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A hybrid computational approach for detailed scheduling of products in a pipeline with multiple pump stations

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ABSTRACT

Multi-product pipeline is the most effective mode for refined products transportation and is of vital importance in the energy supply chain. The essential task in actual pipeline operation is scheduling delivery and injection of numerous kinds of products. Despite much research was done on products pipeline scheduling issue, little of them focused on multiple pump stations which are significant for long-distance pipelines. The paper establishes a mixed-integer nonlinear programming model (MINLP) for products pipeline with single source and multiple pump stations. The model has taken factors such as batch migration, local electricity price, demand time window, avoidance of idle segment, change of minimum flow rate and nonlinear hydraulic related objective function into consideration. The model contains two parts and is solved by a hybrid computational approach, the ant colony optimization algorithm (ACO) and the simplex method (SM). Finally, the formulation is successfully applied to a virtual and a real-world pipeline to verify the stability, convergence and practicability.

1. Introduction

1.1. Background

At present, the imports and exports of refined products over the world have come up to about 21.516 million barrels per day. 79.609 million barrels or so are transported to refineries getting processed per day while 95.008 million barrels are consumed. And the consumption is growing at a rate of 2% per year [1]. The multi-product pipeline has been the major mode to transport refined products for a long period, replacing the traditional modes of transportation such as railways and roads. As a large amount of refined oil is transported around the world, transporting refined oil is of vital importance in the energy supply chain [2]. Global economic growth has made many countries constantly construct multi-product pipelines with multiple pump stations.

The most significant feature of multi-product pipeline is market-oriented. According to the scheduling plan, large volumes of various refined products are transported to respective distribution terminals along the pipeline route, being divided in numerous batches [3]. Due to the fact that batches of refined products are pumped back-to-back without separation devices in the pipeline, adjacent batches inevitably lead to a mixed oil interface, affecting the oil quality. The quantity of mixed oil is subjected to the two adjacent oil's property. Considering product contamination cost, the sequence of batches should be determined carefully. The essential task in scheduling is to make the dispatching plan which can meet the requirements of upstream and downstream demand simultaneously [4], ensure pipeline safety, operate efficiently and minimize costs [5]. Additionally, adjusting pumping rates according to the time of use [6] and region-related electricity price should be taken into account to decrease the transportation cost [7]. Moreover, in spite of being more economical and safer, operating a large and complex pipeline system poses difficulty related to hydraulic constraint [8]. As a result, scheduling product batches in pipelines is complicated for it involves factors such as the coordination of oil source production, market demand, time-sensitive electricity prices [9] and pipeline system capacity [10].

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1.2. Related work

Since detailed pipeline operation scheduling is a complex problem, to simplify the nonlinear coupling relationship between the variables in the model, detailed pipeline schedules were obtained through methods based on discrete presentations in previous researches [11]. The approach divides the pipeline volumes and study planning horizon into a number of isometric [12] or prespecified packs and intervals [13]. Rejowski and Pinto [14], as a representative, formulated a discrete-time MILP model for the single pipeline scheduling issues considering the time-of-use of electricity price. Herr et al. [15] presented a new discrete mathematical approach to solve short-term operational planning of multi-pipeline systems with dividing product into packages of equal volume.

On the other hand, the hybrid methodologies, such as heuristic modules [16], discrete-event simulations [17] and constraint programming [18], have been applied to the operational scheduling of pipeline networks with more complex structures. Lopes et al. [19] proposed a hybrid framework based on a two-phase problem decomposition strategy to deal with a real-world multiproduct pipeline planning and scheduling problem. Magatão et al. [20] proposed a decomposition approach to generate the operational scheduling plan for a real-world pipeline. The pre-processed data were used by a continuous time MILP model to obtain the optimal detailed scheduling considering the time-related electrical energy costs. Subsequently, Boschetto et al. [21] proposed a novel hierarchical approach based on Ref. [20], which was applied to a large real-world pipeline system with more than 14 derivatives being transported and distributed between supply and demand nodes. In this research, the scheduling model is divided into four blocks to solve the four primary models (assignment of resources, sequencing of activities, simulating of parameters to the timing block and timing determination for resource utilization), and the result is more visualized and realistic than that of Ref. [20].

