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An Efficient Approach to the Operational Scheduling of a Real-World Pipeline Network

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Abstract

This paper addresses the problem of developing an optimisation structure to aid the operational decision-making of scheduling activities in a real-world pipeline network. During the scheduling horizon, many batches are pumped from (or passing through) different areas. Pipes are a disputed resource. Scheduling details must be given, including pumping sequence in each area, batches' volume, tankage constraints, timing issues, while respecting a series of operational constraints. In addition, the electric energy presents on-peak demand hours, typically, from 5:30 p.m. to 8:30 p.m., and this feature also influences operational decisions. The balance between demand requirements and production campaigns, while satisfying inventory management issues and pipeline pumping procedures, is a difficult task. The proposed approach has been successfully applied to industrial-size scenarios. Many insights have been derived from the obtained solutions.

Keywords: Scheduling, Pipeline, MILP, Heuristics, Real-World Scenario.

1. Introduction

Scheduling activities related to oil product distribution have received growing interest in the last years. Distribution and transfer operations of such products can be carried out by road, railroad, vessels, and pipelines. Pipeline transportation is a reliable and economical mode for large quantities of products. Some papers have already addressed scheduling decisions within pipeline networks [1,2,3,4], but the scenario in this paper is particularly complex. The real system operation demands that a series of temporal details be specified by the specialist. Thus, determining the short-term scheduling within the considered scenario is a difficult task.

2. Problem Statement

The scenario, illustrated in Fig.1, involves 9 areas (nodes), including 3 refineries (nodes N1, N3, and N7), 1 harbour (N9), which either receives or sends products, and 5 distribution centres. In addition, it includes 15 pipes, each one with a particular volume (e.g. pipe 1 has more than 42000 m^3). The nodes are "connected" by various pipes (*e.g.* pipes 3, 4, and 5 connect nodes 2 and 3). However, the list of products that can be pumped by a specific pipe is limited (*e.g.* pipe 3 is typically used to transport gasoline and naphtha). A product can take many hours to reach the final destination. A batch can remain in a pipe until another batch pushes it. Pipes 5, 7, and 15 can have the flow direction reverted, according to operational procedures. Each product presents a specific tankfarm within the considered node. More than 10 oil derivatives can be transported. For instance, a typical "operation" involves pumping a batch from N3 to N8, passing by N2, N5, and N7. In that case, the product is pumped through pipes 4, 8, 12, and 14.

3. Paper approach

3.1. Methodology

The computational burden of determining the short-term scheduling within the considered scenario is a relevant issue. Therefore, a decomposition approach is proposed to address such real-world problem (Fig.2). This decomposition is based on the three key elements of scheduling: assignment of resources, sequencing of activities, and determination of resource timing utilization by these activities [5]. A pre-processing block (heuristic procedure) takes into account production and consumption functions and typical batch volumes (lot sizes) in order to determine a set of candidate sequences of pumping. In addition, the pre-processing procedure indicates time-windows to the established sequences. Then, the pre-processed data are used by a continuous-time MILP model, which determines the operational short-term scheduling for the entire pipeline network. The previously determined time-windows should be respected in order to keep inventory management issues within operational levels. The MILP model considers, for instance, the pumping route (source or pumping origin, pipes, and destination), volume and flow rate for each product from a source. Particular attention is given to the fact that pipes have a considerable volume and they always operate completely filled. Thus, they can "store" different products during pumping procedures. While a new product is sent from a source, previously "stored" products are pushed out according to the new product flow rate. Moreover, stored products should be routed to their original destination. At each area, products arriving from pipes can be pumped to tanks or routed to other pipes. A set of tanks in each area can store different products. Inventory level can increase or decrease according to the volume and flow rate of each product pumping or due to local production and consumption. In addition the MILP model considers the seasonal cost of electric energy and a series of operational requirements. Details of the obtained scheduling can be visualized by a series of user-developed interfaces (*e.g.* Fig.3).

