18th European Symposium on Computer Aided Process Engineering – ESCAPE 18
Bertrand Braunschweig and Xavier Joulia (Editors)

An Integrated Framework for 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 nodes (refineries, harbours or distribution terminals). Pipelines are shared resources operated and monitored 365 days a year, 24 hours per day. Scheduling details must be given, including pumping sequence in each node, volume of batches, tankage constraints, timing issues, while respecting a series of operational constraints. The balance between demand requirements and production campaigns, while satisfying inventory management issues and pipeline pumping procedures, is a difficult task. Based on key elements of scheduling, a decomposition approach is proposed using an implementation suitable for model increase. Operational insights have been derived from the obtained solutions, which are given in a reduced computational time for oil industrial-size scenarios.

Keywords: Scheduling, Pipeline Network, MILP, Heuristics, Oil Industry.

1. Introduction

Scheduling activities related to oil product distribution have received a growing interest in the last years. Distribution and transfer operations of such products can be carried out by road, railroad, vessels, or pipelines. Pipelines are one of the most important transportation modes for oil products in Brazil. Some papers have already addressed scheduling decisions for pipeline networks [1,2,3,4]. In this paper, the considered scenario is particularly complex due to the existence of many areas and pipes subject to particular operational constraints. The proposed approach compares to a previously developed work [5] in terms of complexity and computational performance. This paper is organized as follows. Section 2 presents some operational details of the considered pipeline network. The computational framework, including a global view of the optimisation structure, is given on Section 3. Section 4 shows the new implementation used for the optimisation structure, and Section 5 presents the obtained results with conclusions in Section 6.

2. The pipeline network

The considered plant (Fig.1) involves 13 areas (nodes), including 4 refineries (nodes N1, N3, N9, and N11) and 2 harbours (N10 and N13), which receive or send products through 7 distribution terminals. In addition, it includes 29 multiproduct pipelines with particular volumes (*e.g*. pipe 1 has more than 42000 m^3). Nodes are "connected" through pipes (*e.g.* pipes 3, 4, and 5 connect nodes N2 and N3). A product can take many hours to reach its final destination. A batch can remain in a pipe until another one pushes it. Many pipes can have their flow direction inverted due to operational procedures (*e.g.* pipes 5, 7, and 15). Each product has to be stored in a specific tankfarm within a node. More than 14 oil derivatives can be transported in this network. Adjacent products can share an undesirable interface, *e.g*. alcohol pumped just after diesel. In this case, it is necessary to pump another product between them (*e.g*. gasoline). Typical transfer tasks can involve pumping a batch through many areas. For instance, a batch can be pumped from node N3 to N7 through nodes N2, N5, and N8. In that case, the batch uses pipes 4, 8, 12, and 14.

3. The Computational Framework

The computational burden to obtain a short-term scheduling for 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 used by these activities [6]. A Resource Allocation block (batch sequencing) takes into account production and consumption functions and typical volume of batches (lot sizes) in order to determine a set of candidate sequences of pumping. For instance, node N3 usually has a planning of diesel that can be (partially) stored within its limited tankage scenario. However, after some refining time, a batch must be sent, otherwise the diesel campaign has to be reduced due to lack of tankage. The Pre-Analysis gathers information provided by the Resource Allocation and calculates a series of temporal and volume parameters (bounds). Such bounds give a preliminary indication about scheduling feasibility. Then, the Pre-Analysis pre-processed data are used by a continuous-time MILP model, which determines the operational short-term scheduling for the pipeline network. 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 fulfilled. Thus, they can “store” different products during pumping procedures. While a new product is sent from a source, previously “stored” products are pushed 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 graphical user interfaces (*e.g.* Fig.3).

