

Multiperiod Planning of Multiproduct Pipelines

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Abstract

Scheduling product batches in pipelines is a very complex task with many constraints to be considered. Several papers have been published on the subject during the last decade. Most of them are based on large-size MILP discrete time scheduling models whose computational efficiency greatly diminishes for rather long time horizons. By introducing an MILP continuous representation in both time and volume, Cafaro and Cerdá (2004) recently developed a more rigorous problem description providing better schedules at much lower computational cost. However, all model-based scheduling techniques were applied to examples featuring short time horizons and a unique due-date for all deliveries at the horizon end. Pipeline operators generally use a recurring monthly schedule involving several periods, with product demands to be satisfied at the end of each period. Because of the pipeline time delay, most of the market demands over short horizons are fulfilled through inventories already available at depot tanks or in pipeline transit. Therefore, the scheduled pumping runs have nothing to do with future product demands at distribution terminals and are aimed at simply moving product slugs along the duct. To overcome such drawbacks of current approaches, this work presents an efficient MILP continuous framework for the dynamic scheduling of pipelines over a multiperiod rolling horizon. At the completion of the current period, another one is added at the end of the rolling horizon and the re-scheduling process is triggered again over the new horizon. Pumping runs may extend for two or more periods. The approach successfully solved a real-world pipeline scheduling problem involving the transportation of four products to five destinations over a rolling horizon always comprising four one-week periods.

Keywords: multiproduct pipelines; multiperiod planning; MILP approach

1. Introduction

The scheduling of multiproduct pipelines transporting refined petroleum products from a single origin to multiple destinations has attracted increasing attention among researchers in the last decade. Two different types of approaches have been proposed: knowledge-based search techniques (Sasikumar et al., 1997) and mixed-integer linear mathematical programming (MILP) formulations. Depending on whether or not the pipeline volume and the time horizon are both discretized, model-based methods can be grouped into two classes: discrete and continuous MILP approaches. Most of the

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proposed optimization models not only partitioned the horizon into time intervals of equal or unequal sizes but also the pipeline volume is divided into a number of single-product packs (Rejowski and Pinto, 2003; Magatão, Arruda and Neves, 2004). In contrast, Cafaro and Cerdá (2004) developed a novel MILP continuous formulation that requires neither time discretization nor pipeline division. In comparison with heuristic search techniques, one of the major drawbacks of the optimization approaches is the use of much shorter time horizons comprising just a few days. In this way, the model size remains reasonable and the optimal solution can be efficiently found. On the other hand, a common feature of all pipeline scheduling methodologies is the planning of pumping runs over a single-period time horizon and the specification of a unique due-date for every product demand just at the horizon end. However, pipeline operators generally use a recurring monthly schedule involving several periods, each one varying from 6 to 10 days. Moreover, multiple due-dates for the product deliveries to local markets are usually fixed at the period ends.

One of the major challenges in the operation of pipelines is to meet just-in-time large product demands along the pipeline at different due-dates over a rather long multiperiod horizon. Since new transportation requests are placed by customers as time proceeds, the information on the problem is indeed time-dependent and the pumping run schedule should be periodically updated. But the dynamic nature of the problem forcing to periodically update the pipeline schedule has the delivery time delay as another major source. In fact, there usually is a time delay, as large as 3 to 10 days depending on the pipeline length and the depot location, between the batch injection into the pipeline and the actual delivery to its destination; i.e. the transportation lead-time. Over scheduling horizons shorter than the transportation lead-time, most of market demands are fulfilled through inventories already available at depot tanks or in pipeline transit. New pumping runs have just the purpose of moving product batches along the pipeline from their current locations to the nominated terminals. As a result, planned product injections have nothing to do neither with product demands to meet during the current horizon nor with still unknown future requirements. As time passes and new product needs at distribution terminals are considered, the update of the current pipeline schedule usually yields a completely different sequence of pumping runs.

To overcome such limitations of the pipeline scheduling techniques proposed in the literature, it must be developed a new solution strategy for the dynamic pipeline scheduling problem (DPSP). In the DPSP, the information on new transportation requests becomes available as the time horizon rolls and a new period is incorporated at the horizon end to replace the first one already vanished. The DPSP is solved by tackling a sequence of static pipeline scheduling problems, a different one for every new time horizon. This work introduces an efficient multiperiod MILP continuous approach to the DPSP based on the formulation of Cafaro and Cerdá (2004) for the static pipeline scheduling problem. The novel approach is capable of optimally updating the sequence of pipeline product injections over a rolling horizon.

