tank operating rules
  - Minimum settling time
- Rules for feeding the distillation unit

DECISION VARIABLES



REAL-WORLD EXAMPLE

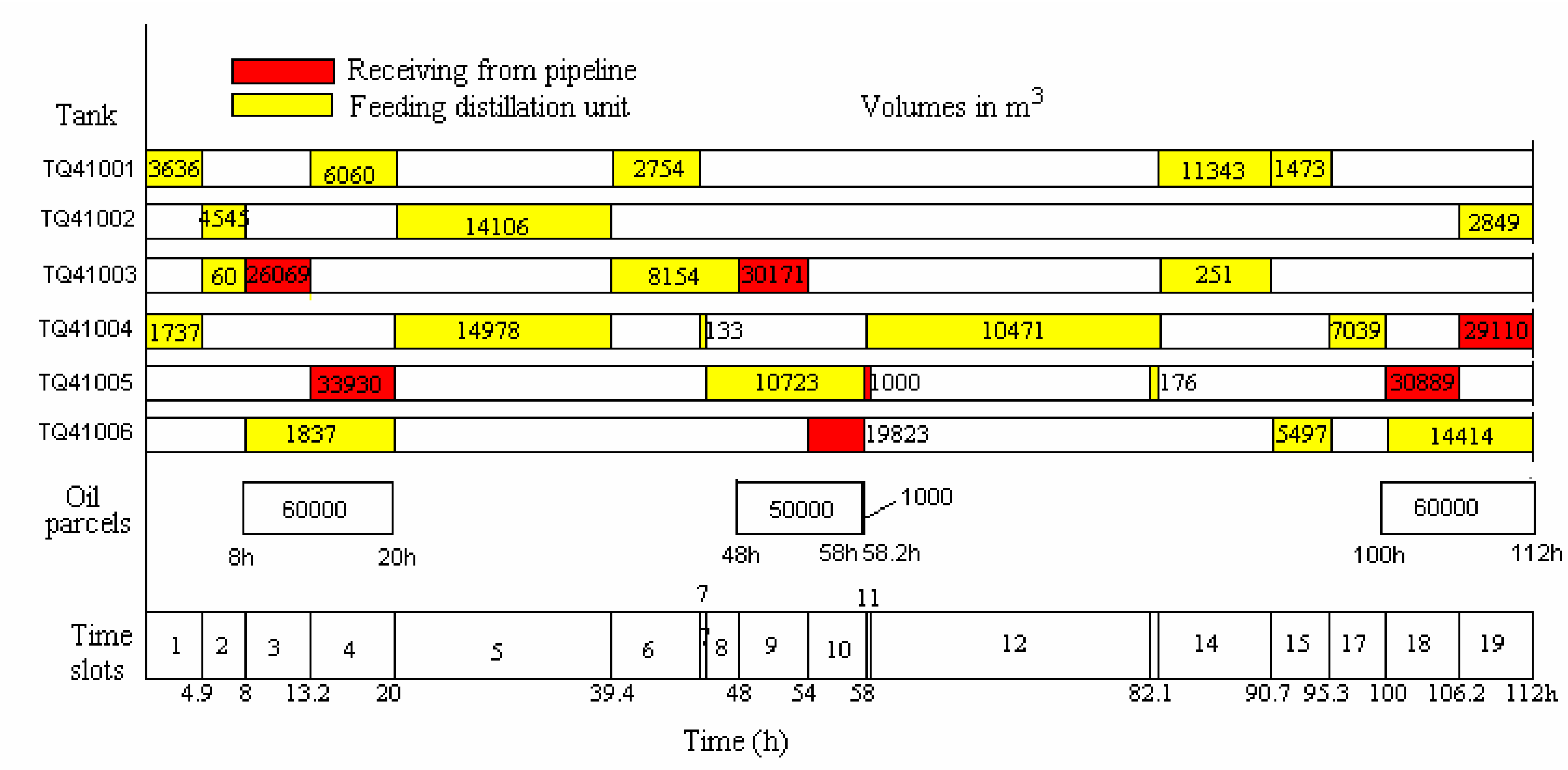


Oil parcel	Volume (m^3)	Start time (h)	End Time (h)	Composition
1	60,000	8	20	100% Bonito
2	50,000	48	58	100% Marlin
3	1,000	58	58.2	100% Marlin
4	60,000	100	112	100% RGN

Tank initial conditions

Distillation target flowrate = 1500 m^3/h

RESULTS


Receiving from pipeline
Feeding distillation unit
Volumes in m3
Tank
TQ41001
3636
6060
2754
11343
1473
TQ41002
4545
14106
2849
TQ41003
60
26069
8154
30171
251
TQ41004
1737
14978
133
10471
7039
29110
TQ41005
33930
10723
1000
176
30889
TQ41006
1837
19823
5497
14414
Oil parcels
60000
50000
1000
60000
8h
20h
48h
58h
58.2h
100h
112h
Time slots
1
2
3
4
5
6
7
8
9
10
11
12
14
15
17
18
19
4.9
8
13.2
20
39.4
48
54
58
82.1
90.7
95.3
100
106.2
112h
Time (h)

MODEL SOLUTION

- GAMS / OSL
- CPU time

  2.80 hrs (Pentium II 266 MHz 128 MB RAM)
- Variable size time slot model

  912 discrete variables

  3237 continuous variables

  5599 equations
- Fixed size time slot model

  21504 discrete variables !

OUTLINE

- *Introduction*
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- *Scheduling models*
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  - *fuel oil / asphalt area*
- *Logistics*
  - *oil supply model*
- *Conclusions*

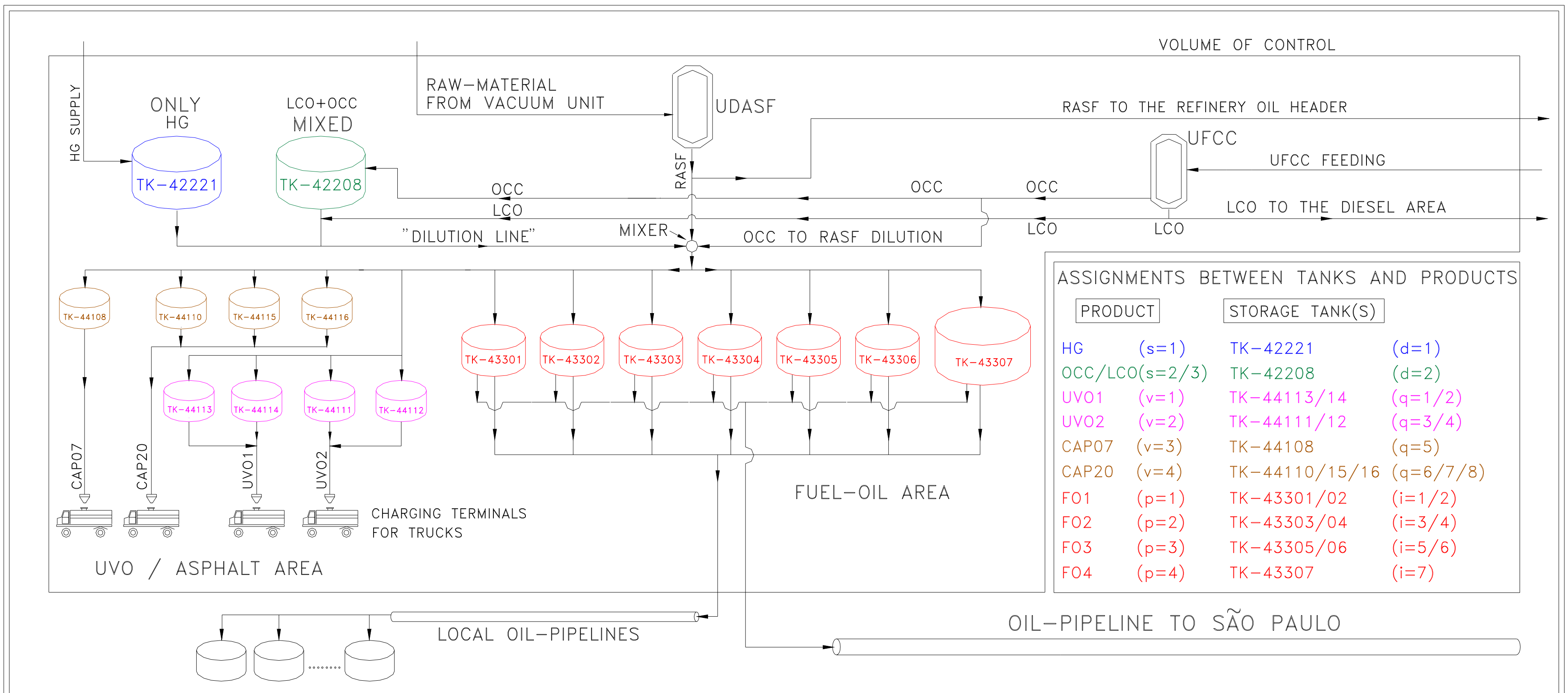
FUEL OIL/ASPHALT PRODUCTION SCHEDULING PROBLEM

- The plant produces ≅ 80% of all Brazilian fuel oil;
- The plant has relevant storage limitations;
- Complexity of distribution operations;
- End of the monopoly in the Brazilian oil sector.

Product	*Base*	*Diluent used*
FO1	**RASF**	**OCC+LCO or OCC or LCO**
FO2	**RASF**	**OCC+LCO or OCC or LCO**
FO3	**RASF**	**OCC+LCO or OCC or LCO**
FO4	**RASF**	**OCC+LCO or OCC or LCO**
UVO1	**RASF**	**pure LCO**
UVO2	**RASF**	**pure LCO**
CAP07	**RASF**	**pure HG**
CAP20	**RASF**	**pure HG**

major specification:

viscosity



MATHEMATICAL MODELS

- Uniform Discretization of Scheduling Horizon;
- Objective Function: **Minimize the Operational Cost**.

First Approach:

- non-convex **MINLP** (5 bilinear products in the viscosity constraints);

Linear Transformation

↓

Second Approach:

- **MILP**;

MINLP MODEL

Minimize:

COST = Raw-Material Costs + Inventory Costs +
+ Pumping Costs + Transition Costs

$$COST = \sum_{t=1}^{T}[\sum_{s=1}^{S}(CD_s \cdot FDC_{s,t}) + CD_2 \cdot FOCCR_t + CD_3 \cdot FRLCO_t + CR \cdot FRASFM +$$
$$+\sum_{i=1}^{I}(CINVI_i \cdot VI_{i,t}) + \sum_{q=1}^{Q}(CINVQ_q \cdot VQ_{q,t}) + \sum_{d=1}^{D}(CINVD_d \cdot VQ_{d,t}) +$$
$$+\sum_{i=1}^{I}\sum_{o=1}^{O}(CB_i \cdot FID_{i,o,t})] + \sum_{o=1}^{O}\sum_{p=1}^{P}\sum_{n=1}^{N}(TRAN_{o,p,n} \cdot CHANGE_{p,n})$$

Subject to:

Material Balance Constraints:

volume in ***i*** at ***t'*** = initial volume in ***i*** + [inputs in ***i* up to *t'*** - (outputs from ***i* up to *t'***)]

the volume capacities of all tanks are also subject to bounds

Demand Supply of Plant Products

Operating Rules for the Plant:

at each ***t***, the plant production must be stored in one single tank

$$\underbrace{\sum_{i=1}^{I}(XIC_{i,t})}_{\textbf{FO area}} + \underbrace{\sum_{q=1}^{Q}(XQC_{q,t})}_{\textbf{UVO/asphalt area}} = 1 \qquad t = 1,\ldots,T$$

simultaneous tank loading and unloading is not allowed (**exception: HG storage tank**)

$$XIC_{i,t} + \sum_{o=1}^{O}(XID_{i,o,t}) \leq 1 \qquad i = 1,\ldots,I; \;\; t = 1,\ldots,T$$

FO area

Operating Rules for the Plant (continuation):

UVO / Asphalt may be sent to truck terminals only between 6:00 a.m. and 6:00 p.m.

$$XQD_{q,t} \leq HT_b$$

$$b = 1,\ldots,[T/(12/DT)]; \quad (12/DT)\cdot(b-1)+1 \leq t \leq (12/DT)\cdot b; \quad q = 1,\ldots,Q$$

while a asphalt is produced, the RASF diluent must be HG

$$\sum_{q=5}^{8}(XQC_{q,t}) - XDRASF_{1,t} = 0 \qquad t = 1,\ldots,T$$

while asphalt is produced, the OCC stream from UFCC must be directed to storage in TK-42208

$$XDRASF_{1,t} + (1 - XZ_t) \leq 1 \qquad t = 1,\ldots,T$$

Material Flow Constraints:

flowrates to oil-pipelines must obey pump limitations

$$0 \leq FID_{i,o,t} \leq XID_{i,o,t} \cdot FID^{max} \qquad i = 1,\ldots,I;\; o = 1,\ldots,O;\; t = 1,\ldots,T$$

flowrates to truck terminals must obey pump limitations

$$0 \leq FQD_{q,t} \leq XQD_{q,t} \cdot FQD^{max} \qquad q = 1,\ldots,Q;\; t = 1,\ldots,T$$

Viscosity Constraints:

at each ***t***, the viscosity adjustment must be done regarding the kind of product

$$VISC_t = \sum_{q=1}^{Q} \sum_{v \in V_q} (MIUV_v \cdot XQC_{q,t}) + \sum_{i=1}^{I} \sum_{p \in P_i} (MIFO_p \cdot XIC_{i,t}) \quad t = 1,\ldots,T$$

also, the availability of diluents should be considered

$$\frac{\{[\sum_{d=1}^{D} \sum_{s \in S_d}^{s \le 2} (FDRASF_{d,t} \cdot MID_s) + FRASFU_t \cdot MIRASF + FOCCR_t \cdot MID_2 + FRLCO_t \cdot MID_3]}{[(\sum_{d=1}^{D} (FDRASF_{d,t}) + FRASFU_t + FOCCR_t + FRLCO_t]\}} = VISC_t$$

$$t = 1,\ldots,T$$

or

$$\underbrace{\begin{aligned}&\{[\sum_{d=1}^{D} \sum_{s \in S_d}^{s \le 2} (FDRASF_{d,t} \cdot MID_s) + FRASFU_t \cdot MIRASF + FOCCR_t \cdot MID_2 + FRLCO_t \cdot MID_3] = \\ &= VISC_t \cdot [(\sum_{d=1}^{D} (FDRASF_{d,t}) + FRASFU_t + FOCCR_t + FRLCO_t]\}\end{aligned}}_{} \qquad t = 1,\ldots,T$$

5 bilinear products → **non-convex MINLP**

EXACT MILP MODEL

Characteristics:

- Similar MINLP model structure;
- More continuous variables than MINLP model;
- More constraints than MINLP model;
- Combinatorial feature of the MINLP model **preserved**.

Structure:

non-convex

MILP Model = MINLP Model +

– Nonlinear Viscosity Constraints

\+ Linearized Constraints

CONSTRAINTS FOR LINEAR TRANSFORMATION

Material Balance

$$VIK_{i,t'} = VIZ_i \cdot MI_i + \sum_{t=1}^{t'} [FIRASFK_{i,t} - \sum_{o=1}^{O} (FIDK_{i,o,t})] \qquad i = 1,\ldots,I;\ t' = 1,\ldots,T \qquad \textbf{(46)}$$

$$VQK_{q,t'} = VQZ_q \cdot MQ_q + \sum_{t=1}^{t'} (FQRASFK_{q,t} - FQDK_{q,t}) \qquad q = 1,\ldots,Q;\ t' = 1,\ldots,T \qquad \textbf{(47)}$$

$$FRASFU_t \cdot MIRASF + \sum_{d=1}^{D} \sum_{s \in S_d}^{s \le 2} (FDRASF_{d,t} \cdot MID_s) + FOCCR_t \cdot MID_2 +$$

$$+ FRLCO_t \cdot MID_3 = \sum_{i=1}^{I} (FIRASFK_{i,t}) + \sum_{q=1}^{Q} (FQRASFK_{q,t}) \qquad t = 1,\ldots,T \qquad \textbf{(48)}$$

Flow

$$FIRASFK_{i,t} \le XIC_{i,t} \cdot U \qquad U = constant \qquad i = 1,\ldots,I;\ t = 1,\ldots,T \qquad \textbf{(49)}$$

$$FQRASFK_{q,t} \le XQC_{q,t} \cdot U \qquad U = constant \qquad q = 1,\ldots,Q;\ t = 1,\ldots,T \qquad \textbf{(50)}$$

Viscosity

$$VI_{i,t} \cdot MI_i = VIK_{i,t} \qquad i = 1,\ldots,I;\ t = 1,\ldots,T \qquad \textbf{(51)}$$

$$VQ_{q,t} \cdot MQ_q = VQK_{q,t} \qquad q = 1,\ldots,Q;\ t = 1,\ldots,T \qquad \textbf{(52)}$$

$$FID_{i,o,t} \cdot MI_i = FIDK_{i,o,t} \qquad i = 1,\ldots,I;\ o = 1,\ldots,O;\ t = 1,\ldots,T \qquad \textbf{(53)}$$

$$FQD_{q,t} \cdot MQ_q = FQDK_{q,t} \qquad q = 1,\ldots,Q;\ t = 1,\ldots,T \qquad \textbf{(54)}$$

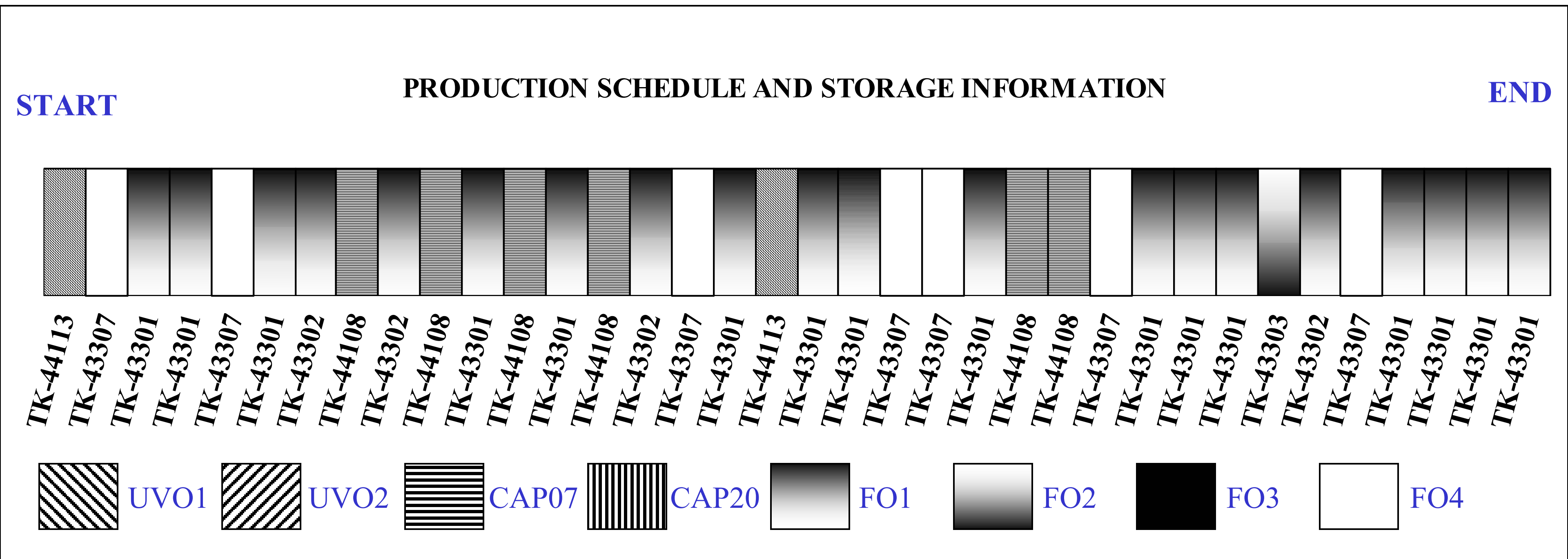
REAL-WORLD EXAMPLE

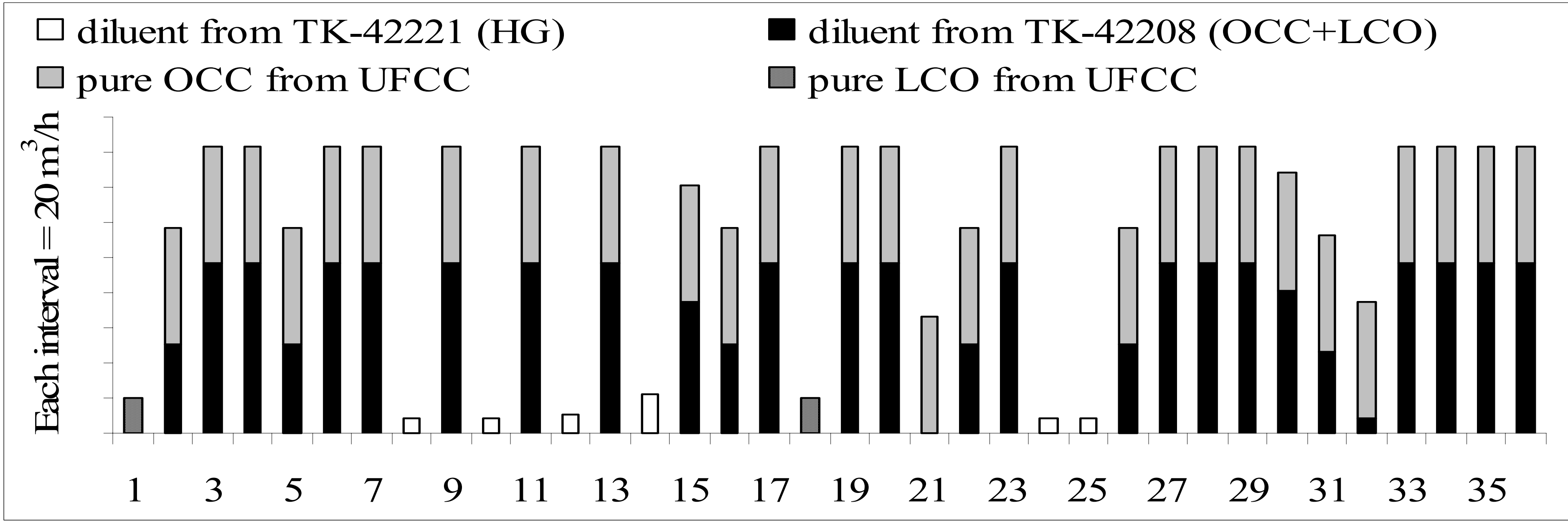
instance evaluated

Scheduling horizon: **3 days**

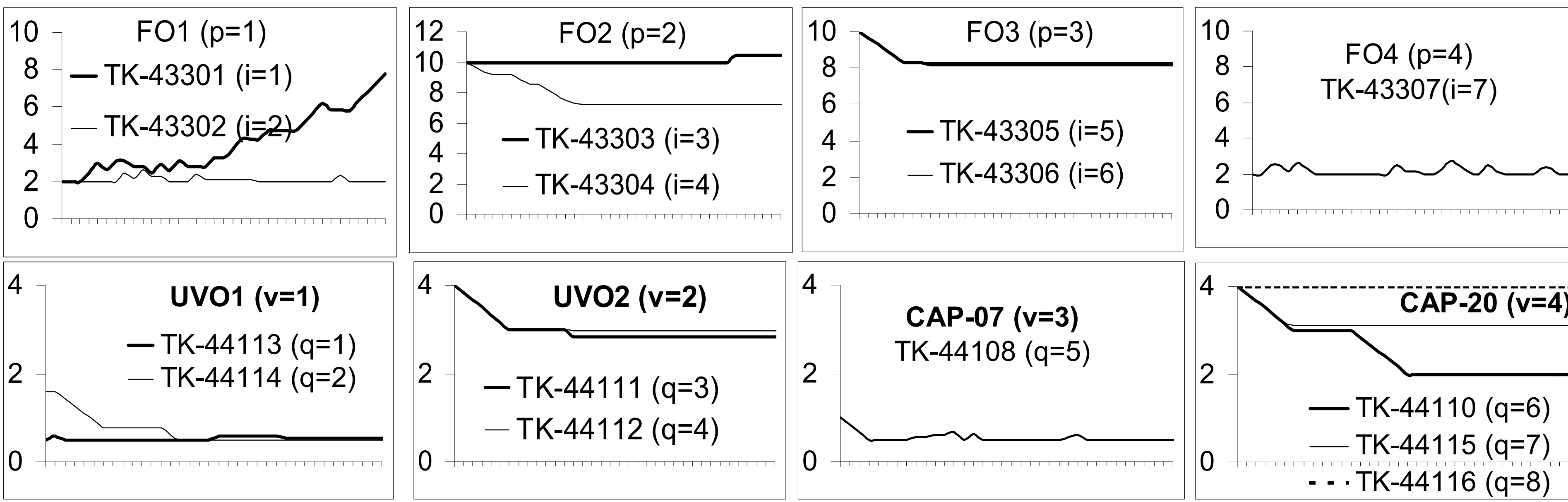
Time span: **2 hours**

Nominal production: **200,000 m^3/month**



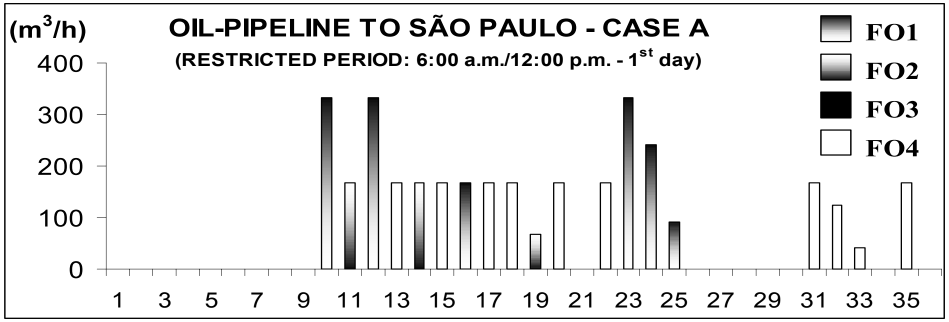


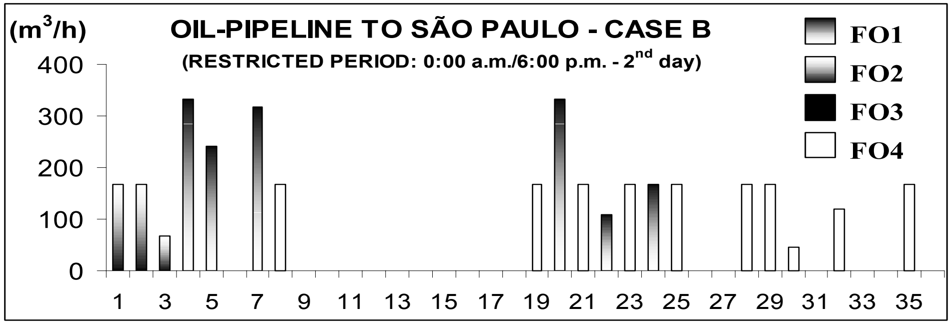
Schedule of diluents in the mixer

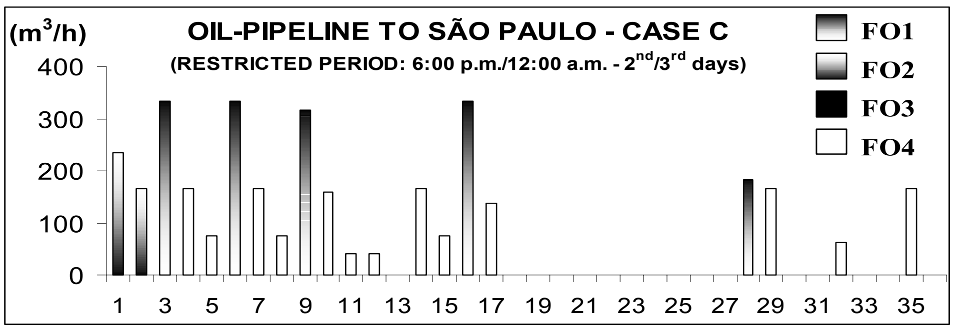


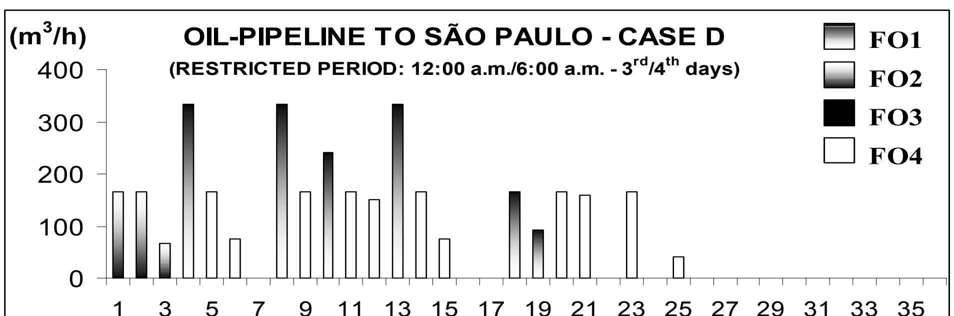
Volume (x 10^{-3} m^3) in product storage tanks