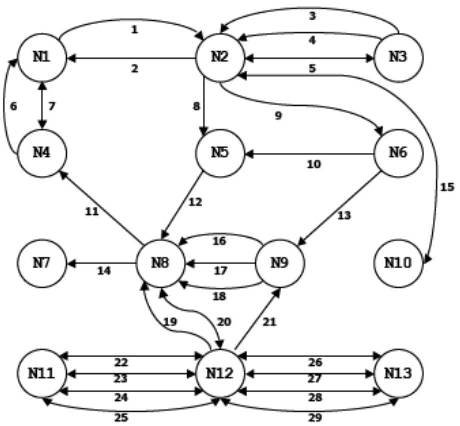

Fig.1 – Pipeline Network

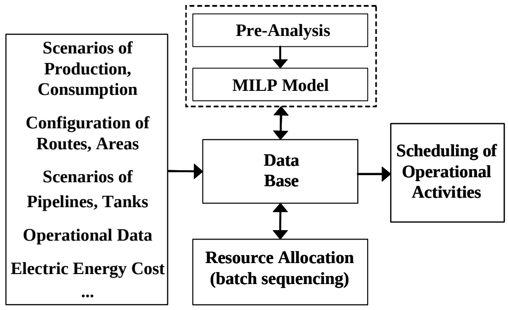

Fig.2 – Optimisation Structure

4. The Optimisation Structure

4.1. Pre-Analysis

In this work, the continuous-time MILP model previously presented [5] was restructured, and a novel computational procedure (Pre-Analysis) is proposed. The Pre-Analysis uses information provided by the Resource Allocation (batch sequencing) unit. Based on the list of demanded batches supplied by this unit, the Pre-Analysis calculates a series of temporal and volume parameters (bounds). The underlying idea here is to provide structured sequences (not necessarily optimal) in a reasonable computation time. As an advantage of this approach, the computational burden to generate the minimum temporal blocks (pumping and receipt times) is removed from the MILP model. Furthermore, the complexity of the temporal constraints may vary from scenario to scenario, and the Pre-Analysis unit aids the description of these constraints included in the MILP optimisation model. During the scheduling horizon many batches may remain stopped within a pipeline, which causes different volumes of products to be effectively received and pumped at each operational area. As an output, the Pre-Analysis specifies the precise volumes to be pumped ($volbom_{b,n,n',d}$) and received ($volrec_{b,n,n',d}$) in a destination node. In addition, it establishes, for instance, the minimum time that a destination node could start to receive ($tmin\_ir_{b,n,n',d}$) and could finish to receive ($tmin\_fr_{b,n,n',d}$) a product (*e.g.* Eq.(1)). In Eq.(1), average flow rates are known ($vz_{bi,n,n',d}$ and $vz_{bkir,n,n',d}$) as well as volume of pipes (vp_d) and the number of necessary products for a batch to achieve a specific (intermediate) node (*kir*). Since the exact duration of activities involves pipeline stoppages and a series of operational constraints, these conditions should be addressed by the MILP model.

$$tmin\_ir_{b,n,n',d} = \sum_{i=1}^{kir-1} \frac{volbom_{b_i,n,n',d}}{vz_{b_i,n,n',d}} + \frac{vp_d - \sum_{i=1}^{kir-1} volbom_{b_i,n,n',d}}{vz_{b_{kir},n,n',d}} \tag{1}$$

4.2. MILP Model

The model relies on MILP with a continuous-time approach. 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 ($n \neq n' \in N$) through 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 order to determine the value of these variables, the parameters $tmin\_ir_{b,n,n',d}$ and $tmin\_fr_{b,n,n',d}$, previously calculated in the Pre-Analysis are used. In particular, the Pre-Analysis unit indicates the minimum pumping and receipt times of a batch. The formulation was extensively studied, and binary variables were used to enforce seasonality conditions of electric energy. Specific constraints were created in order to deal with inventory issues. So that, the MILP model tries to manage the operational scheduling in each node in order to minimize violations on time intervals. Each node has particular operational features, and the mathematical model has to address them. For instance, batches can be pumped from N8 by pipes 11, 14, and 20. At this node there exist a limited number of pumps and just one batch is allowed to be sent from N8 at a specific time. Thus, in a hypothetical case that various batches are to be sent from N8, the model must manage pumping start/finish times in order to respect this “local” characteristic. Another issue is that many pipes 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 (*e.g.* [3]) this has been proved to be a difficult issue. In addition, from node to node, a product typical flow rate can vary. For example, diesel is normally pumped from source N8 to final destination N1. At this case, the product “passes” through the intermediate node N4. The operation involves, respectively, pipes 11 and 6. From N8 to N4 by pipe 11 the average flow rate is 450 m^3/h; from N4 to N1 by pipe 6 the average flow rate is 330 m^3/h.

