OIL PIPELINE LOGISTICS

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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

ACKNOWLEGMENT

The material included in this presentation

have been extracted from

DIEGO C. CAFARO's Doctoral Thesis

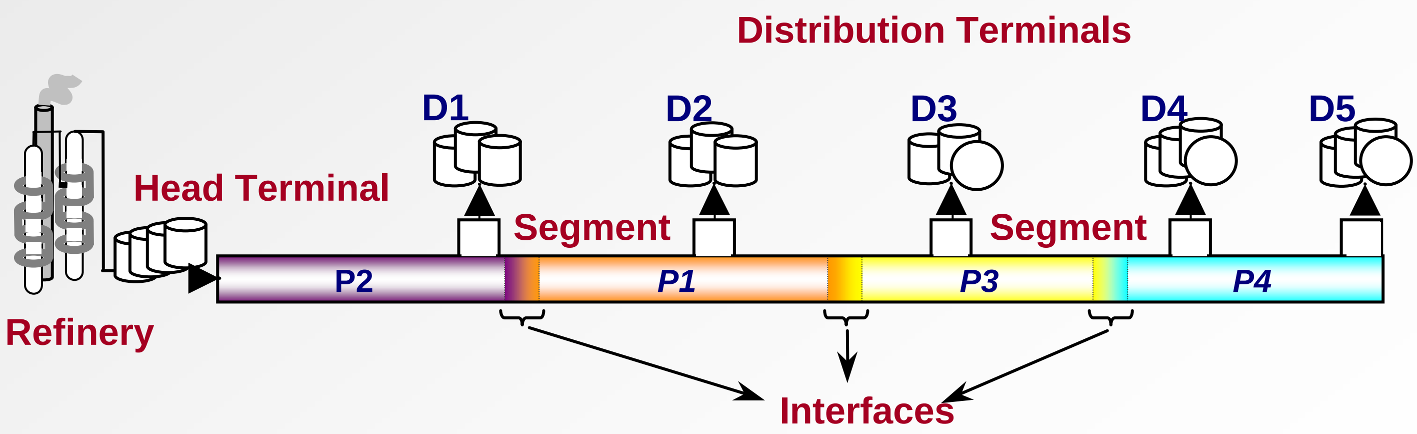
currently in preparation

LIQUID PIPELINE OVERVIEW

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.

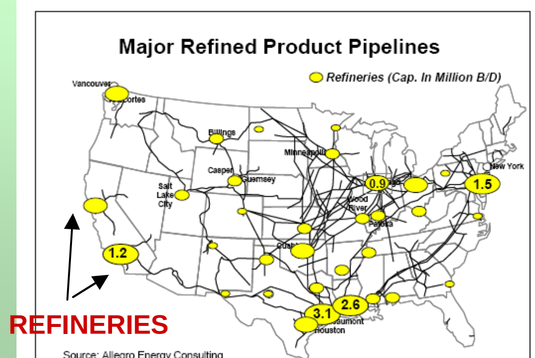
Batches move forward in the line and products are transferred to terminals whenever a new batch is injected at the head terminal.

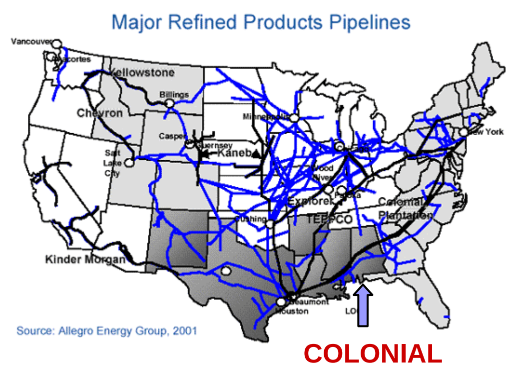


PIPELINE MAJOR FEATURES

- 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.

Trans Alaska Pipeline System





Colonial Pipeline

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

BUT THE SLOWEST MODE
(*3 TO 8 MPH*)

- 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

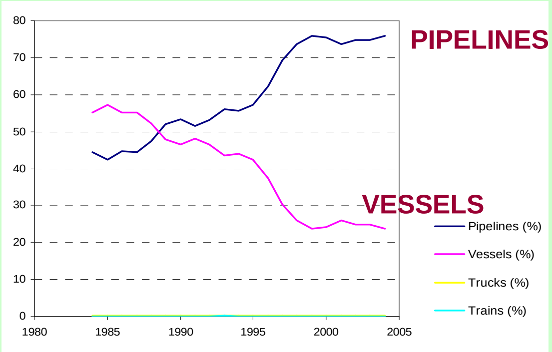
THE SAFEST MODE

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

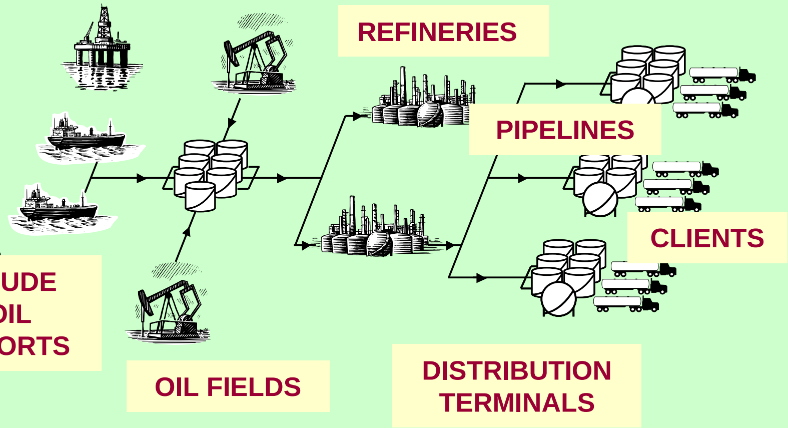
Scraper PIGS

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



CRUDE OIL DOMESTIC TRANSPORT MARKET IN USA



MONITORING BATCH STATUS

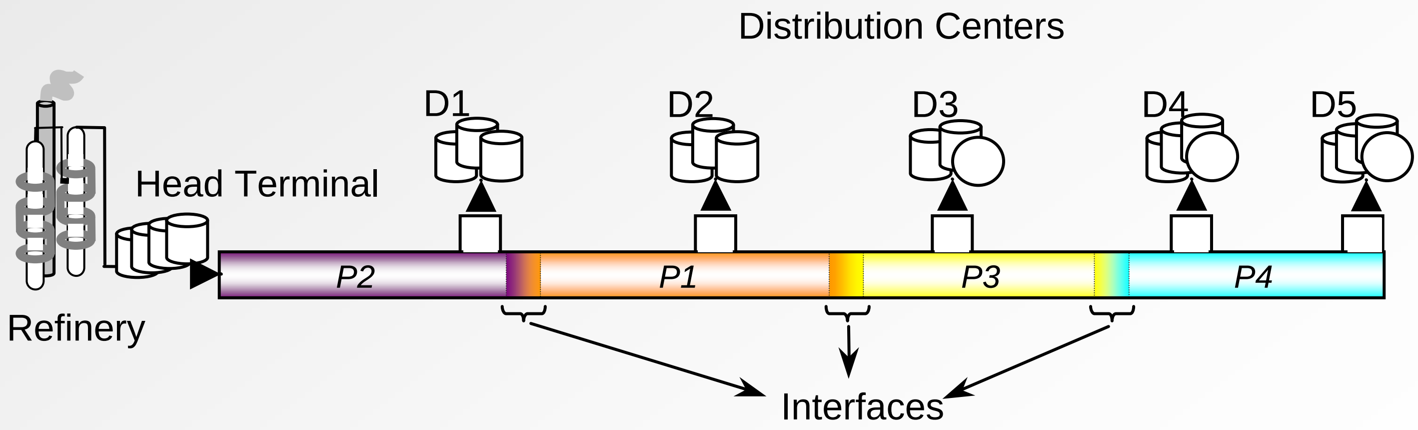
The specific gravity of the flow is continuously monitored at every terminal

When it changes, the operator knows that:

- one product batch is ending
- another product batch is beginning to arrive

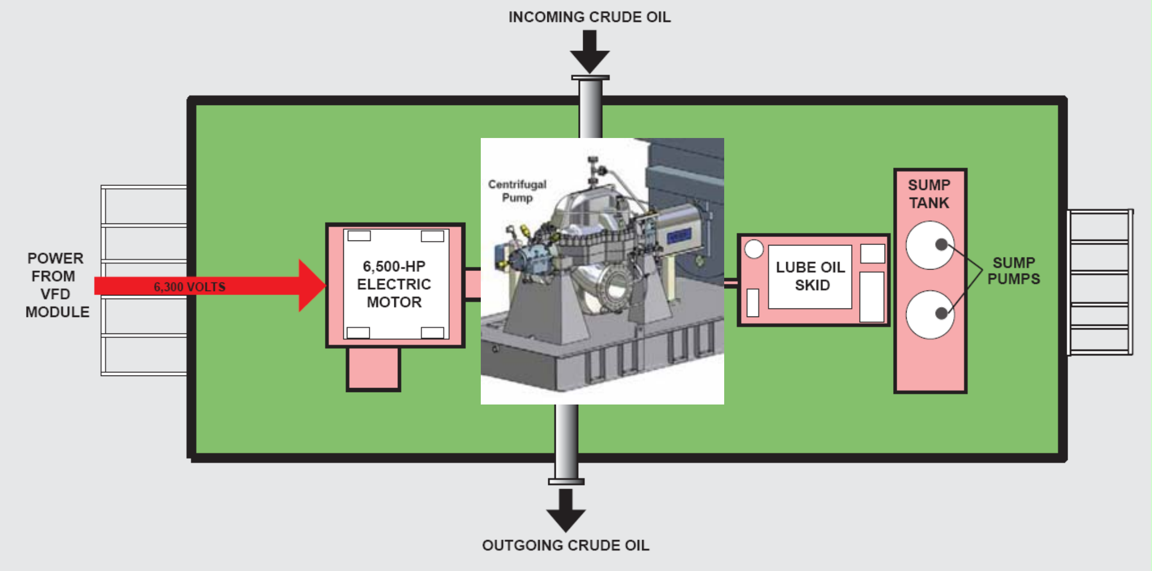
Refined products are often "color-coded" with dye

The operator can visually observe the transition



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.



INTERFACE MATERIAL

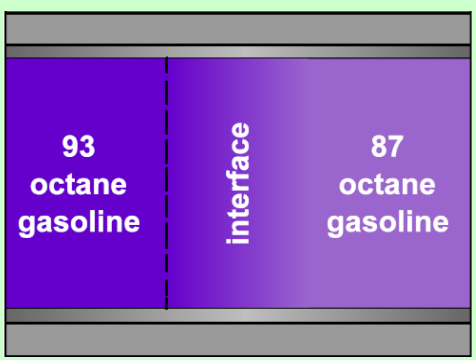
- Pipelines move different grades of a product or distinct products sequentially through the same line in “**batches**”.
- At the **boundary** of two consecutive batches some **mixing** occurs.

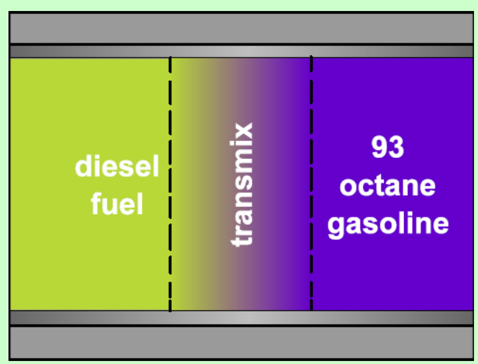
Between batches of **different grades** → Interface → Mixed with the lower grade product

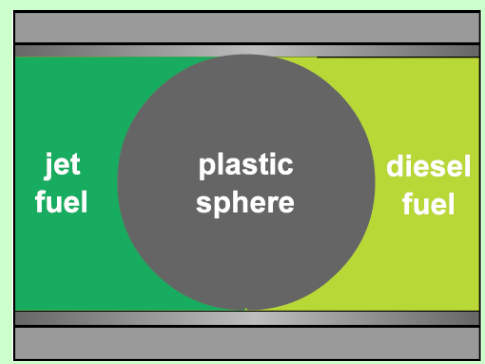
PRODUCT DEGRADATION

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

TRANSMIX REPROCESSING







INTERFACE COSTS

- Product degradation and transmix reprocessing costs both significantly contribute 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 a serious product degradation.