2. Problem Definition

Given: (a) the multiproduct pipeline structure; (b) the available tanks at every depot; (c) the product demands at every depot to meet at the end of each time period; (d) the

sequence of slugs inside the pipeline at the starting time; (e) the scheduled product output at the refinery during the scheduling horizon; (f) initial inventory levels in refinery and depot tanks; (g) maximum injection rate in the pipeline, supply rate from the pipeline to depots and delivery rate from depots to local markets, (h) the number of periods involved in each time horizon and (i) the series of horizons to be considered for solving the DPSP. The problem goal is to dynamically establish/update the optimal sequence of pumping runs over a multiperiod time horizon in order to: (1) meet every product demand at each period in a timely fashion; (2) maintain the inventory level in refinery and depot tanks within the permissible range and (3) minimize the sum of pumping, transition and inventory carrying costs.

3. Mathematical Formulation

3.1 New problem variables

The continuous mathematical model introduced by Cafaro and Cerdá (2004) for the static pipeline scheduling problem with a common due date for all product demands at the horizon end should be properly extended to tackle the DPSP. By considering a multiperiod planning horizon, the new formulation is capable of handling multiple due-dates for the product deliveries to different distribution terminals which are supposed to occur at period ends. Let T be the ordered set of periods into which the planning horizon has been divided. The model parameters IP_t and FP_t represent the initial and final time of period t , respectively, while $Dem_{p,j}^{(t)}$ stands for the demand of product $p \in P$ at depot $j \in J_p$ to be satisfied before the end of period t . The additional constraints to deal with the DPSP are given below. Other restrictions can be found in Cafaro and Cerdá (2004).

3.2 The completion time period of a new pumping run $i \in I^{new}$

Let us define a new binary variable $w_{i,t}$ to denote that the pumping run $i \in I^{new}$ is completed inside or at the end of period t ($w_{i,t} = 1$). The use of $w_{i,t}$ instead of the old variable w_i prevent us from defining a different set of pumping run candidates for each period. By doing that, just a single set of new runs I^{new} is to be considered and consequently the increase in both the number of potential product injections and the problem size for multiperiod horizons remains quite reasonable. Every non-fictional run $i \in I^{new}$ featuring a finite length L_i and containing a particular product $p \in P$ ($\sum_p y_{i,p} = 1$) must be completed at some period of the planning horizon.

$$\sum_{t \in T} w_{i,t} = \sum_{p \in P} y_{i,p} \quad \forall i \in I^{new} \quad (1)$$

If run $i \in I^{new}$ is completed in period t , then the following conditions must be fulfilled:

$$C_i \geq IP_t * w_{i,t} \quad (2)$$

$$C_i \leq FP_t + (1 - w_{i,t}) * MT \quad \forall i \in I^{new}, t \in T \quad (3)$$

where MT is a sufficiently large number. Otherwise, constraints (2) and (3) both become redundant. Note that run $i \in I^{new}$ can be started at some period t' and finished at another period $t > t'$ since nothing is said about the interval t' at which run i begins.

3.3 Delivery due-date constraints

In the formulation of Cafaro and Cerdá (2004), the variable $qm_{p,j}^{(i)}$ denotes the amount of product p transferred from depot j to the local market during the injection of a new run $i \in I^{new}$, i.e. over the interval $[C_{i-1}, C_i]$. If $vm_{p,j}$ stands for the maximum discharge rate of product p at terminal j , then:

$$qm_{p,j}^{(i)} \leq (C_i - C_{i-1}) * vm_{p,j} \quad \forall i \in I^{new}, p \in P, j \in J_p \quad (4)$$

Let us assume that the pumping run $i \in I^{new}$ is the last one completed in period t . The amount of product p transferred from depot j to the local market while injecting new pumping runs $\{1, 2, 3, \dots, i-1, i\}$ must be large enough to meet all p th-product demands at depot j from the initial time to the end of period t . But the last pumping run i completed at period t is not known beforehand. Consequently, the following conditional constraint must be incorporated in the problem formulation:

$$\sum_{\substack{\ell=1 \\ \ell \in I^{new}}}^i qm_{p,j}^{(\ell)} \geq \left(\sum_{k=1}^t Dem_{p,j}^{(k)} \right) * (w_{i,t} - w_{i+1,t}) \quad (5)$$

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

where the set T_{pj} stands for the periods at which $Dem_{p,j}^{(i)}$ takes a finite value. If run $i \in I^{new}$ is the last one completed in period t , then $w_{i,t} = 1$ and $w_{i+1,t} = 0$. Therefore, the total amount of product p dispatched from terminal j to the local market will permit to meet the demand of p from $t=1$ to $t=t$. Otherwise, the constraint (5) becomes redundant.

