OUTLINE

- Motivation
- The multiproduct pipeline planning problem
- Available pipeline planning approaches
- Presentation of a continuous planning approach
- Critical operational decisions & major problem constraints
- An illustrative example
- Static vs dynamic planning problem
- The detailed weekly pipeline schedule
- Conclusions
ACKNOWLEDGMENT

The material included in this presentation have been extracted from

DIEGO C. CAFARO’s Doctoral Thesis

currently in preparation
Most reliable, safest and cheapest way of delivering large volumes of a wide range of refined products from refineries to distant depots.

Batches of different grades and products are pumped back-to-back in the line without any separating device.

Batches move forward in the line and products are transferred to terminals whenever a new batch is injected at the head terminal.
PIPELINE MAJOR FEATURES

- Usually buried and invisible to the public
- With several intermediate entry and exit points
- With segments of varying diameter
- Large diameter pipelines due to high construction costs
- With crude oil and refined products moving in separate lines
- Always remaining full of liquid and pumping in only one direction.
PIPELINE OWNERSHIP – REMOTE OPERATION

- Owned by a large number of companies, almost all are common carriers
- An increasing number are owned by non-oil companies
- Operations are fully automated and remotely performed
- From centrally located control rooms, operators direct the product flow
- From there, they start & stop pumps, open & close valves, fill & empty tanks
- Supervisory control & data acquisition systems, known as SCADA, are used
- SCADA continuously monitors: pump pressures, flow rates, batch locations, tank levels
PIPELINE ADVANTAGES

- Operate around the clock all seasons and under all weather conditions
- No container moves with the cargo. Products only move.
- No backhauls
- Employment is only 1% of that of the trucking industry

THE CHEAPEST MODE OF TRANSPORTATION

- Very low transport damage to products and especially to the environment.
- Lines coated with corrosion-resistant chemicals to prevent corrosion
- Chance of leaks reduced by an extensive maintenance program
- “Smart pigs” sent through the line
  - detect dents and imperfections
  - measure wall thickness

THE SAFEST MODE

- “Scraper pigs” clean the inside of a line by removing residual material clinging to the walls

BUT THE SLOWEST MODE (3 TO 8 MPH)

Scaper PIGS
INTERMODAL PRODUCT MOVEMENTS

- Pipelines dominate the oil industry transportation
- Participate in intermodal product movements with other modes of transportation
  - tankers & pipeline combination for crude oil
  - pipeline/truck combination for refined products
- A batch in the line arriving at a terminal:
  - can be placed in a tank
  - can be rerouted into another pipeline
- Lines provide tanks to buffer the flow rates between two connecting pipelines or line segments of different diameters
MONITORING BATCH STATUS

The specific gravity of the flow is continuously monitored at every terminal.

When it changes, the operator knows that:
- one product batch is ending
- another product batch is beginning to arrive

Refined products are often “color-coded” with dye.

The operator can visually observe the transition.

Distribution Centers:

Refinery

Head Terminal

Interfaces

P1

P2

P3

P4
Power Consumption

- Liquid products are propelled by centrifugal pumps sited at the **pumping stations** one at the origin and the others distributed along the line.

- The capacity of a pipeline can be increased by installing additional pumping stations along the line to rise pressure.

- The power consumption is the largest pipeline operating cost.
Pipelines move different grades of a product or distinct products sequentially through the same line in "batches".

At the boundary of two consecutive batches some mixing occurs.

**INTERFACE MATERIAL**

- **Between batches of different grades**
  - Interface
  - Mixed with the lower grade product

- **Between batches of different products**
  - Transmix
  - Separated and sent back to the refinery

**PRODUCT DEGRADATION**

**TRANSMIX REPROCESSING**

- 93 octane gasoline
- Interface
- 87 octane gasoline
- Diesel fuel
- Transmix
- 93 octane gasoline
- Jet fuel
- Plastic sphere
- Diesel fuel
PRODUCT DEGRADATION AND TRANSMIX REPROCESSING COSTS SIGNIFICANTLY CONTRIBUTES TO THE PIPELINE OPERATING COST.

**Amount of Interface**

**Number of batches**

**Arrangement of batches in the line**

Some products are prohibited to be consecutively injected to avoid serious product degradation.

**Critical Decisions**

- Keep similar products from different refiners together
- Inject the lowest possible number of product batches

**Batch sequencing**

- Sequence batches by specific gravities

Batch sequencing is also important to meet product delivery due dates at terminals.
More stringent environmental regulations on car fuels have resulted in a proliferation of refined products.

