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Detailed Scheduling of Oil Products Pipelines with Parallel Batch Inputs at Intermediate Sources

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Pipelines constitute the dominant inland transportation mode for crude oil and oil products. Lots of refined products such as gasoline, jet fuel and diesel are shipped from refineries and seaports to truck-loading terminals by multiproduct pipelines. Planning the operation of multiproduct pipelines is a very difficult task demanding efficient tools to get safe, on-time, low-cost and high-quality movement of the oil products. Some approaches have been recently proposed to cope with the detailed scheduling of unidirectional pipelines featuring a single input at the origin and multiple receiving terminals along the line. However, many pipelines present several input stations at intermediate locations and even dual-purpose (input/output) nodes. Therefore, it becomes necessary to reformulate detailed scheduling models to account for pipeline systems with multiple sources and intermediate offtake points. The new mathematical formulation developed in this work permits to obtain the optimal sequence of detailed pumping and stripping tasks that minimizes the overall flow restart and stoppage costs, through the least number of operations. The advantages of the new approach are illustrated by solving a real-world case study.

1. Introduction

Pipelines are an important and extensive mode of transportation for liquid and gaseous products. They operate around the clock in all seasons under almost all weather conditions, and present much lower operating costs compared with other inland transportation modes. Oil pipeline routes link isolated crude oil production areas to refineries, while refined products pipelines connect these facilities to major populated regions to carry large volumes of oil derivatives. In the United States, there are 409,000 miles of pipelines carrying 17 % of all ton-miles of freight. Batches with homogeneous grades of the same petroleum product, even supplied by different refiners, may be merged and shipped as a common stream. Major lines, like the Colonial Pipeline in the U.S., can have multiple entry and exit points, whose operation demands a high degree of automation. From a central control room, pipeline operators direct the product flow, start and stop pumps, open and close valves, fill and empty tanks, trace and divert batches over the entire pipeline system. Such operations should be effectively planned to lower the power consumption, the largest single operating cost. But even today, the planning and scheduling of real-world multiproduct pipelines is often performed based on simple worksheets that use fixed-rate pipeline models and tank-to-tank operations. This type of method involves multiple trial-and-error iterations and is therefore very time consuming.

To overcome this issue, event driven simulation frameworks that facilitate the pipeline scheduler´s task were recently proposed (Heckl et al., 2009; Cafaro et al., 2011). Moreover, Cafaro and Cerdá (2009) and Castro (2010) developed the first MILP continuous formulations, in both time and volume domains, for the scheduling of unidirectional pipelines with multiple origins and destinations. Later on, Cafaro and Cerdá (2010) extended their approach to allow simultaneous batch injections at several input terminals. In this manner, the overall time needed to meet specific demands of refined products at distribution terminals is substantially decreased through a better use of the pipeline transport capacity. These works permitted to demonstrate that the inclusion of multiple sources to the pipeline scheduling problem brings many complexities that should be carefully studied, as early stated by Hane and Ratliff (1995). In fact, most of pipeline scheduling approaches do not consider the possibility of injecting lots at intermediate points

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(Rejowski and Pinto, 2003; Boschetto et al., 2010). However, continuous approaches for multi-source pipelines do not specify in which order the prescribed set of pumping and stripping operations should be done over each pumping run. Moreover, there is sometimes no feasible way to implement the specified product deliveries by making a single cut on each batch, and several non-consecutive cuts are needed. In consequence, the detailed sequence of actions performed by the pipeline operator to accomplish the transport plan is not still available. In other words, the transport plan does not indicate the times at which pumps should be turned on/off and valves should be open/closed to start/end each pumping and delivery cut operation. It is said that just an aggregate schedule is given.
In that sense, Cafaro et al. (2012) presented an MILP mathematical formulation for the detailed scheduling of unidirectional pipelines that allows the execution of parallel cuts, i.e. simultaneous stripping operations during a single input event. It is able to properly adjust the product amounts delivered from in-transit batches to receiving terminals so as to keep the stream flow rate within the allowable interval in every pipeline segment. But such tool is not capable of managing multiple input stations.
Overcoming the limitations of previous models dealing with the detailed operation of single-source pipelines, this paper presents a continuous-time, mixed-integer linear programming (MILP) formulation for the detailed scheduling of refined products pipeline networks with multiple entry points. Parallel batch injections each one causing one or multiple deliveries can be performed. The problem goal is to minimize the cumulative flow restart and pump maintenance costs. A real-world case study is solved to show the quality of the proposed solution and the computational advantage of the methodology.