CRITICAL DECISIONS

Batching Operations

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

Batching Sequencing

Sequence batches by specific gravities

- Batch sequencing is also important to meet product delivery due dates at terminals

PIPELINE OPERATING MODES

- 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

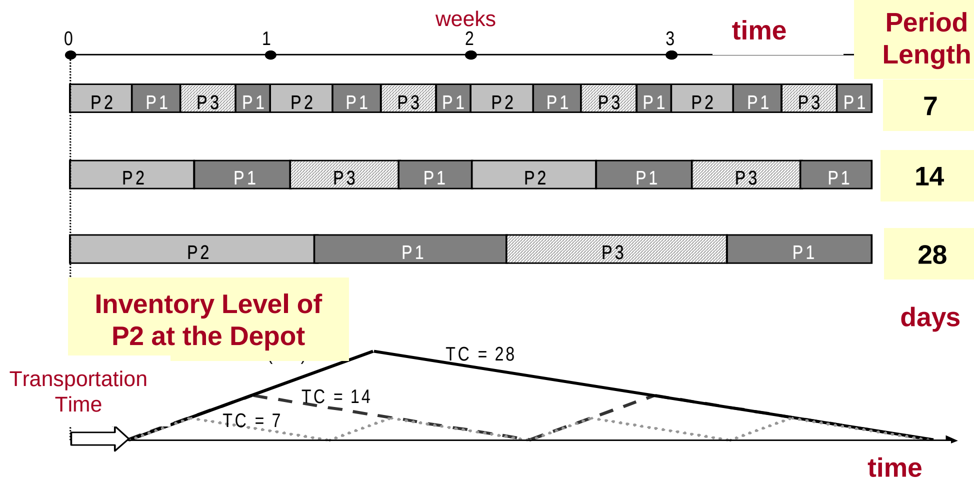
PIPELINE BATCHING OPERATIONS

THREE PRODUCTS : P1, P2 , P3

SELECTED BATCH SEQUENCE: P1 – P3 – P1 – P2

THE SAME AMOUNT OF PRODUCTS SHIPPED TO TERMINALS

TIME HORIZON: 4 WEEKS



Period Length	Number of batches	
7	16	4-PERIOD HORIZON
14	8	2-PERIOD HORIZON
28	4	ONE-PERIOD HORIZON
days		

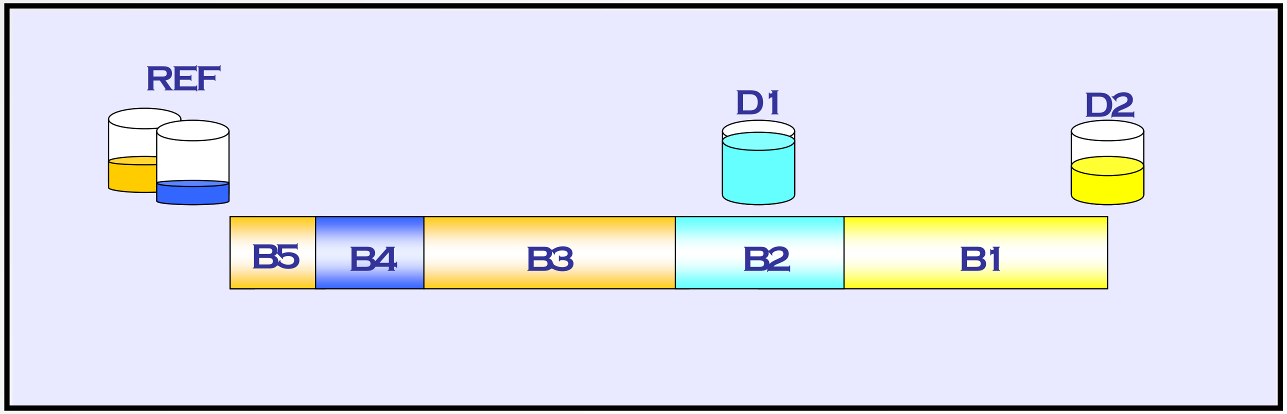
SHORTER PERIOD LENGTH – SAME BATCH SEQUENCE IN EACH PERIOD

LARGER NUMBER OF BATCHES AND INTERFACE COSTS

SMALLER BATCHES AND LOWER TERMINAL TANK CAPACITIES

STRIPPING OPERATIONS ("CUTS")

- 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.



BATCH DUE DATES & DELIVERY LEAD-TIME

- 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.

Fungible batch → Multiple destinations

Fungible batch → Multiple due dates

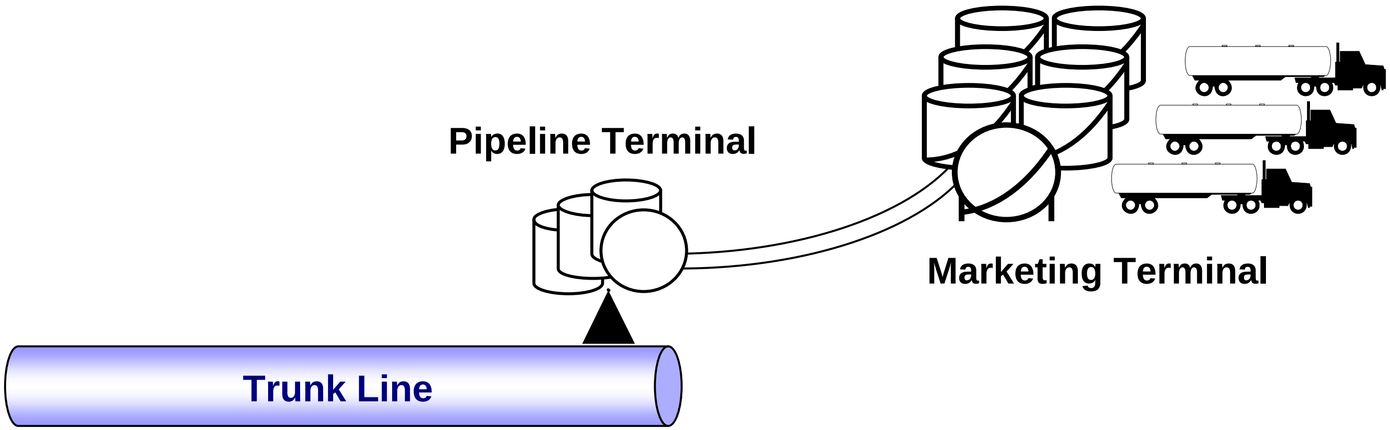
- A batch can travel to the farthest destination for 7-14 days ("delivery lead-time").

Delivery lead-time → Is a function of →
- Depot location
- Pumping rate
- Pipeline idle time

- Most short-term product requirements are satisfied by batches currently in transit.

LOADING & UNLOADING OPERATIONS

- Terminals have few tanks just to facilitate stripping operations and quality control tasks.
- In fungible mode, a fewer number of larger storage tanks is usually needed.
- Tanks for long-term storage must be provided by the customer at entry & exit points.
- A common carrier pipeline terminal typically connects to the marketing terminals of its main shippers or to public storage terminals.
- Gasoline tank trucks are loaded from storage tanks at marketing terminals



SHIPPER NOMINATIONS

- 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.

THE PIPELINE SCHEDULING TASK

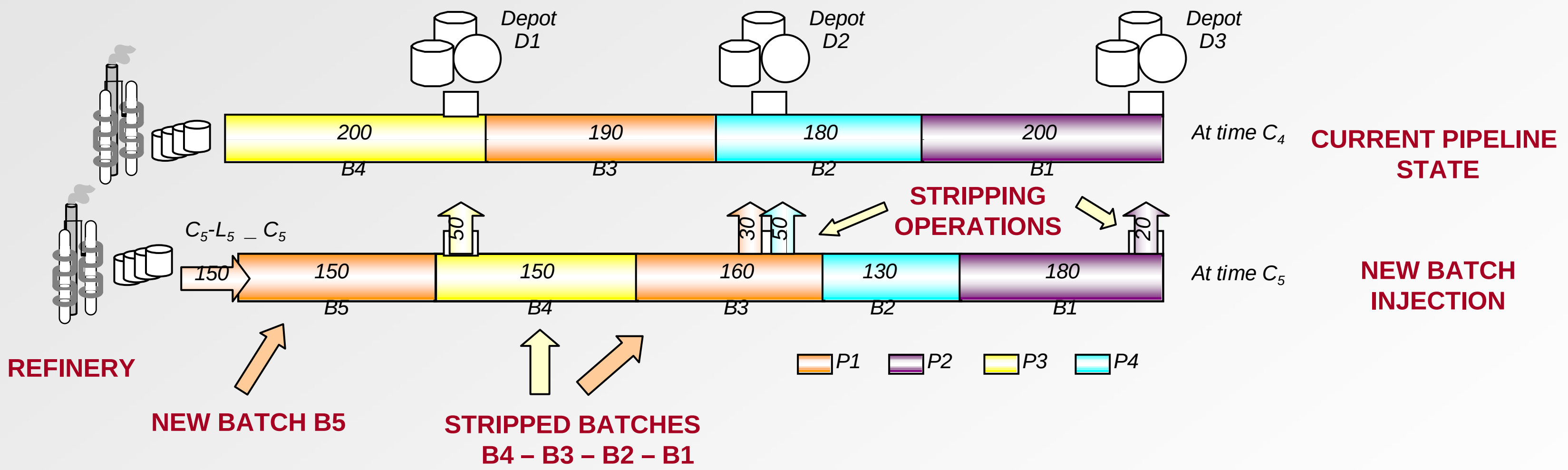
- Planning pipeline operation in fungible mode implies to choose:
  - the set of batches of each product to be injected, and the batch sizing
  - the sequence of batch injections
  - batch injection rates and starting times

- 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

BATCH INJECTION & STRIPPING OPERATIONS



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.

PIPELINE SCHEDULING APPROACHES

- 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)

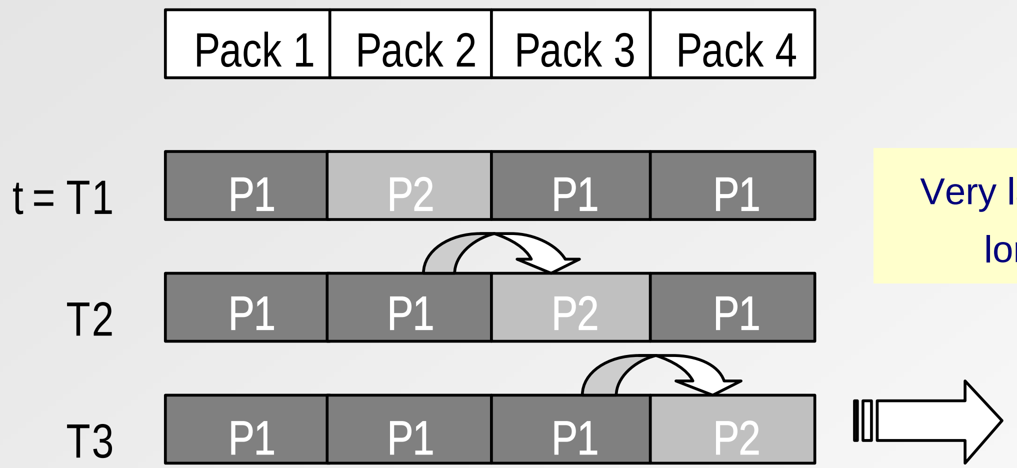
- Cyclic Scheduling Techniques (Used by pipeline schedulers)

- 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)

MIP DISCRETE FORMULATIONS

- **Discrete Formulations** (Rejowski & Pinto, 2003)



Very large MILP formulations for longer planning horizons

- 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.