Major refined product pipelines currently move 100-120 distinct products compared with 10-20 in the ‘60s.

**OPERATING MODES**

**BATCH MODE**
- the same volume accepted for shipment to a particular depot is the one delivered to that destination
- LARGER NUMBER OF BATCHES
- HIGHER INTERFACE COSTS

**FUNGIBLE MODE**
- standard refined products from different refiners are consolidated into a single batch
- SMALLER NUMBER OF BATCHES
- LOWER INTERFACE COSTS
PIPELINE BATCHING OPERATIONS

THREE PRODUCTS: P1, P2, P3
SELECTED BATCH SEQUENCE: P1 – P3 – P1 – P2
THE SAME AMOUNT OF PRODUCTS SHIPPED TO TERMINALS
TIME HORIZON: 4 WEEKS

SHORTER PERIOD LENGTH – SAME BATCH SEQUENCE IN EACH PERIOD

LARGER NUMBER OF BATCHES AND INTERFACE COSTS
SMALLER BATCHES AND LOWER TERMINAL TANK CAPACITIES
Every new batch injection pushes some batches forward while others that arrive at their destinations are partially or completely sent out of the line ("stripping operations") and loaded in the terminal tank.

Therefore, both the size and the location of every batch in the line can change during the pumping of a new batch.

Batch stripping takes place if the batch has arrived at the terminal and enough storage capacity to receive the material is available.

Otherwise, the line should be temporarily stopped and deliveries are interrupted.
A fungible batch may satisfy several product requirements at different terminals, i.e. multiple destinations.

A fungible batch with multiple destinations will undergo several stripping operations ("cuts") along the journey.

Every product delivery has its own due date.

A batch can travel to the farthest destination for 7-14 days ("delivery lead-time").

Most short-term product requirements are satisfied by batches currently in transit.
A common carrier pipeline terminal typically connects to the marketing terminals of its main shippers or to public storage terminals.

In fungible mode, a fewer number of larger storage tanks is usually needed.

Terminals have few tanks just to facilitate stripping operations and quality control tasks.

Tanks for long-term storage must be provided by the customer at entry & exit points.

Gasoline tank trucks are loaded from storage tanks at marketing terminals.

LOADING & UNLOADING OPERATIONS
US pipelines are mostly COMMON CARRIERS, i.e. services are provided to multiple oil refiners.

Customers contact the pipeline operator to place their shipment orders for the next month, called NOMINATIONS.

A NOMINATION specifies the product and the quantity to be shipped.

Customers should make the product timely available at the input terminal and provide enough storage capacity at its destinations.

The monthly planning horizon is composed by a number of periods, called CYCLES.

Every nomination is divided into a number of equal-size batches, one for each cycle.

A cyclic schedule is usually performed.
Operational decisions concerning to every batch to be injected include:
- the assigned destinations (terminals)
- the amount allocated to each destination (the cut sizing)

Operational decisions related to each batch pumping run include:
- the set of “stripping operations” to be carried out
  in-transit batches to be stripped out - receiving depots - cut sizes
- the location & size of every in-transit batch at the end of a batch injection
PIPELINE SCHEDULING GOALS

- To minimize operating costs including:
  - the transmix reprocessing cost & the product degradation cost
  - the pumping cost
  - the inventory costs in refinery and depot storage tanks

- To meet product delivery requests on time

- To keep the pipeline running at nearly maximum capacity during off-peak hours

- To enhance the information on the current status of batch movements
PROBLEM DATA

- The sequence of “old” batches already inside the pipeline.
- Their locations & volumes at the initial time of the planning horizon.
- The scheduled production runs at the refinery.
- The inventory levels in refinery and terminal tankage at the initial time.
- The set of shipment requests, each one involving a refined product, the assigned terminals and the delivery due dates.
Knowledge-based Search Techniques (Sasikumar et al., 1997)

Metaheuristic Search Algorithms
- Greedy algorithms (Hane & Rattliff, 1995)
- Genetic algorithms (Nguyen & Chan, 2006)
- Tabu search (García et al., 2008)

Cyclic Scheduling Techniques (Used by pipeline schedulers)

Mixed-Integer Mathematical Programming Formulations
- Discrete Formulations (Rejowski & Pinto, 2003)
- Continuous Formulations (Cafaro & Cerdá, 2004 & 2008; Relvas et al., 2007)

Discrete Event Simulation (Maruyama Mori et al., 2007)
Discrete Formulations (Rejowski & Pinto, 2003)

- The pipeline is divided into packs of uniform size at each segment
- Each pack contains exactly one product
- The time scale is divided into slots of fixed length (fixed pumping rate)
- Whenever a pack of product enters a segment, the content of the first pack in that segment is displaced to the next pack.