2. MILP model for the detailed scheduling of multi-source pipelines

In this section we present the mathematical model for the detailed scheduling problem of multi-source pipelines. The proposed MILP optimization approach is able to consider the execution of parallel batch injections and simultaneous product deliveries to distribution terminals. In other words, two or more input stations can concurrently inject new lots into the line and multiple depots may be simultaneously receiving some amounts of products from in-transit batches. During a combined input operation, the number of parallel product deliveries can be even greater than the number of simultaneous batch injections. Therefore, a batch input may cause multiple product deliveries to an equal number of receiving terminals. The proposed model will also account for nodes having a dual (input/output) purpose, i.e. they can receive and inject products, even at the same disaggregate operation.

2.1 Problem assumptions

The MILP model is based on the following assumptions. (1) The pipeline system transports incompressible liquid products. (2) An aggregate transportation plan obtained through a continuous approach is available. (3) Pumping runs taking place at different input stations can be simultaneously performed. (4) Every product delivery from a batch in the pipeline is caused by only one batch injection. (5) Each individual batch injection may produce concurrent product deliveries to an equal number of receiving depots, i.e. a multi-cut operation. (6) If simultaneous deliveries are performed during a disaggregate operation, none of them can have a delayed start or be interrupted before completing the operation. (7) The flow-rate in each pipeline segment keeps the same value all over a detailed operation. (8) Energy consumption costs depend on the volume of pipeline sections where the flow is stopped and restarted.

2.2 Model elements and constraints

The mathematical model is formulated in terms of six major sets: (a) the pipeline terminals $j \in J = \{j_o\ j1\ j2\ \ldots\}$, including input, receiving and dual-purpose stations; (b) the pipeline segments $J' = J - \{j_o\} = \{j1\ j2\ \ldots\}$ with segment j connecting terminals j-1 and j; (c) the batches $i \in I$ moving through the pipeline along the planning horizon; (d) the chronologically ordered blocks of parallel pumping runs $b \in B$ specified by the aggregate schedule; (e) the individual batch injections $r \in R$ planned at the aggregate level; and (f) the ordered set of detailed operations $k \in K$ representing the sequence of disaggregate actions performed by the pipeline operator over the planning horizon to accomplish the aggregate schedule (starting and stopping pumps, opening and closing valves).

Pumping run decomposition. Every batch injection planned at the aggregate level is here decomposed into detailed input operations. The total volume pumped into the pipeline at the active input terminal of the individual run r of block b should be equal to the specified amount qq_r given by the aggregate plan.

$$\sum_{k \in K_b} Q_{r,k} = qq_r \qquad \forall b \in B,\ r \in R_b \tag{1}$$

A detailed input operation k $\in$ K_b making part of the block of parallel runs b and possibly involving multiple batch injections must never start before completing the previous operation (k-1) $\in$ K_b.

$$C_k - L_k \geq C_{k-1} \quad \forall (k-1), k \in K_b, b \in B \tag{2}$$

In addition, the first and the last detailed operations of the block b must respect the starting and ending times (st_b and ft_b) given for that block of pumping runs.

$$C_k - L_k = st_b \quad \forall b \in B, k = first(K_b) \quad C_k = ft_b \quad \forall b \in B, k = last(K_b) \tag{3}$$

Batch tracking. By continuity, the front coordinate of batch (i+1) at time C_k, i.e. $F_{i+1}^{(k)}$, is equal to the back coordinate of the preceding lot i $\in$ I_b given by [$F_i^{(k)}$ - $W_i^{(k)}$], where $W_i^{(k)}$ is the size of batch i at time C_k. In constraint Eq (4), the set I_b includes batches travelling through the pipeline within the time interval [st_b, ft_b].