MILP CONTINUOUS APPROACH

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

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MILP CONTINUOUS APPROACH

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

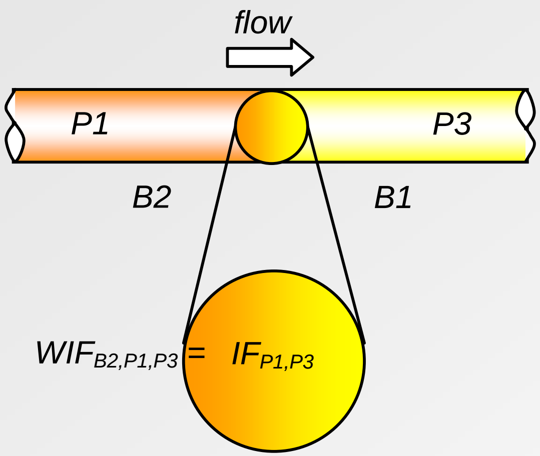
- Starting and completion times of new batch injections (the time events)
- Initial sizes of batches to inject in the pipeline
- Location and size of in-transit batches at the end of a new batch injection
- Stripping operations to take place during a batch injection (batch to be stripped, cut size, receiving 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**

$$\sum_{p\in P} y_{i,p} \le 1 \qquad \forall i \in I^{new}$$

- **The size of the interface between consecutive batches depends on the assigned products**



$$WIF_{i,p,p'} \ge IF_{p,p'} * (y_{i-1,p'} + y_{i,p} - 1) \quad \forall i \in I, i > 1 \; p, p' \in P$$

- **A new batch injection can be started after completing the previous one**

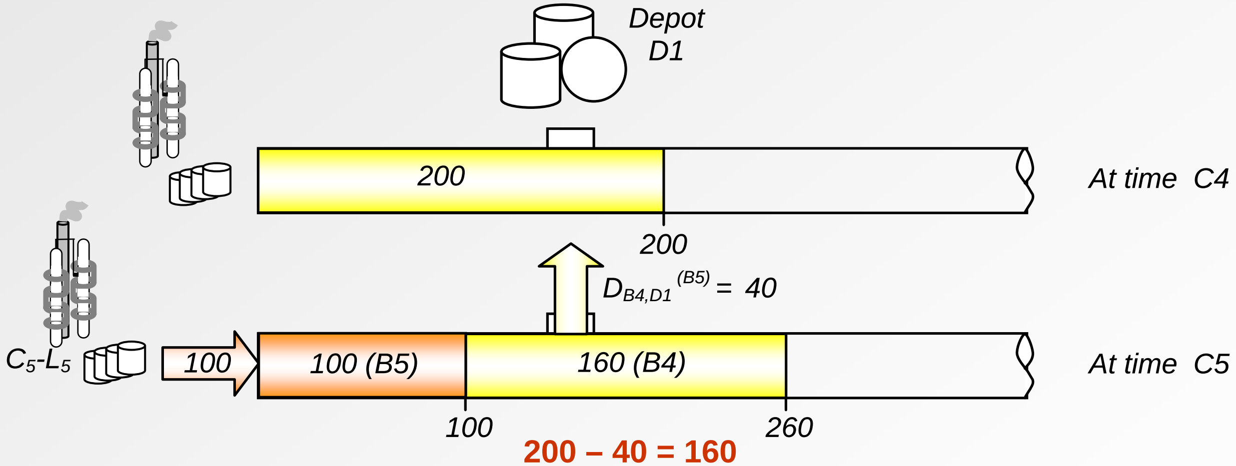
$$C_i - L_i \ge C_{i-1} + \tau_{p,p'} * (y_{i-1,p'} + y_{i,p} - 1) \quad \forall i \in I^{new}; p, p' \in P \qquad L_i \le C_i \le h_{max} \quad \forall i \in I^{new}$$

MAJOR MODEL CONSTRAINTS

- **The length of a pumping run depends on the batch size & the pumping rate**

$$vb_{\min} * L_i \leq Q_i \leq vb_{\max} * L_i \quad \forall i \in I^{new}$$

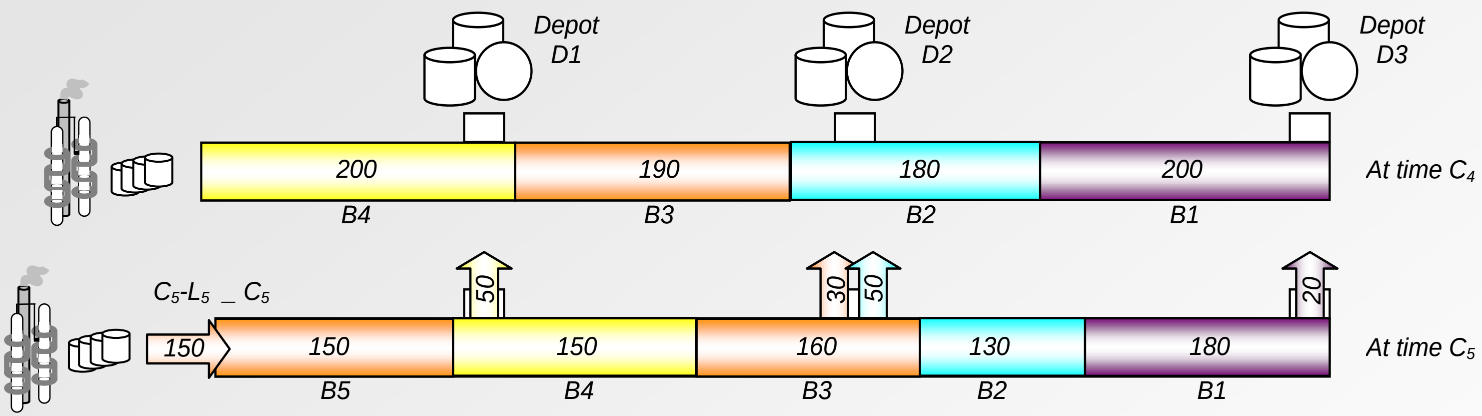
- **The size of a flowing batch changes during a batch injection due to the execution of stripping operations**



$$W_i^{(i')} = W_i^{(i'-1)} - \sum_{j \in J} D_{i,j}^{(i')} \quad \forall i \in I, \forall i' \in I^{new}, i' > i$$

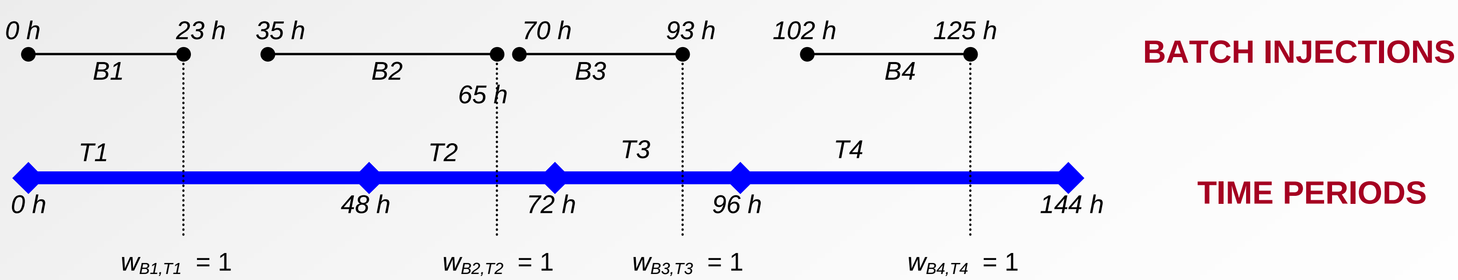
MAJOR MODEL CONSTRAINTS

- The overall amount of products delivered to terminals through stripping operations is equal to the size of the new batch injected in the line



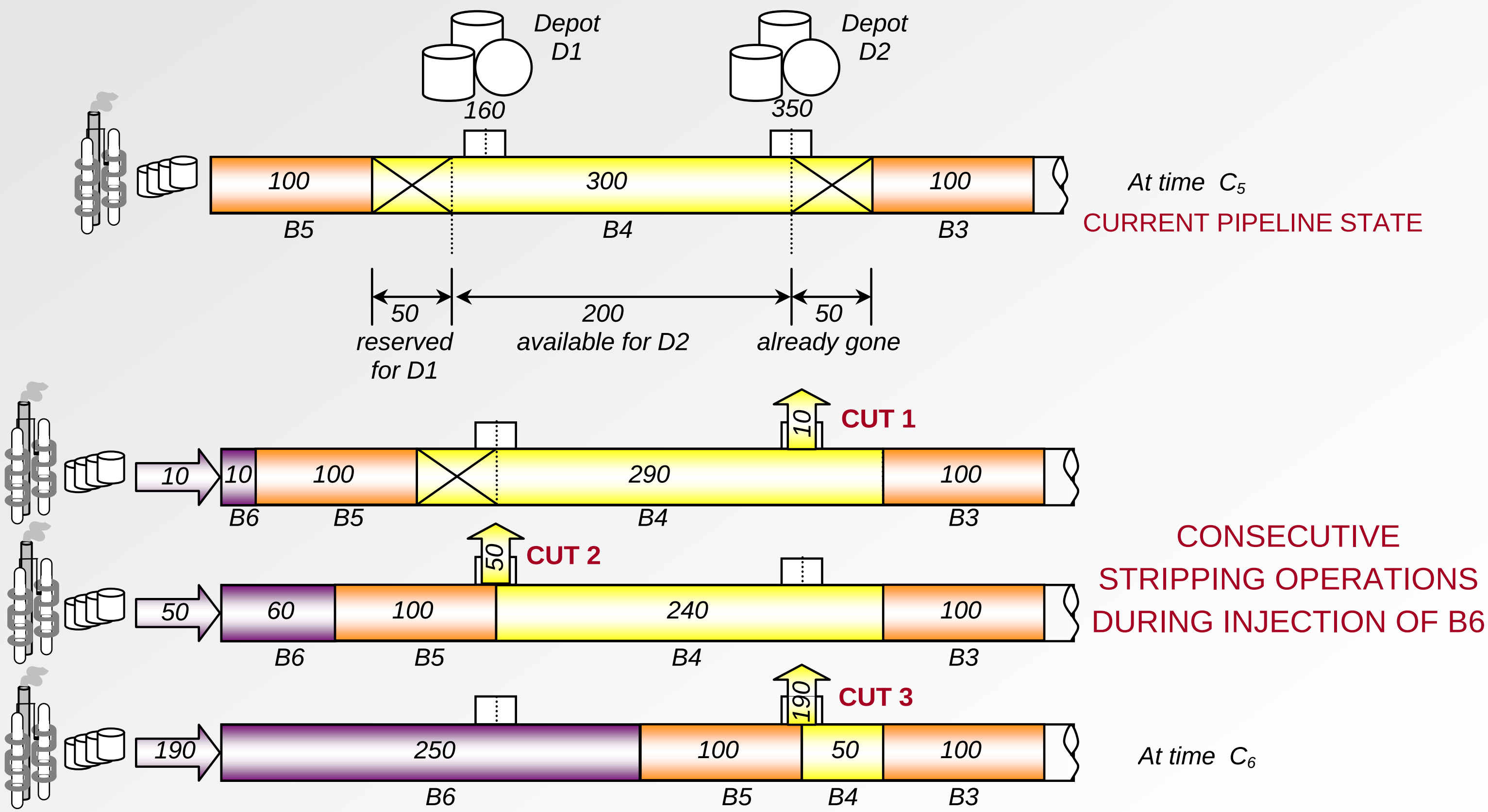
150 (in) = 50 + 30 + 50 + 20 (out)

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



MAJOR MODEL CONSTRAINTS

- 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*

$$\sum_{\substack{\ell=1 \\ \ell\in I^{new}}}^{i} DM_{p,j}^{(\ell)} \geq \left(\sum_{k=1}^{t} dem_{p,j,k} * (w_{i,t} - w_{i+1,t}) \right) - B_{p,j,t} + B_{p,j,(t-1)}$$

$$\forall p \in P, j \in J_p, t \in T, i \in I^{new}$$

OBJECTIVE FUNCTION

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

$$\begin{aligned} Min \;\; z = & \sum_{p\in P} \sum_{j\in J} \left(cp_{p,j} * \sum_{i\in I} \sum_{i'\in Inew} DP_{p,i,j}^{(i')} \right) + \rho \; H \\ & + \sum_{\substack{p'\in P \\ p'\neq p}} \sum_{\substack{i\in I \\ i>1}} cf_{p,p'} \; WIF_{i,p,p'} + \sum_{p\in P} \sum_{j\in J} \sum_{t\in T} cb_{p,j}^{(t)} * B_{p,j,t} \\ & + cu \left(h_{\max} - PH_{\max} - \sum_{i\in Inew} L_i \right) \\ & + \frac{1}{card\;(I^{new})} \sum_{p\in P} \left[\sum_{j\in Jp} cid_{p,j} * \left(\sum_{i'\in Inew} ID_{p,j}^{(i')} \right) + cir_p * \left(\sum_{i'\in Inew} IRS_p^{(i')} \right) \right] \end{aligned}$$