Transfer schedule for fuel oils

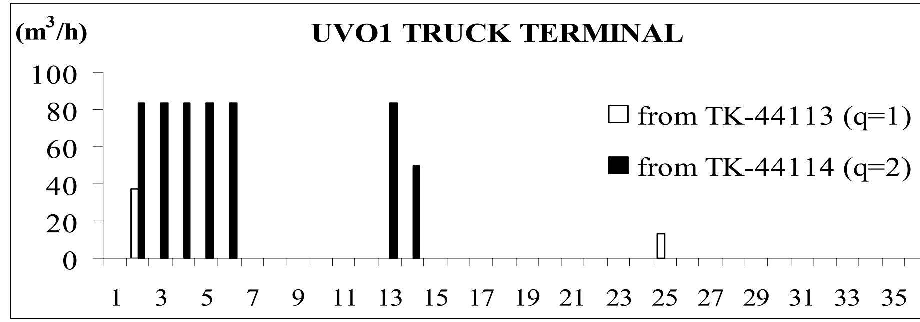


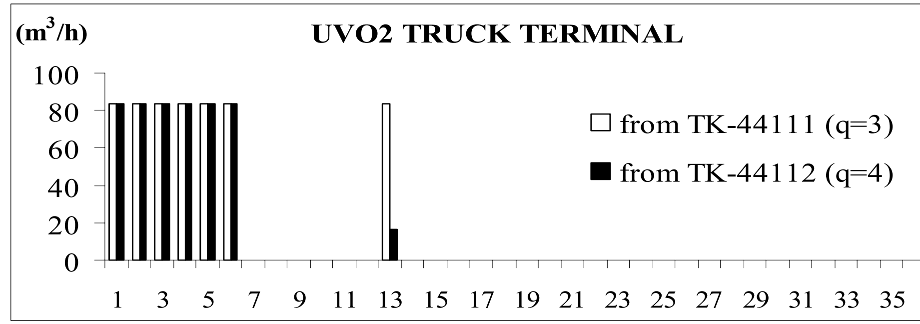


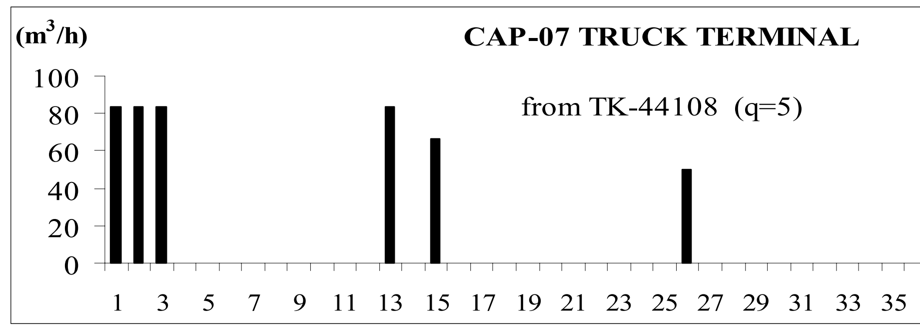


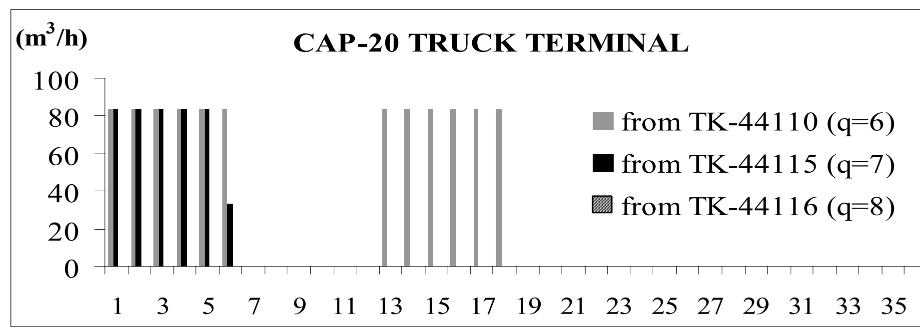


Dispatch schedule for ultra-viscous oil

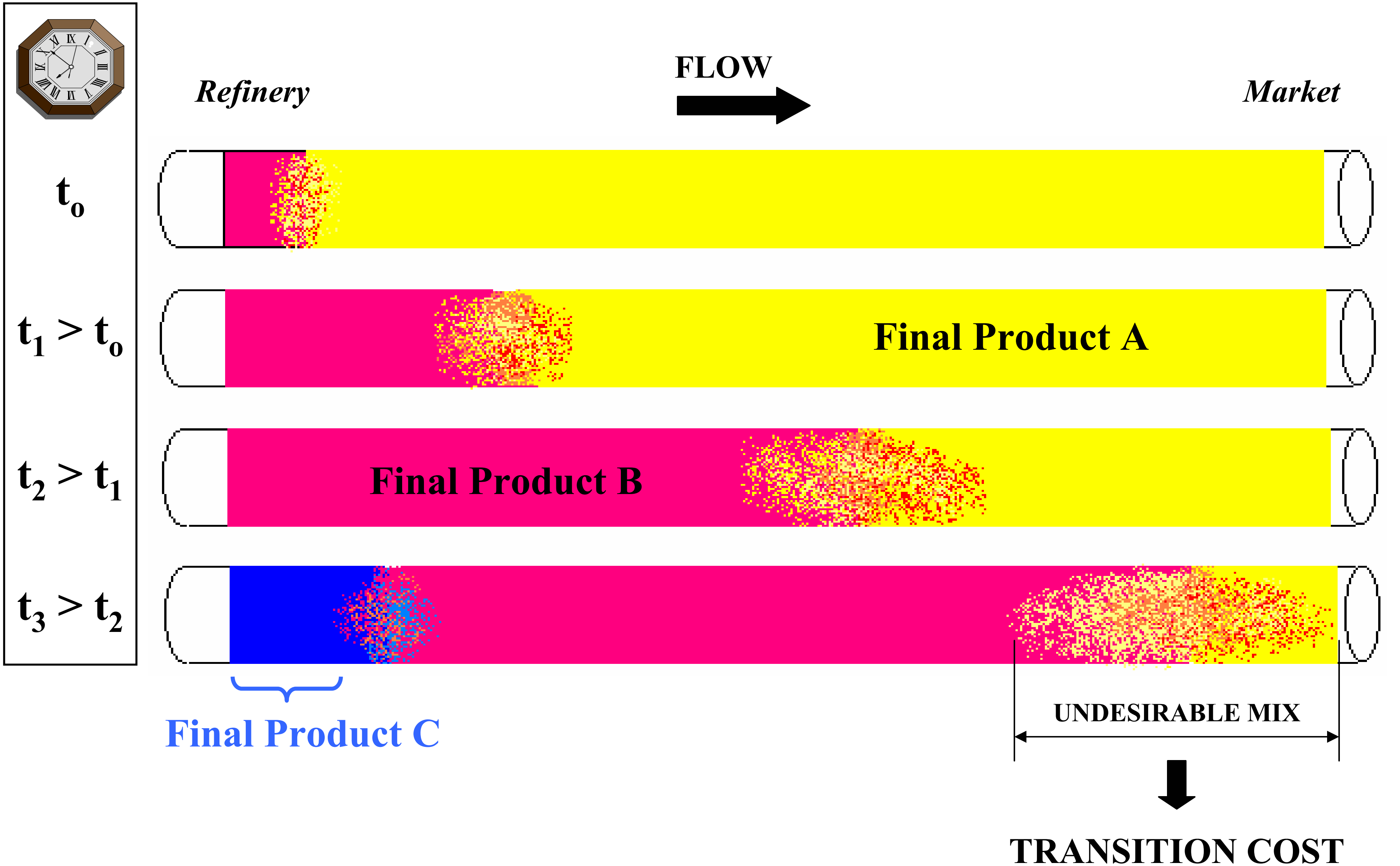


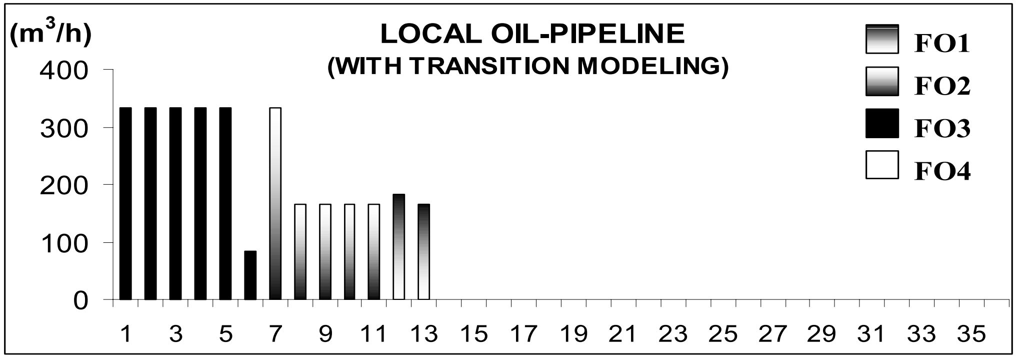


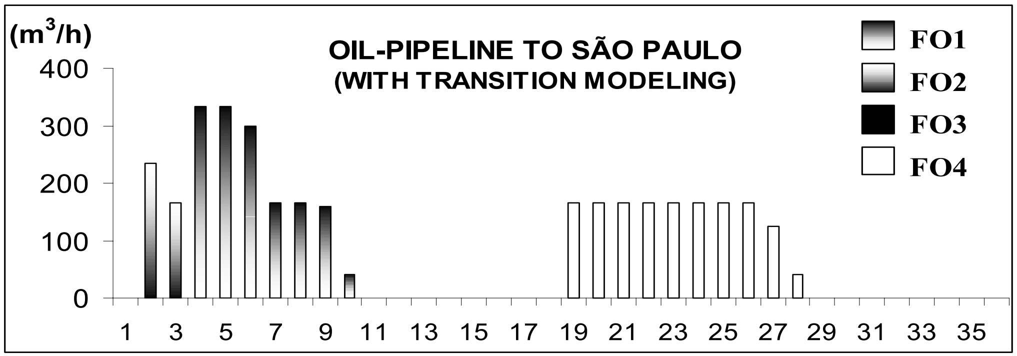


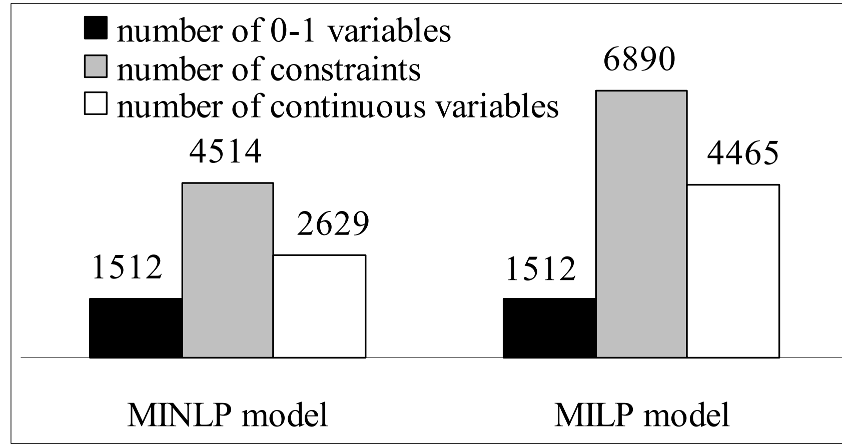


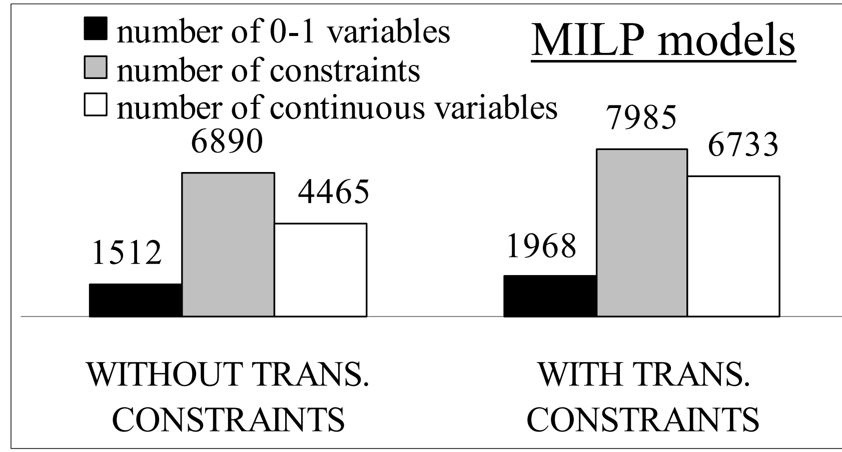
TRANSITION PROCESS IN OIL-PIPELINES











case	*MIP model*	*nodes*	*iterations*	*CPU time (s)*	*objective*
A	MILP	937	15674	570.46	969.61
	MINLP	-	13815	335.36	966.99
B	MILP	1296	16626	711.01	965.72
	MINLP	-	15508	391.45	961.14
C	MILP	764	13086	490.86	954.99
	MINLP	-	23792	531.98	956.99
D	MILP	1197	23080	851.78	950.65
	MINLP	-	12845	299.30	959.49

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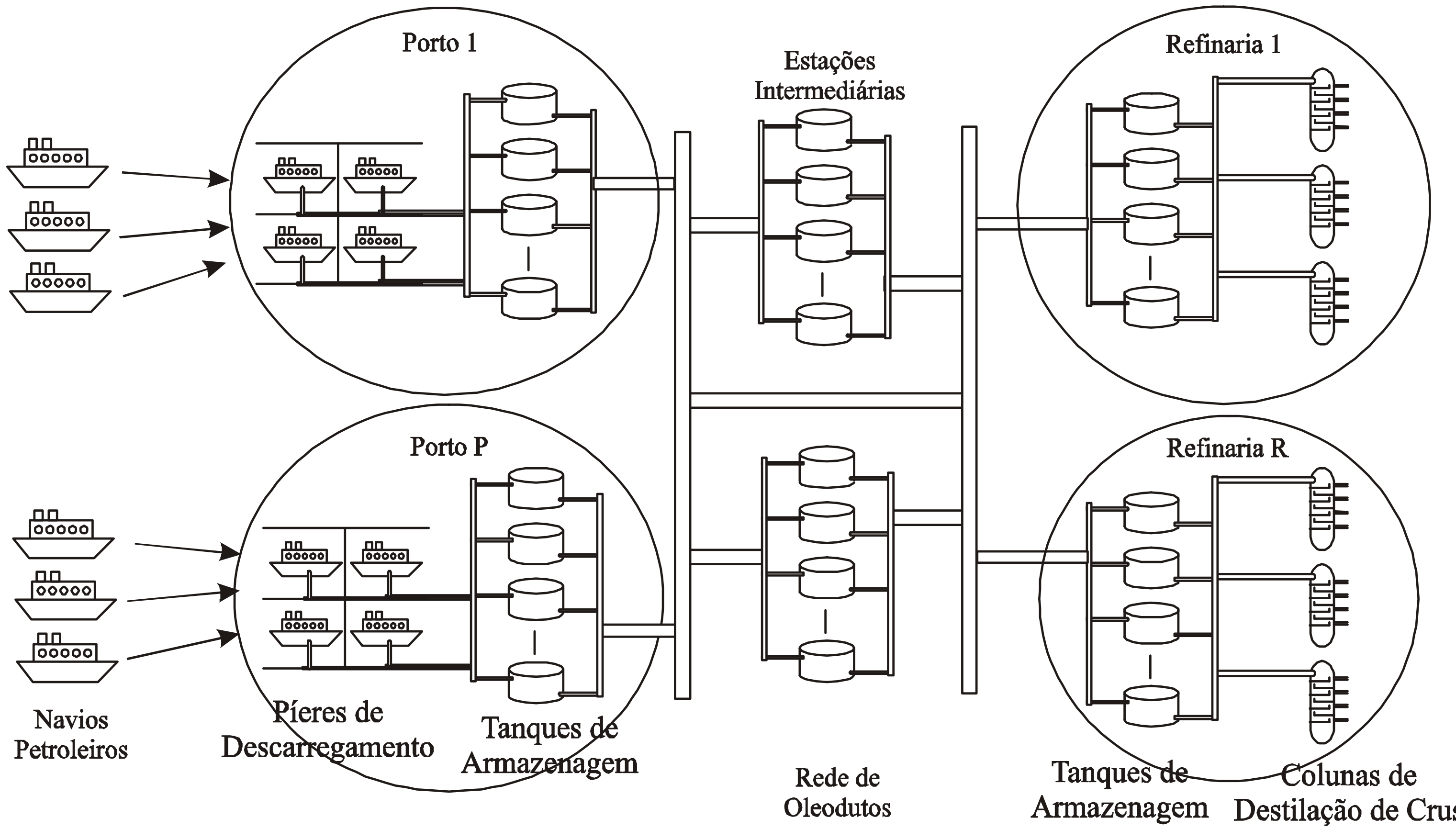
CRUDE OIL SUPPLY PROBLEM

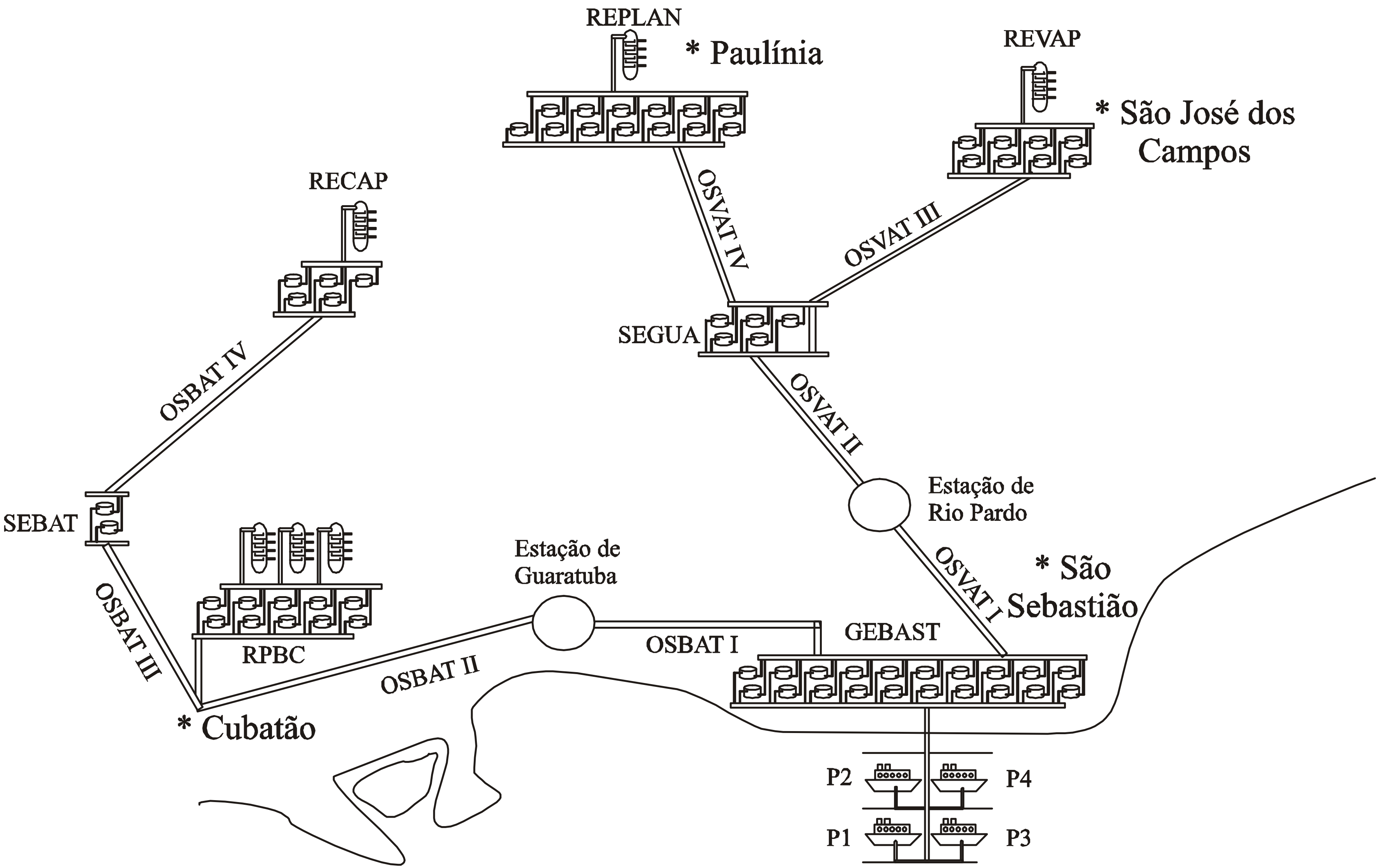
- Solution of oil supply problems among crude oil terminals and refineries



MOTIVATION

- Increasing utilization of the system
  - Larger crude oil demand for crude oil in refineries
  - Outsource of transportation
- Potential economic impact
  - No systematic scheduling
  - Operations involve high costs and aggregated values
- Petrobras distribution complex
  - 4 refineries in the State of Sao Paulo