$$F_{i+1}^{(k)} = F_i^{(k)} - W_i^{(k)} \quad \forall b \in B, i \in I_b, k \in K_b \tag{4}$$

The size of batch i at time C_k can be computed from its value at the end time of the previous operation [$W_i^{(k-1)}$] by adding the volume injected to batch i through the individual pumping run r, and subtracting the volume delivered from batch i to receiving terminals j.

$$W_i^{(k)} = W_i^{(k-1)} + \sum_{r \in Rb} \left[a_{i,r} Q_{r,k} - \sum_{j \in J_{i,r}^{\oplus}} D_{i,j}^{(k)} \right] \quad \forall b \in B, i \in I_b, k \in K_b \tag{5}$$

In Eq (5), the set $J_{i,r}^{\oplus}$ represents the active distribution terminals receiving material from batch i throughout run r. Moreover, the continuous variable $D_{i,j}^{(k)}$ denotes the amount delivered from batch i to terminal j $\in$ $J_{i,r}^{\oplus}$ during the operation k performing the individual run r. The parameter $a_{i,r}$ is equal to one if batch i receives an additional amount of product through run r. Otherwise, it takes a null value.
A limit on the size of a product delivery is defined by Eq (6). The binary variable $x_{i,j}^{(k)}$ will be equal to one just in case a product delivery from batch i to terminal j during operation k is accomplished. d_{min} is a relatively small value, while $dd_{i,j}^{(r)}$ is the total amount of batch i to be supplied to j during the whole run r.

$$d_{min}\, x_{i,j}^{(k)} \leq D_{i,j}^{(k)} \leq dd_{i,j}^{(r)}\, x_{i,j}^{(k)} \quad \forall b \in B, i \in I_b, r \in R_b, j \in J_{i,r}^{\oplus}, k \in K_b \tag{6}$$

In addition, no product deliveries from batches moving through the pipeline to receiving terminals can occur at fictitious (i.e. non-performed) operations k, whenever the binary variable u_k is null.

$$\sum_{i \in I_b} x_{i,j}^{(k)} \leq u_k \quad \forall b \in B,\ r \in R_b, j \in J_r^{\oplus}, k \in K_b \tag{7}$$

Preventing from solution degeneracy, fictitious operations k $\in$ K_b of block b $\in$ B will always arise last in the set K_b, as stated by constraint Eq (8).

$$u_k \leq u_{k-1} \quad \forall b \in B, (k-1), k \in K_b \tag{8}$$

Input/Output rates. Assuming that the model parameters l_{min} and l_{max} represent the minimum/maximum allowed lengths of a detailed operation, and $vb_{min}^{(r)}$ and $vb_{max}^{(r)}$ stand for the minimum/maximum injection rates at the active input terminal of the individual run r $\in$ R_b, then the admissible ranges for the length and the volume injected during an operation k are defined by constraints Eq (9) and Eq (10),

$$l_{\min}\, u_k \leq L_k \leq l_{\max}\, u_k \quad \forall b \in B, k \in K_b \tag{9}$$

$$vb_{min}^{(r)}\, L_k \leq Q_{r,k} \leq vb_{max}^{(r)}\, L_k \quad \forall b \in B, r \in R_b, k \in K_b \tag{10}$$

If $vd_{max}^{(j)}$ denotes the maximum admissible rate for diverting products from the pipeline into terminal j, an upper bound on the size of every single product delivery during operation k is imposed by constraint Eq (11).

$$D_{i,j}^{(k)} \le vd_{max}^{(j)} \; L_k \quad \forall b \in B, i \in I_b, r \in R_b, j \in J_{i,r}^{\oplus}, k \in K_b \tag{11}$$

Conditions for batch deliveries. A product delivery from batch i to terminal j during operation k can occur only if: (a) batch i has reached the location of terminal j at the end of operation (k-1), and (b) batch i has not surpassed terminal j at the end of operation k, to avoid diverting the succeeding batch too. Such feasibility conditions are forced through constraints Eq (12) and Eq (13). The parameter σ_j is the volumetric coordinate of terminal j, while pv denotes the total volume of the pipeline system.