Very large MILP formulations for longer planning horizons
MAJOR FEATURES

- Continuous time & volume representation
- Pre-defined ordered sequence of empty batch slots of variable-size
- Multiperiod planning horizon
- Explicit treatment of interface volumes
- Delivery due dates at the end of every planning period
- A “cheap” generalization to pipelines with several intermediate input and exit points
MAJOR DECISION VARIABLES

- Allocation variables assigning products to “empty” batch slots
- Control variables indicating the arrival of a batch at the assigned terminal to start the stripping operation
- Assignment variables denoting the planning period at which a batch injection ends

MAJOR CONTINUOUS VARIABLES

- Starting and completion times of new batch injections (the time events)
- Initial sizes of batches to inject in the pipeline
- Location and size of in-transit batches at the end of a new batch injection
- Stripping operations to take place during a batch injection (batch to be stripped, cut size, receiving terminal)
- Inventory levels at refineries and pipeline terminal tanks at every time event
MAJOR MODEL CONSTRAINTS

- A single product can at most be assigned to a batch slot
  \[ \sum_{p \in P} y_{i,p} \leq 1 \quad \forall i \in I^{\text{new}} \]

- The size of the interface between consecutive batches depends on the assigned products
  \[ WIF_{i,p,p'} \geq IF_{p,p'}^* (y_{i-1,p'} + y_{i,p} - 1) \quad \forall i \in I, i > 1, p, p' \in P \]

- A new batch injection can be started after completing the previous one
  \[ C_i - L_i \geq C_{i-1} + \tau_{p,p'}^* (y_{i-1,p'} + y_{i,p} - 1) \quad \forall i \in I^{\text{new}}, p, p' \in P \]
  \[ L_i \leq C_i \leq h_{\text{max}} \quad \forall i \in I^{\text{new}} \]
MAJOR MODEL CONSTRAINTS

- The length of a pumping run depends on the batch size & the pumping rate
  \[ v b_{\text{min}} * L_i \leq Q_i \leq v b_{\text{max}} * L_i \quad \forall i \in I^{\text{new}} \]

- The size of a flowing batch changes during a batch injection due to the execution of stripping operations

\[ W_i^{(t)} = W_i^{(t-1)} - \sum_{j=1}^{i} D_{i,j}^{(t)} \quad \forall i \in I, \forall i' \in I^{\text{new}}, i' > i \]
The overall amount of products delivered to terminals through stripping operations is equal to the size of the new batch injected in the line.

A single time period will contain the completion time of a pumping run.

$150 \text{ (in)} = 50 + 30 + 50 + 20 \text{ (out)}$
Feasibility conditions for stripping operations
- An upper bound on the cut size
- The flowing batch has reached or will reach the depot during the pumping run
THE OBJECTIVE FUNCTION

- **Delivery time constraints**
  Batch injections completed up to period $t$ are available to meet product requirements to be delivered to terminals before the end of period $t$
  \[
  \sum_{t=1}^{i} DM_{p,j}^{(t)} \geq \left( \sum_{k=1}^{t} dem_{p,j,k} \cdot (w_{i,d} - w_{i+1,d}) \right) - B_{p,j,t} + B_{p,j,(t-1)}
  \]
  $\forall p \in P, j \in J, t \in T, i \in I_{new}$

**OBJECTIVE FUNCTION**

- Minimize pumping cost, interface reprocessing cost, pipeline idle time and inventory carrying cost

\[
Min \quad z = \sum_{p \in P} \sum_{j \in J} \left( cp_{p,j} \cdot \sum_{i \in I} \sum_{i' \in I_{new}} DP_{p,i,j}^{(i)} \right) + \rho H + \\
\sum_{p' \in P} \sum_{i \in I} \sum_{i' \in I_{new}} \left( cf_{p',p,j} \cdot WIF_{i,p',p} + \sum_{p \in P} \sum_{j \in J} \sum_{i \in I} cb_{p,j}^{(i)} \right) \cdot B_{p,j,t} + \\
\sum_{i \in I_{new}} \left( cu \left( h_{max} - PH_{max} - \sum_{i \in I_{new}} L_{i} \right) \right) + \\
\left( \frac{1}{\text{card} (I_{new})} \sum_{p \in P} \sum_{j \in J_p} cid_{p,j} \cdot \left( \sum_{i' \in I_{new}} ID_{p,j}^{(i')} \right) + cir_{p} \cdot \left( \sum_{i' \in I_{new}} IRS_{p}^{(i')} \right) \right)
\]
A REAL-WORLD PIPELINE PLANNING EXAMPLE