PETROBRAS DISTRIBUTION COMPLEX



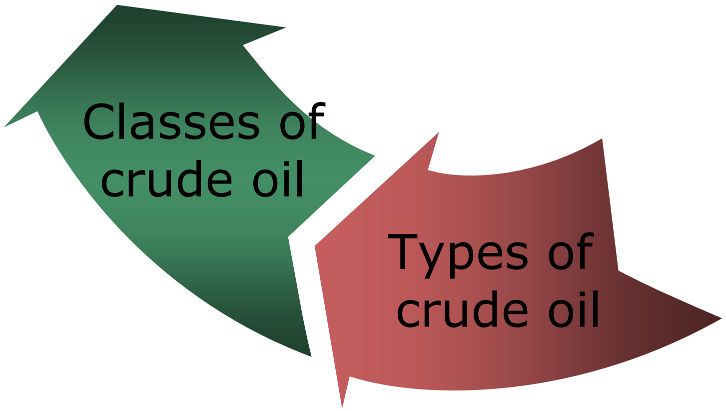
PROBLEM SPECIFICATION

Determined by the petroleum origin

Approximately 42 types of crude oil may be processed

Types of crude oil

PROBLEM SPECIFICATION

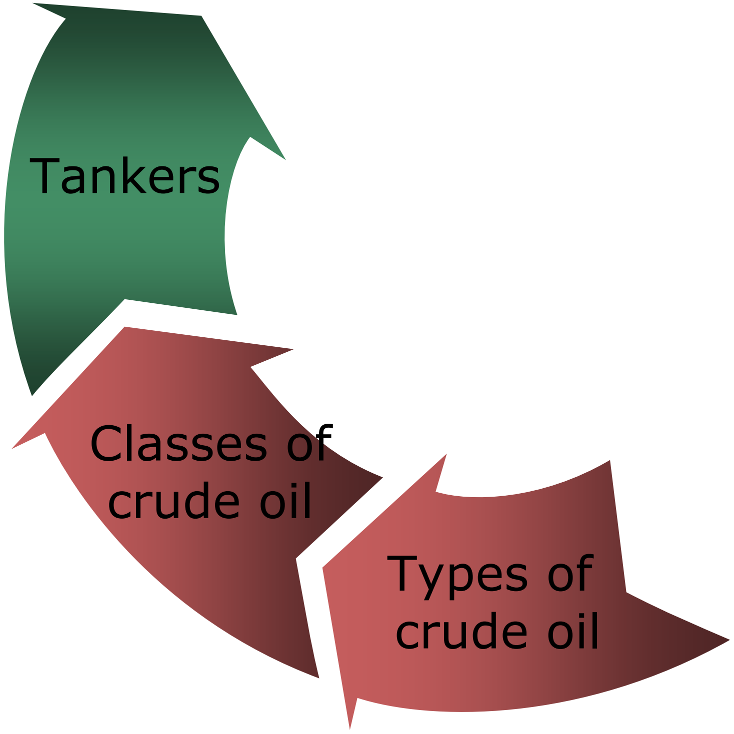


Sets of crude oil types with similar properties

Necessary due to limited amount of tanks

7 classes

PROBLEM SPECIFICATION

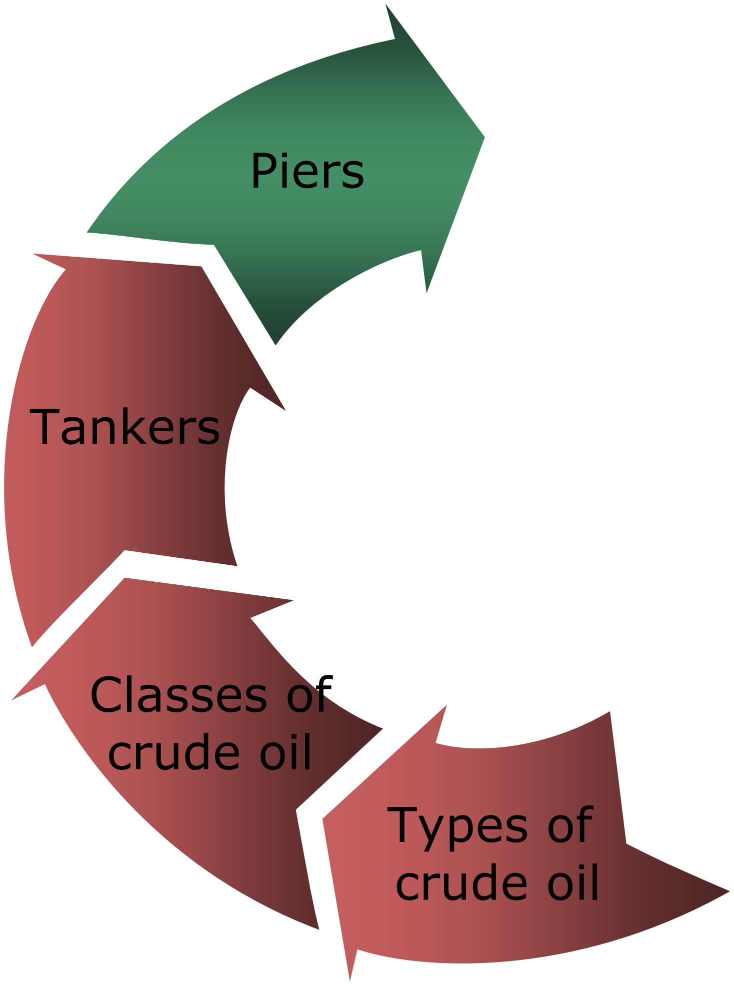


Transport types of crude oil

Overstay incurs in additional costs

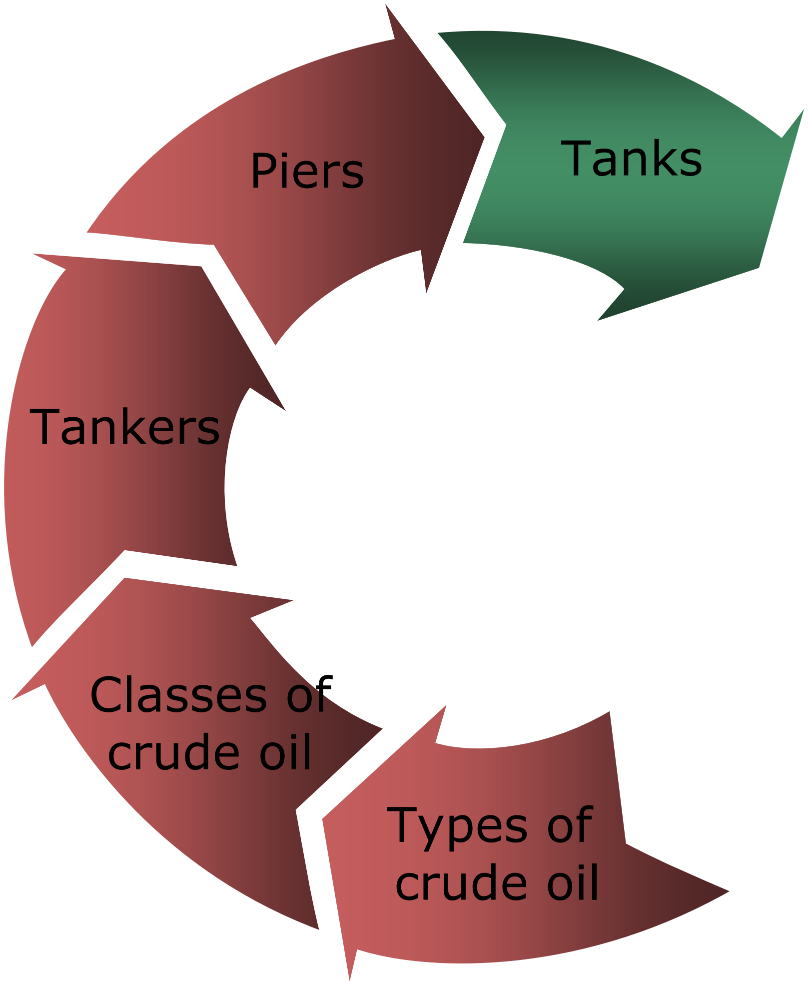
US$ 10 k to US$ 20 k per day

PROBLEM SPECIFICATION



Different capacities

PROBLEM SPECIFICATION

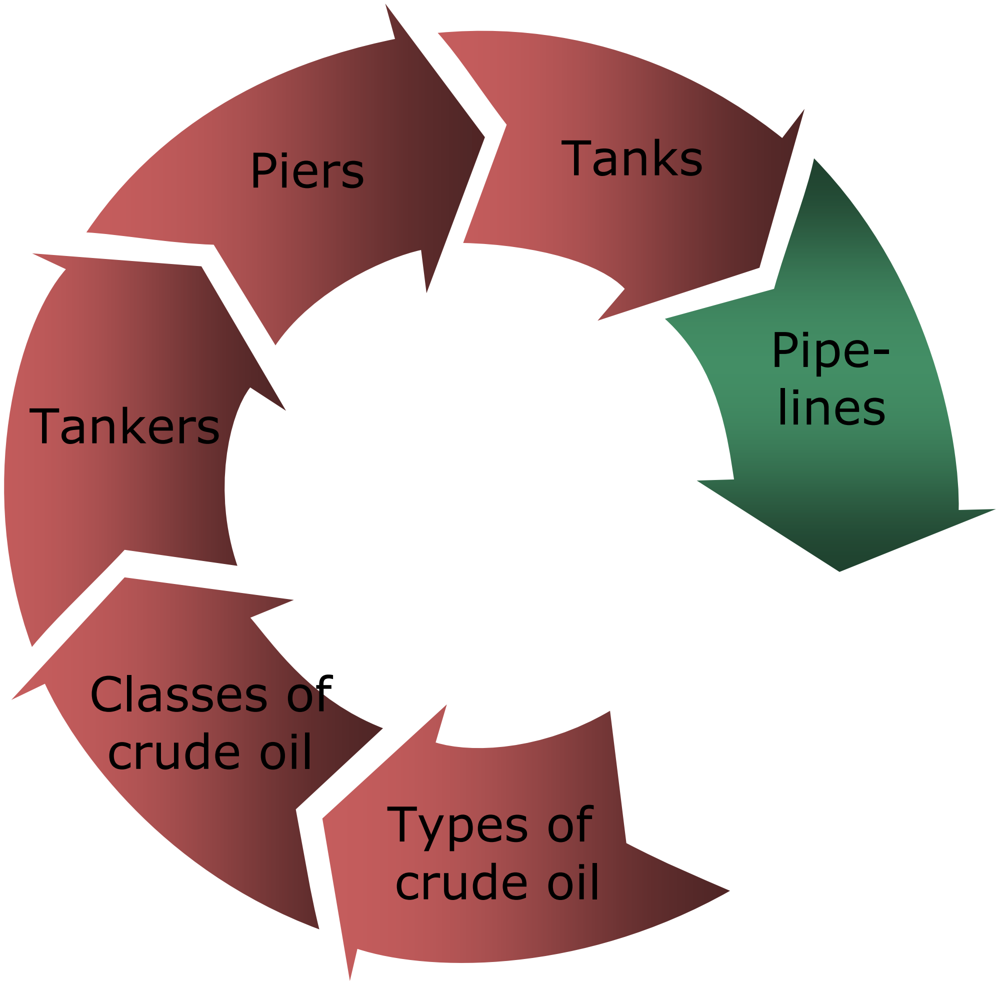


Store classes of crude oil

Minimum storage levels

Settling time between loading and unloading operations

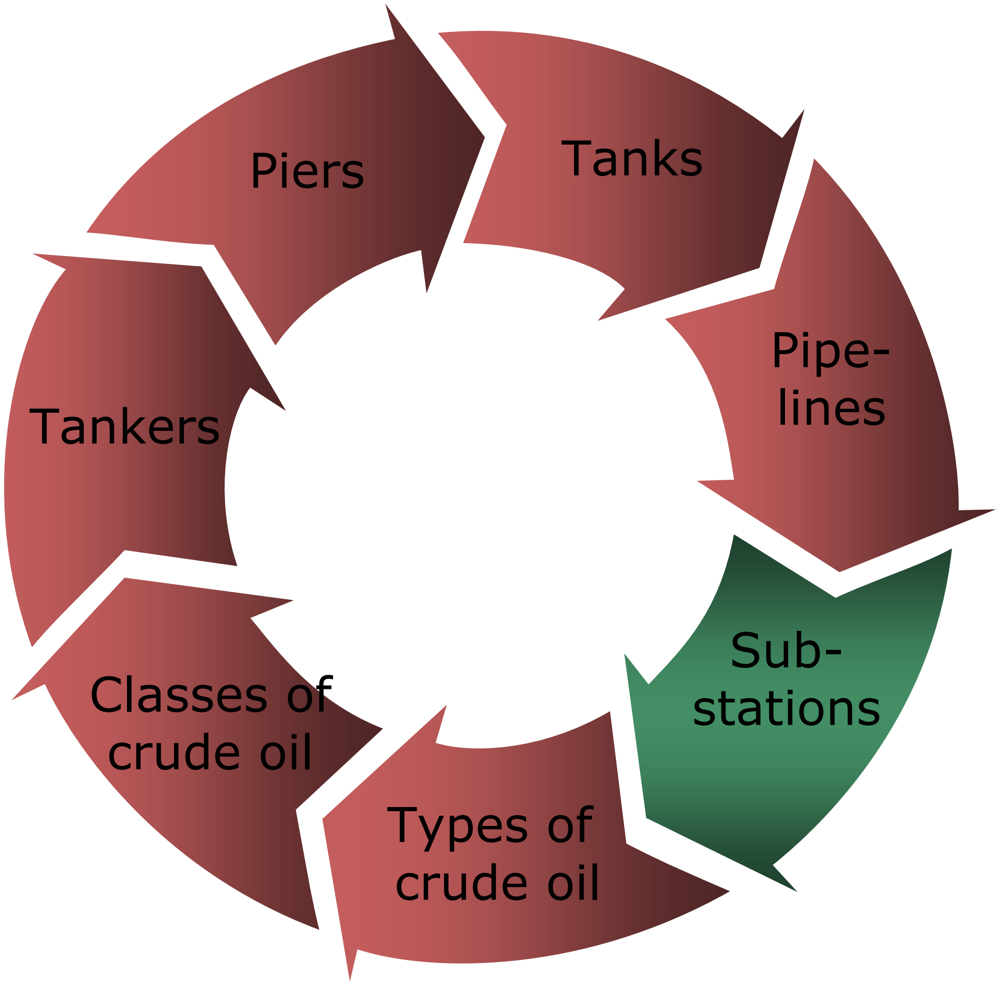
PROBLEM SPECIFICATION



Flow rate at each pipeline limited by the density of the heaviest crude oil class

Possible to connect to at most one tank at every time

PROBLEM SPECIFICATION

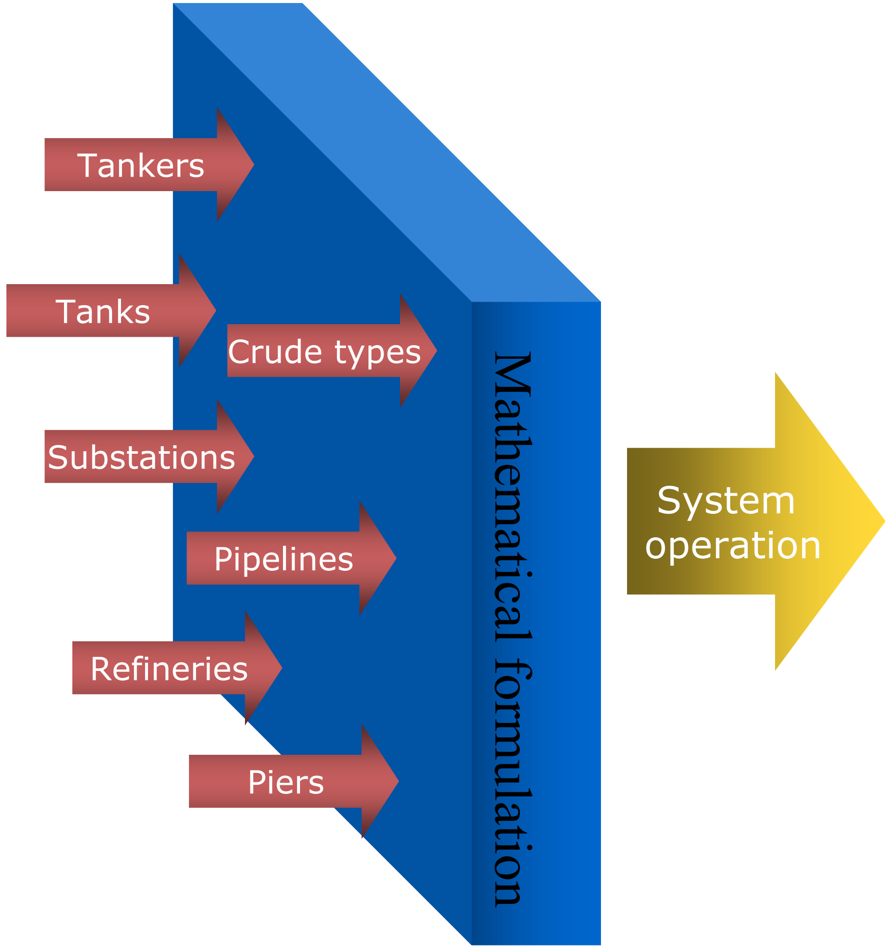


Buffer operations between terminal and refineries

Store difference in flow rate between inlet and outlet pipelines

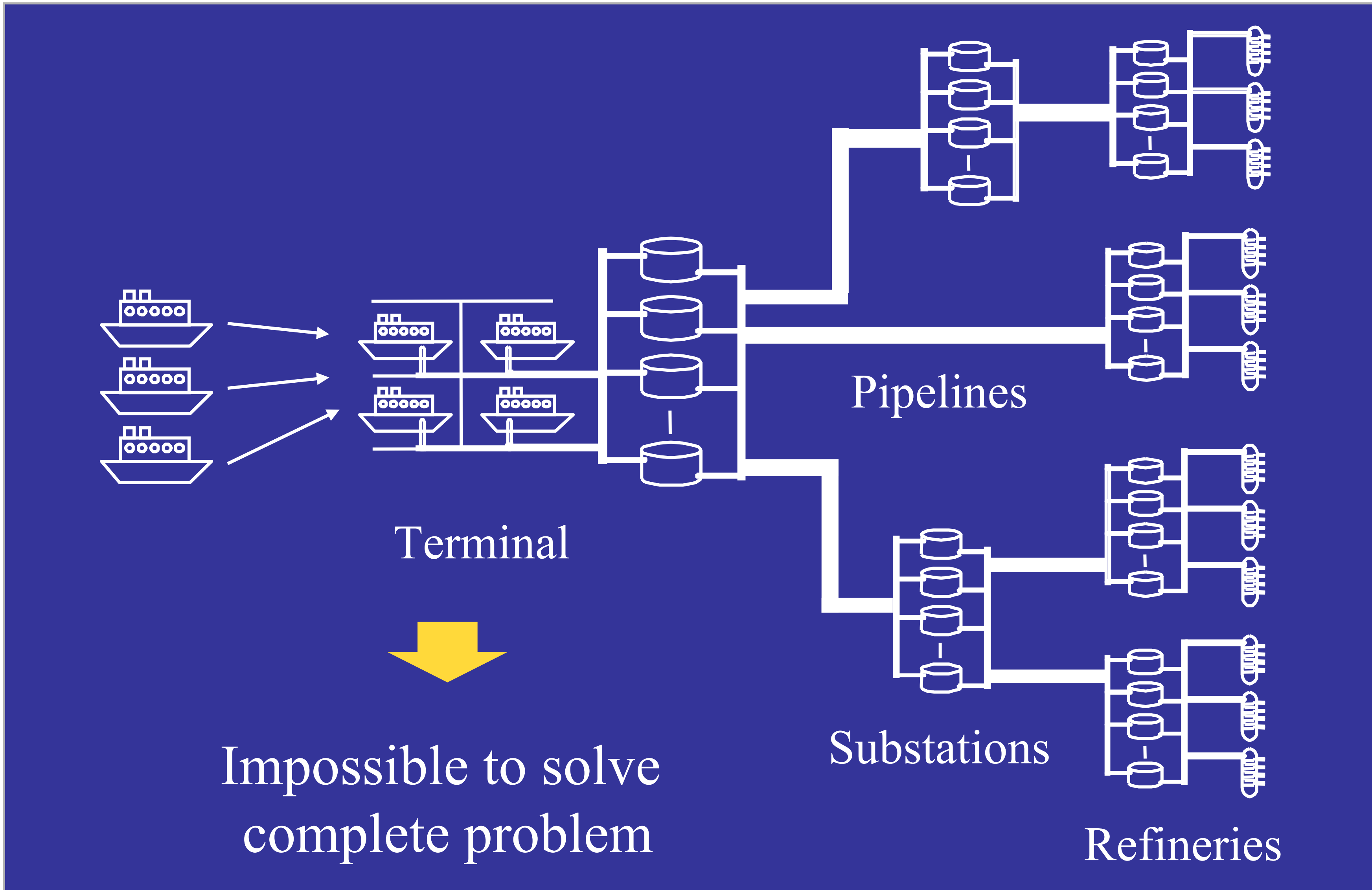
OBJECTIVES

- Input parameters
  - Operating constraints
  - Initial inventory
  - Costs
  - Possible allocations



- Schedules
  - Allocation of crude oil types to classes
  - Assignment of tankers to piers
  - Loading
  - Unloading
  - Settling

PROPOSED STRATEGY



PROPOSED STRATEGY

- Decomposition of the problem in three formulations

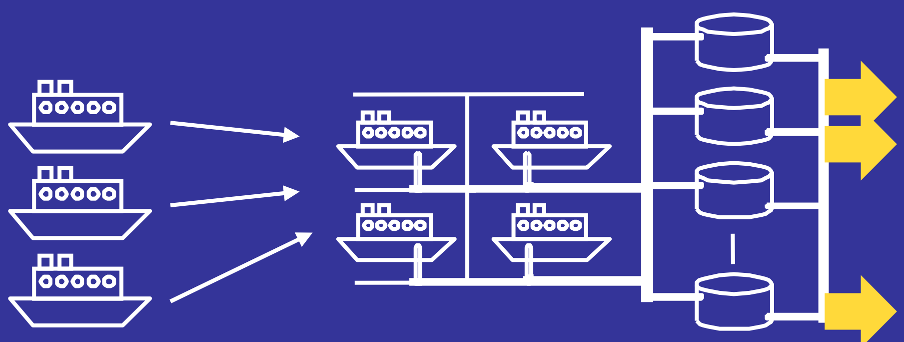
  - Port Model

  - Substation Model

  - Algorithm to adjust timing of pipelines

PROPOSED STRATEGY

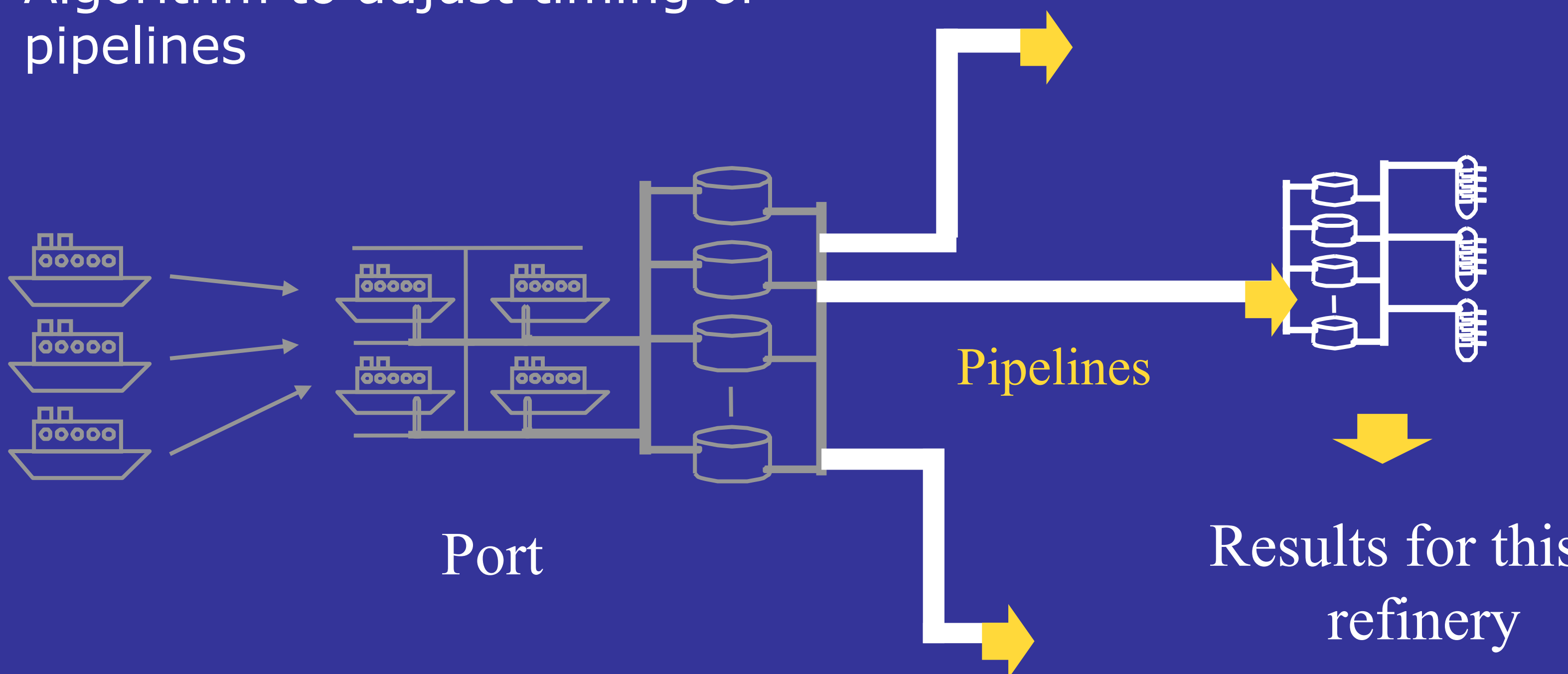
- *Port Model*



- Results
  - Allocation of tankers to piers
  - Loading and unloading profiles of tanks
  - Loading of pipelines
  - Timing of interfaces in pipelines