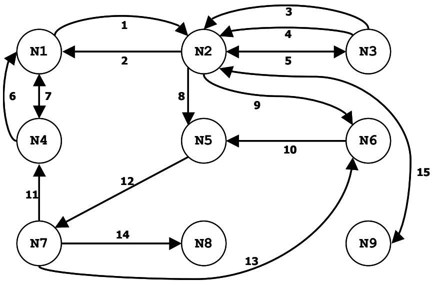

Fig.1 – Pipeline Network

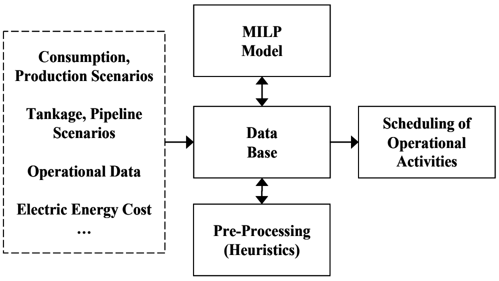

Fig.2 – Optimisation Structure

3.2. MILP Model

The model relies on MILP with a continuous time approach (*e.g* Eq.(1)). Variables were created in order to determine the exact time that a pumping procedure of a batch ($b \in B$) is started ($ib_{b,n,n',d}$) and finished ($fb_{b,n,n',d}$) from a node ($n \neq n' \in N$) trough a specific pipe ($d \in D$, where d connects n and n'). In a similar approach, other continuous variables determine the time that a destination node starts to receive ($ir_{b,n,n',d}$) and finishes to receive ($fr_{b,n,n',d}$) a product. In addition, maintaining a batch stopped within a pipeline ($fstop_{b,n,n',d}$; $istop_{b,n,n',d}$) is a valid condition, but it influences the operational cost. The formulation was extensively studied, and binary variables were just used to enforce seasonality conditions of electric energy. Thus, the model avoids pumping procedures during periods of high energy cost. The objective function is weighted by operational cost factors (ktb , $ktstop$, ktd , kto). Specific constraints were created in order to attend inventory management issues. In particular, the pre-processing unit indicates time-windows to the demanded batches. So that, the MILP model tries to manage the operational scheduling in each node in order to respect determined time limits. However, some time-windows' violation can be accepted either in the pumping origin ($ao_{b,n,n',d}$; $do_{b,n,n',d}$) or at the final product destination ($ad_{b,n,n',d}$; $dd_{b,n,n',d}$), but are undesirable. Each node has particular operational features, and the mathematical model has to address them. For instance, batches can be pumped from N7 by pipes 11, 13, and 14. At this node there exists a limited number of pumps and just one batch is allowed to be sent from N7 at a specific time. Thus, in a hypothetical case that various batches are to be sent from N7, the model must manage pumping start times and pumping finish times in order to respect this "local" characteristic. Another issue is that pipes 5, 7, and 15 can have the flow direction reverted, according to operational convenience. A specific set of constraints was created to manage such operational condition. In the pipeline-scheduling literature [3] this has been proved to be a complicating issue. In addition, from node to node, a product typical flow rate can vary. For example, naphtha is normally pumped from source N7 to final destination N1. At this case, the product "passes" trough the intermediate node N4. The operation involves, respectively, pipes 11 and 7. From N7 to N4 by pipe 11 the average flow rate is 450 m^3/h; from N4 to N1 by pipe 7 the average flow rate is 190 m^3/h. Alternatively, the product can be directly pumped from N7 to N1 at 190 m^3/h. In that case, the pumps of node N4 are not used. However, it is operationally recommended that naphtha be pumped from N7 to N4 at 450 m^3/h, be stored in a tank at N4, and then, meanwhile, be pumped from N4 to N1 at 190 m^3/h. This would "release" N7 before from this specific pumping of naphtha. As previously stated, there are local constraints, and the starting of other pumping procedures at N7 can be dependent upon the finishing of the naphtha pumping. Thus, a specific set of constraints was created in order to manage such operational condition. Sparcity of sets was exploited to the model generation.

$$
\begin{aligned}
&\min \\
&\sum_{b\in B}\sum_{n\in N}\sum_{n'\in N,n\neq n'}\sum_{d\in D}\left(ib_{b,n,n',d}+fb_{b,n,n',d}+ir_{b,n,n',d}+fr_{b,n,n',d}\right)*ktb+ \\
&\sum_{b\in B}\sum_{n\in N}\sum_{n'\in N,n\neq n'}\sum_{d\in D}\left(fstop_{b,n,n',d}-istop_{b,n,n',d}\right)*ktstop+ \\
&\sum_{b\in B}\sum_{n\in N}\sum_{n'\in N,n\neq n'}\sum_{d\in D}\left(ad_{b,n,n',d}+dd_{b,n,n',d}\right)*ktd+ \\
&\sum_{b\in B}\sum_{n\in N}\sum_{n'\in N,n\neq n'}\sum_{d\in D}\left(ao_{b,n,n',d}+do_{b,n,n',d}\right)*kto
\end{aligned}
\qquad (1)
$$