$$F_i^{(k-1)} \ge \sigma_j \; x_{i,j}^{(k)} \quad \forall b \in B, i \in I_b, r \in R_b, j \in J_{i,r}^{\oplus}, k \in K_b \tag{12}$$

$$F_i^{(k)} - W_i^{(k)} \le \sigma_j + (pv - \sigma_j)(1 - x_{i,j}^{(k)}) \quad \forall b \in B, i \in I_b, r \in R_b, j \in J_{i,r}^{\oplus}, k \in K_b \tag{13}$$

Volume balance. Due to the product incompressibility assumption, an exact balance between input and output volumes at every operation k must be defined through Eq (14).

$$\sum_{i \in Ib} \sum_{j \in J_{i,r}^{\oplus}} D_{i,j}^{(k)} = Q_{r,k} \quad \forall b \in B, \; r \in R_b, k \in K_b \tag{14}$$

Demand fulfillment. The total volume diverted from batch $i \in I_b$ to the receiving terminal $j \in J_{i,r}^{\oplus}$ during the whole run $r \in R_b$ of block b (i.e., through all the detailed operations $k \in K_b$) must be equal to the prescribed aggregate delivery $dd_{i,j}^{(r)}$, aiming to fulfill customers' orders.

$$\sum_{k \in Kb} D_{i,j}^{(k)} = dd_{i,j}^{(r)} \qquad \forall b \in B, i \in I_b, r \in R_b, j \in J_{i,r}^{\oplus} \tag{15}$$

Active and idle segments. Let us define the continuous variable $\omega_j^{(k)}$ to represent the state of the pipeline segment $j \in J'$ during the operation k. Its value is confined to closed interval [0, 1]. Segment j will be active at operation k if there is a fluid movement through it and consequently $\omega_j^{(k)} = 1$. Otherwise, segment j is idle and $\omega_j^{(k)} = 0$. To characterize the state of a pipeline segment at a non-fictitious operation, the proposed formulation incorporates constraints (16) and (17) for each individual run $r \in R_b$ of any block b.

$$\omega_j^{(k)} \ge \sum_{i \in Ib} x_{i,j'}^{(k)} \qquad \forall \; b \in B, r \in R_b, j \in J_r, j' \in J_r^{\oplus} (j' \ge j), \; k \in K_b \tag{16}$$

$$\omega_j^{(k)} \le \left[\sum_{i \in Ib} \sum_{\substack{j' \in J_r^{\oplus} \\ j' \ge j}} x_{i,j'}^{(k)} \right] - u_k + 1 \qquad \forall b \in B, r \in R_b, j \in J_r, k \in K_b \tag{17}$$

Pipeline segments $j \in J_r$ are those that can be activated through the individual run r, while depots $j' \in J_r^{\oplus}$ stand for terminals receiving products over run r. Consequently, pipeline segments not belonging to any set J_r will be surely idle at every operation of block b, as stated by Eq (18).

$$\omega_j^{(k)} = 0 \qquad \forall \; b \in B, j \notin \bigcup_{r \in R_b} J_r, k \in K_b \tag{18}$$

To avoid symmetric solutions, it is important that the value of $\omega_j^{(k)}$ for fictitious operations resembles the state of segment j at the last non-fictitious element k' < k. This is achieved by including constraint (19), which is redundant if $u_k = 1$. In other words, $\omega_j^{(k)} = \omega_j^{(k-1)}$ for any fictitious operation k.

$$\omega_j^{(k-1)} - u_k \le \omega_j^{(k)} \le \omega_j^{(k-1)} + u_k \qquad \forall \; b \in B, (k-1), k \in K_b, j \in J' \tag{19}$$