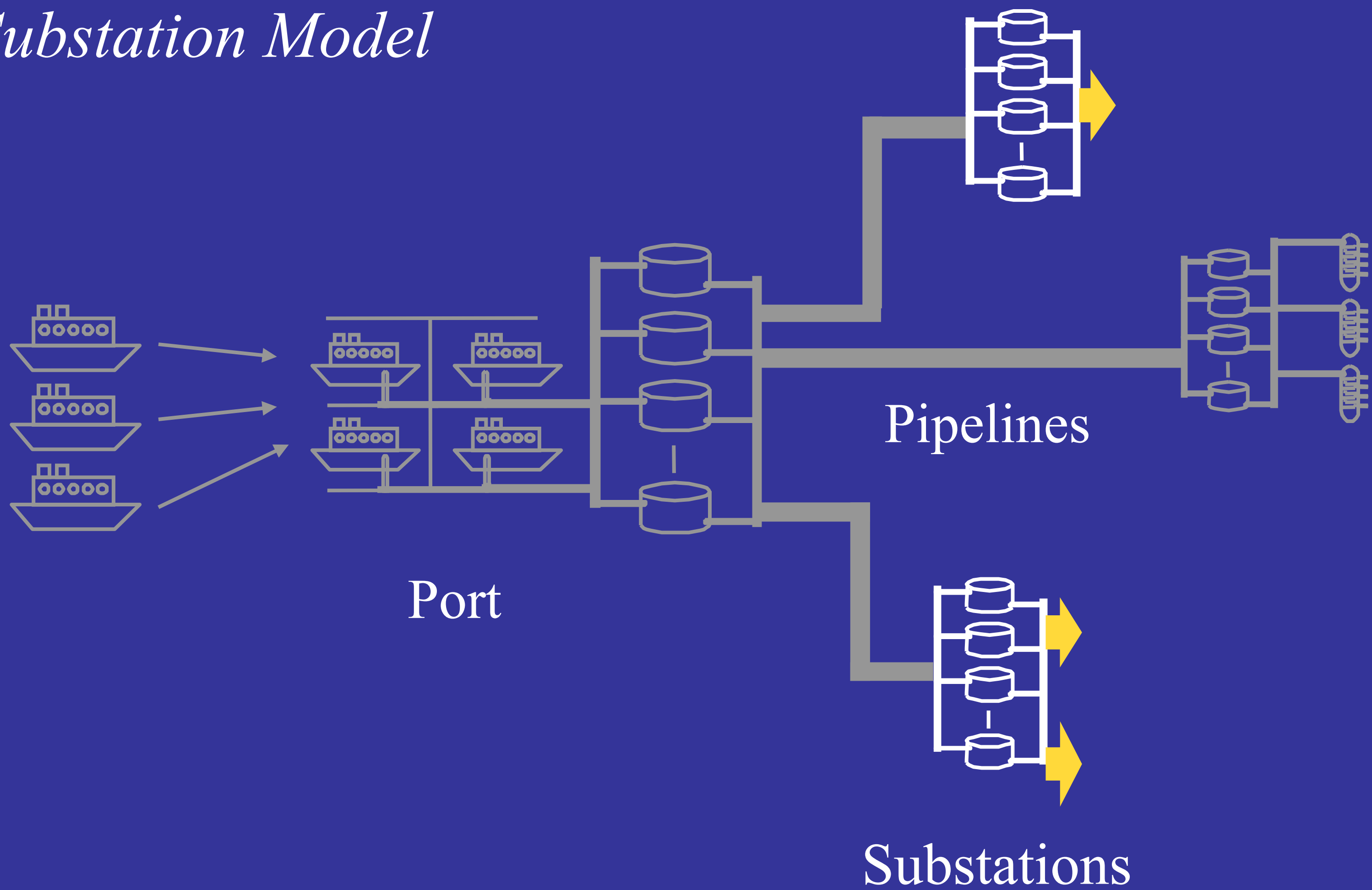
PROPOSED STRATEGY

- Algorithm to adjust timing of pipelines



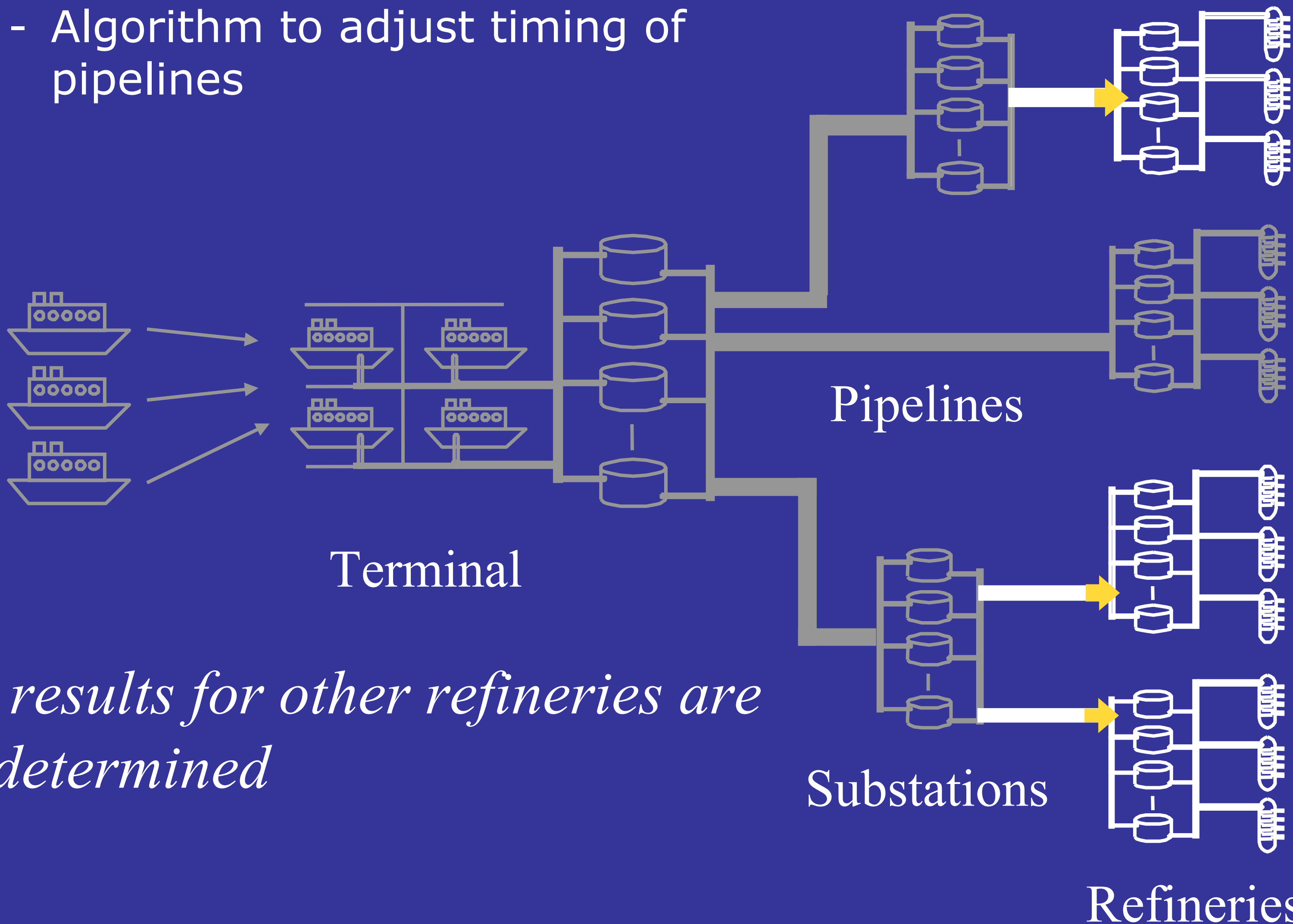
PROPOSED STRATEGY

- *Substation Model*



PROPOSED STRATEGY

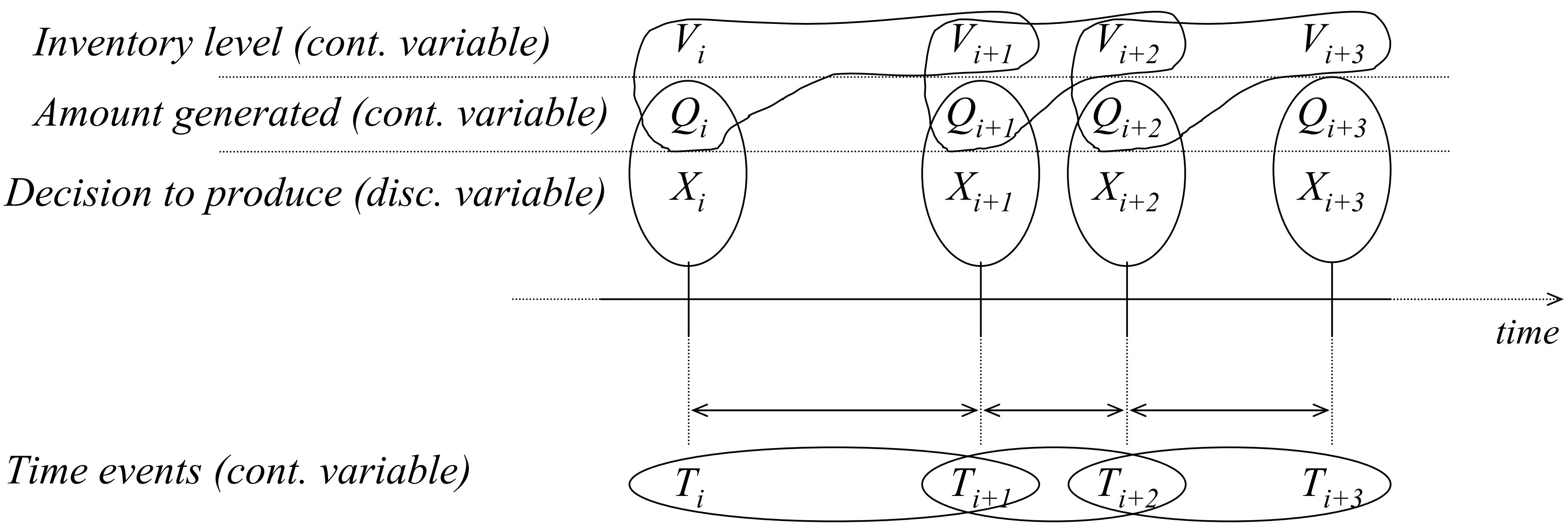
- Algorithm to adjust timing of pipelines



… results for other refineries are determined

MATHEMATICAL FORMULATION

- MILP model formulation
- Time representation
  - Continuous
  - Based on events



PROPOSED MODEL - VARIABLES

- Binary variables – Decisions
  - Assignment of ship *n* to pier *p*: $A_{n,p}$
  - Unloading of ship *n* to tank *t:* $LT_{n,t,e}$
  - Unloading of tank *t* to oil pipeline *o*: $UT_{t,o,e}$

- Continuous variables
  - Timing
  - Inventory
  - Flowrates
  - Operating profit

MODEL ASSUMPTIONS AND OPERATING RULES

- Ships with earlier arrival date unload first in the same pier
- Each ship unloads to only one tank at any time
- Each pipeline receives crude oil from at most one tank at any time
- Each refinery is connected to the docking stations from one and only one oil pipeline
- The same crude oil class has constant flowrates

PROPOSED MODEL - TIMING

- Ships, tanks and pipelines
  - Timing variables in each time event
    - Initial
    - Final
- Matching of the timing variables
  - Unloading from ship *n* to tank *t*

$$TN_{n,e}^{s} = TT_{t,e}^{s} \qquad TN_{n,e}^{f} = TT_{t,e}^{f}$$

  - Unloading from tank *t* to pipeline *o*

$$TT_{t,e}^{s} = TD_{o,e}^{s} \qquad TT_{t,e}^{f} = TD_{o,e}^{f}$$

PORT MODEL - CONSTRAINTS

- Decisions
  - Assignment of tanker *n:* $\sum_{p \in P_n} A_{n,p} = 1$
  - Operation of tank *t:* $\sum_{n \in N_t} LT_{n,t,e} + \sum_{o \in O_t} UT_{t,o,e} \leq 1$
  - Operation of tanker *n:* $\sum_{t \in T_n} LT_{n,t,e} \leq 1$
  - Operation of oil pipeline *o:* $\sum_{t \in T_o} UT_{t,o,e} \leq 1$

PROPOSED MODEL – CONSTRAINTS

- Material balances
  - Tanks, Refineries
- Operational constraints
  - Ships and tanks: flowrate bounds
- Timing
  - Ships

$$TN^{s}_{n,e} \geq TN^{f}_{n,e-1}$$

$$TN^{s}_{n,e} \geq \sum_{p \in P_n} \left(\tau^{start}_{n,p} + A_{n,p}.\theta^{ent}_{n,p} \right)$$

$$TN^{f}_{n,e} \leq \sum_{p \in P_n} \tau^{end}_{n,p}$$

  - Tanks

$$TT^{s}_{t,e} \geq TT^{f}_{t,e'} + \Delta^{dec}_{t}.(\sum_{o \in O_t} UT_{t,o,e} + \sum_{n \in N_t} LT_{n,t,e'} - 1)$$

$$TT^{f}_{t,e} \leq H \qquad TT^{s}_{t,e} \geq TT^{f}_{t,e-1}$$

PROPOSED MODEL – CONSTRAINTS

- Matching of timing variables
  - Ships ↔ Tanks

$$TN_{n,e}^{s} - H.(1 - LT_{n,t,e}) \le TT_{t,e}^{s} \le TN_{n,e}^{s} + H.(1 - LT_{n,t,e})$$

$$TN_{n,e}^{f} - H.(1 - LT_{n,t,e}) \le TT_{t,e}^{f} \le TN_{n,e}^{f} + H.(1 - LT_{n,t,e})$$

  - Tanks ↔ Pipelines

$$TT_{t,e}^{s} - H.(1 - UT_{t,o,e}) \le TD_{o,e}^{s} \le TT_{t,e}^{s} + H.(1 - UT_{t,o,e})$$

$$TT_{t,e}^{f} - H.(1 - UT_{t,o,e}) \le TD_{o,e}^{f} \le TT_{t,e}^{f} + H.(1 - UT_{t,o,e})$$

PROPOSED MODEL – OBJECTIVE FUNCTION

$$\max\ profit\ = \sum_{r}\sum_{cl\in CLR_r} REVR_{cl,r}^{class}\cdot\left[\sum_{o\in O_r}\ \sum_{t\in\left(T_{cl}\cap T_o\right)}\ \sum_{e'=1}^{E-1} Qut_{t,o,e'}\right] \quad \text{(oil revenue to the refineries)}$$

$$+\sum_{cl} REVP_{cl}^{class}\cdot\sum_{t\in T_{cl}}\left(V_{t,E}^{T}-V_{t}^{0}\right) \quad \text{(final - initial oil revenue in the port)}$$

$$-\sum_{c} COST_{c}^{crude}\cdot\left(\sum_{n\in N_c} C_{n,c}\right) \quad \text{(oil cost in the tanks)}$$

$$-\sum_{p} COST_{p}^{pier}\cdot\left[\sum_{n\in N_p}\left(\tau_{n,p}^{end}-\tau_{n,p}^{start}\right)\right] \quad \text{(pier utilization cost)}$$

$$-\sum_{n} COST_{n}^{se}.T_{n}^{se} \quad \text{(overstay cost of the oil tankers)}$$

$$-\sum_{o}\ \sum_{cl\in CLO_o}\ \sum_{\substack{cl'\in CLO_o\\ cl'\neq cl}} COST_{cl,cl'}^{face}\cdot\sum_{e=1}^{E-1} INT_{cl,cl',o,e} \quad \text{(interface cost)}$$

SUBSTATION MODEL - MAIN ASSUMPTIONS

- Tanks cannot be loaded and unloaded simultaneously
- Outlet pipelines cannot be loaded by inlet pipelines and tanks simultaneously
- Substation must receive crude oil at the flow rates generated by the Pot Model
  - Lots of crude oil

SUBSTATION MODEL – SUMMARY

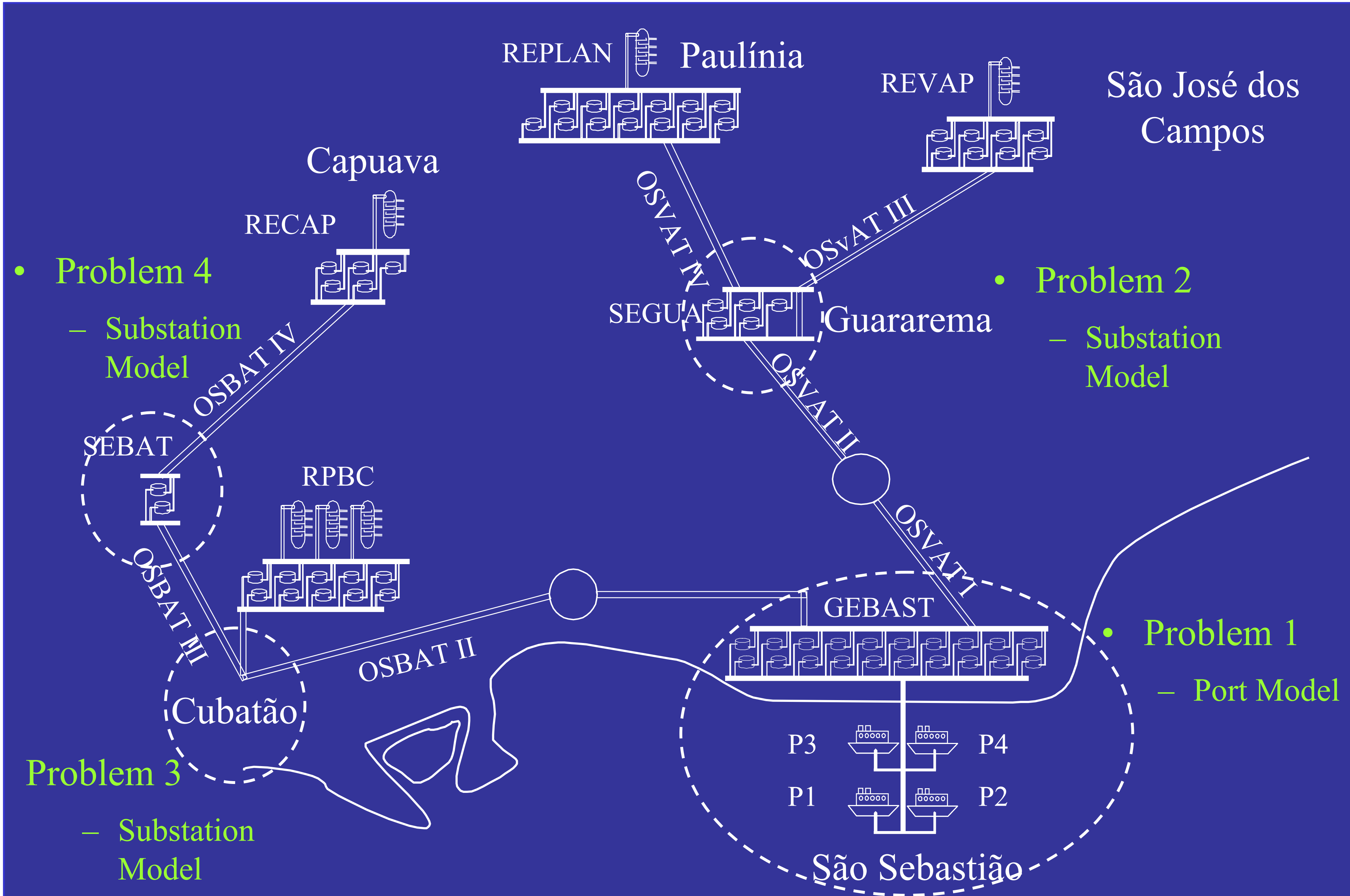
Minimize

Cost = cost of tank loading/unloading +
cost of pipeline alignment +
cost of interface

Subject to:

- Assumptions of the substation model
- Operating constraints
  - Tank loading/unloading
  - Pipeline operation
- Timing constraints
  - Inlet pipelines
  - Tanks
  - Outlet pipelines

REAL-WORLD PROBLEM

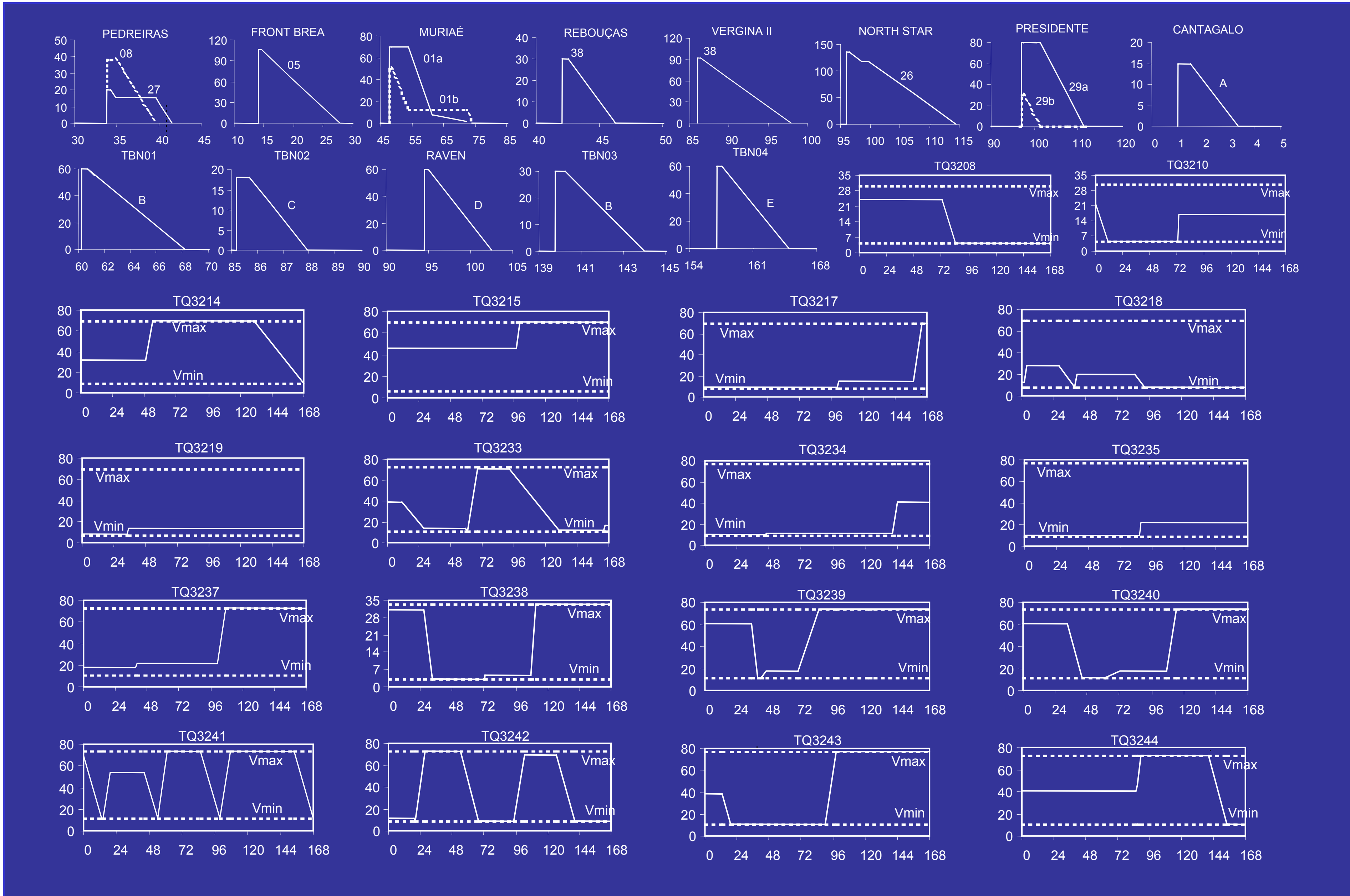


COMPUTATIONAL RESULTS

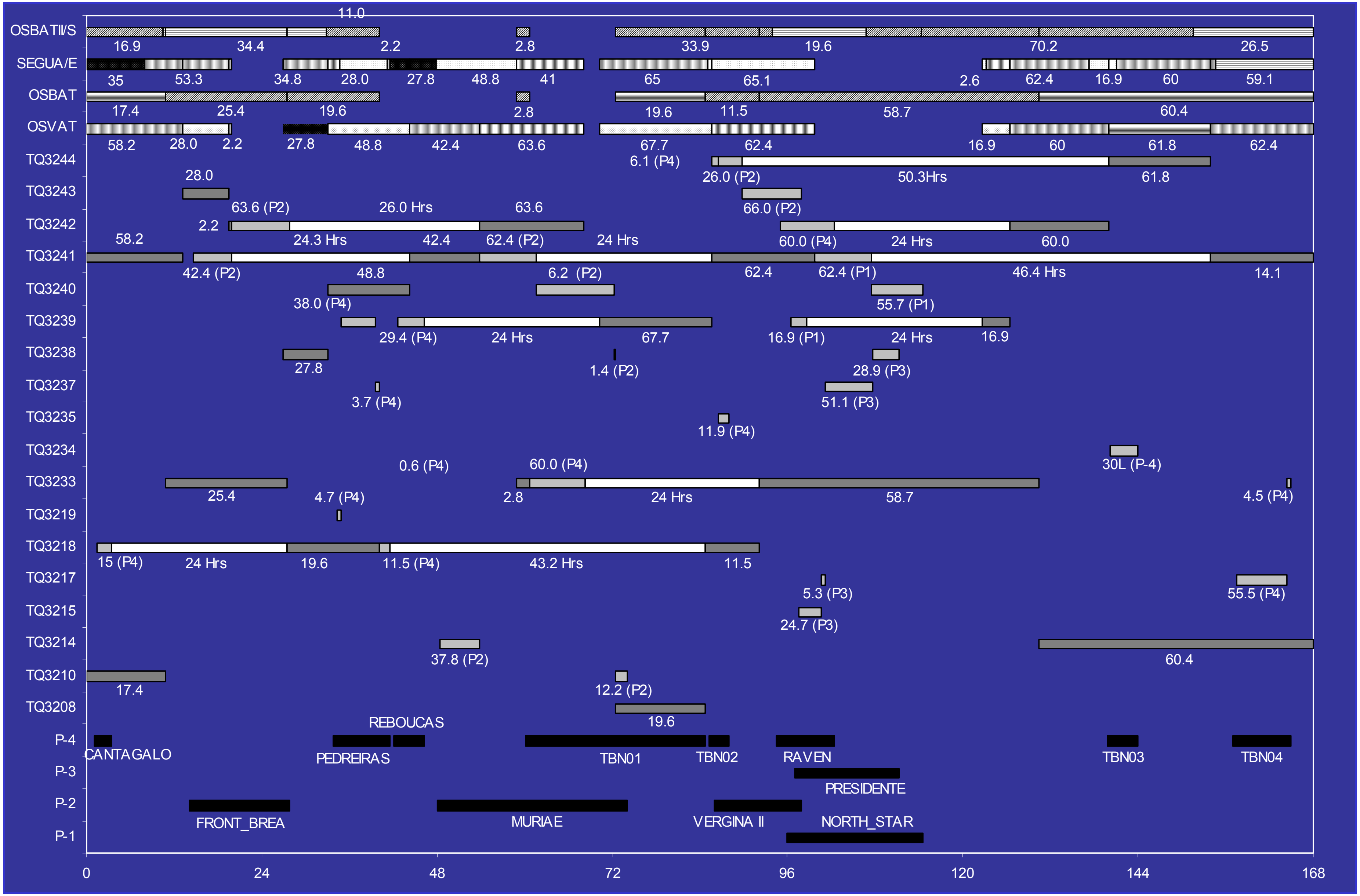
- Smaller optimality gaps for the Port Model
- Large variation on computational times

	Problem 1	*Problem 2*	*Problem 3*	*Problem 4*
Number of continuous variables	1996	4954	712	703
Number of binary variables	1039	759	66	123
Number of constraints	7203	10337	1158	1682
Relaxed LP solution	21,768.32	23.00	11.00	11.39
Best Integer Objective	20,073.96	42.00	21.00	15.00
Optimality gap	**7.78%**	**82.61%**	**90.91%**	**31.74%**
Nodes	1118	3784	3921	422
Iterations	62313	74410	19321	5244
CPU time (Pentium III 450MHz)	**1,457.51 s**	**3,602.07 s**	**134.69 s**	**28.28 s**
	Port Model	Substation Models		