A REAL-WORLD PIPELINE PLANNING EXAMPLE

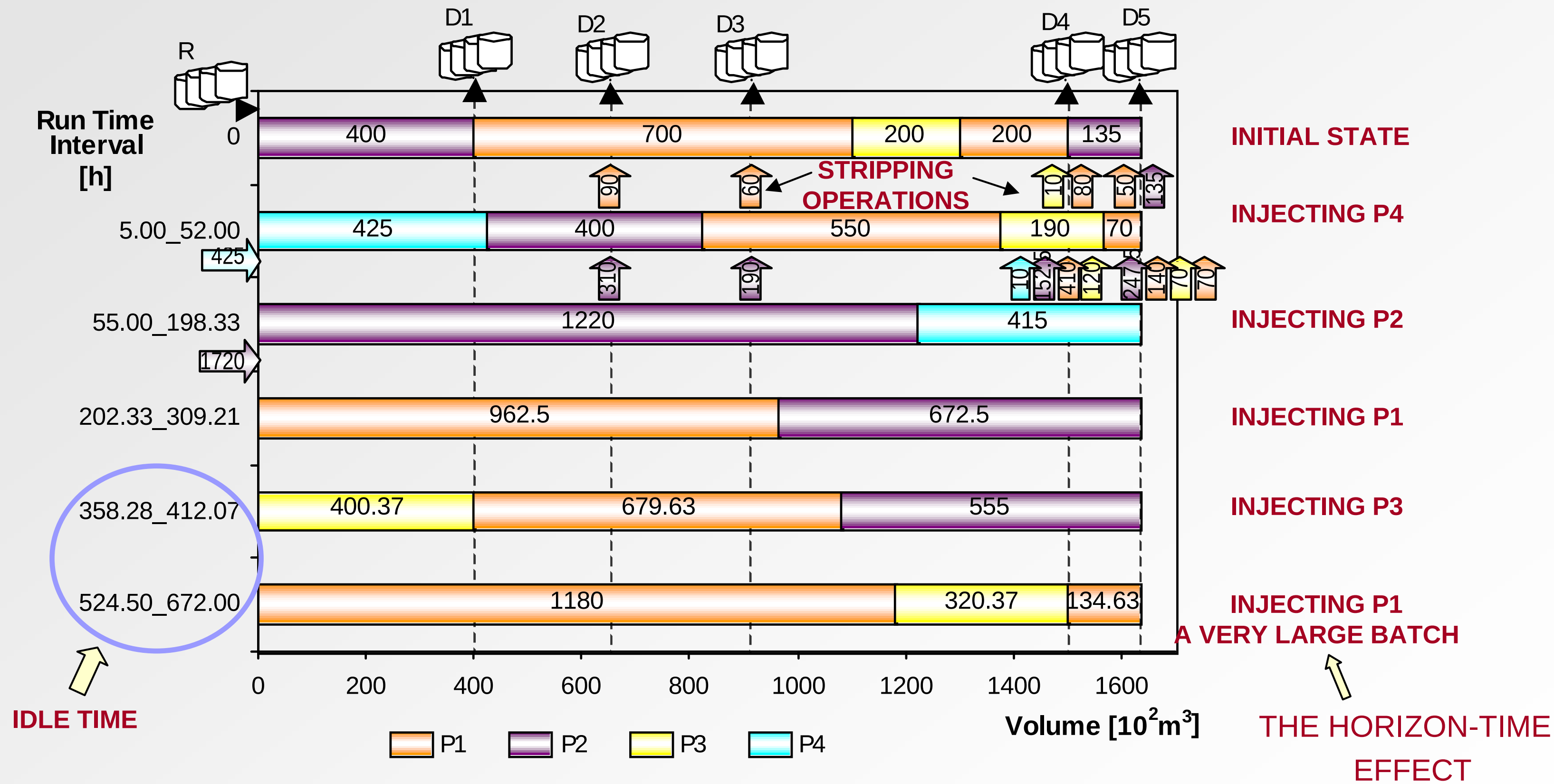
PROBLEM DATA

- 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 m^3 per hour

OPTIMAL STATIC PLANNING

- ASSUMING A FIXED PLANNING HORIZON

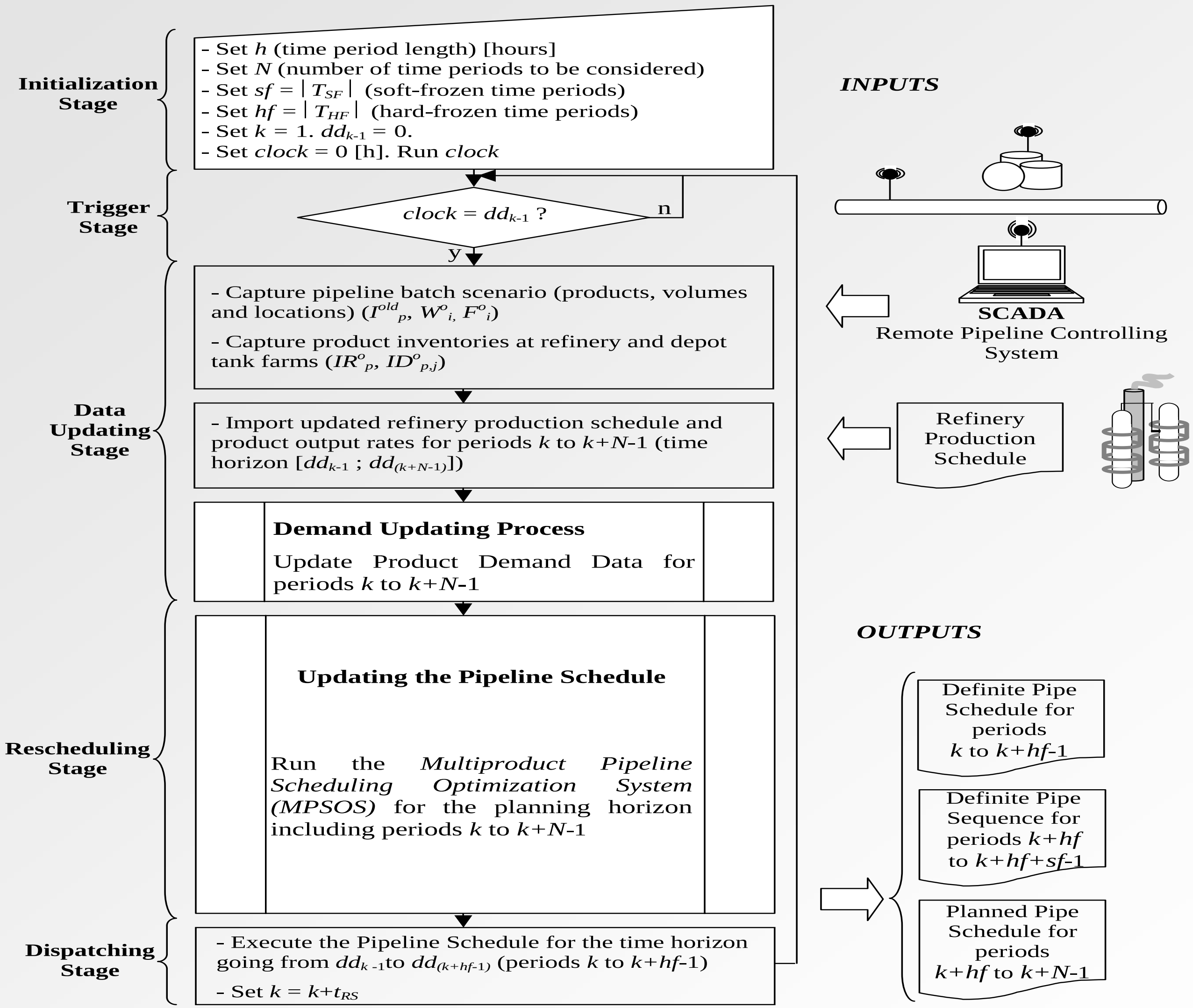
FIVE BATCH INJECTIONS



DYNAMIC PIPELINE PLANNING TASK

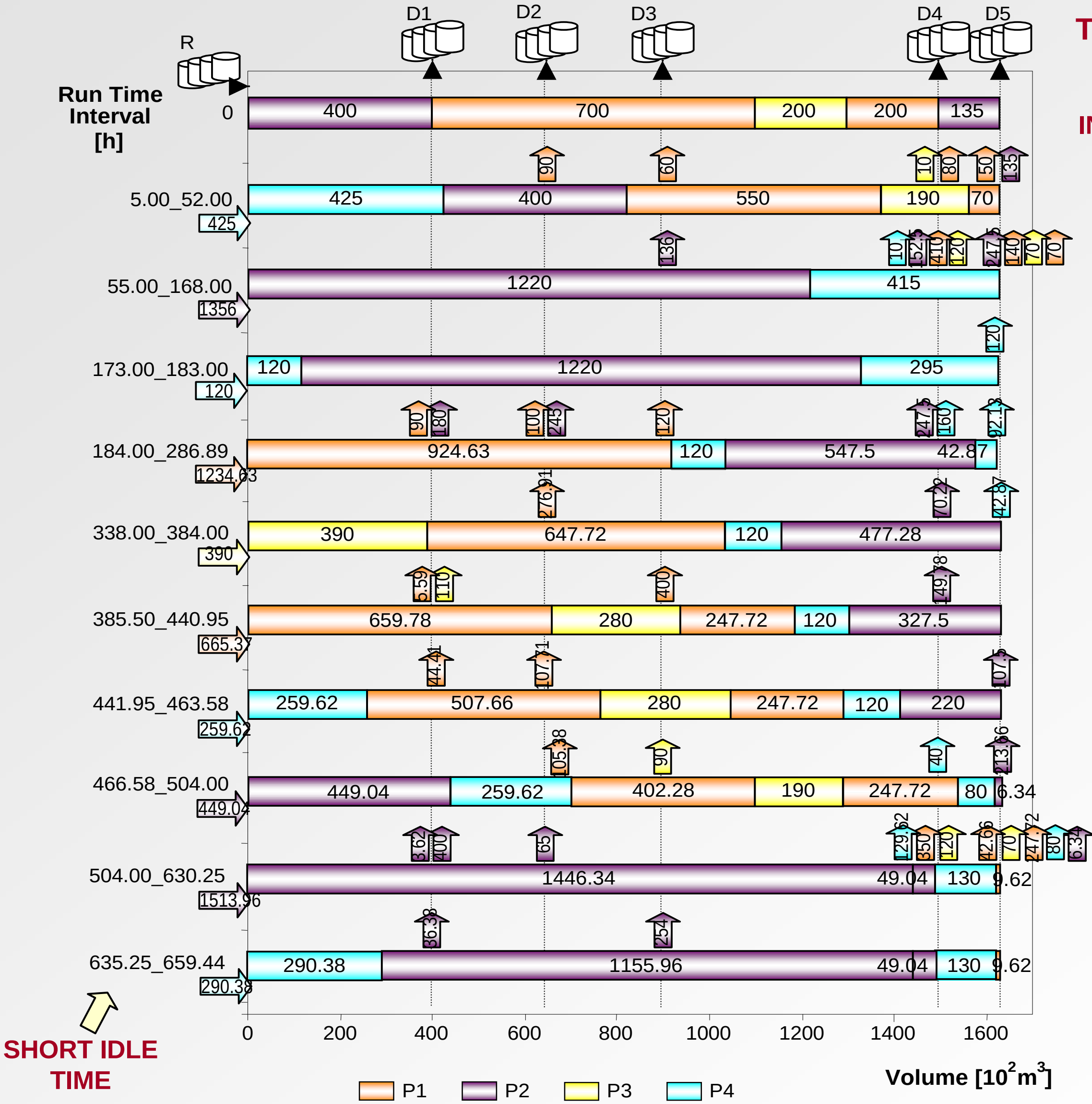
- As time goes on, new transport requests are received and others are cancelled
- The current pipeline schedule should be periodically updated at the start of a new period
- A sufficiently long rolling time horizon should be considered
- Periodical planning update permits to eliminate the horizon-end 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