PROBLEM DATA

- A pipeline system with a single entry point and multiple exit points (5 terminals)
- Four different products (gasoline, diesel, LPG, jet fuel) are sent to terminals
- Time horizon length: 4 weekly periods (672 h)
- Unidirectional flow
- Pipeline Length: 955 km
- Variable Segment Diameter: 12 – 20 in
- Pump rate range: 800 – 1200 m³ per hour
OPTIMAL STATIC PLANNING

- ASSUMING A FIXED PLANNING HORIZON

**Run Time Interval [h]**

- **0** to **400**
  - INJECTING P4
  - STRIPPING OPERATIONS
- **5.00 to 52.00**
  - INJECTING P4
  - INJECTING P2
- **55.00 to 198.33**
  - INJECTING P2
  - INJECTING P1
  - INJECTING P3
- **202.33 to 309.21**
  - INJECTING P1
  - A VERY LARGE BATCH
- **358.28 to 412.07**
  - INJECTING P1
- **524.50 to 672.00**
  - THE HORIZON-TIME EFFECT

**Volume [10^2 m^3]**

- **P1**
- **P2**
- **P3**
- **P4**

**Initial State**

**Injecting P4**

**Stripping Operations**

**Injecting P2**

**Injecting P1**

**Injecting P3**

**Injecting P1**

**A Very Large Batch**

**The Horizon-Time Effect**
DYNAMIC PIPELINE PLANNING TASK

- As time goes on, new transport requests are received and others are cancelled
- The current pipeline schedule should be periodically updated at the start of a new period
- A sufficiently long rolling time horizon should be considered
- Periodical planning update permits to eliminate the horizon-end time effect and, more important, the pipeline idle time
- The horizon-time effect arises because later batch injections have the only purpose of pushing batches to their destinations
- As the planning horizon rolls, such later batches will be injected because of new real shipment requests
DYNAMIC PIPE PLANNING ALGORITHM

Initialization Stage
- Set \( h \) (time period length) [hours]
- Set \( N \) (number of time periods to be considered)
- Set \( sf = |T_{SF}| \) (soft-frozen time periods)
- Set \( hf = |T_{HF}| \) (hard-frozen time periods)
- Set \( k = 1, \; d_{d-1} = 0 \).
- Set \( \text{clock} = 0 \) [h]. Run \( \text{clock} \)

Trigger Stage
- Capture pipeline batch scenario (products, volumes and locations) \((I_{mp}^{old}, W_{i}^{old}, F_{i}^{old})\)
- Capture product inventories at refinery and depot tank farms \((IR_{mp}, ID_{mp})\)

Data Updating Stage
- Import updated refinery production schedule and product output rates for periods \( k \) to \( k+N-1 \) (time horizon \([d_{d-1}; d_{d(k+N-1)}]\))
- Demand Updating Process
  Update Product Demand Data for periods \( k \) to \( k+N-1 \)

Rescheduling Stage
- Updating the Pipeline Schedule
  Run the Multiproduct Pipeline Scheduling Optimization System (MPSOS) for the planning horizon including periods \( k \) to \( k+N-1 \)
  - Execute the Pipeline Schedule for the time horizon going from \( d_{d-1} \) to \( d_{d(k+hf-1)} \) (periods \( k \) to \( k+hf-1 \))
  - Set \( k = k+T_{GS} \)

Dispatching Stage

INPUTS
- SCADA Remote Pipeline Controlling System
- Refinery Production Schedule

OUTPUTS
- Definite Pipe Schedule for periods \( k \) to \( k+hf-1 \)
- Definite Pipe Sequence for periods \( k+hf \) to \( k+hf+sf-1 \)
- Planned Pipe Schedule for periods \( k+hf \) to \( k+N-1 \)
OPTIMAL DYNAMIC PIPELINE PLANNING

ASSUMING A 4-WEEK ROLLING PLANNING HORIZON

TEN BATCH INJECTIONS

INITIAL STATE

SHORT IDLE TIME
ADDITIONAL RESULTS

**Pipeline Usage**

![Pipeline Usage Diagram]

**Refinery Inventory Profiles**

![Refinery Inventory Profiles Diagram]
MULTIPLE-SOURCE TRUNK PIPELINES

- So far, we deal with single-source multiple-destination trunk pipelines
- Multiple-source pipelines include additional input terminals at non-origin points to collect oil product batches from downstream refineries

Need of choosing the input terminal where the next pumping run will occur

At intermediate input terminals, a new batch can be injected or the size of a flowing batch can be increased
In multiple-source trunk pipelines, batches are not sequenced in the same order that they were injected in the line.