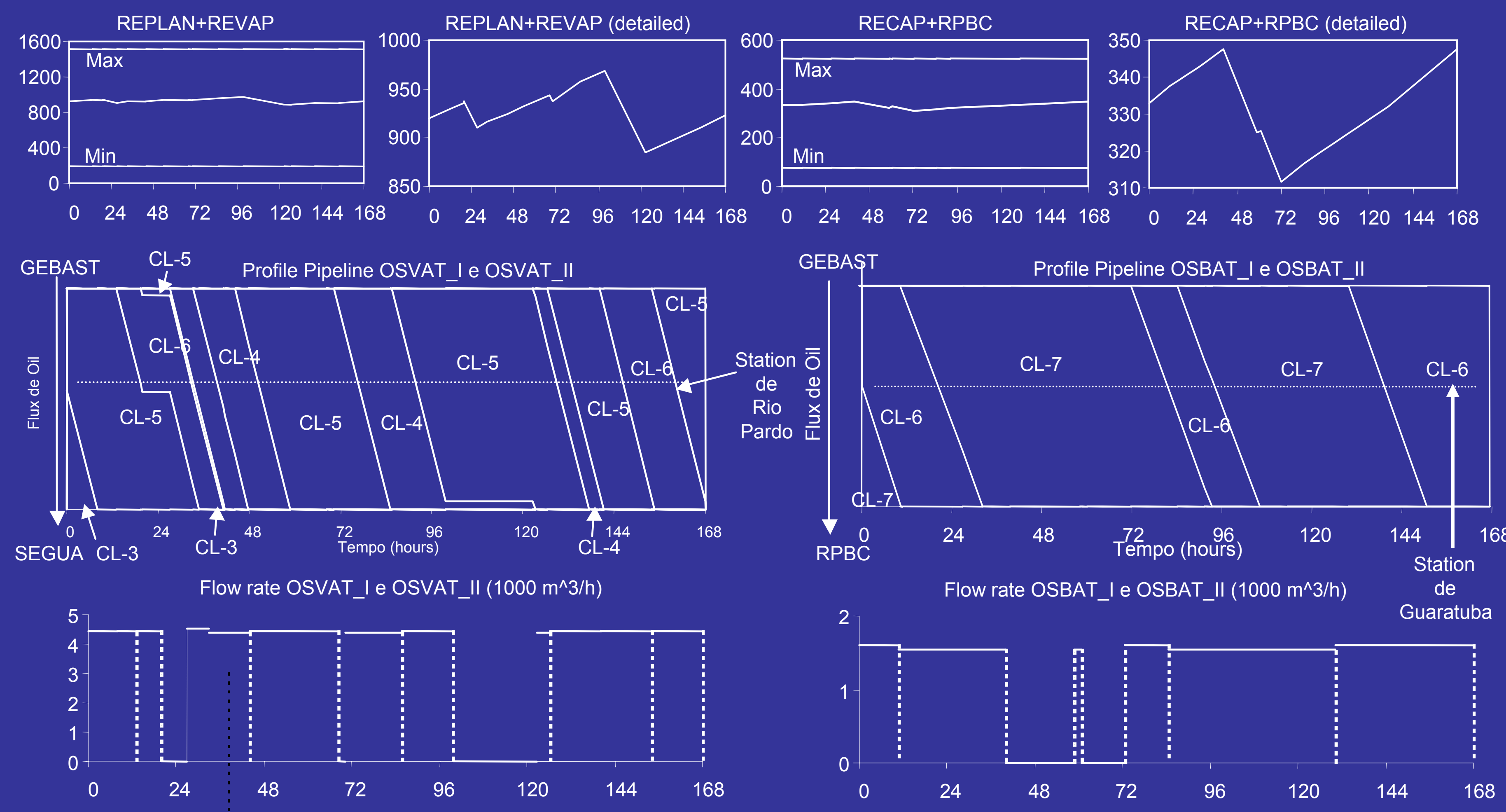
PROBLEM 1 – TANKERS AND TANKS



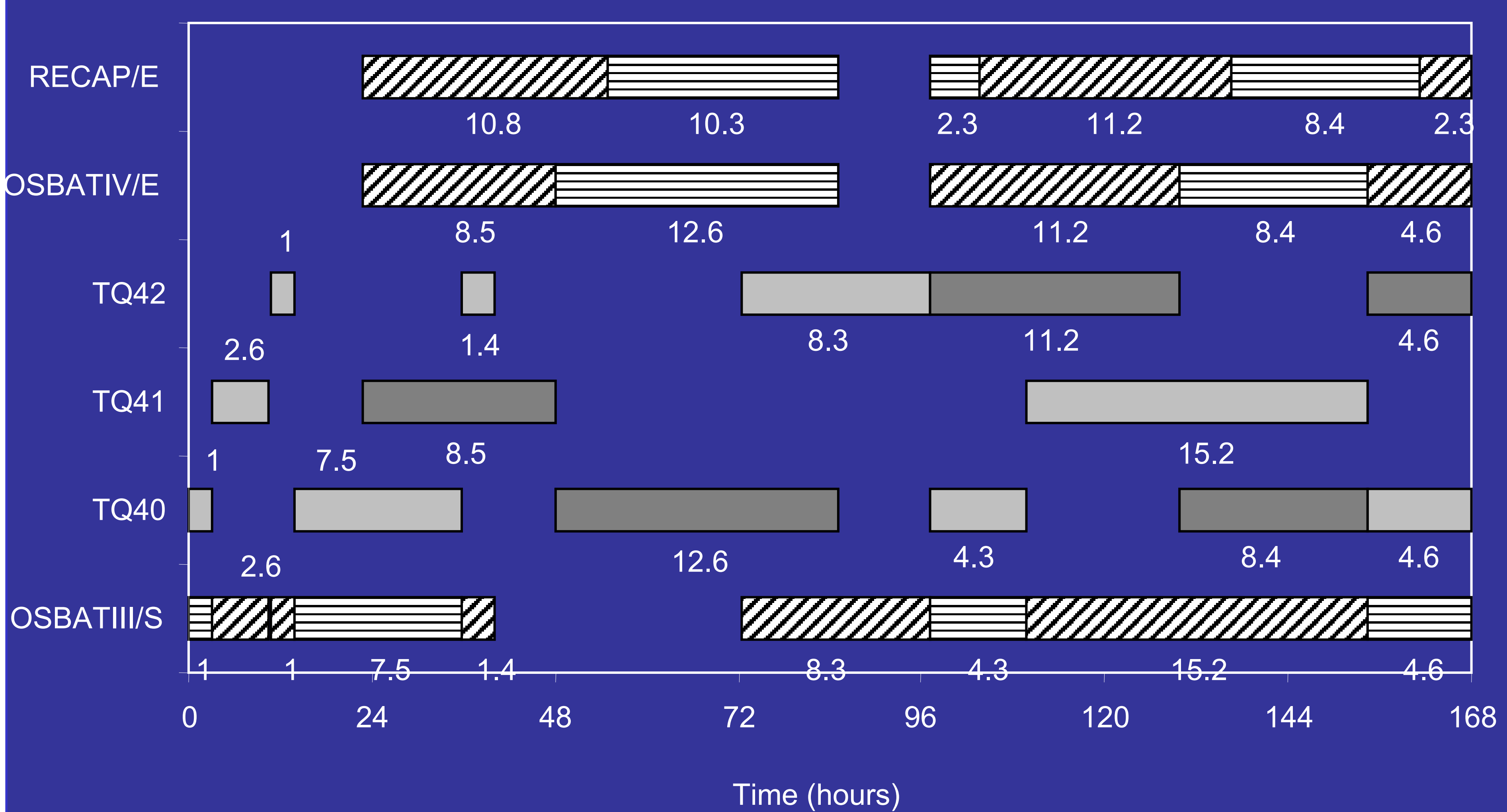
PROBLEM 1 – GANTT CHART



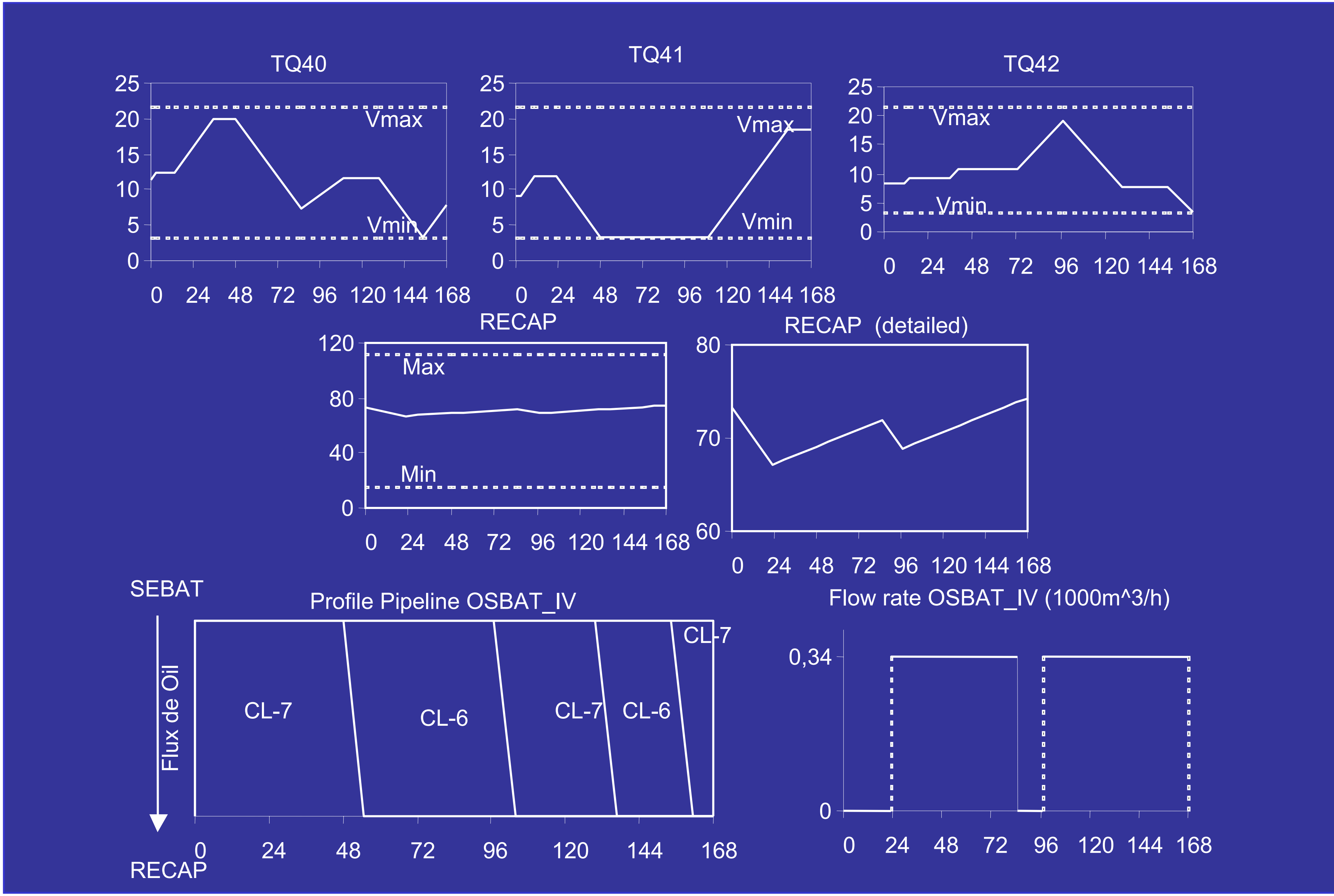
PROBLEM 1 – REFINERIES AND PIPELINES



PROBLEM 4 – GANTT CHART



PROBLEM 4 – TANKERS, REFINERIES AND PIPELINES



OUTLINE

- *Introduction*
- *Planning Models*
  - *refinery diesel production*
- *Scheduling models*
  - *crude oil scheduling*
  - *fuel oil / asphalt area*
- *Logistics*
  - *oil supply model*
- *Conclusions*

CONCLUSIONS

- **Problems can be modeled as large scale MILPs / non-convex MINLP;**
- **The LP based Branch and Bound Method (*solver* OSL):**
  - **is satisfactory to generate "good" feasible solutions;**
  - **no guarantee of global optimum solutions for all instances;**
- **The OA/ER/AP Method (*solver* DICOPT++):**
  - **is efficient to circumvent the non-convexity problem;**
  - **is satisfactory to generate feasible solutions;**
  - **has computational performance similar to MILP model.**
- **Issues:**
  - **time representation**
  - **blending/pooling**
  - **transitions**

CONCLUSIONS - CHALLENGES

Large Scale Systems - Main theoretical difficulties:

- **Complex problems with high combinatorial features;**

  → ***NP-Complete* Problems** → **Infeasible computational times**

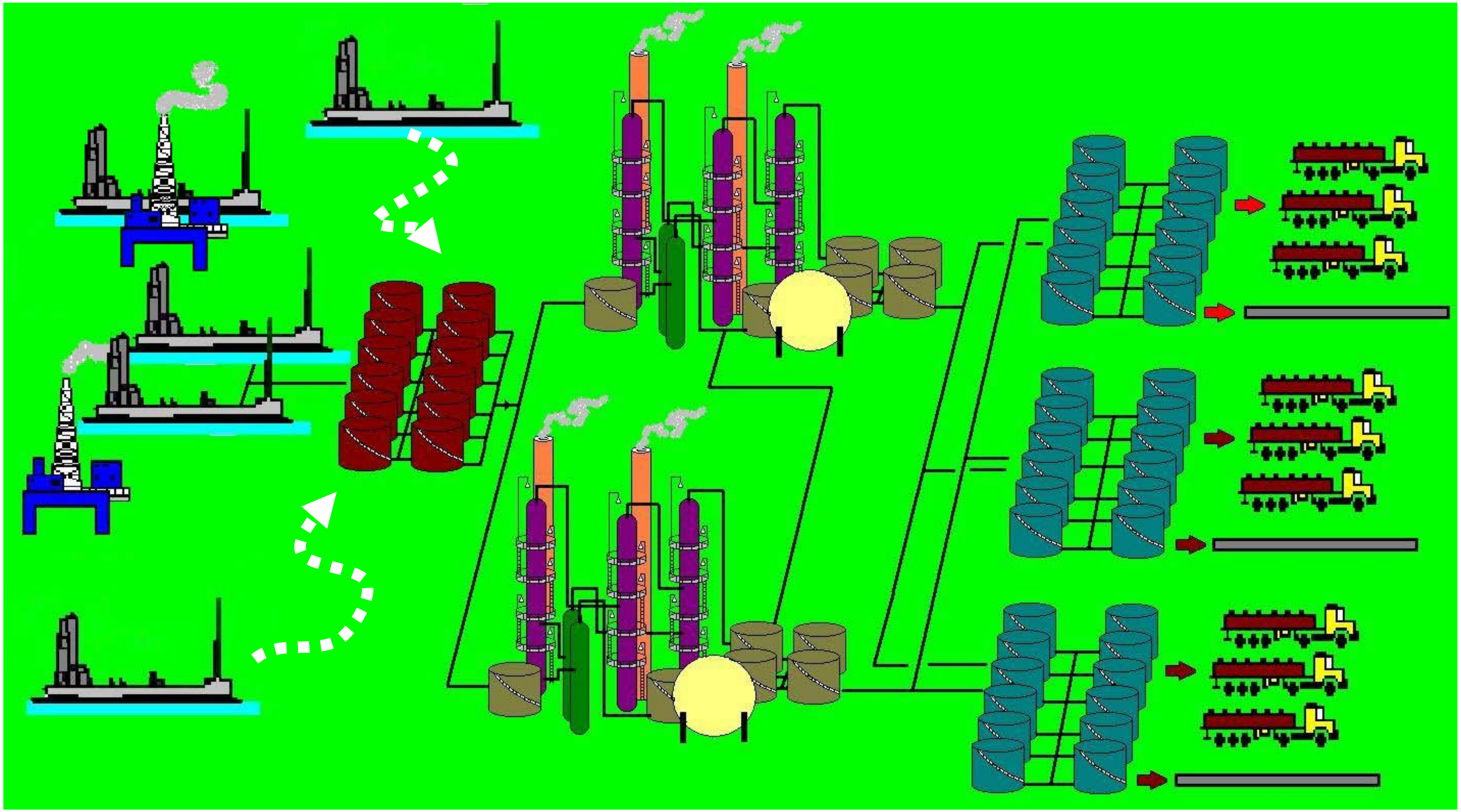
Large Scale Systems - Main practical difficulties

- **The understanding of the problem itself can constitute the major difficulty;**
- **The cooperation between the modeler level and the plant floor level is essential and remains as the main challenge for the Operational Research**
- **Continuous work necessary due to the dynamic nature of scheduling problems.**

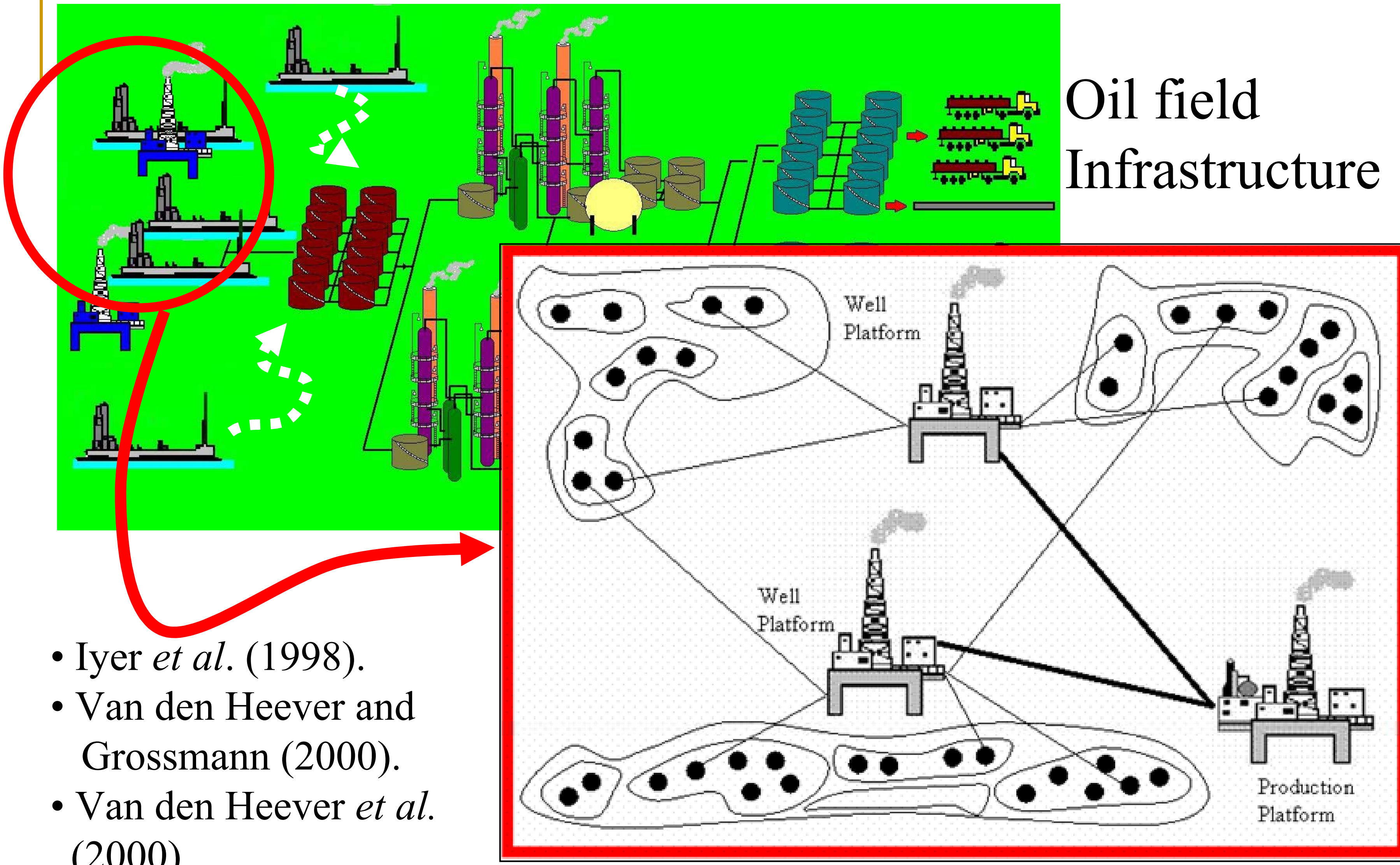
ACKNOWLEDGEMENTS

Researchers	Engineers	Financial Support
M. Joly	C.A. Gratti	Petrobras
R. Más	M. F. Lehner	
L. Moro	M.V. Magalhães	CAPES
R. Rejowski	A.C. Zanin	CNPq
P. Smania		FAPESP

General Petroleum Supply Chain



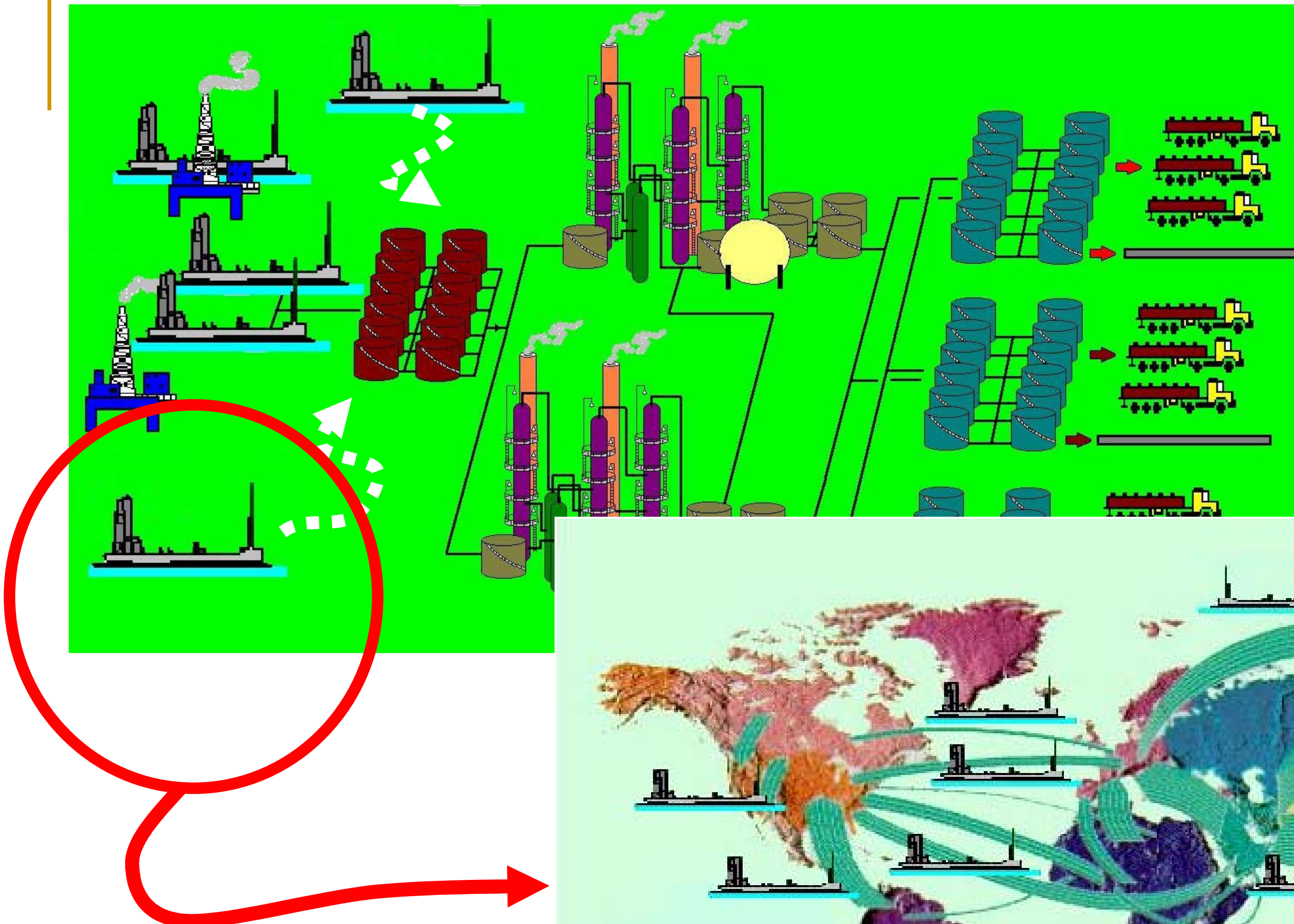
Oil field Infrastructure



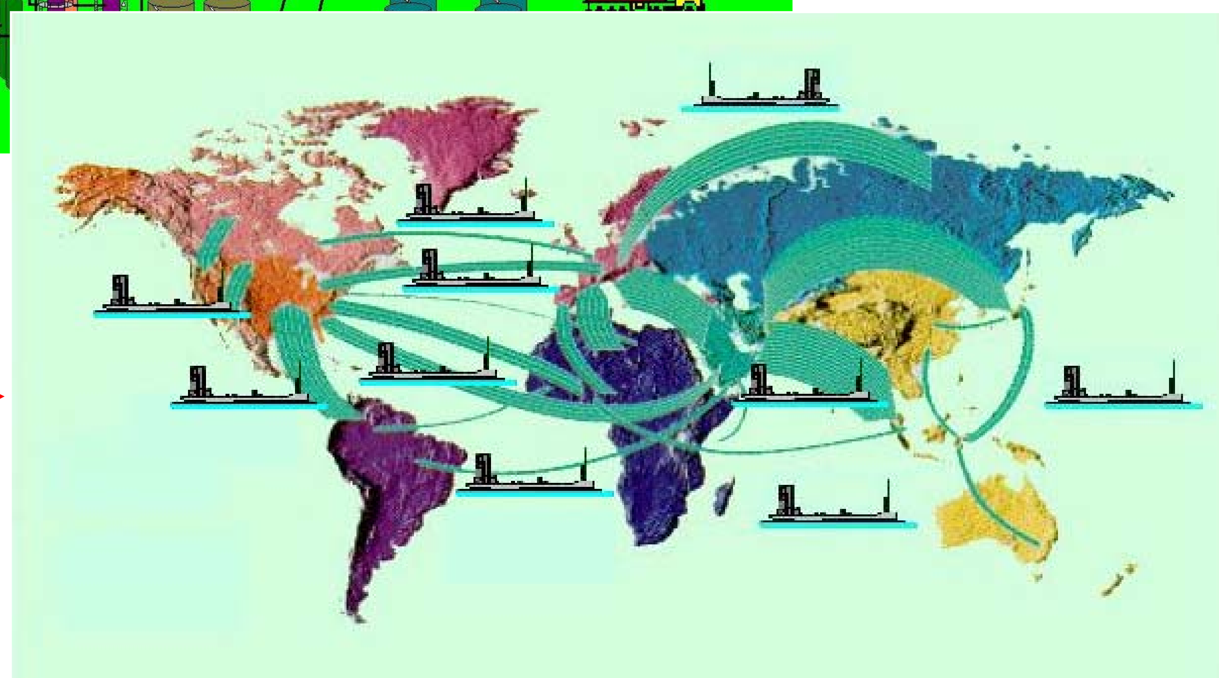
- Iyer *et al*. (1998).
- Van den Heever and Grossmann (2000).
- Van den Heever *et al.* (2000).

Ierapetritou *et al.* (1999).

- Kosmidis (2002).
- Barnes *et al.* (2002).

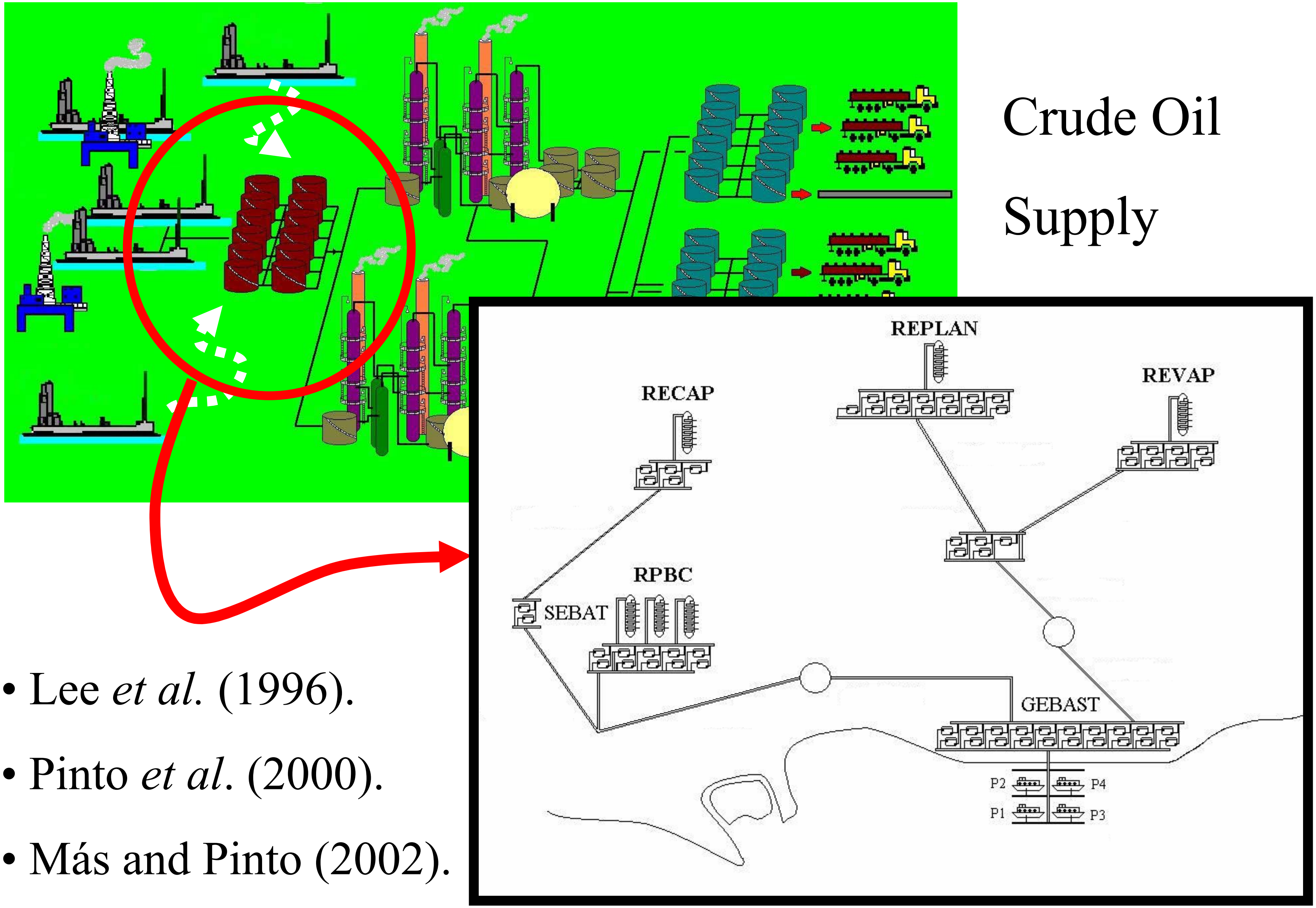


International Petroleum Commerce



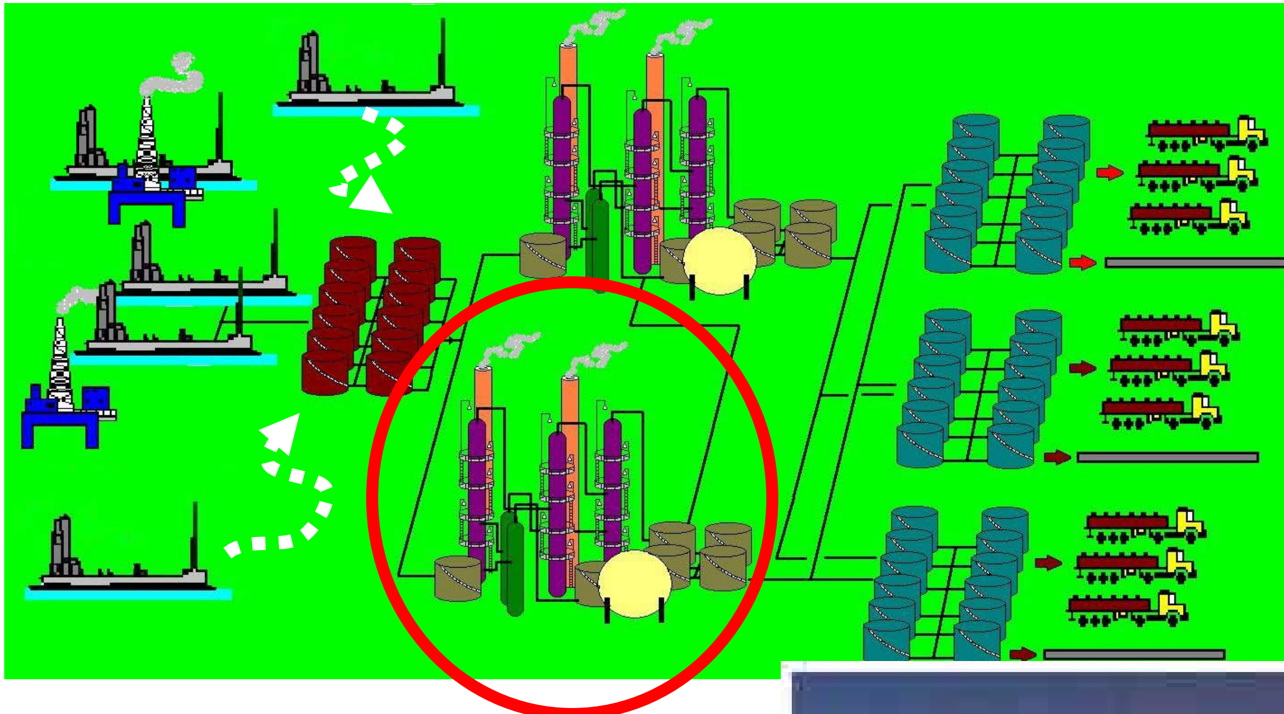
- Operations

Research.