4. Results and Discussion

To illustrate the advantages of the proposed dynamic pipeline scheduling approach, the real-world example introduced by Rejowski and Pinto (2003) was solved but this time a much longer multiperiod horizon and multiple delivery due-dates were considered. The example involves the distribution of four refined petroleum products ($P1$ - $P4$) through a single pipeline of 955 km to five terminals ($D1$ - $D5$) over a planning horizon steadily comprising four weekly periods. Product demands at depots $D1$ - $D5$ to be satisfied at the end of periods $t1$ - $t4$ are given in Table 1. Demand data for the subsequent time intervals $t5$ - $t7$ still unknown at the time of developing the static pipeline schedule for the initial horizon $\{t1$ - $t4\}$ become available as the four-period horizon rolls. Let us assume a similar demand profile and refinery outputs for the next three time periods $t5$ - $t7$ than the ones reported for $t1$ - $t3$. The remaining data can be found in Rejowski and Pinto (2003). The pumping unit cost is assumed to be time-independent. The optimal static pipeline schedule for the initial horizon $\{t1$ - $t4\}$ is shown in Figure 1. Details on pumping runs and deliveries from the pipeline to distribution terminals are only given for period $t1$ (0h, 168h), i.e. for the “action” period of the initial horizon. The proposed pipeline schedule includes a sequence of five pumping runs involving the following products and volumes: $P4^{425} / P2^{1115} / P1^{650.3} / P3^{825} / P1^{870}$. Since the pipeline planning should be

Table 1. Product demands at the five distribution terminals for periods t1-t4 ($Dem_{p,j}^{(t)}$)

	Product demands																			
	D1				D2				D3				D4				D5			
	t1	t2	t3	t4	t1	t2	t3	t4	t1	t2	t3	t4	t1	t2	t3	t4	t1	t2	t3	t4
P1	40	30	50	50	100	100	150	120	90	120	100	110	140	180	170	150	100	120	90	100
P2	100	120	100	120	100	100	100	110	70	80	70	60	200	200	200	220	220	210	250	220
P3	30	40	30	20	0	0	0	0	20	30	20	30	50	60	50	40	30	20	20	40
P4	0	0	0	0	0	0	0	0	0	0	0	0	60	80	60	70	70	80	60	90