3.3. Results

The model has been extensively tested in typical operational scenarios. At these cases, the pre-processing block takes the planning of production/consumption of each product in each node during a month. Then, it determines candidate sequences of pumping and time-windows to the established sequences. This operation takes less then a CPU second (Pentium 4, 2.4 GHz, 1GB RAM). The pre-processed data are used by a continuous-time MILP model. Typical instances yield large-scale MILPs with roughly 6000 variables (3000 binary) and 20000 constraints. Such models have been solved to optimality in few CPU seconds using a commercial package [6]. To previously address the sequencing part has been a fundamental issue to reduce the computational burden. Many insights have been derived from the obtained solutions, and the proposed approach can aid the decision-making process. Fig.3 illustrates a Gantt chart of a real-world scenario involving 71 batches pumped during a month. Information about scheduled batches can be derived from this chart. In particular, each batch has an identifying number, which remains the same as the batch passes through different pipelines. For example, batch 26 passes trough pipes 1, 8, 12, and 14. Details about the scheduling (hour:minute) in each pipe can be better visualized by means of a zoom functionality. Furthermore, the right-side vertical label indicates the average pipeline "usage" rate. For instance, pipe 11 remained in used during approximately 85% of the scheduling time. Therefore, this pipe, at this scenario, is a potential bottleneck. The optimization structure allows that the system operator visualize the short-term scheduling of operational activities in advance of many days, avoiding pumping troubles.

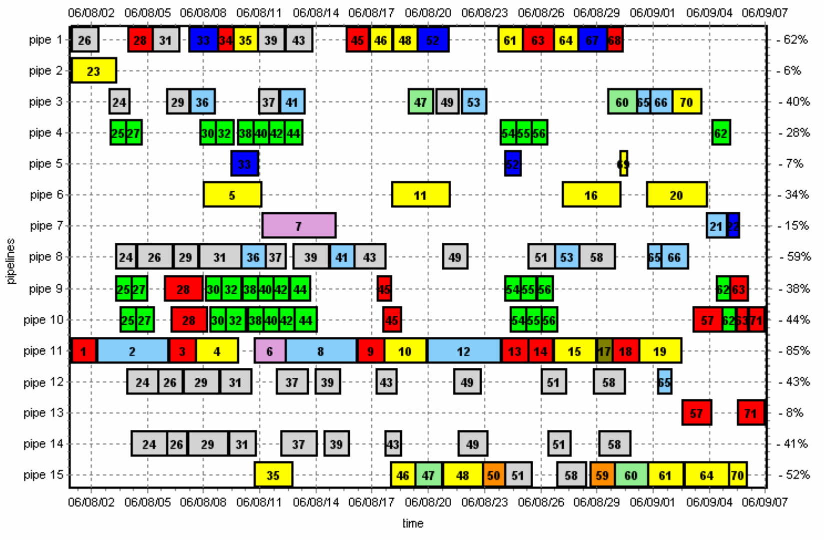

Fig.3 – Gantt Chart

4. Conclusions

An optimisation structure (Fig.2) for the scheduling of operational activities in a real-world pipeline network (Fig.1) has been addressed in this paper. The considered scenario is particularly complex Thus, determining the short-term scheduling is a difficult task. A major challenge was to find an approach that provides short-term scheduling details at low CPU effort. In order to achieve this goal, a decomposition approach was used. This decomposition relied on a pre-processing block, which takes into account production/consumption functions and typical lot sizes to determine a set of candidate sequences of pumping. In addition, the pre-processing indicates time-windows to the established sequences. Then, the pre-processed data are used by a continuous-time MILP model, which indeed determines the short-term scheduling of each batch in each node of the pipeline network. A series of operational requirements have been addressed (sections 3.1 and 3.2). The model formulation has been extensively studied, and integer variables were only used to avoid pumping during time periods of high-energy costs. The optimisation structure has been successfully tested in industrial-size scenarios, which yield, roughly, 6000 variables and 20000 constraints. The implemented structure can be used, for instance, to identify system bottlenecks and to test new operational conditions. Computation time has remained at few CPU seconds. The proposed approach have allowed that a month planning of production and consumption be detailed in short-time scheduling operations within the considered pipeline network. Thus, many insights can be derived from the obtained solutions.

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