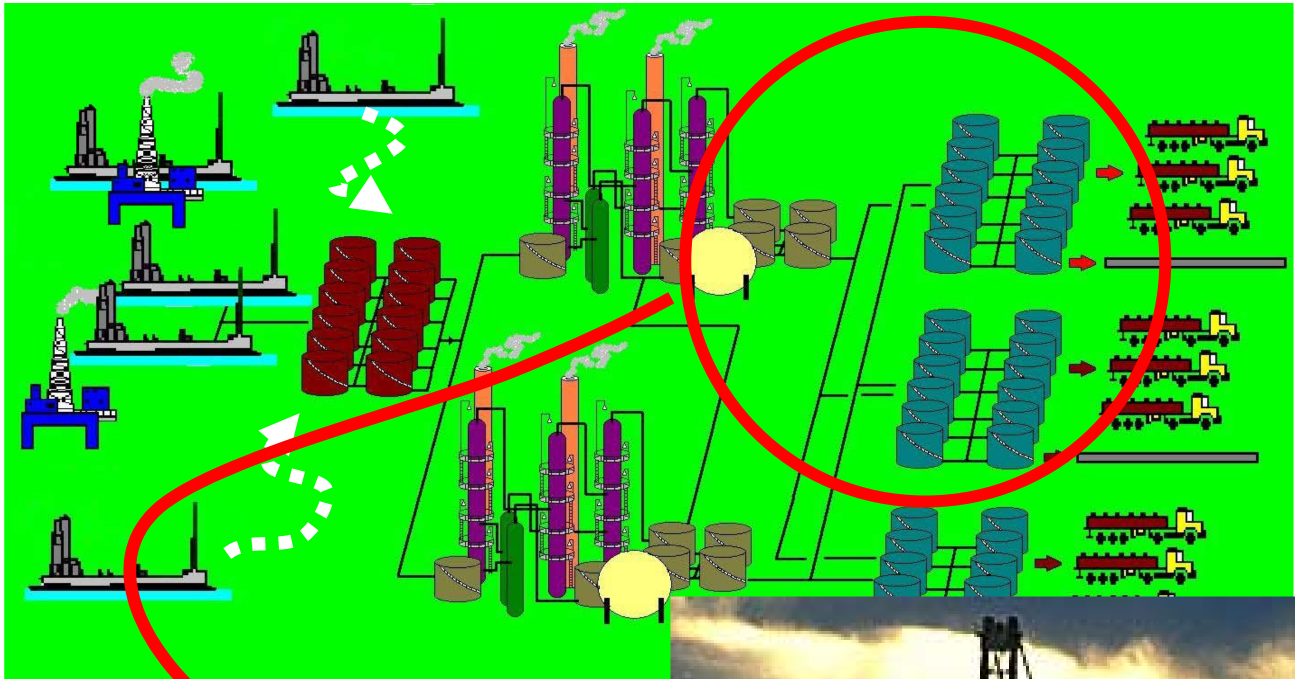
Crude Oil Supply

- Lee *et al*. (1996).
- Pinto *et al*. (2000).
- Más and Pinto (2002).



Refinery - Planning/ Scheduling

- Ponnambalam (1992).
- Bok *et al*. (1998).
- Pinto and Moro (2000).



Distribution

- Ross (2000).
- Iakovou (2001).
- Magatão *et al*. (2002).
- Stebel *et al*. (2002).
- Rejowski and Pinto (2003).

Objective

Development of an optimization model

that is able to represent

a petroleum supply chain

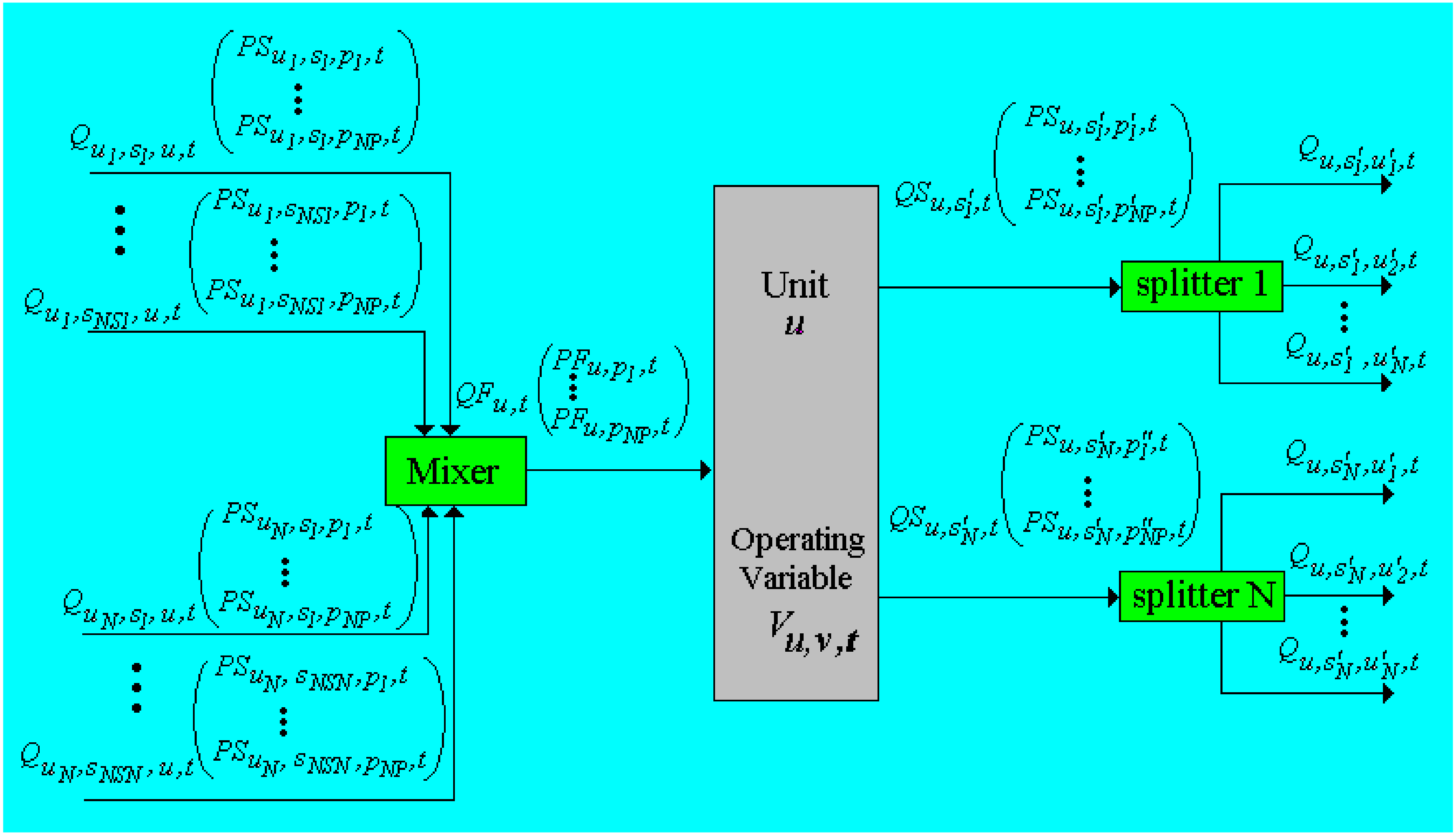
to support the

decision making planning process

of

supply, production and distribution

Refinery - Processing Unit Model



$$
\left.
\begin{aligned}
QF_{u,t} &= \sum_{(u',s)\in \mathbf{US}_u} Q_{u',s,u,t} \\
PF_{u,p,t} &= \frac{\displaystyle\sum_{(u',s)\in \mathbf{US}_u} Q_{u',s,u,t}.PS_{u',s,p,t}}{\displaystyle\sum_{(u',s)\in \mathbf{US}_u} Q_{u',s,u,t}}
\end{aligned}
\right\}
$$

Feed mixing

$$
\left.
\begin{aligned}
QS_{u,s,t} &= QF_{u,t}.f_{u,s}\left(PF_{u,p,t}\right) + \sum_{u\in \mathbf{VO}_u} QGain_{u,s,v}.V_{u,v,t} \\
PS_{u,s,p,t} &= f_{u,s,p}(PF_{u,p,t} \mid p \in \mathbf{PI}_u, QF_{u,t}, V_{u,v,t} \mid v \in \mathbf{VO}_u)
\end{aligned}
\right\}
$$

Unit model

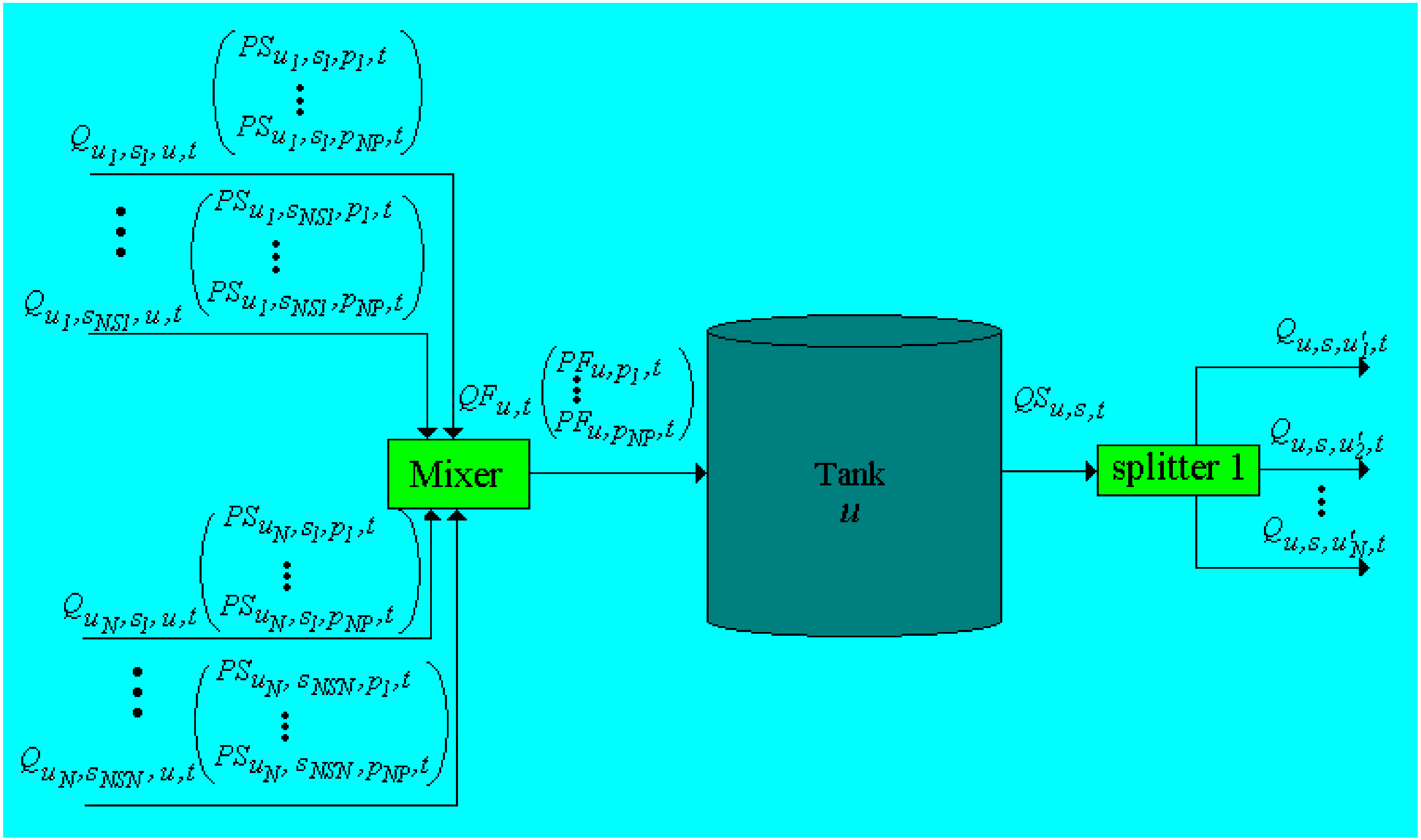
$$
\left. QS_{u,s,t} = \sum_{u'\in \mathbf{UO}_{u,s}} Q_{u,s,u',t} \right\}
$$

Product splitting stream

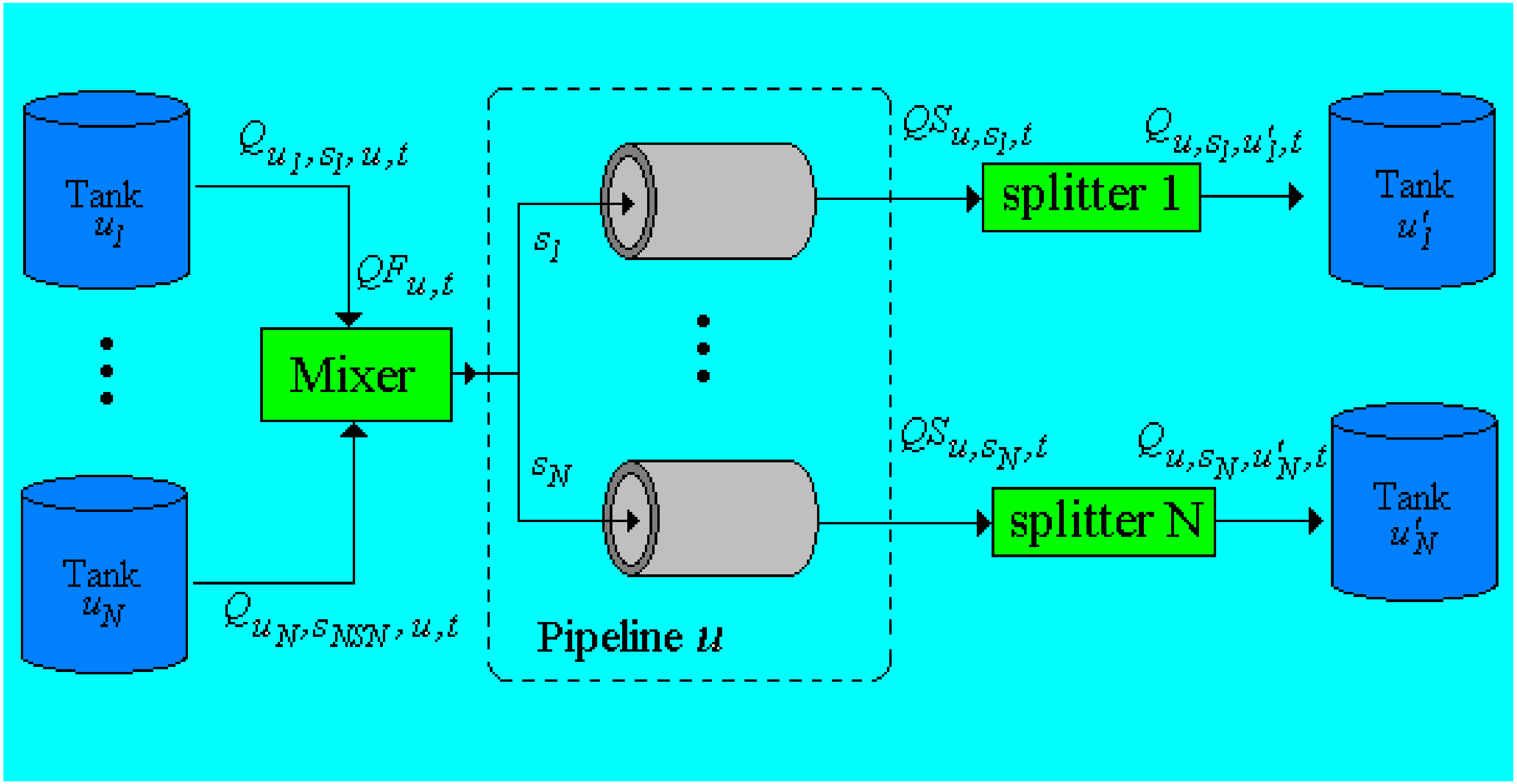
$$
\left. QF_u^L \le QF_{u,t} \le QF_u^U \qquad V_{u,v}^L \le V_{u,v,t} \le V_{u,v}^U \right\}
$$

Bounds

Supply, Distribution – Storage Model



Supply, Distribution - Pipeline Model



$$\boxed{QF_{u,t} = \sum_{(u',s)\in \mathbf{US}_u} Q_{u',s,u,t}}$$

$$\boxed{QS_{u,s,t} = Q_{u',s,u,t}}$$

$$\boxed{QS_{u,s,t} = Q_{u,s,u',t}}$$

$$\boxed{QF_{u,t} \le QF_u^U}$$

Supply Chain Model

Large Scale MINLP

PSC

$$Max\ \ Z = \sum_{u \in \mathbf{U}_{dem}} \sum_{t \in \mathbf{T}} Cp_{u,t}.\left(QF_{u,t} - Vol_{u,t}\right) - \sum_{u \in \mathbf{U}_{SB}} \sum_{t \in \mathbf{T}} .Cpet_{u,t}.Lot_{u,t}$$

$$- \sum_{u \in \mathbf{U}} \sum_{t \in \mathbf{T}} [\, Cr_u + \sum_{v \in \mathbf{VO}_u} \left(Cv_{u,v}.V_{u,v,t}\right) \,]\ .QF_{u,t} - \sum_{u \in \mathbf{U}_f} \sum_{t \in \mathbf{T}} Cinv_u.Vol_{u,t}$$

$$- \sum_{u \in \mathbf{U}_p} \sum_{t \in \mathbf{T}} Cinv_u.Vol_{u,t} - \sum_{u \in \mathbf{U}_{pipe}} \sum_{t \in \mathbf{T}} Ct_u.QF_{u,t}$$

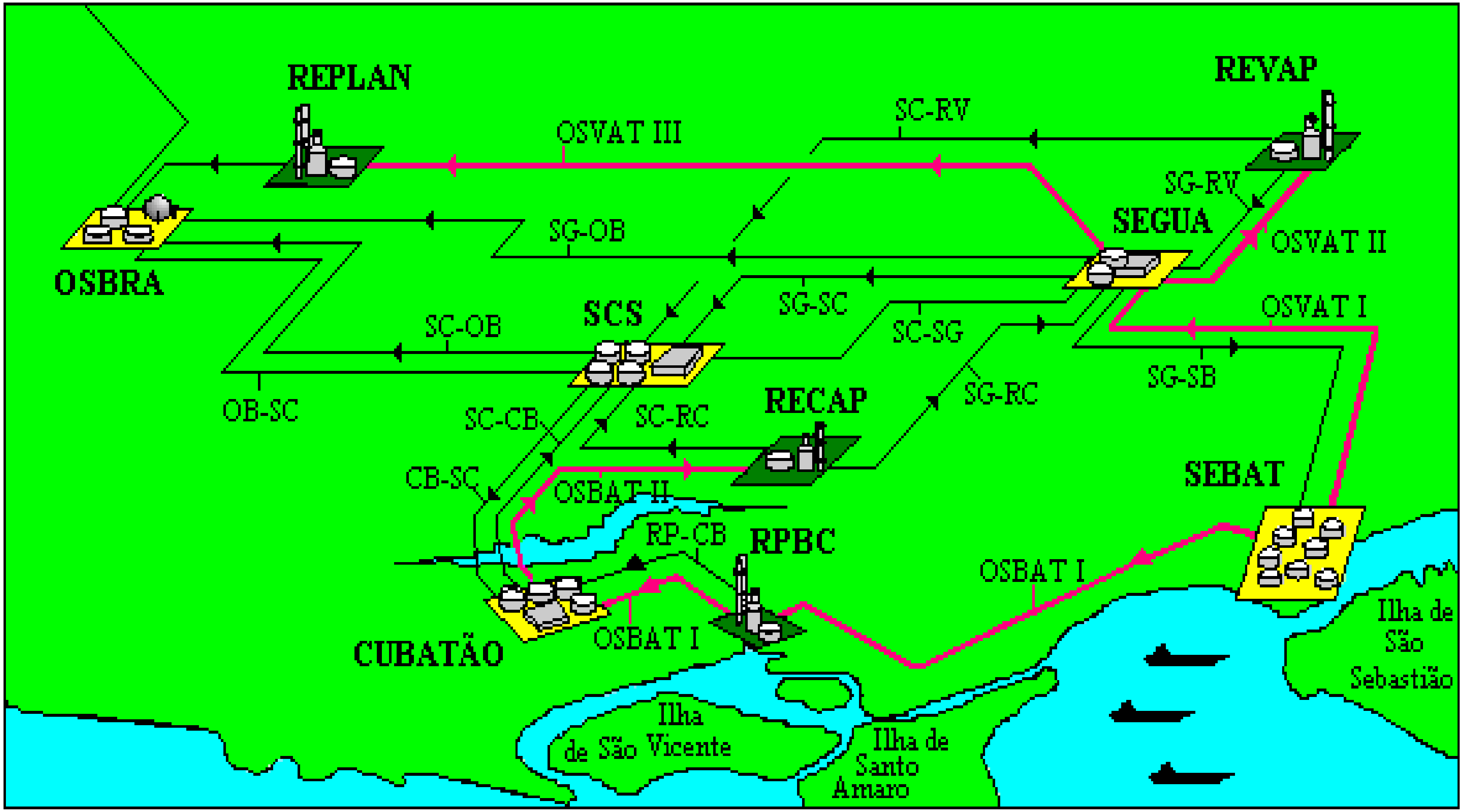
Supply Chain Model – cont. from previous slide

subject to the models of:

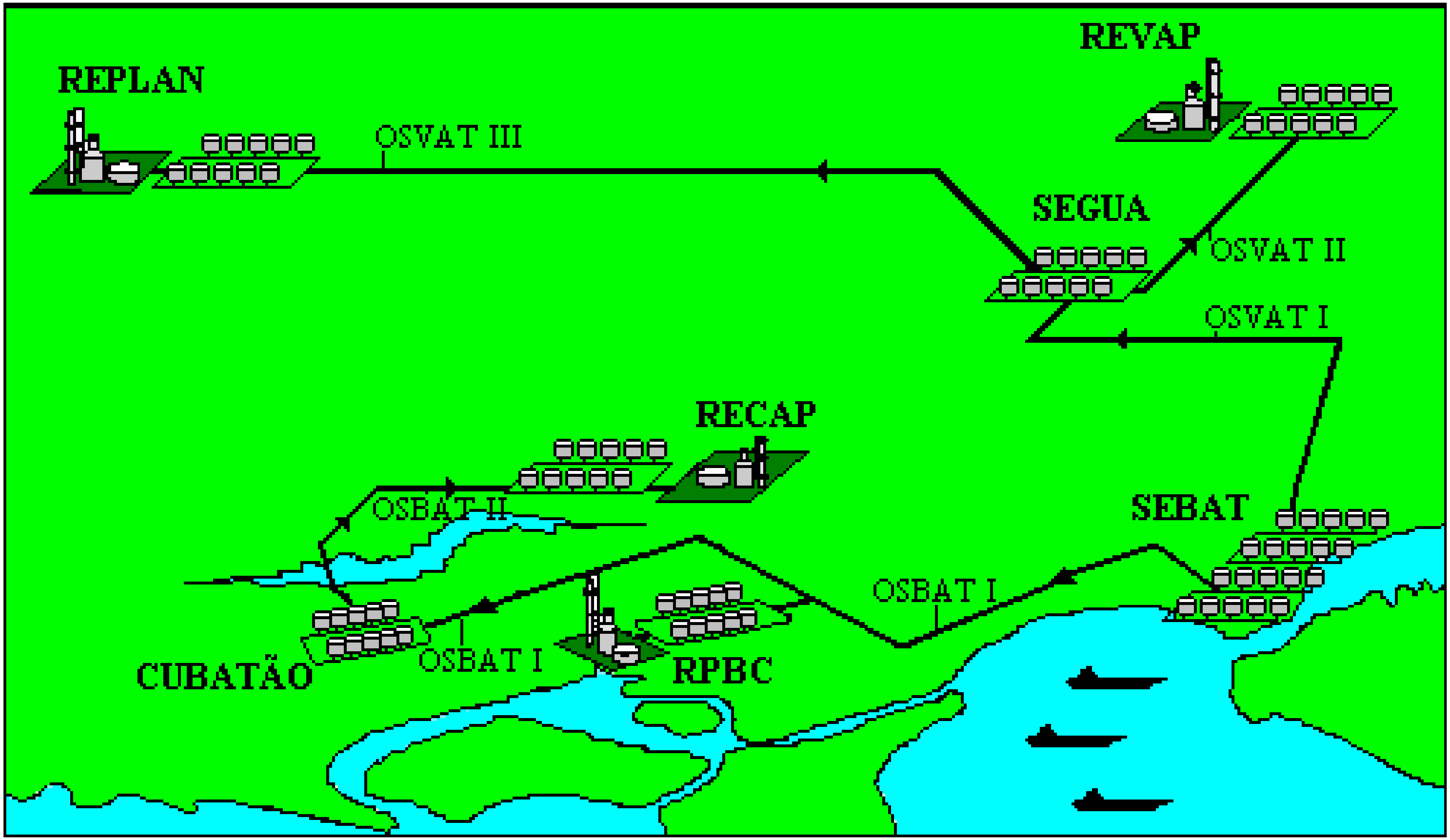
- processing units
  - units that compose refinery topology
  - refineries that compose the supply chain
- tank
  - petroleum and product tanks that compose refineries
  - petroleum and product tanks that compose terminals
  - refineries and terminals that compose the supply chain
- pipeline
  - pipeline network for petroleum supply
  - pipeline network for product distribution

$$QF, QS, Q, Vol, Lot \in \Re^{+} \qquad PF, PS, V \in \Re \qquad y \in \{0,1\}$$