Flow rate control. The stream flow rate at each active segment j verifying $\omega_j^{(k)} = 1$ should belong to the admissible range given by $[vb_{min}^{(j)}; vb_{max}^{(j)}]$. The total volume flowing through segment j at operation k is computed by summing all the product deliveries $D_{i,j}^{(k)}$ to downstream terminals $j' \ge j$ during operation k.

$$vb_{min}^{(j)}\,L_k - q_{max}\,(1-\omega_j^{(k)}) \le \sum_{i\in I_b}\ \sum_{\substack{j'\in J_{i,r}^{\oplus}\\ j'\ge j}} D_{i,j'}^{(k)} \le vb_{max}^{(j)}\,L_k \qquad \forall\, b\in B, r\in R_b\,, j\in J_r\,, k\in K_b \tag{20}$$

Start/Stop volumes. To determine operative costs at each detailed operation it is necessary to identify the pipeline segments where the stream flow is stopped or restarted. This is achieved by comparing the state of each pipeline segment j ∈ J' in two successive operations. The volume of a pipeline segment j connecting terminals (j - 1) and j can be computed through the difference of the corresponding volumetric coordinates σ_j and σ_{j-1}, with $\sigma_o = 0$ representing the input terminal at the pipeline origin. Then, the stopped and activated volumes at operation k are defined by constraints Eq (21) and Eq (22).

$$SV_j^{(k)} \ge (\sigma_j - \sigma_{j-1})(\omega_j^{(k-1)} - \omega_j^{(k)}) \qquad \forall\, j\in J', k\in K \tag{21}$$

$$AV_j^{(k)} \ge (\sigma_j - \sigma_{j-1})(\omega_j^{(k)} - \omega_j^{(k-1)}) \qquad \forall\, j\in J', k\in K \tag{22}$$

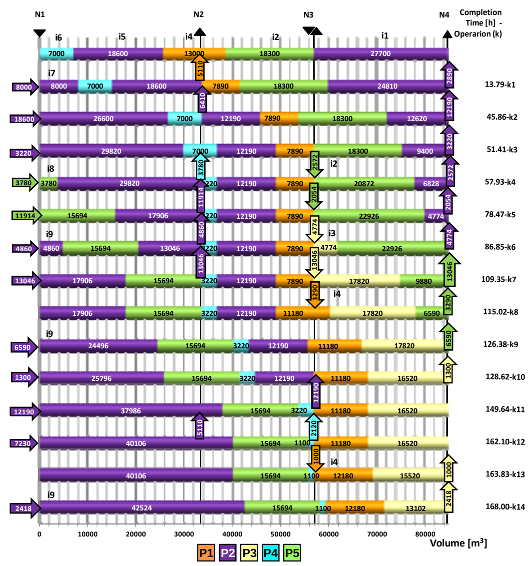
2.3 Objective function

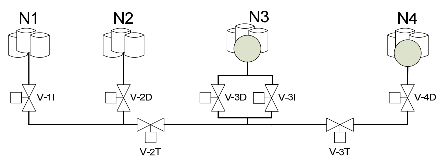
The problem goal is to develop a detailed pipeline schedule that fulfills the aggregate output plan at minimum flow restart and on/off pump switching costs, through the least number of operations.

$$Min\ z = \sum_{k\in K}\sum_{j\in J'}(cs\ SV_j^{(k)} + ca\ AV_j^{(k)}) + \sum_{k\in K} fco\ u_k \tag{23}$$

3. Case study

The proposed formulation is applied to the refinement of an aggregate schedule of a real-world pipeline system. This example considers a pipeline network consisting of a series of four logistic nodes (N1, N2, N3, N4), with two of them (N1 and N3) acting as input terminals, close to important refineries. Simultaneous batch injections from nodes N1 and N3 into the line are permitted. N3 is indeed a dual-purpose station that can inject and receive products into/from the pipeline. The pump rate at the two input terminals should be kept between 100 and 580 m^3/h. The length of the planning horizon within which the depot demands must be satisfied is equal to 168 h (a weekly horizon). Products demands at receiving depots and initial product inventories at source nodes can be found in Cafaro and Cerdá (2010). The overall length of the pipeline system from node N1 (at the origin) to terminal N4 (at the pipeline end) is over 1,000 kilometres, and the volumes of the three pipeline segments (N1-N2, N2-N3 and N3-N4) are 336, 233, and 277 [10^2 m^3], respectively.