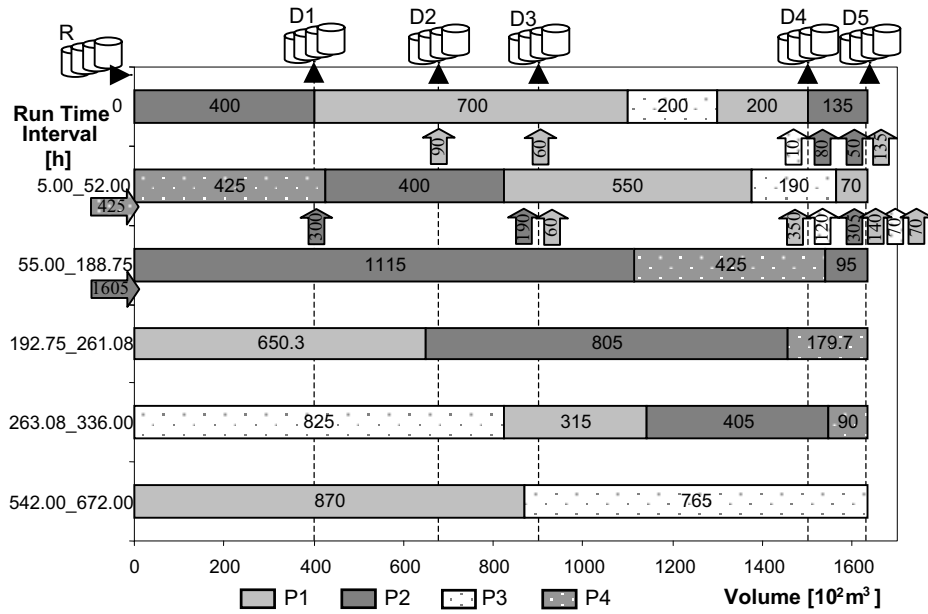


Figure 1. Optimal static pipeline schedule for the time periods t1-t4

updated at the start of week t2 when demand data for period t5 become available, then the previous schedule is to be frozen just for the “action” period t1. As the four-period scheduling horizon has rolled from {t1-t4} to {t4-t7} and new demand data were considered, the sequence of pumping runs and the amounts of products delivered from the pipeline to terminals specified for the action period undergo significantly changes. Figure 2 shows the dynamic pipeline schedule finally proposed for periods t1-t4 at the start of the last horizon {t4-t7} through using the proposed DPS approach. It comprises a sequence of 9 pumping runs: $P4^{425}/P2^{1115}/P1^{1392}/P3^{360}/P1^8/P2^{1065}/P4^{600}/P2^{850}/P1^{281.4}$ including a P1-plug to avoid the forbidden interface between products P3 and P2.

5. Conclusions

A new MILP framework for the dynamic scheduling of products pipelines over a multiperiod horizon has been developed. The approach allows to consider multiple due-

dates at period ends. Results show that the sequence of pumping runs finally executed over the horizon looks quite different from the one found through a static pipeline scheduling technique. Pumping runs become shorter and the number of them grows from 5 to 9, including a plug of P1 to avoid the forbidden sequence P3-P2. Moreover, the scheduled pipeline idle time mostly vanishes and consequently the pipeline utilization is largely increased from 67.3% to 94.8% of the total available time.

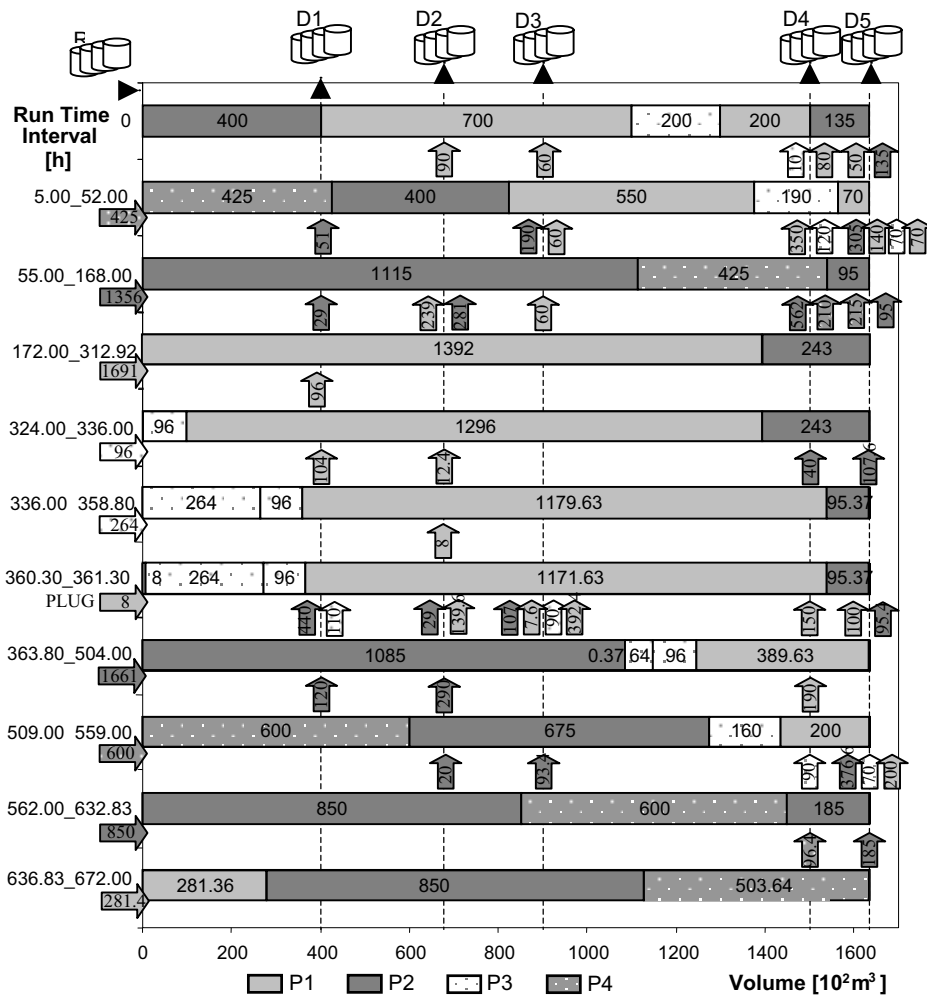


Figure 2. Optimal dynamic pipeline schedule for the time periods t1-t4

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