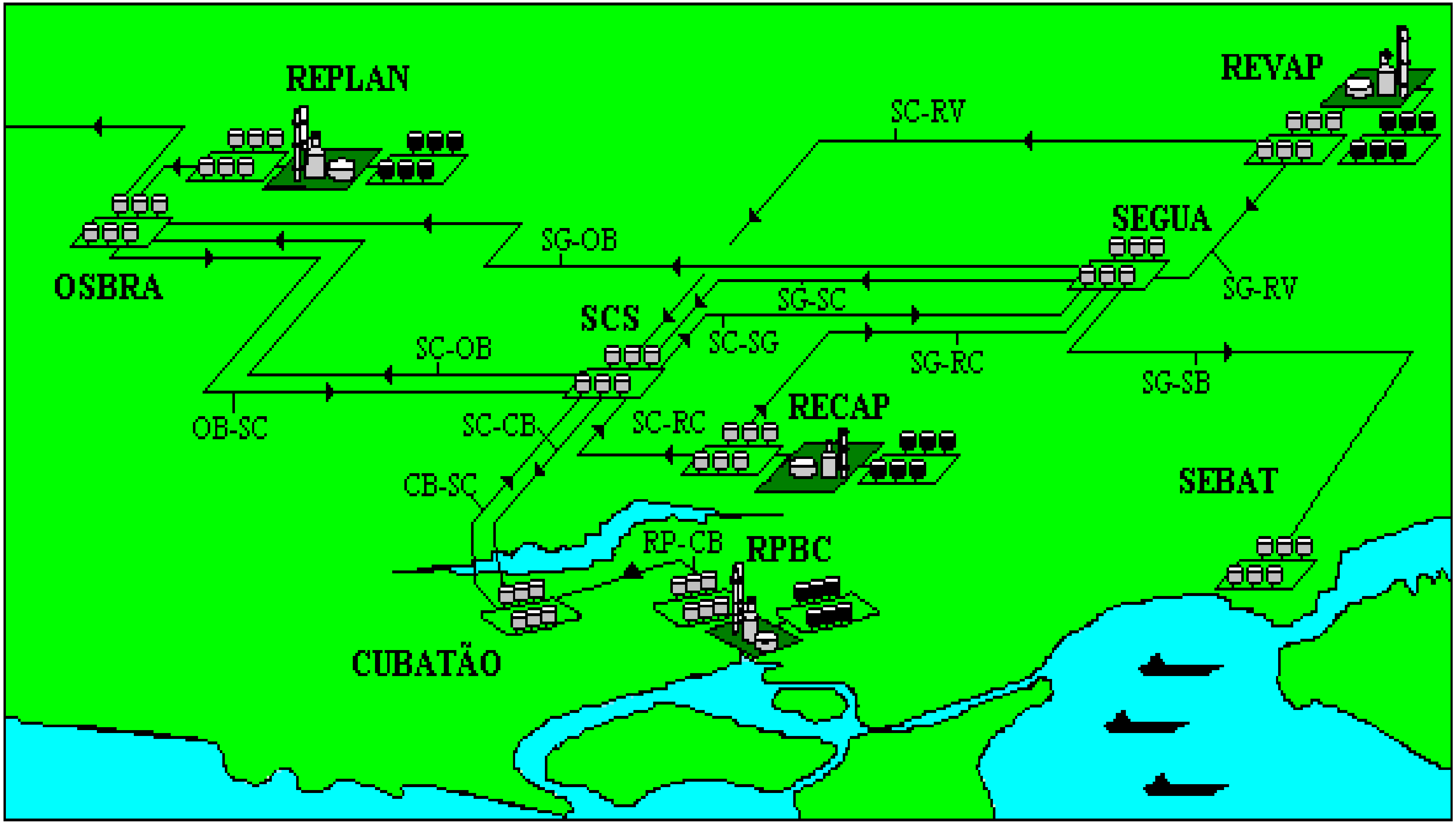
Supply Chain Components



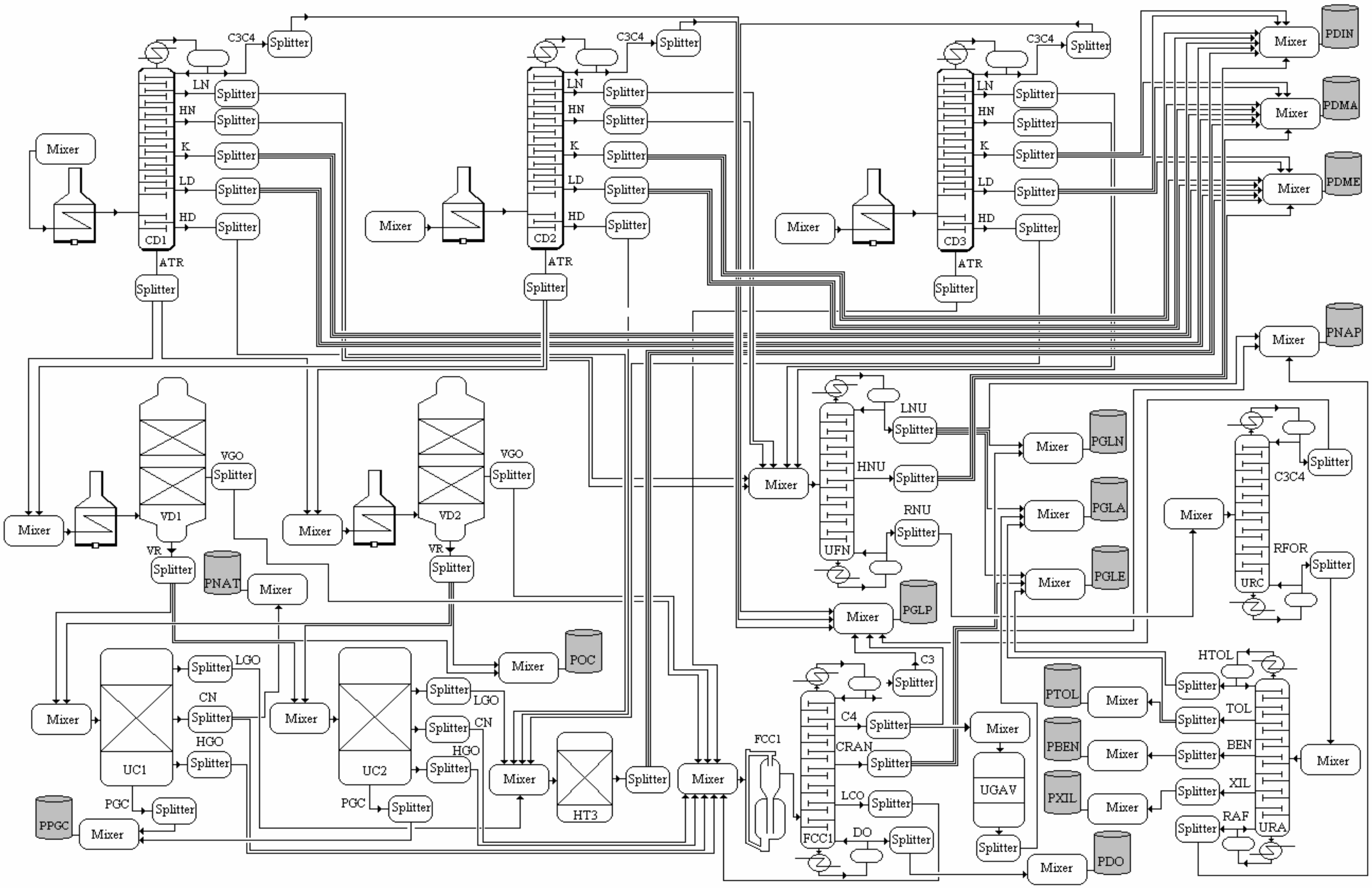
Petroleum Distribution Overview



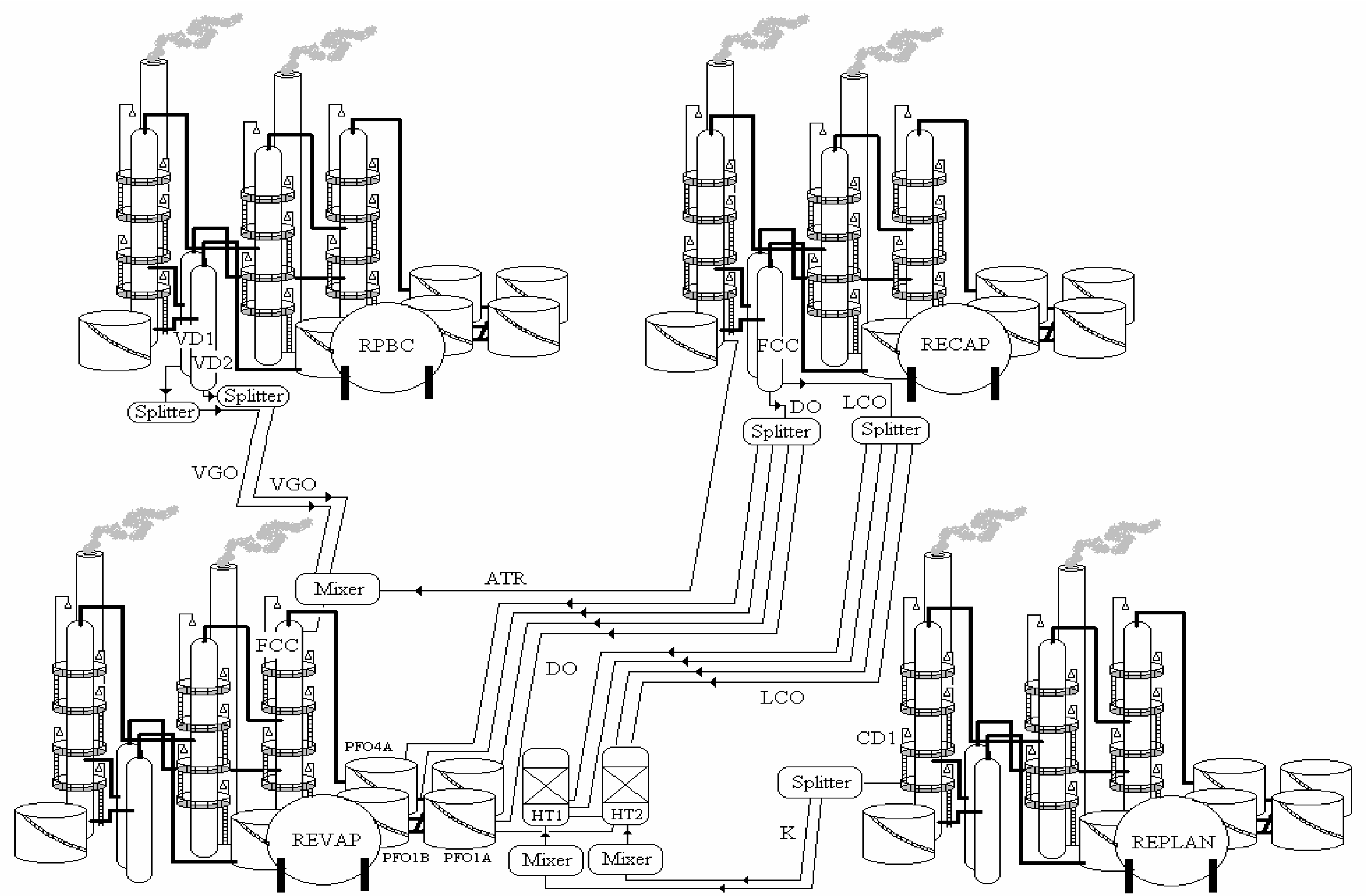
Product Distribution Overview



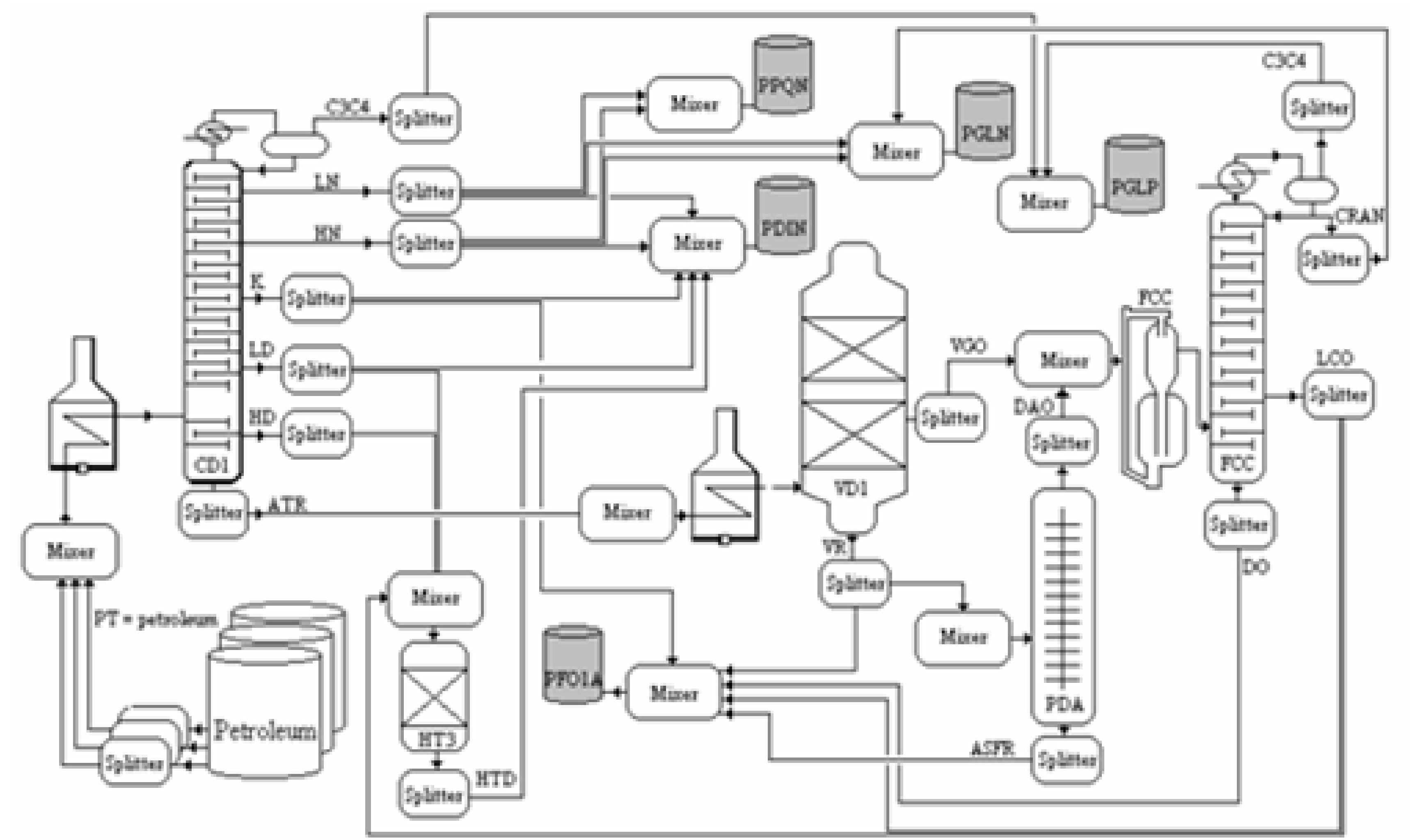
RPBC flowsheet



Intermediate connections



Modeling Example



Tanks and CD1 Model

$$PS_{CD1,s,p,t} = Prop_{CD1,s,p} + PGain_{CD1,s,p}.V_{CD1,V1,t} \quad \forall, s \in \mathbf{SO}_{CD1}, p \in \mathbf{PO}_{CD1,s}, t$$

$$QS_{CD1,s,t} = \sum_{u' \in \mathbf{UO}_{CD1,s}} Q_{CD1,s,u',t}$$

$$Gain_{CD1,s,V_1}.V_{CD1,V_1,t}, \forall t$$

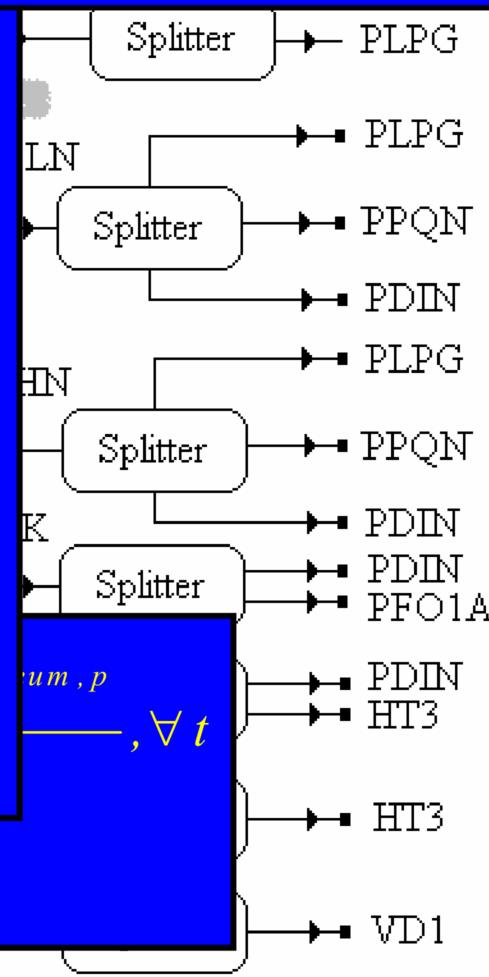
$$\left\{ \begin{array}{ccc} C3C4 & \rightarrow & YC3C4 \\ LN & \rightarrow & YLN \\ HN & \rightarrow & YHN \\ K & \rightarrow & YK \\ LD & \rightarrow & YLD \\ HD & \rightarrow & YHD \\ ATR & \rightarrow & YATR \end{array} \right\}$$

um, p

$, \forall t$

$u' \in \{tank\ 1,2,3\}$

$$p \in \{YC3C4, YLN, YHN, YK, YLD, YHD, YATR\}$$



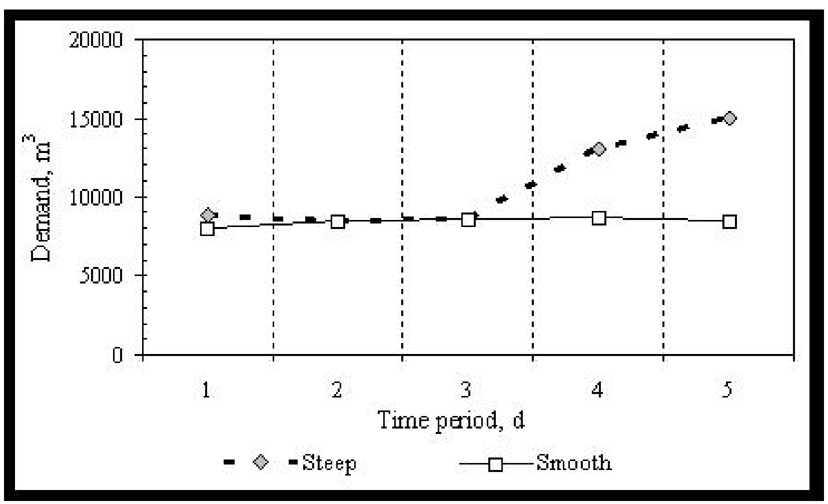
Refinery Multiperiod Planning – REVAP results

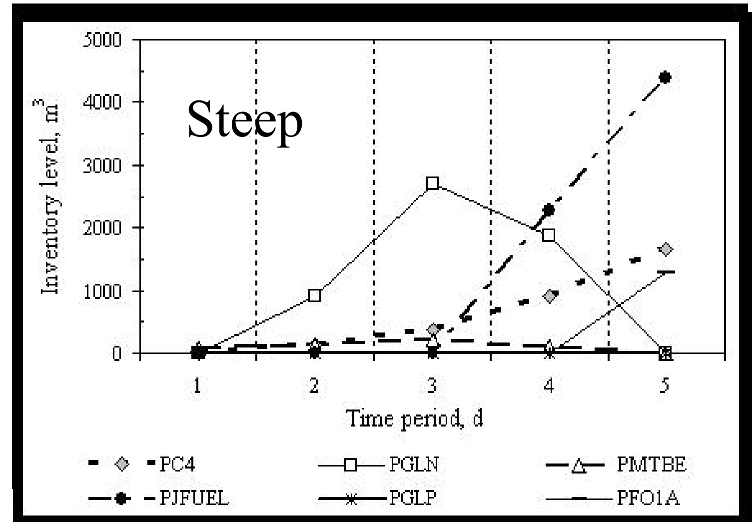
DICOPT

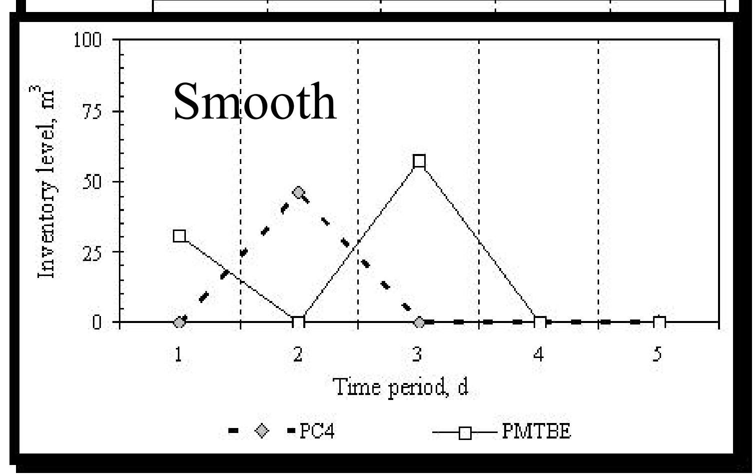
(NLP CONOPT++)

(MIP OSL, CPLEX)

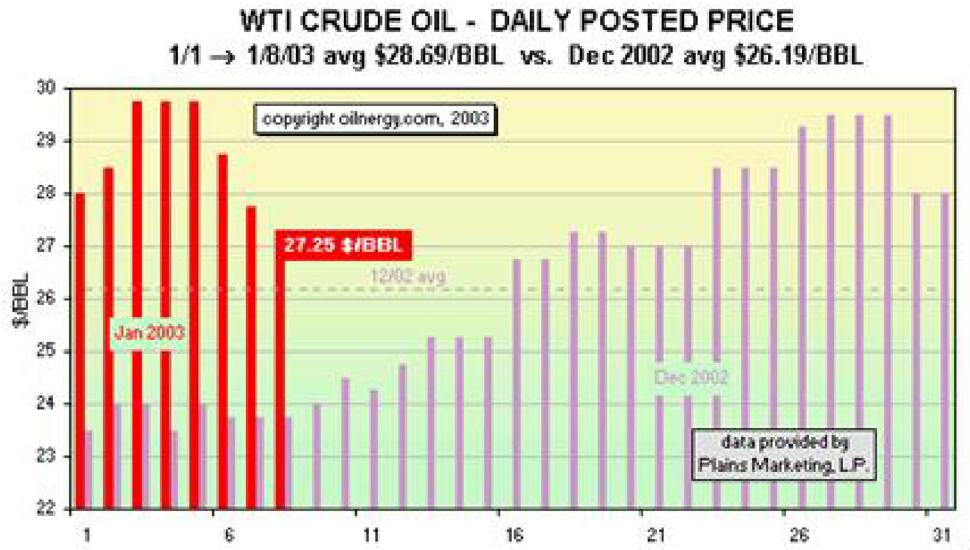
Demand profile - GLN







Refinery Planning – Model with Uncertainty



Discrete Scenarios

$c1$	$c2$	cN
P1%	P2%	PN%

$$\sum_{c \in \mathbf{C}} prob_{c,t} = 1$$

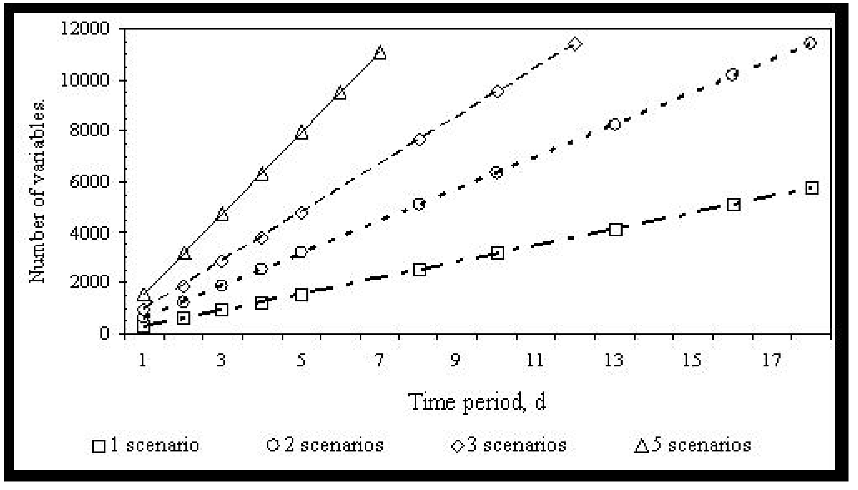
$$Max\ Z = \sum_{c\in\mathbf{C}}\sum_{t\in\mathbf{T}}\left(\sum_{u\in\mathbf{U}_p} prob_{c,t} Cp_{u,t,c}\left(QF_{u,t,c} - Vol_{u,t,c}\right)\right) - \sum_{c\in\mathbf{C}}\sum_{t\in\mathbf{T}}\left(\sum_{u\in\mathbf{U}_f}\sum_{s\in\mathbf{SO}_u} prob_{c,t} Cf_{u,t,c} QS_{u,s,t,c}\right)$$

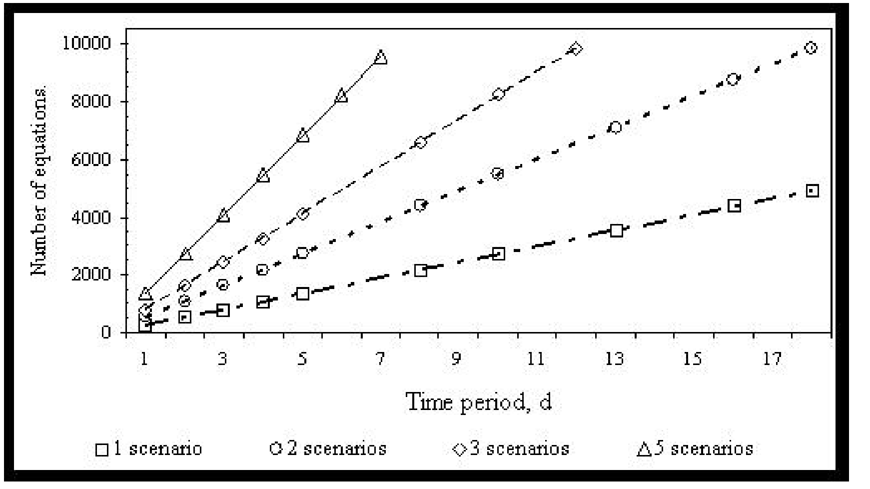
$$-\sum_{c\in\mathbf{C}}\sum_{t\in\mathbf{T}}\left(\sum_{u\in\mathbf{U}_f} Cb_u y_{u,t,c}\right) - \sum_{c\in\mathbf{C}}\sum_{t\in\mathbf{T}}\left(\sum_{u\in\mathbf{U}\setminus\{\mathbf{U}_f,\mathbf{U}_p\}} [Cr_u + \sum_{v\in\mathbf{VO}_u}(Cv_{u,v}.V_{u,v,t})]\ QF_{u,t}\right)$$