OPTIMAL DYNAMIC PIPELINE PLANNING

- ASSUMING A 4-WEEK ROLLING PLANNING HORIZON

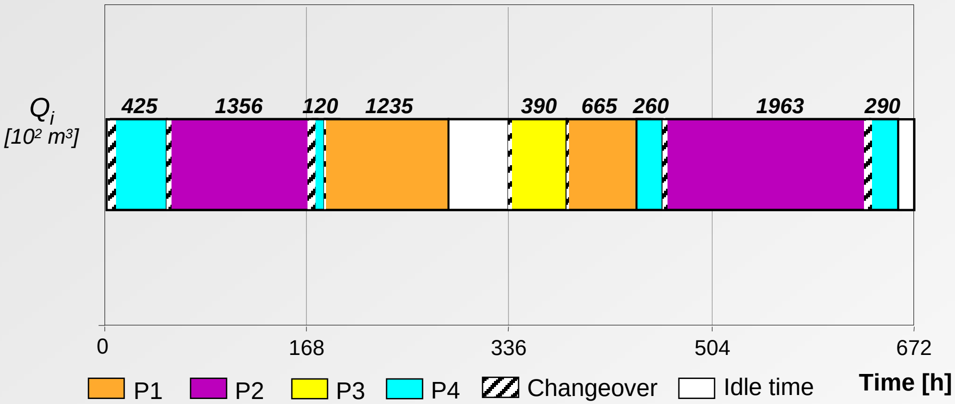


TEN BATCH INJECTIONS

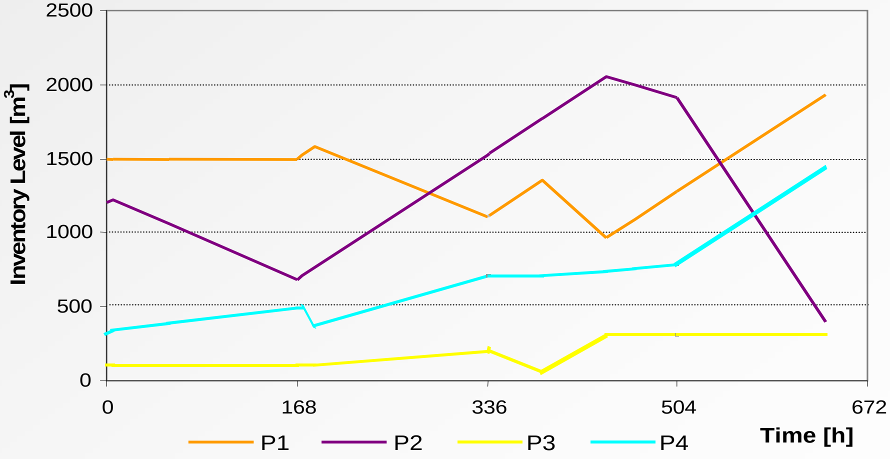
INITIAL STATE

ADDITIONAL RESULTS

Pipeline Usage

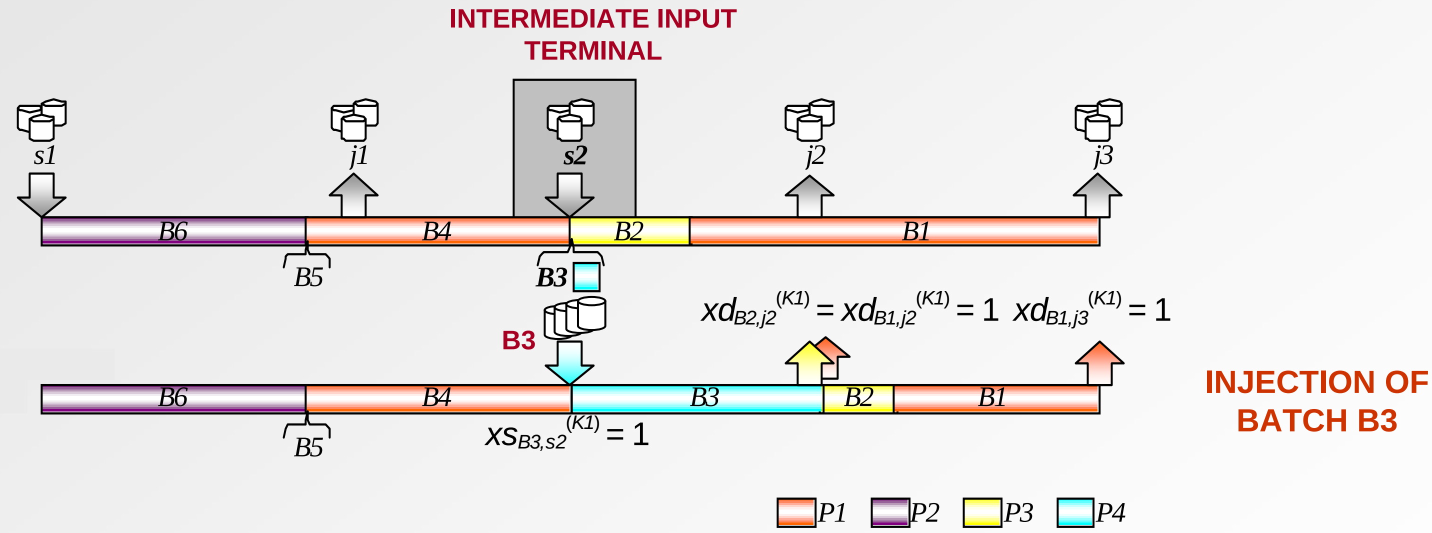


Refinery Inventory Profiles



MULTIPLE-SOURCE TRUNK PIPELINES

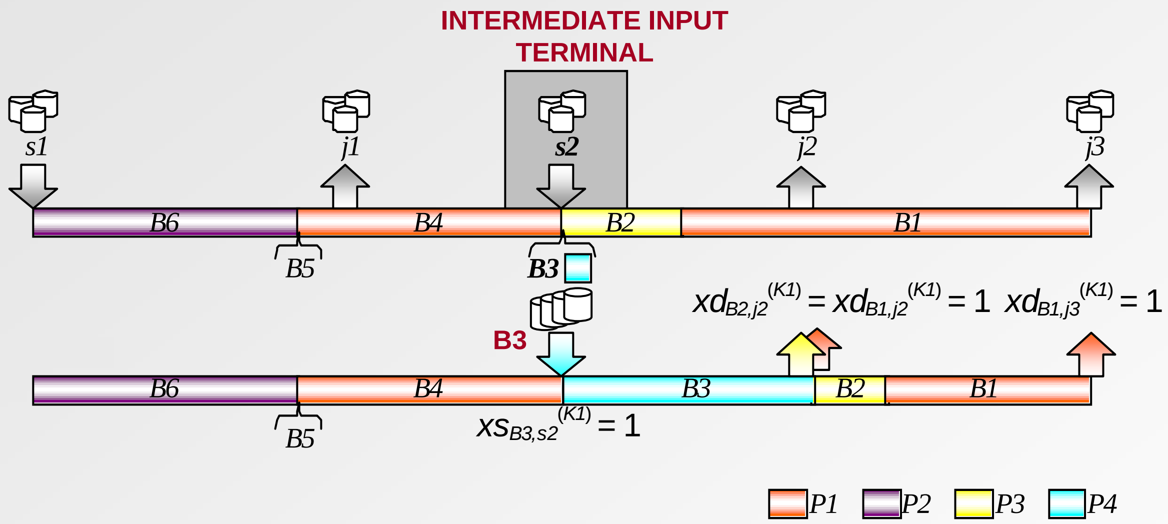
- So far, we deal with single-source multiple-destination trunk pipelines
- Multiple-source pipelines include additional input terminals at non-origin points to collect oil product batches from downstream refineries



- 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

MULTIPLE-SOURCE TRUNK PIPELINES

- 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

DETAILED PIPELINE SCHEDULE

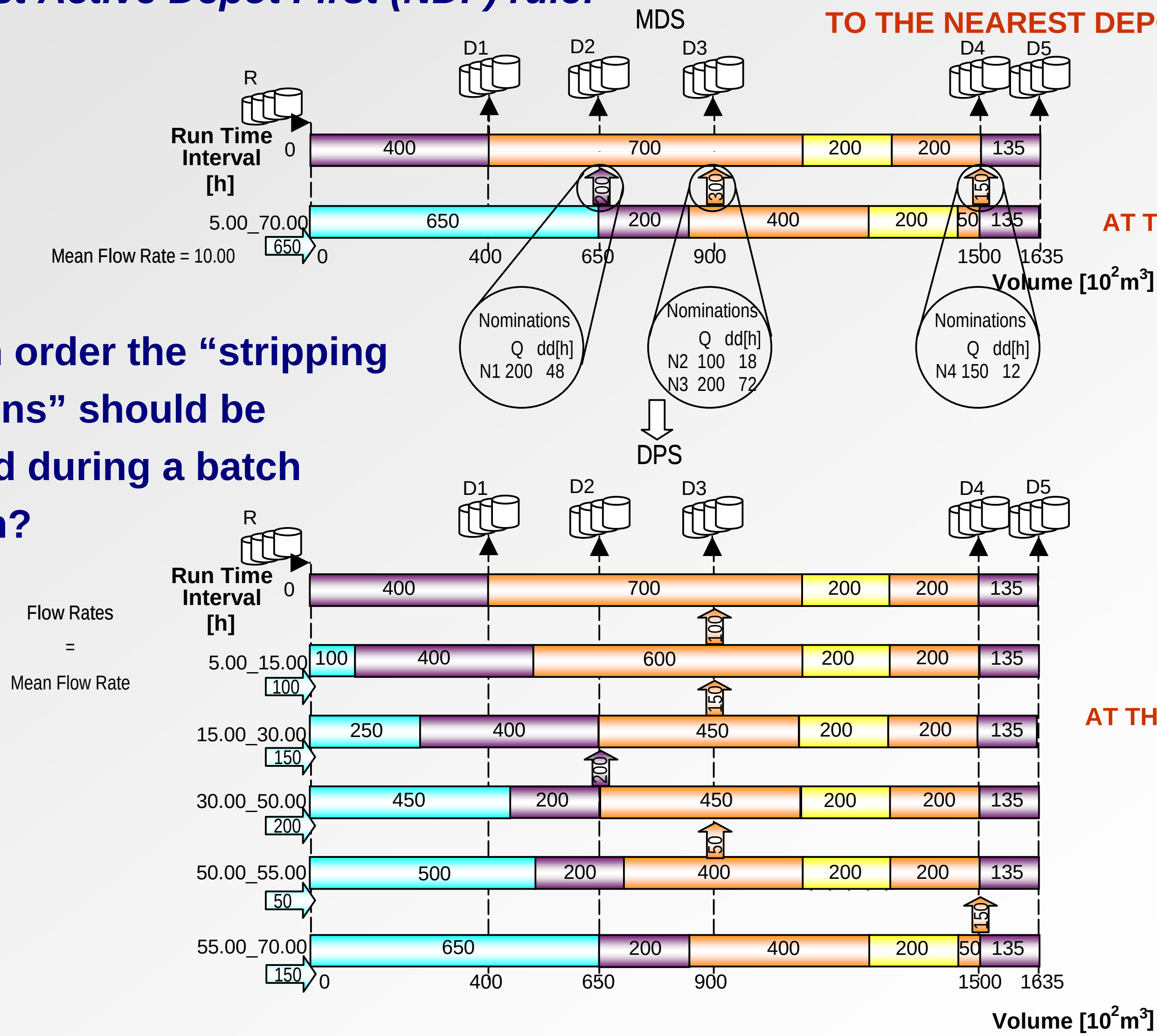
- Just the batch injections and stripping operations planned for the first period of the current time horizon are to be performed
- At the very operational level, a detailed pipeline schedule for the action period of the current horizon must be prepared
- A more detailed definition of the stripping operations 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:

