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Optimization model for the detailed scheduling of multi-source pipelines

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ABSTRACT

Pipeline networks are the shippers' first choice for carrying large volumes of refined petroleum products from oil refineries to distant distribution terminals. Optimization approaches for solving the pipeline scheduling problem proceed in two hierarchical stages: the aggregate and the detailed planning steps. The aggregate plan determines the batch sizes, the sequence of batch injections, and the allocation of batches to customers. The subsequent stage refines the aggregate plan to find the detailed schedule of batch input and output operations. This paper presents a mixed-integer linear programming (MILP) formulation for the detailed scheduling of multi-source pipelines that accounts for parallel batch injections and simultaneous product deliveries to multiple terminals. It overcomes a critical drawback of previous models that assume single source configurations. Modeling multi-source pipeline networks is a great challenge, requiring a completely revised approach. The new model finds cost-effective solutions with remarkable efficiency.

1. Introduction

The two most efficient ways to transport oil products in large volumes are ships and pipelines. Compared to water transportation, pipelines operate around the clock in all seasons under almost all weather conditions, at low operation costs. Oil pipeline routes link isolated crude oil production areas to refineries, while refined products pipelines connect these facilities to major populated regions, transporting large volumes of different products through the same line. In the United States, there are 409,000 miles of pipelines carrying 17% of all ton-miles of freight (Trench, 2001). 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., have multiple entry and exit points with several tanks, gauges, pumps, and valves, requiring a high degree of automation to operate efficiently. From a central control room, pipeline operators manage the product flows, start and stop pumps, open and close valves, and follow the batches along the pipeline network (Trench, 2001). Such tasks should be effectively planned to lower the power consumption, the largest pipeline operation cost. Since different petroleum products are pumped back-to-back into the same pipeline rarely using separation devices, some mixing occurs. In fact, smaller batch sizes make interface losses proportionally more important, while some product sequences are directly forbidden. Planning pipeline operations involves several decisions such as the sequence of products to inject at the source nodes, the batch sizes, the start/end times of every injection, and the sequence of product deliveries, among others. According to Siswanto, Essam, and Sarker (2011), transportation scheduling problems can be divided into four sub-problems to be solved sequentially or simultaneously: route selection, batching, loading, and unloading activity procedures.

There are several tools for scheduling transport operations: mathematical programming, heuristics, and hybrid techniques, among others. But even today, the planning and scheduling of real-world multiproduct pipelines is often based on simple worksheets (Ball, Dickerson, & Hertel, 2011) that assume a fixed flow rate of oil in the pipeline, to easily follow the batch movements. These simplified methods involve multiple trial-and-error iterations and are therefore very time consuming (Reddy, Karimi, & Srinivasan, 2004). Moreover, the assumption of a fixed flow rate does not allow the optimal utilization of the transport capacity.

More rigorous scheduling approaches have been developed over the last decade. On the one hand, discrete and continuous mathematical formulations for the optimal scheduling of unidirectional pipelines with a single source and multiple delivery nodes. Discrete approaches divide the pipeline volume into a finite

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Nomenclature

(a) Sets

B	blocks of individual injections
R	individual injections
I	batches moving through the pipeline during the planning horizon
I_b	batches moving through the pipeline during the execution of block b
J	pipeline terminals $\{j_0, j_1, \ldots, J\}$
JS	pipeline segments $\{j_1, \ldots, J\}$
JS_r	string of pipeline segments between the active source node and the farthest terminal for injection r
$J_r^{\oplus}$	active receiving terminals during the injection r
$J_{i,r}^{\oplus}$	active terminals receiving material from batch i while performing the injection r
K	ordered set of detailed pumping operations
K_b	subset of detailed operations of block b
R_b	subset of individual injections in block b