In order to describe the model accurately, the discrete presentation mode requires a large number of time slots, resulting in an increase of model's size [22]. While, the continuous representation is more efficient and terse in formulating the scheduling issues [23]. With development in research of the continuous-time MILP model, the solving methods of operational scheduling of the single pipeline [24], tree-structure pipeline networks [25] and mesh-structure pipeline networks [26] were presented sequentially. Cafaro and Cerdá [27] proposed a novel MILP continuous mathematical formulation that neither uses time discretization nor division of the pipeline into a number of single-product packs. Compared with previous work, this method can find batter solutions at lower CPU time. Later, Cafaro and Cerdá [28] improved the previous MILP formulation to schedule tree-structure pipeline networks. In these researches, the sequence of injected batches and the approximate optimal scheduling plans were obtained, but the exact delivery and injection time of the batches at each station could not be determined. Cafaro et al. [29] developed a continuous-time MINP model to minimize both the restarted volume and the pump-starting frequency. Then three different heuristic rules for selecting the receiving terminal were proposed, which were applied to combination with a discrete-event simulation model to make detailed scheduling plans. On the basis of previous research, Cafaro et al. [30] addressed a more complex scheduling issue. Considering the simultaneous product delivery operation mode, a new MILP continuous formulation was presented to develop the detailed schedules. The solution of the examples implied the significant reductions in both total costs and CPU time in comparison with those of Ref. [29]. Recently, Cafaro et al. [31] introduced a novel MINLP continuous-time formulation for the detailed scheduling of single-source pipelines, considering the constraints presented by Ref. [30]. The hydraulic-related pumping cost and real-world pipeline schedule problems were successfully solved by using GAMS−DICOPT algorithm.

1.3. Contributions of this work

The contributions of this paper are:

- Kinematic viscosity and density of the different products may have large deviations, such as diesel and gasoline. However, these deviations were often neglected in previous researches. Errors may be caused in hydraulic loss and pumping cost without considering the difference of products' physical properties. The paper has taken the above factors into consideration;
- Although idle segment cost has been considered in recent researches, the segment is still inevitable. During the actual operations in pipeline systems with multiple pump stations, however, idle segments should be avoided in general, which will be discussed in detail in next section. The idle segments can be avoided through solving the model proposed in the paper;
- In previous researches on detailed scheduling issue, the limits of delivery or injection size were regarded as the parameters in the models. But in the real operation, these limits are the time-related variables. This paper takes the limit of flow rate into consideration instead of the ranges of operational volume size;
- Considering pump capacity, the flow rate of the pipeline should be within a certain range during the actual operation. Due to the interface between gasoline and diesel (IGD) in a pipeline segment, the Reynold number of the fluid must be larger than the critical one to avoid an increase in mixed oil rapidly. Under this condition, constraint of minimum flow rate is more rigid. The paper has considered the limit of flow rate that may change with the migration of interfaces.

1.4. Paper organization

The adopted methodology and details of the mathematical model are given in 2nd and 3rd section respectively. The 4th part of the paper gives a description of the method to solve the model. The 5th part has chosen a virtual pipeline as well as a real-world pipeline in China as study objects and demonstrates the model's practicability and convergence through 3 examples. Conclusions are provided in 6th section.

2. Methodology

2.1. Problem description

2.1.1. Pipeline planning with multiple pump stations

As the commodity needs to be transported over a long distance in the pipeline system from the refinery to downstream markets, there are many pump stations in series along the pipeline to boost the products. Fig. 1 shows a typical multi-product pipeline with a single source at the initial station (IS) connected with the refinery, five pump stations: P1, P2, P3, P4 and P5 and four distribution terminals connected to the local market: intermediate depots (D1, D2, D3) and terminal station (TS).

Many formulations presented by previous researches had solved the pipeline scheduling issue aiming at satisfying terminals' demand and minimizing mixed oil, pumping and inventory carrying