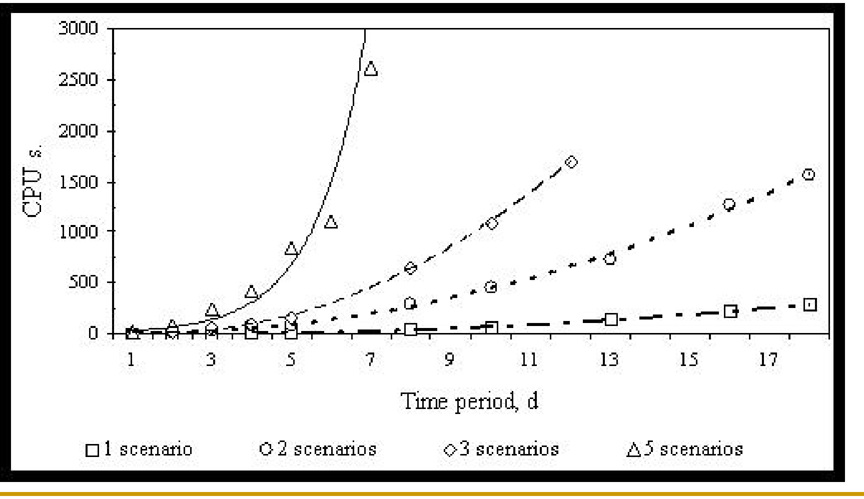
$$-\sum_{t\in\mathbf{T}}\left(\sum_{u\in\mathbf{U}_p} Cinv_{u,t,c} Vol_{u,t,c}\right)$$

s.t. refinery constraints

Planning under Uncertainty - REVAP results

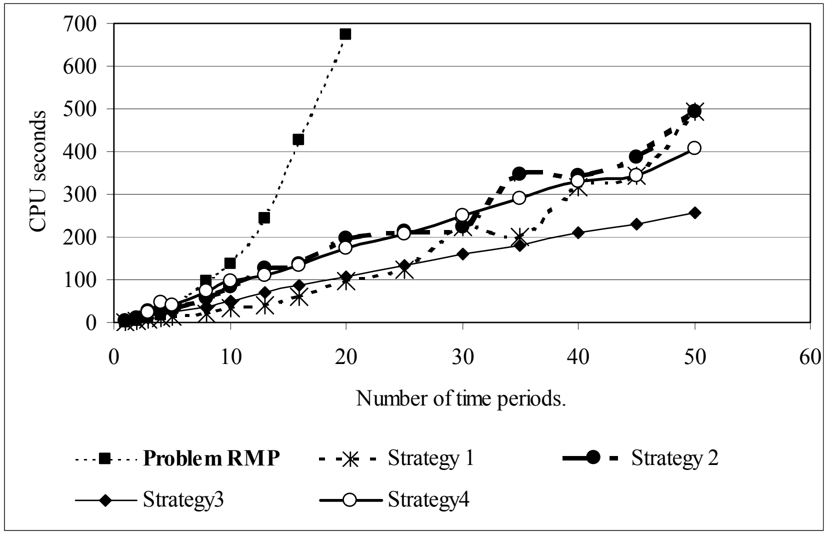






Proposed Strategies and Results

	Primal subproblem	Dual subproblems	Multipliers update
Strategy 1	Fixed assigment	Lagrangean	Subgradient
Strategy 2	Fixed inventory	Lagrangean	Subgradient
Strategy 3	Fixed inventory	Surrogate	Subgradient
Strategy 4	Fixed inventory	Lagrangean	Modified Subgradient



Supply Chain Example

Cases:

1: Complete model

2: Pre-selection of some suppliers

3: Interruption of pipeline segment SG-RV

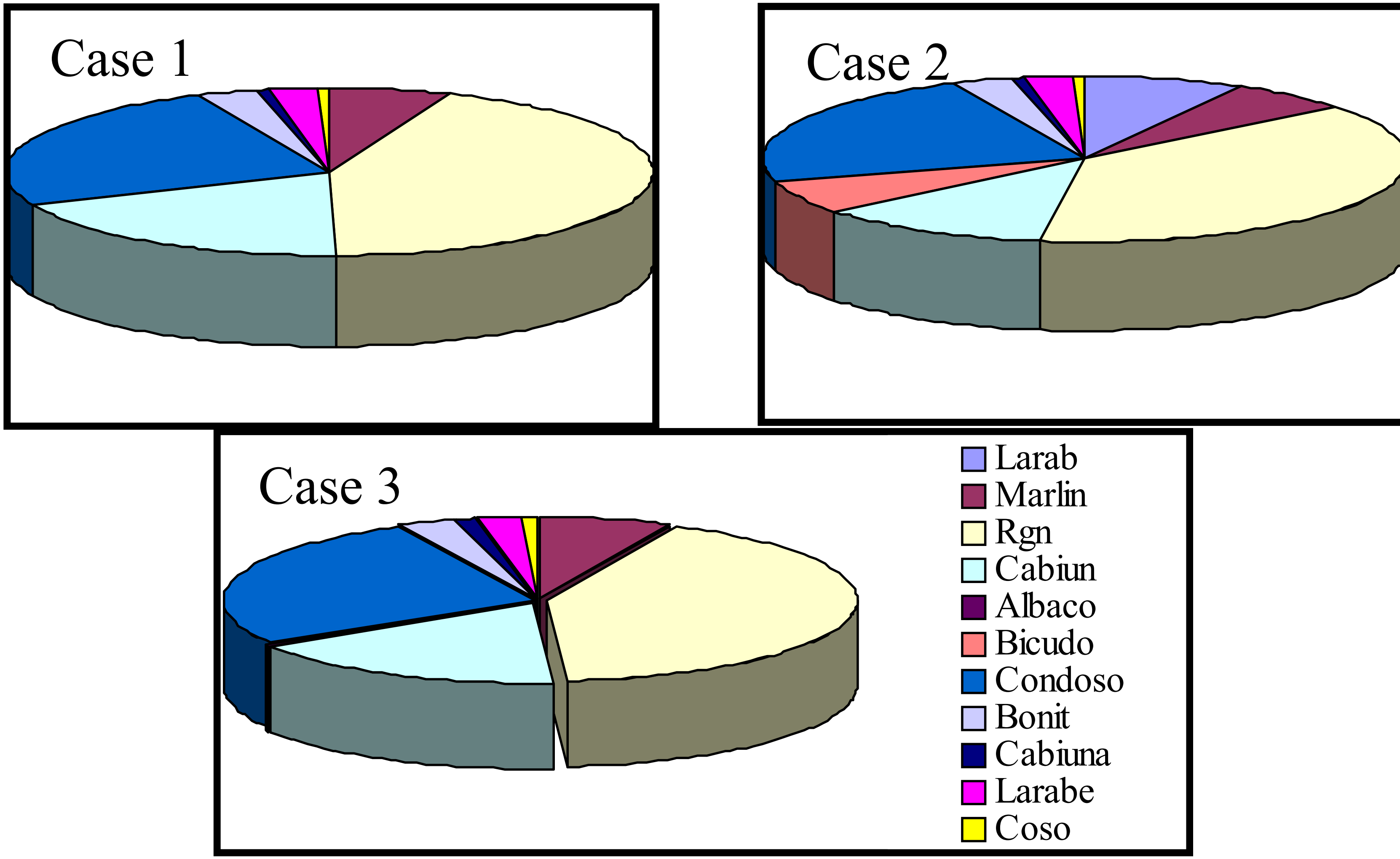
General constraints:

Planning horizon: one / two time periods

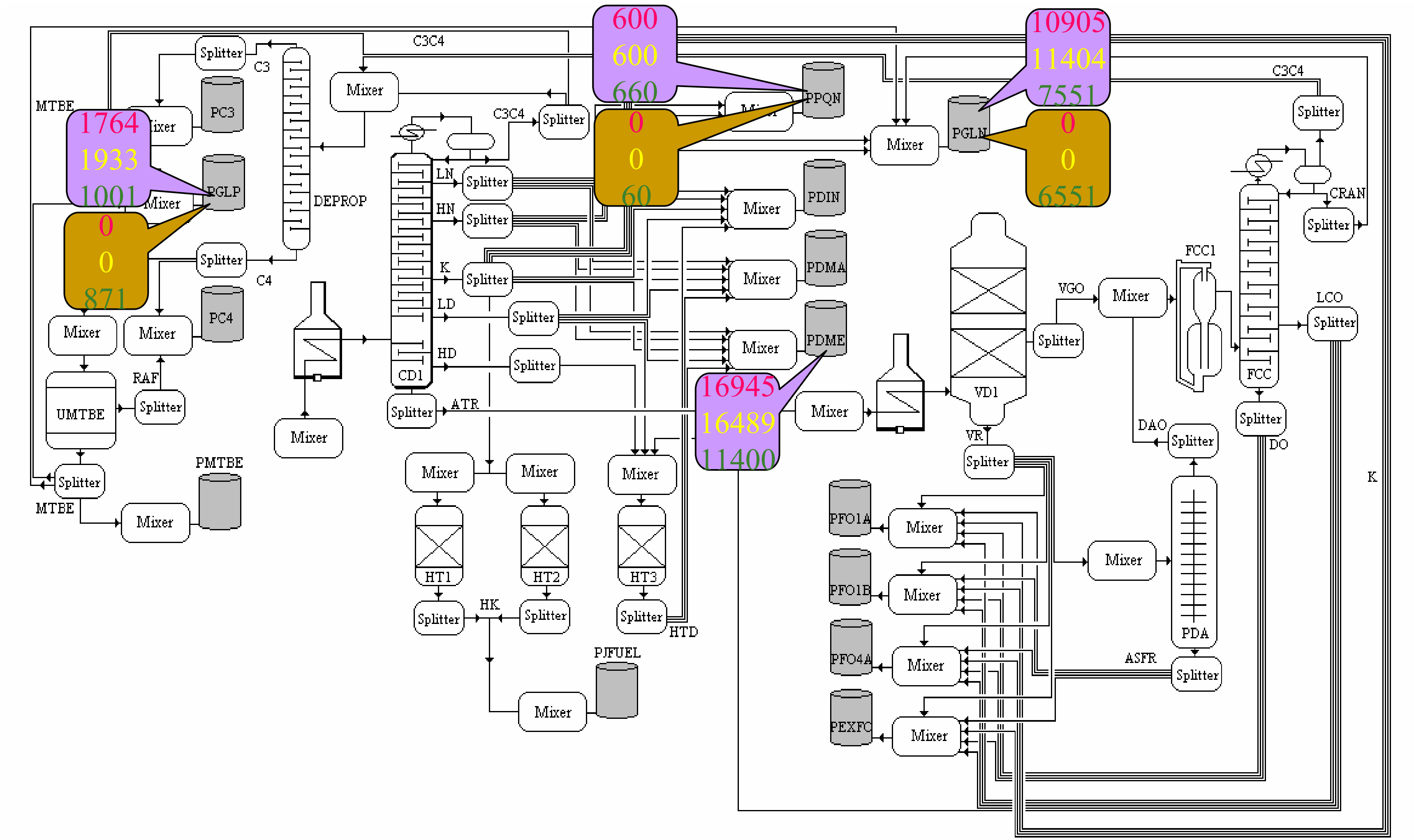
Supply of 20 oil types

Generation of 32 products (6 transported with pipelines)

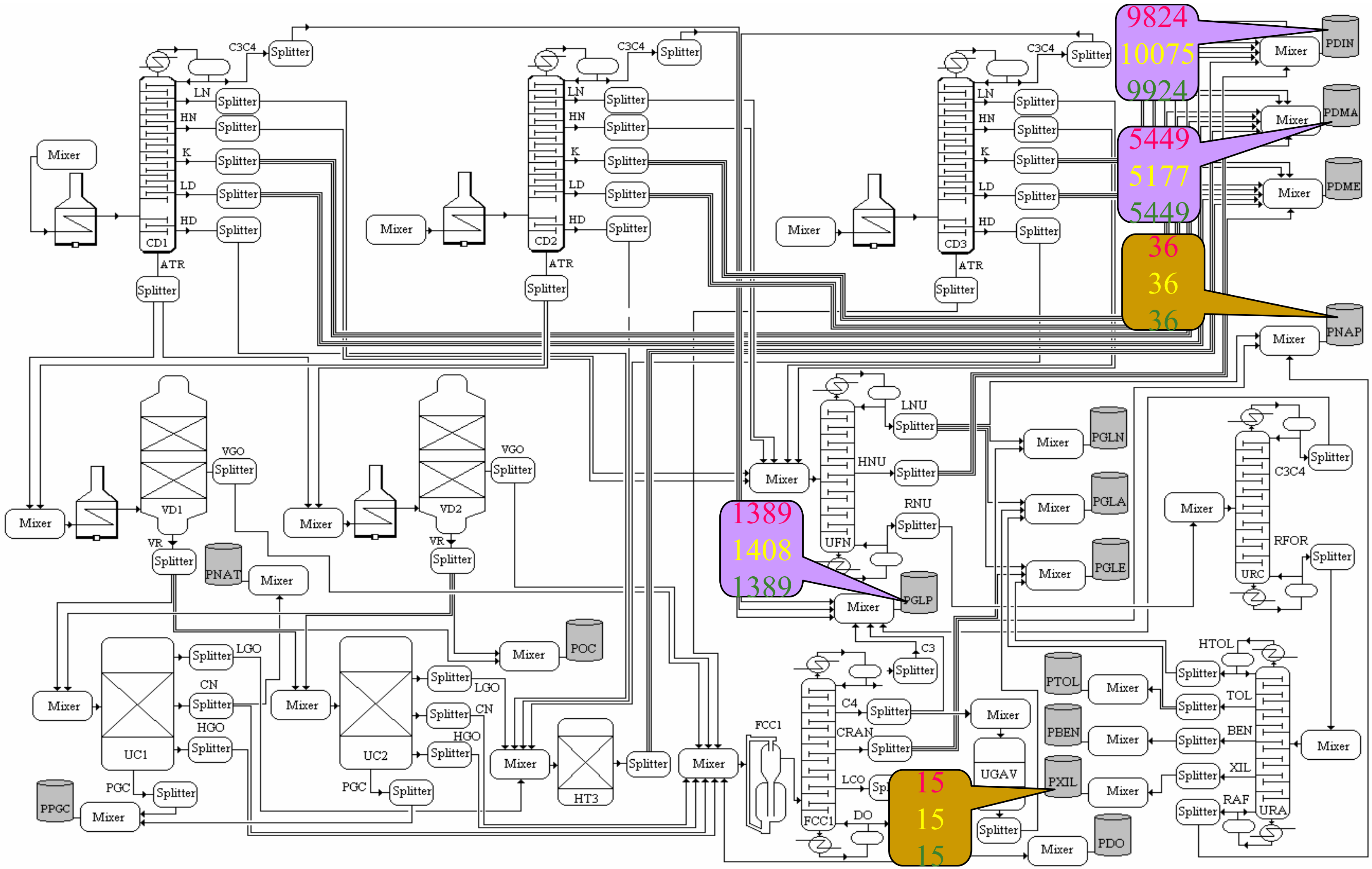
Supply Chain Example – Petroleum Selection



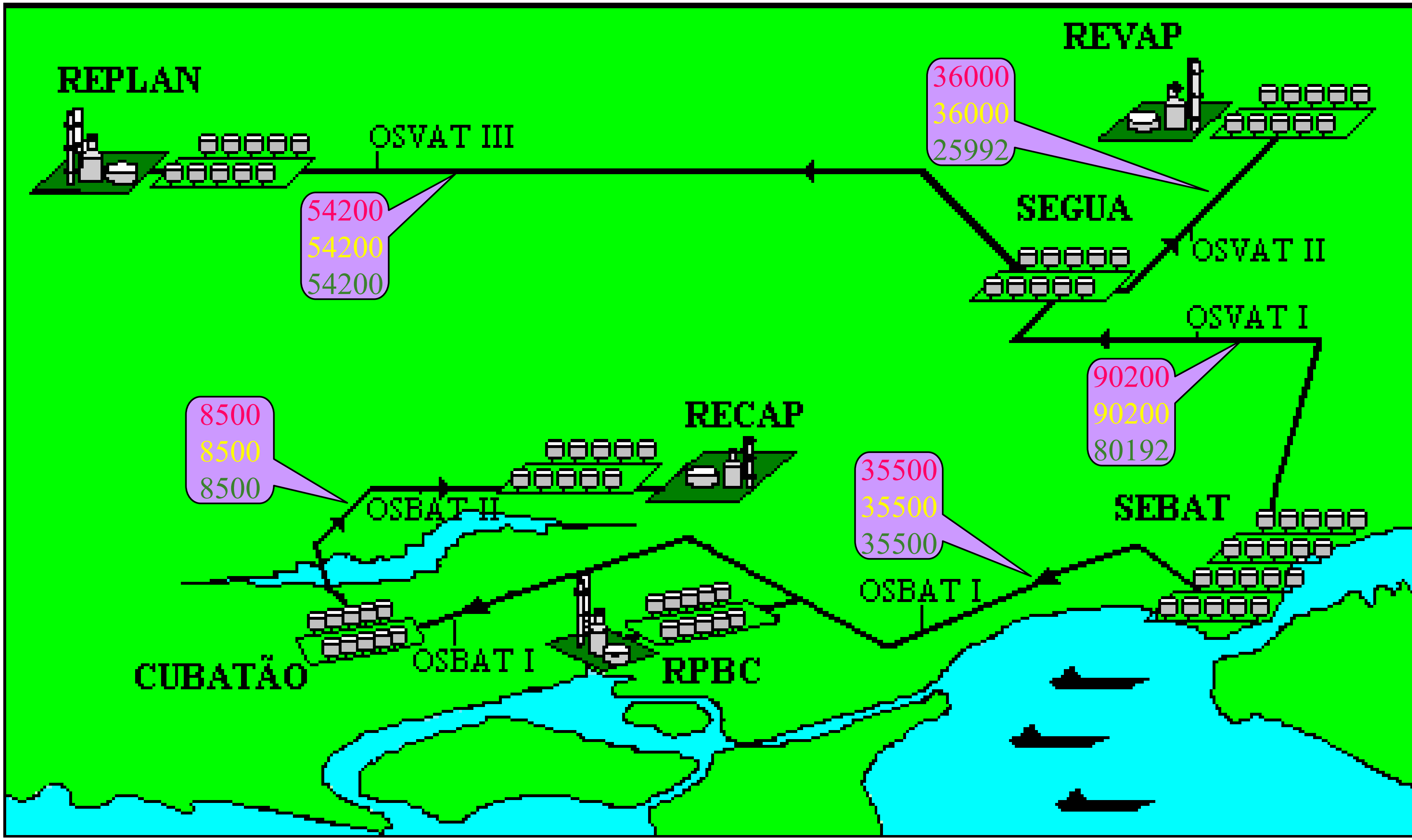
Supply Chain Example – REVAP



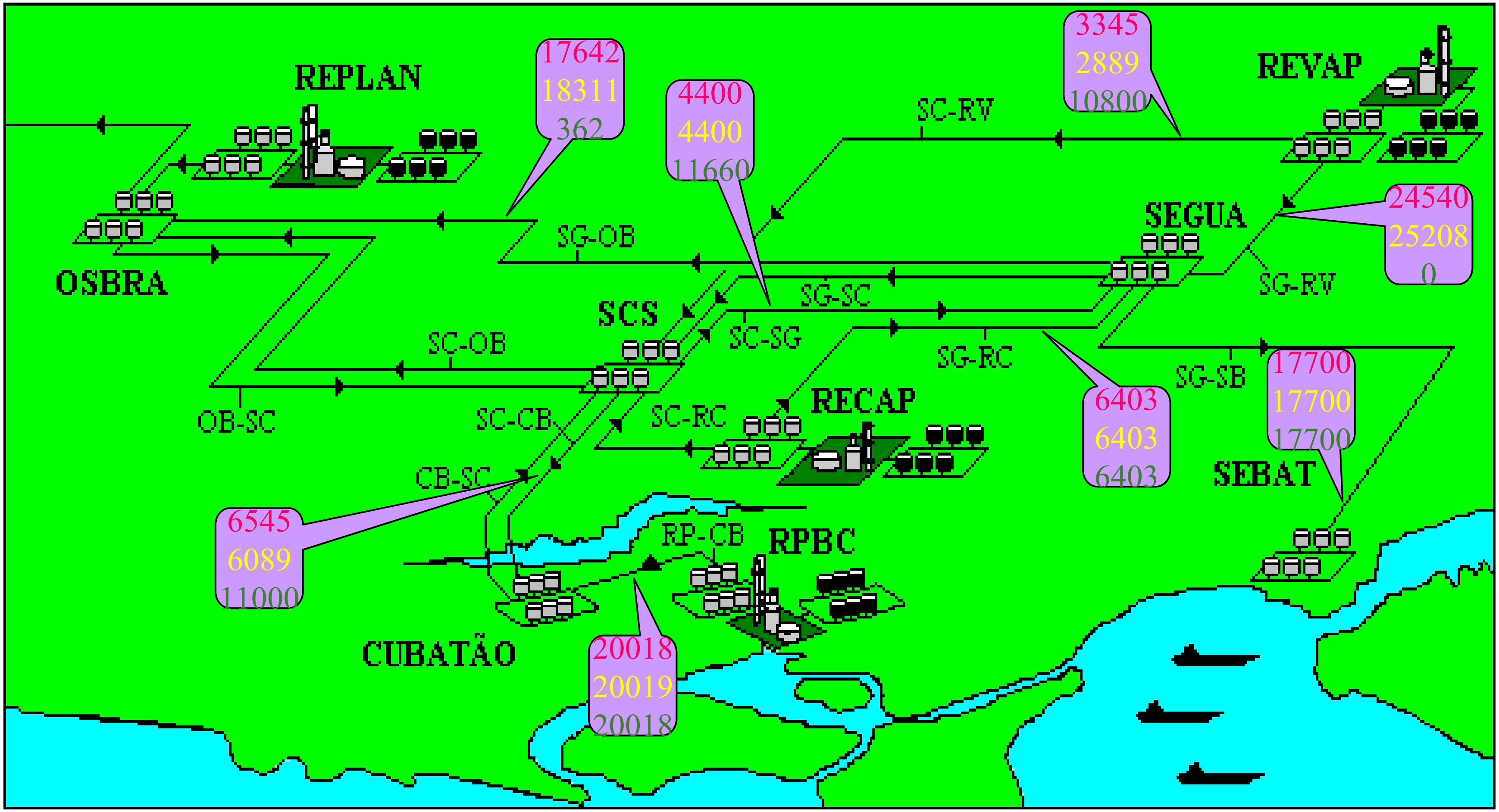
Supply Chain Example – RPBC



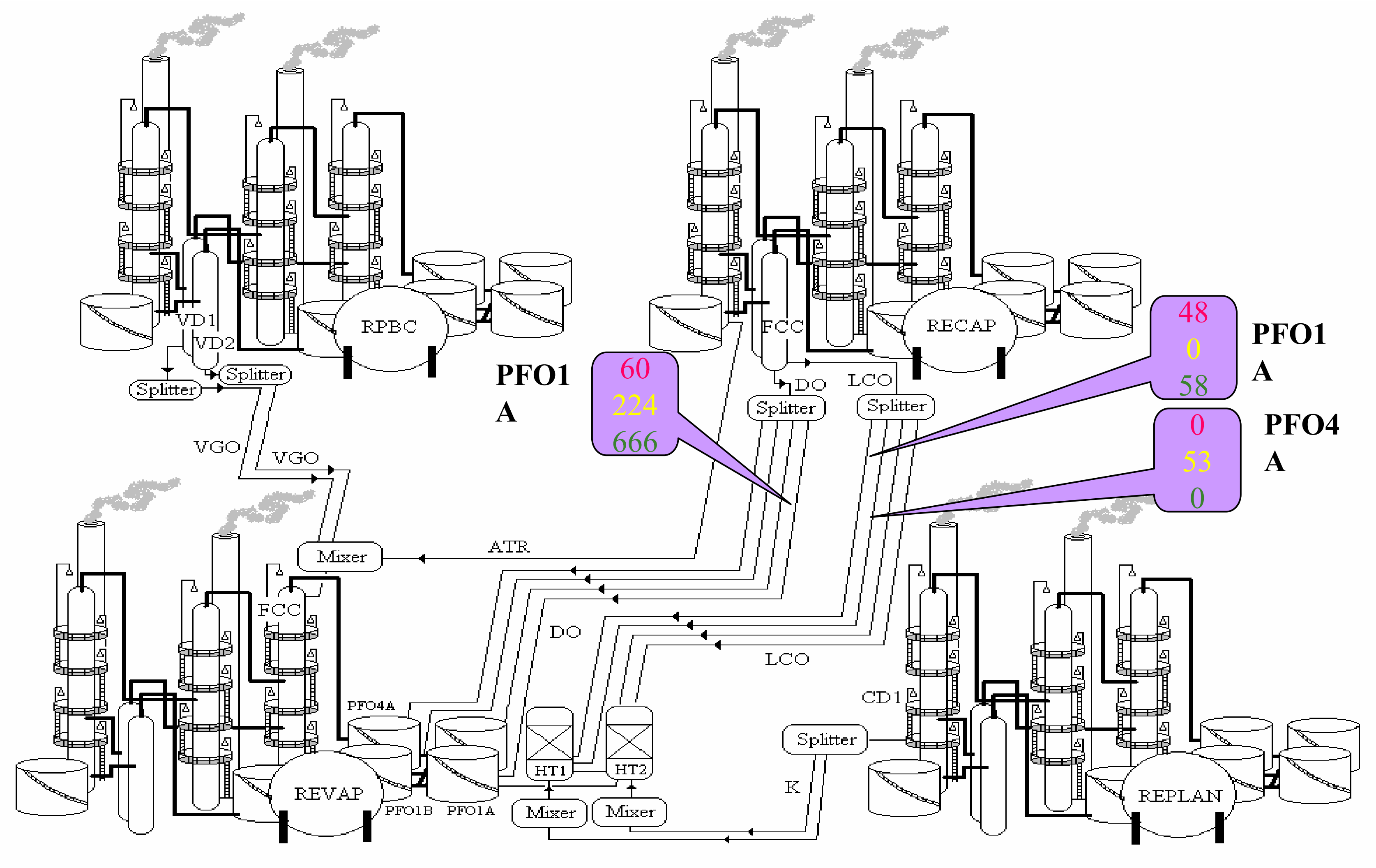
Supply Chain Example – Oil Supply



Supply Chain Example – Product Supply



Supply Chain Example – Intermediate Streams



Supply Chain Example – Computational Results

Case	Case 1		Case 2		Case 3	
Number of time periods	1	2	1	2	1	2
Constraints	2304	4607	2306	4611	2304	4607
Variables	2544	5087	2544	5087	2544	5087
Discrete variables	195	390	195	390	195	390
Solution time (CPU s)	116.8	656.2	152	915.6	157.8	2301
Objective Value ($ x10^6)	20.4	41.3	20.3	41.1	18.0	36.3

Conclusions

- **Mathematical programming**

  -General refinery topology

  -General petroleum supply chain representation

  -Representation of nonlinear properties and multiple periods

  -Non-convex Large-Scale MINLP

Real-world applications

  -General planning trends along multiple periods

  -Analysis of scenarios (discrete probabilities)

  -Intensive computational effort

Research needs

- **Modeling**
  - Upstream-Downstream Integration
  - Multi country supply chains (royalties, tariffs)
  - Modeling of uncertainties
- **Efficient solution methods**
  - Decomposition (spatial, temporal, functional)
  - Approaches (Lagrangean Relaxation, Cross Decomposition)