(b) Parameters

$a_{i,r}$	denotes that batch i is partially or fully pumped by injection r, in case $a_{i,r} = 1$
ca	unit flow restart cost
cs	unit flow stoppage cost
$dd_{i,j}^{(r)}$	total amount of product delivered from batch i to terminal j during the injection r
$d_{\min}$	minimum delivery size for a single operation
fco	fixed cost for performing a detailed operation
$l_{\min}/l_{\max}$	minimum/maximum allowed length of a detailed operation
pv	total pipeline volume
qq_r	total volume pumped during injection r
$q_{\max}$	maximum size of a product injection
st_b/ft_b	starting/completion time of block b given by the aggregate plan
$vb_{\min}^{(r)}/vb_{\max}^{(r)}$	minimum/maximum injection rate at the active source of r
$vb_{\min}^{(j)}/vb_{\max}^{(j)}$	minimum/maximum flow rate in pipeline segment j
$vd_{\max}^{(j)}$	maximum delivery rate from the pipeline to the receiving terminal j
wo_i	initial volume of batch i
σ_j	volumetric coordinate of depot j from the origin of the pipeline network

(c) Variables

Continuous variables

$AV_{j,k}$	volume of segment j activated at the start of operation k
C_k/L_k	completion time/length of the detailed operation k
$D_{i,j,k}$	volume of batch i diverted to depot j while performing operation k
$F_{i,k}$	front coordinate of batch i at time C_k
$Q_{r,k}$	volume of injection r pumped into the pipeline during operation k
$SV_{j,k}$	volume of segment j stopped at the start of operation k
$W_{i,k}$	size of batch i at time C_k
$\omega_{j,k}$	denotes the state of the pipeline segment j during operation k (it is limited to the closed interval [0; 1])

Binary variables

u_k	denotes the existence of the detailed operation k
$x_{i,j,k}$	denotes the existence of a delivery from batch i to depot j while performing the detailed operation k

number of "packs", and the planning horizon into time intervals of fixed duration. Most of them generally use a uniform time and volume partitioning scheme (Hane & Ratliff, 1995; Herrán, de la Cruz, & de Andrés, 2010; Magatão, Arruda, & Neves, 2004; Rejowski & Pinto, 2003; Zyngier & Kelly, 2009). Instead, mathematical representations based on continuous time and volume domains lead to more efficient and rigorous formulations of the pipeline scheduling problem (Cafaro & Cerdá, 2009; Castro, 2010). On the other hand, the scheduling of more complex pipeline configurations generally relies on hierarchical decomposition strategies, making the most critical decisions based on heuristic search techniques (Sasikumar, Prakash, Patil, & Ramani, 1997). The sequence of batch injections at every source node and the allocation of batches to customers are two of the key operational issues heuristically determined (Boschetto et al., 2010; García-Sánchez, Arreche, & Ortega-Mier, 2008; Lopes, Ciré, de Souza, & Moura, 2010; Moura, de Souza, Cire, & Lopes, 2008; Neves et al., 2007). The next step is to find out the timing of input and output operations using discrete-event simulation (Cafaro, Cafaro, Méndez, & Cerdá, 2011; Gleizes, Herrero, Cafaro, Méndez, & Cerdá, 2012; Mori et al., 2007), constraint programming (Moura et al., 2008), or optimization models (Cafaro, Cafaro, Méndez, & Cerdá, 2012; Cafaro et al., 2011).

Cafaro et al. (2011) propose one of the most effective approaches to tackle this problem. It consists of two hierarchical steps, each one involving a mixed-integer linear programming (MILP) formulation. Both models are based on continuous representations of the volume and time domains. All operating decisions made at the first stage are hard constraints for the second. At the first step, the sequence of product injections, batch sizes, and mean pump rates are found. The issue of how to perform the planned product deliveries is left to the second model. The so-called detailed optimization model refines the aggregate plan to determine the scheduling of input and output operations, and the flow rate profile at every pipeline segment. But up to now, optimization approaches for the detailed scheduling of oil products pipelines have assumed single source configurations.

This paper presents the first MILP formulation based on continuous time and volume scales for the detailed scheduling of pipeline networks with multiple sources. It assumes that the aggregate transportation plan is already available. The new model can be regarded as an extension of the model recently proposed by Cafaro et al. (2012), but unlike that approach, the new formulation can effectively handle parallel injections at two or more source nodes. In addition, several product deliveries to multiple terminals can simultaneously occur. The problem goal is to minimize the operation costs. As shown in the following sections, the inclusion of multiple sources performing parallel injections lead to a major rethinking of the optimization model. Computational experiments prove the model efficiency and show significant cost reductions with regards to other approaches typically used in practice.

2. Literature review

The relevant literature related to this work falls into three major topics: (1) optimization models for the pipeline transportation planning (batch sizing, batch sequencing, and allocation of batches