A batch is not necessarily preceded by those previously pumped in the line.

Batch B4 is preceded by batch B3 even though B4 was inserted before.

Need of separately handling the pumping run sequence and the batch sequence.
At the very operational level, a detailed pipeline schedule for the action period of the current horizon must be prepared. Just the batch injections and stripping operations planned for the first period of the current time horizon are to be performed. A more detailed definition of the stripping operations to execute during a batch injection is required: sequence, timing and extent of stripping operations. The basic information is provided by the monthly pipeline planning. Additional systematic heuristic/algorithmic procedures providing a detailed description of the required stripping operations are to be applied.
DETAILED PIPELINE SCHEDULE

**Nearest Active Depot First (NDF) rule:**

In which order the “stripping operations” should be executed during a batch injection?

**Prioritize deliveries to the nearest depot**

**At the planning level**

**At the operational level**
**DETAILED PIPELINE SCHEDULE**

**MILP Formulation:**

<table>
<thead>
<tr>
<th>Flow Rates</th>
<th>Run Time Interval [h]</th>
<th>Volume $[10^3 \text{ m}^3]$</th>
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<td></td>
<td>450</td>
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<td></td>
<td>200</td>
<td>135</td>
</tr>
<tr>
<td>8.00</td>
<td>18.00_30.50</td>
<td>200</td>
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<tr>
<td></td>
<td>30.50</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>600</td>
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<tr>
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</tr>
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**Comparative Results:**

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<th>Valve operations</th>
<th>Earliness [h]</th>
<th>Tardiness [h]</th>
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<td>NDF</td>
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<td>5</td>
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<td>FARTHEST DEPOT</td>
<td>4</td>
<td>22</td>
</tr>
<tr>
<td>EDD</td>
<td>EARLIEST DUE DATE</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>MILP</td>
<td></td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>
A MULTIPLE-SOURCE PIPELINE SCHEDULE

Horizon Length: 120 hs.
A MULTIPLE-SOURCE PIPELINE SCHEDULE

Inject Product P1 (Batch B5) in Refinery 1

Deliver Product P1 (Batch B5) to Depot 1
A MULTIPLE-SOURCE PIPELINE SCHEDULE

Deliver Product P1 (Batch B5)
to Depot 1

Inject Product P2 (Batch B6)
in Refinery 1
A MULTIPLE-SOURCE PIPELINE SCHEDULE

Deliver Product P1 (Batch B2) to Depot 2

Inject Product P2 (Batch B6) in Refinery 1
A MULTIPLE-SOURCE PIPELINE SCHEDULE

Deliver Product P1 (Batch B2) to Depot 2

Refinery 2 is ready to inject Product P3 in Batch B3

Inject Product P3 (Batch B3) in Refinery 2
A MULTIPLE-SOURCE PIPELINE SCHEDULE

Deliver Product P3 (Batch B3) to Depot 2

Inject Product P3 (Batch B3) in Refinery 2
A MULTIPLE-SOURCE PIPELINE SCHEDULE

Deliver Product P3 (Batch B3) to Depot 2

Inject Product P2 (Batch B6) in Refinery 1
A MULTIPLE-SOURCE PIPELINE SCHEDULE

Deliver Product P2 (Batch B1) to Depot 3

Note that Batch B7 has been preserved to be injected in Refinery 2

Inject Product P1 (Batch B8) in Refinery 1
A MULTIPLE-SOURCE PIPELINE SCHEDULE

Inject Product P2 (Batch B9) in Refinery 1

Deliver Product P2 (Batches B4 & B6) to Depot 3
A MULTIPLE-SOURCE PIPELINE SCHEDULE

Deliver Product P2 (Batch B6) to Depot 3

Refinery 2 is ready to inject Product P3 in Batch B7

Inject Product P3 (Batch B7) in Refinery 2
CONCLUSIONS

- Multiproduct pipeline planning is a very complex industrial problem
- A continuous pipeline planning approach has been presented
- Pipeline planning over a multiperiod rolling horizon with delivery due dates at period ends is performed
- The approach still remains competitive for a monthly time horizon
- The approach can even be applied to multi-source multiproduct pipelines
- Tools for generating a weekly detailed pipeline schedule have also been briefly described
OIL PIPELINE LOGISTICS

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Questions?

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