PRIORITIZE DELIVERIES TO THE NEAREST DEPOT

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

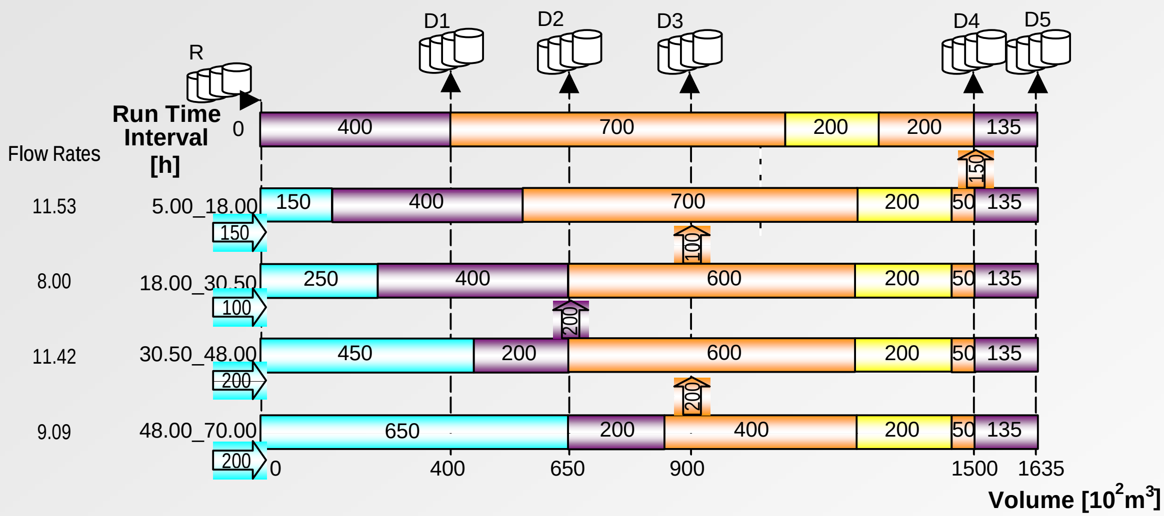


AT THE PLANNING LEVEL

AT THE OPERATIONAL LEVEL

DETAILED PIPELINE SCHEDULE

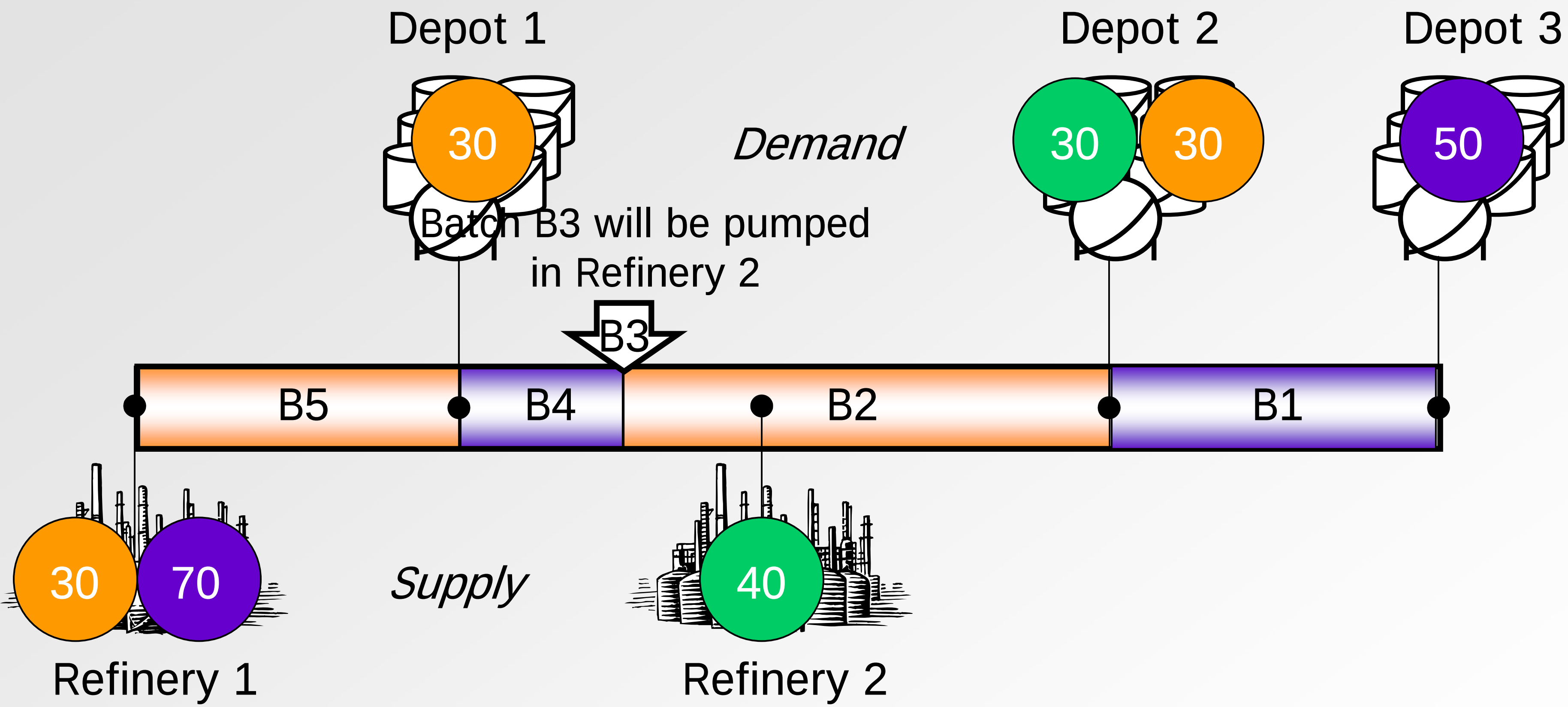
MILP Formulation:



Comparative Results:

Rule		Valve operations	Earliness [h]	Tardiness [h]
NDF	NEAREST DEPOT	5	39	43
FDF	FARTHEST DEPOT	4	22	4
EDD	EARLIEST DUE DATE	4	2	2
MILP		4	2	0

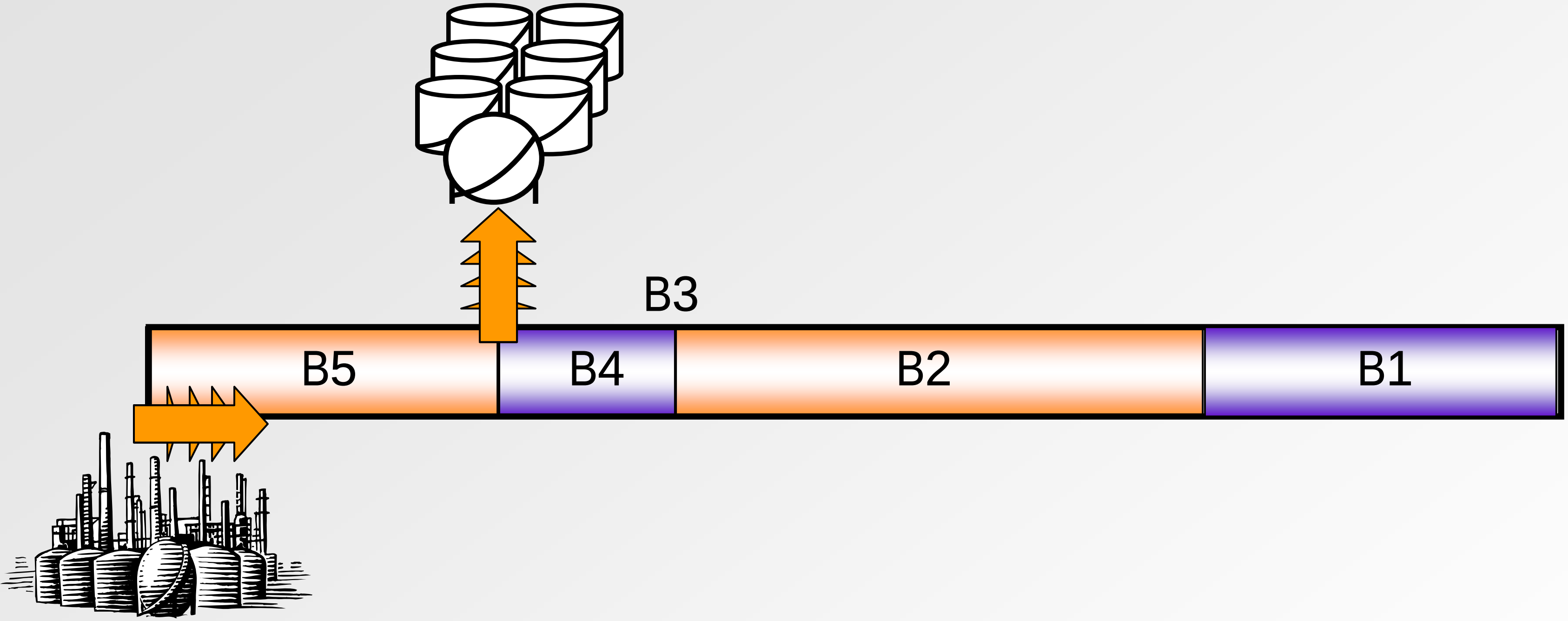
A MULTIPLE-SOURCE PIPELINE SCHEDULE



Horizon Length: 120 hs.

A MULTIPLE-SOURCE PIPELINE SCHEDULE

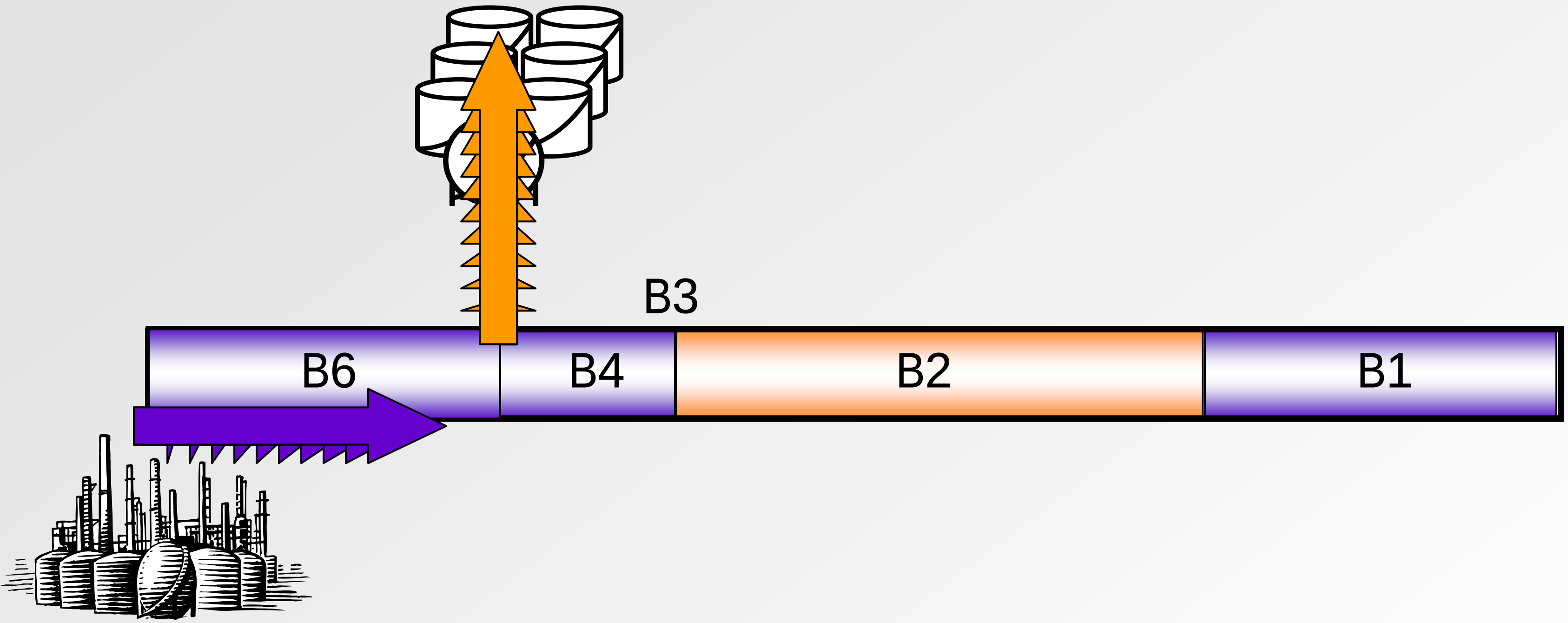
Deliver Product P1 (Batch B5)
to Depot 1