op	Time Interval [h]	V-1I	V-2D	V-2T	V-3D	V-3I	V-3T	V-4D
		Flow Set Point for Each Valve [m^3/h]						
k1	0.00 - 13.79	580	370	210	-	-	210	210
k2	13.79 - 45.86	580	200	380	-	-	380	380
k3	45.86 - 51.41	580	-	580	-	-	580	580
k4	51.41 - 57.93	580	580	-	-	395	395	395
k5	57.93 - 78.47	580	580	-	-	100	100	100
k6	78.47 - 86.85	580	580	-	-	570	570	570
k7	86.85 - 109.35	580	580	-	-	580	580	580
k8	109.35 -115.02	-	-	-	-	580	580	580
k9	115.02 -126.38	580	-	580	-	-	580	580
k10	126.38 -128.62	580	-	580	-	-	580	580
k11	128.62 -149.64	580	-	580	580	-	-	-
k12	149.64 -162.10	580	410	170	170	-	-	-
k13	162.10 -163.83	-	-	-	-	580	580	580
k14	163.83 -168.00	580	-	580	-	-	580	580

Open Close

Figure 1: Detailed pipeline schedule and control valve set points

The aggregate pipeline schedule given as input data comprises a total of 9 batch injections (5 from node N1 and 4 from N3) that are grouped into 7 blocks of pumping runs. Two blocks (b2, b3) consist of a pair of parallel batch injections, and the other five include only one. Since some runs just add further amounts of products to existing batches, a total of 9 lots are transported by the pipeline over the seven-day horizon.
The best detailed schedule found in 0.107 s of CPU time is presented in Figure 1. Assuming that the pipeline is initially idle, there are: (i) three flow restarts in segment N1-N2 at operations k1, k9, k14, (ii) three flow resumes in segment N2-N3 when performing the same operations k1, k9, k14, and (iii) two flow restarts in segment N3-N4 at the detailed runs k1 and k13. Overall, eight segment restarts are planned during the whole week and just five flow stoppages. Three of the eight flow restarts taking place in segments N1-N2 and segment N2-N3 are already prescribed by the aggregate pipeline plan. In addition, three more flow resumes occur because the pipeline is initially idle. On the other hand, though the best detailed schedule includes five stoppages, four of them are pre-established by the aggregate plan. They occur in segments N1-N2 and N2-N3 during detailed operations k8 and k13 executing blocks b4 and b6, respectively. According to the aggregate plan, only the last segment (N3-N4) should be active throughout those blocks. The optimal solution tends to maintain a finite stream flow in every pipeline segment to avoid unnecessary flow restarts. Flow rates at the control valves that remain open during each operation are also presented in Figure 1.

4. Conclusions

A highly-efficient MILP continuous formulation for the comprehensive scheduling of refined products pipeline systems with multiple inputs has been developed. The transportation plan found through a continuous approach is thus refined into a sequence of disaggregate actions to be performed by the pipeline operator. In contrast to previous contributions, each pumping operation can involve the execution of two or more concurrent batch injections at different source nodes. Stream flows caused by such pumping runs never collide because they are confined to non-overlapping chains of pipeline segments. By properly coordinating parallel batch injections and simultaneous product deliveries to multiple receiving terminals, unnecessary flow stoppages can be avoided and subsequent flow restart costs are substantially diminished. Parallel batch injections are effectively managed through a detailed scheduling of pipeline operations (opening/closing valves and turning on/off booster stations) while partial deliveries are practically achieved by siphoning product out of the line as the batches continue moving forward at lower rates to farther destinations. Such model features bring about two advantages. On one hand, the stream flow rate in each pipeline segment can be accurately adjusted, thus handling a specific flow rate range for each pipeline segment. On the other hand, it leads to substantial savings in energy consumption with regards to previous methods by keeping a finite flow in more pipeline sections for a longer period of time.

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