5. Results

The decomposition framework has been extensively tested in typical operational scenarios. At these cases, the Resource Allocation block takes into account the planning of production/consumption of each product in each node during a month. Then, it determines candidate sequences of pumping. The pre-processed data are used by both the Pre-Analysis and the continuous-time MILP model. Typical instances yield large-scale MILPs. Such models have been solved to optimality in few CPU seconds using a commercial package [7]. To previously address the sequencing part has been a fundamental issue to reduce the computational burden. However, the final scheduling is influenced by the pre-determined sequencing. Operational 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 approximately 70 batches pumped during a month. Information about scheduled batches can be derived from this chart. To determine such information used to be not trivial since the system operation was based on human experience without computational aid. As a consequence, operational losses were common. In particular, each batch has an identifying number, which remains as the batch passes through different pipes. One contribution of Pre-Analysis is highlighted in the Gantt. This module indicates the exact volume that is to be pumped along the product pumping route.

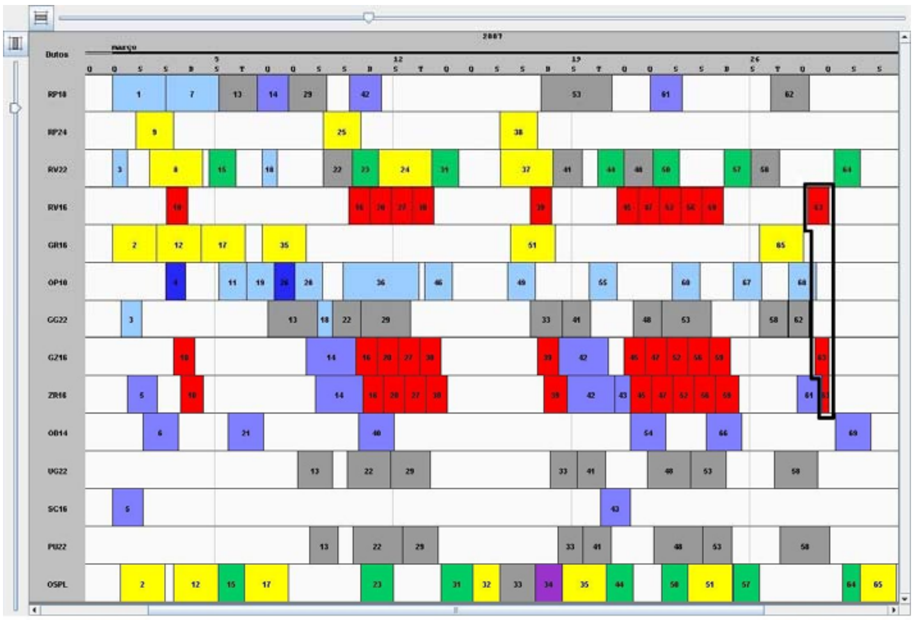

Fig.3 – Gantt Chart

6. Conclusions

A new optimisation structure (Fig.2) for the scheduling of operational activities in a real-world pipeline network (Fig.1) has been addressed in this paper. In addition, a new computational procedure was developed, the Pre-Analysis module. The real scenario could be addressed mostly due to Pre-Analysis scalability. The considered scenario is particularly complex and involves more nodes and pipes, compared to the one discussed in a previous work [5]. In order to address this scenario, a decomposition approach was used. This decomposition relied on a Resource Allocation block, which takes into account production/consumption functions and typical lot sizes to determine a set of candidate sequences of pumping. Furthermore, a Pre-Analysis block uses candidate sequences to determine temporal and volume parameters. These parameters were used in a continuous-time MILP model, which indeed determines the short-term scheduling of each batch in each node of the pipeline network. 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 monthly planning of production and consumption be detailed in short-time scheduling operations within the considered pipeline network. Thus, operational insights can be derived from the obtained solutions. As an ongoing research, the Pre-Analysis would be used to determine other parameters for the MILP model.

Acknowledgements

The authors acknowledge financial support from ANP and FINEP (PRH-ANP / MCT PRH10 UTFPR) and CENPES (Under grant 0050.0017859.05.3).

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