Inject Product P1 (Batch B5)
in Refinery 1

A MULTIPLE-SOURCE PIPELINE SCHEDULE

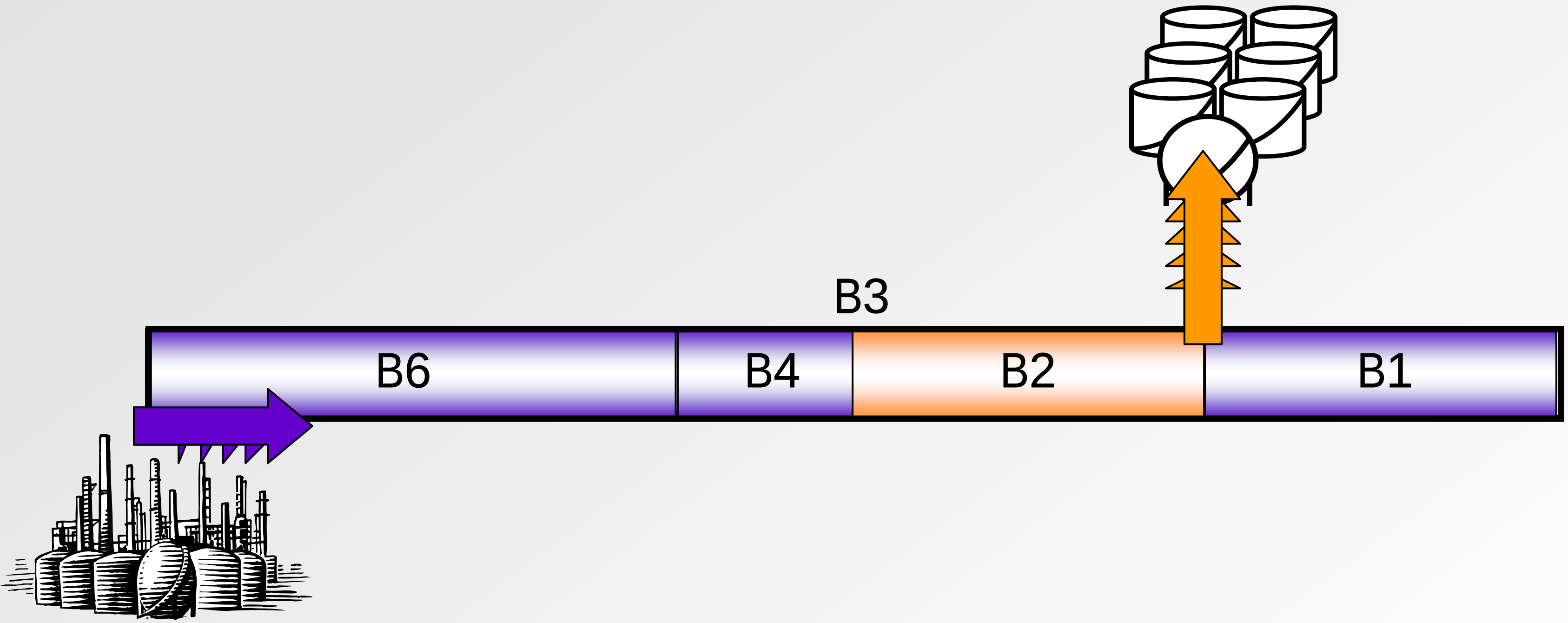
Deliver Product P1 (Batch B5)
to Depot 1



Inject Product P2 (Batch B6)
in Refinery 1

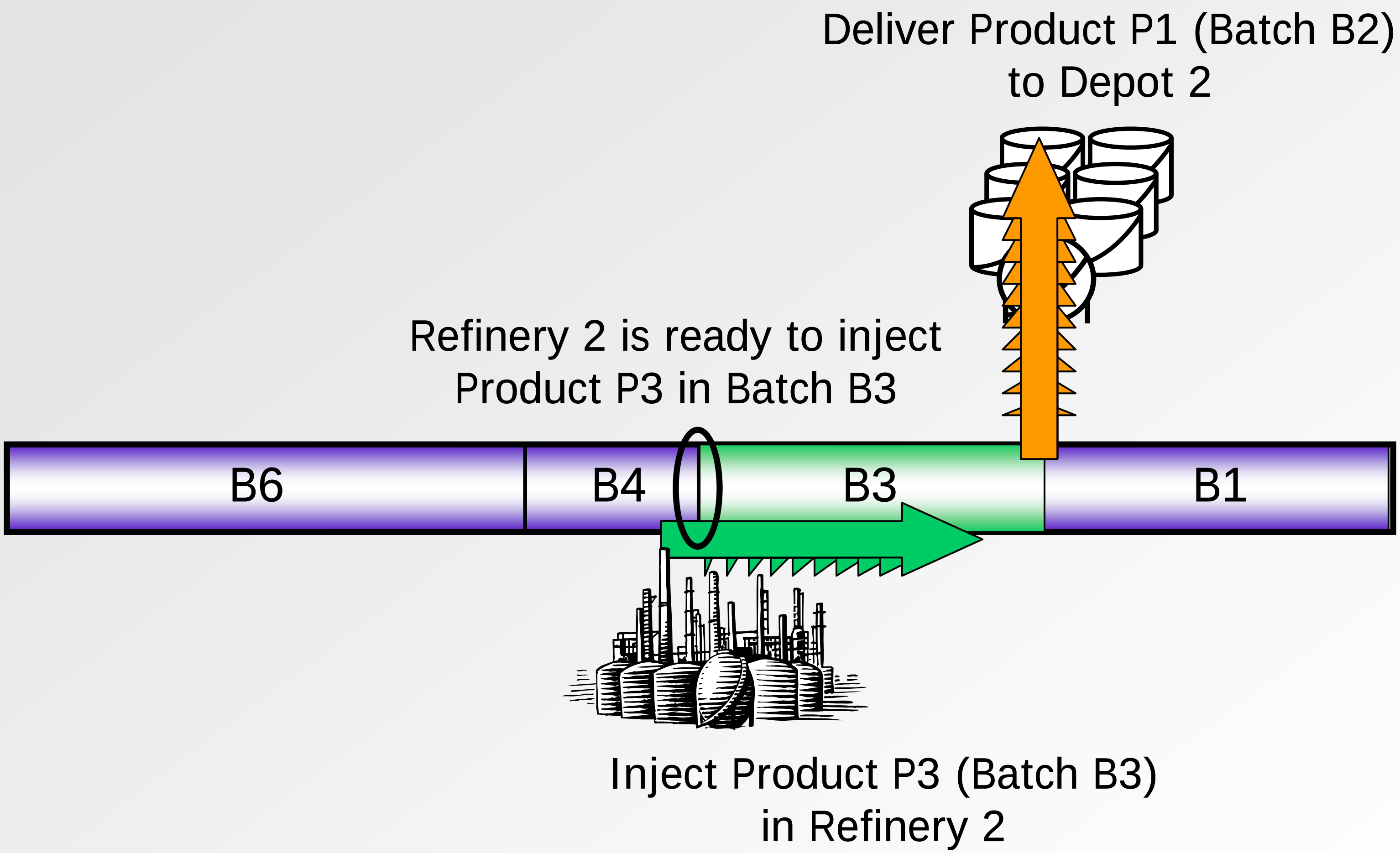
A MULTIPLE-SOURCE PIPELINE SCHEDULE

Deliver Product P1 (Batch B2)
to Depot 2

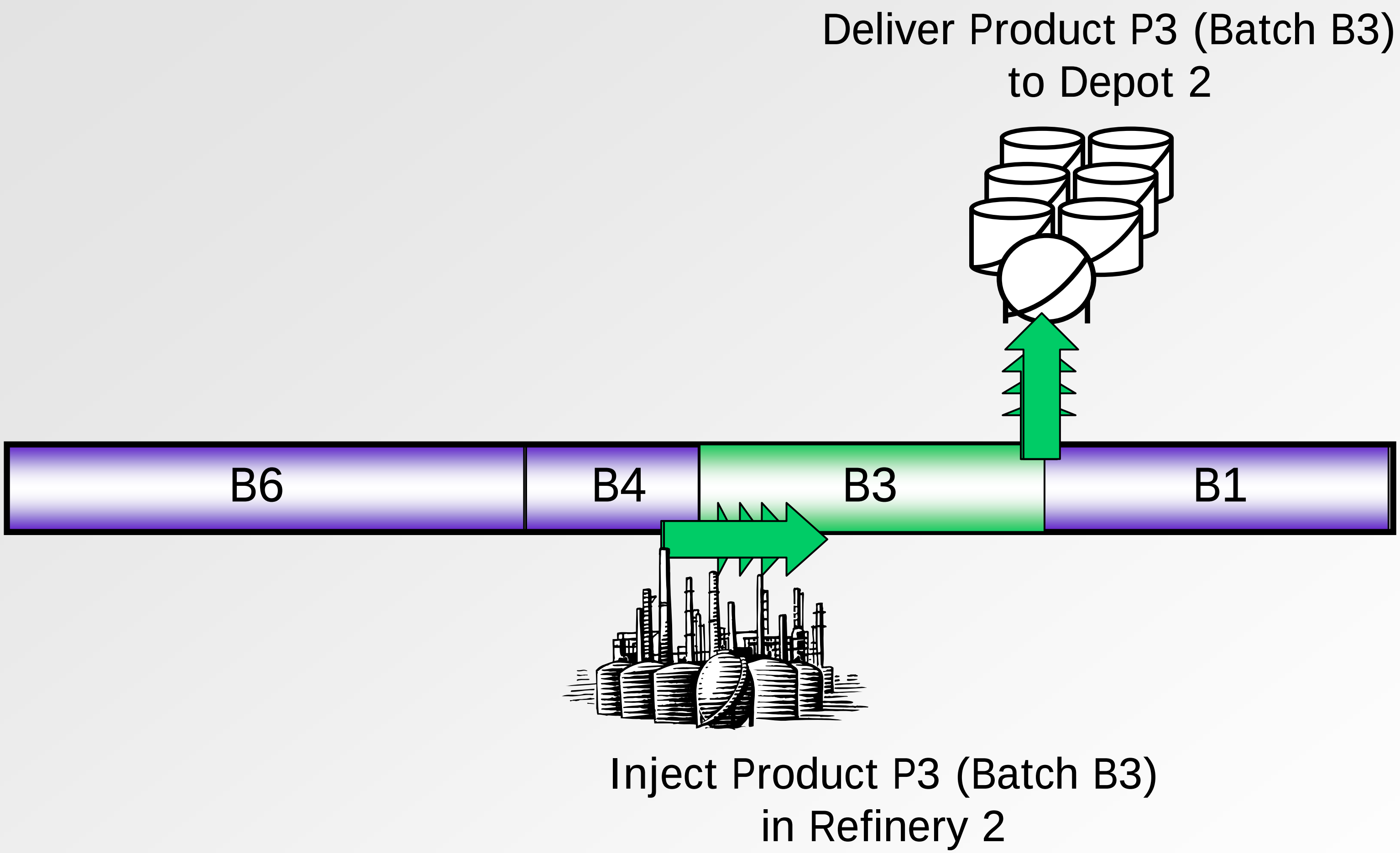


Inject Product P2 (Batch B6)
in Refinery 1

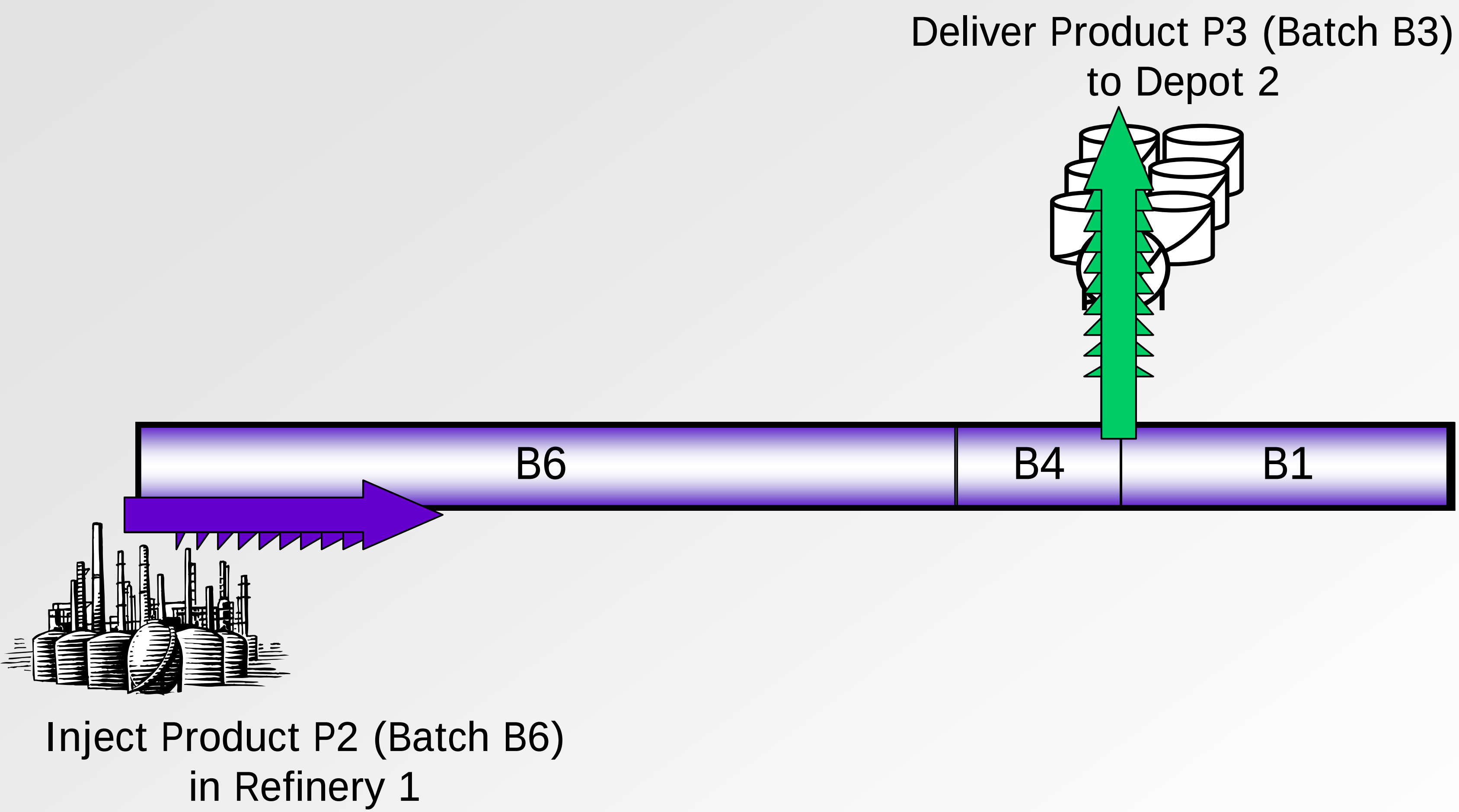
A MULTIPLE-SOURCE PIPELINE SCHEDULE



A MULTIPLE-SOURCE PIPELINE SCHEDULE



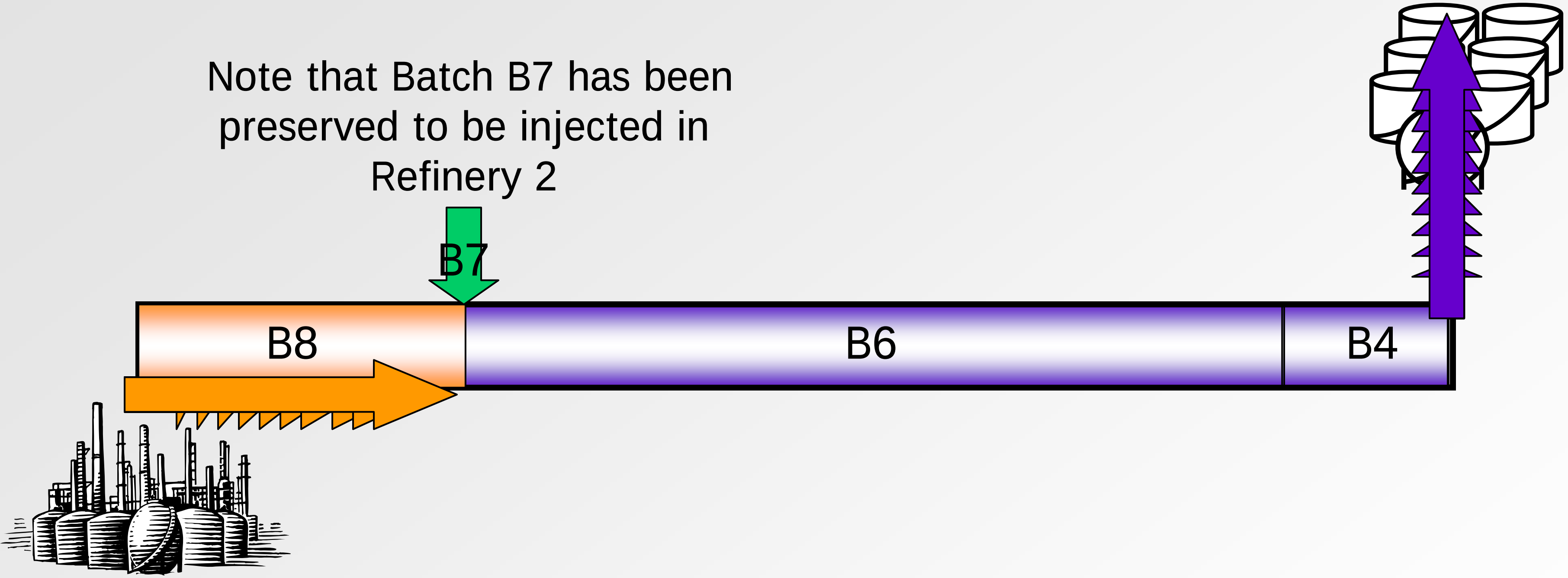
A MULTIPLE-SOURCE PIPELINE SCHEDULE



A MULTIPLE-SOURCE PIPELINE SCHEDULE

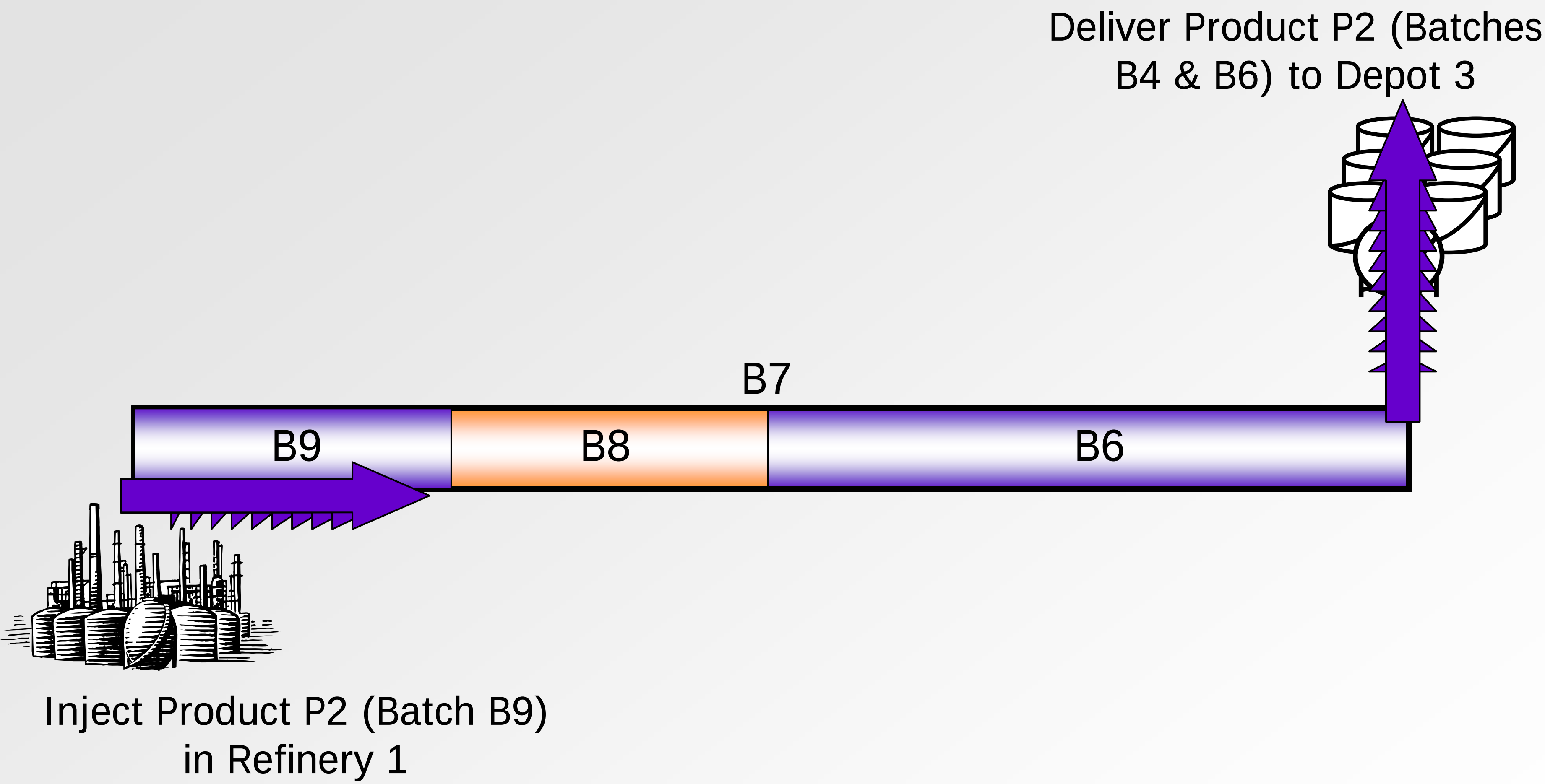
Deliver Product P2 (Batch B1)
to Depot 3

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

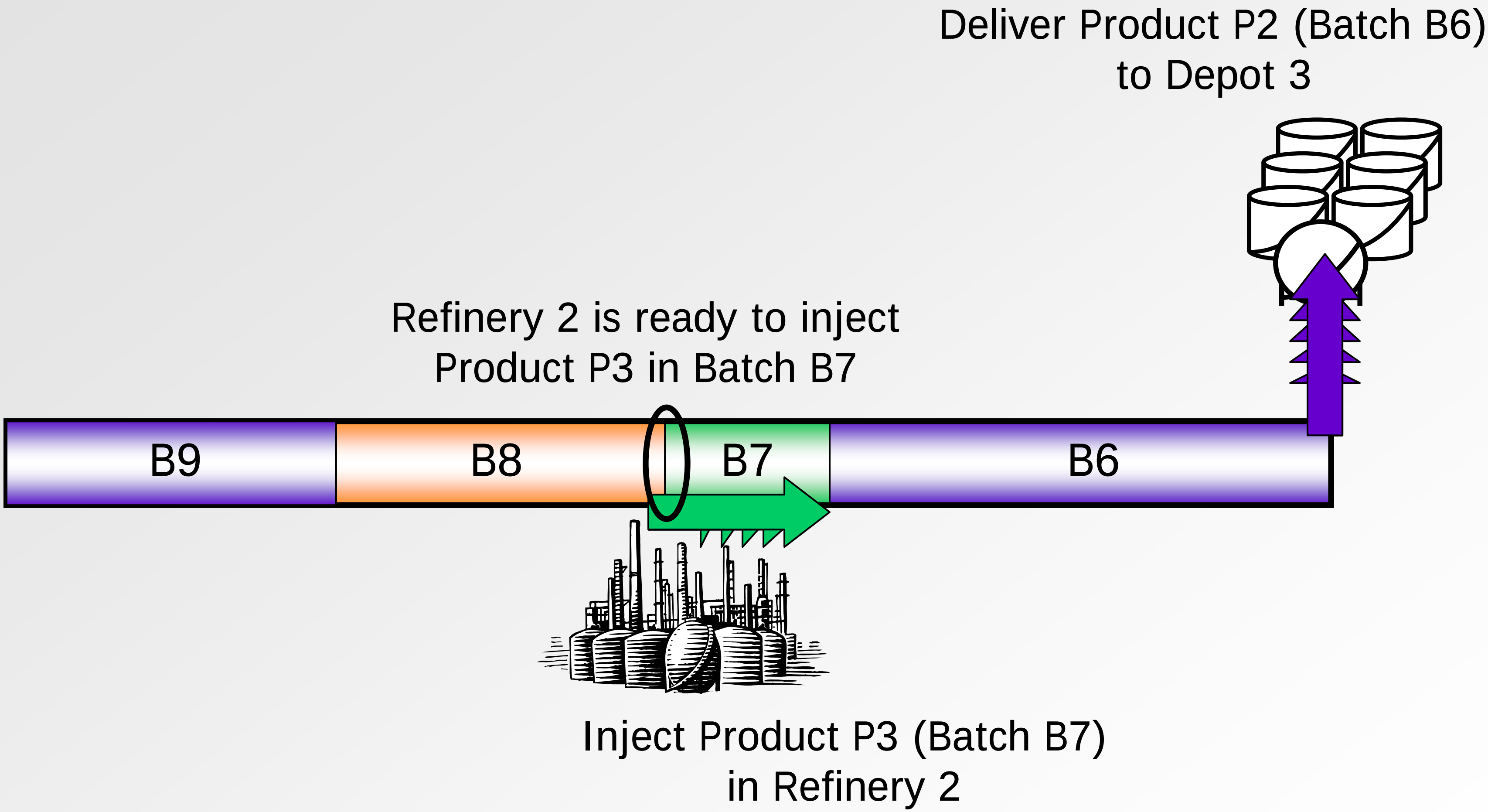


Inject Product P1 (Batch B8)
in Refinery 1

A MULTIPLE-SOURCE PIPELINE SCHEDULE



A MULTIPLE-SOURCE PIPELINE SCHEDULE



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

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OIL PIPELINE LOGISTICS

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Thanks for your attention!

Questions?

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