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Oil products distribution systems: multiproduct pipeline scheduling for effective inventory management

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Abstract

The oil business is facing a competitive and harsh era: margins are low and other energy alternatives start to have a growing importance. In such context logistics can play an important role in optimizing operations and minimizing costs if proper and integrated methods are used. Multiproduct pipeline systems represent one of the most complex equipments to manage in the oil supply chain, where it is essential to integrate transportation operations with inventory management policies at distribution centers. This work addresses such problem through the analysis of a real world case study at a Portuguese company considering a distribution system formed by a multiproduct pipeline and a set of storage tanks. An operations management tool is developed, which is built on an optimization model. Operations management policies are explored and the obtained optimized results are compared to current company procedure illustrating the importance of using integrated operations management tools to optimize real problems.

Keywords: Multiproduct Pipeline, Inventory, Scheduling, MILP, Real Scenario

1. Introduction

Pipelines have been recognized as major solutions for the transportation of oil and oil products, due to its efficient and reliable operation at low cost where product quality is maintained whenever more than one product is pumped. For these reasons, pipelines represented a watershed in the oil industry since the World War II [1]. In the European Union in 2005 (EU-27) the density of oil pipelines was of 8 km/1000 km²,

corresponding to more than 30000 km of lines [2], representing a transportation of 135637 million tkm (ton-kilometer) of oil and oil products [3].

However, the scheduling of operations in this type of equipment is a complex problem. Considering that the pipeline is a transportation mode, it is mandatory to optimize its operation extending the problem to account for its origin and destination's constraints. Since this integrated approach is a hard problem, companies usually maintain trial and error methods based on spreadsheets to perform the scheduling of operations, while commercial tools still remain scarce and mainly based on simulation.

Therefore the gap created between what the oil industry requires for an optimal operations planning and/or scheduling tool and what is currently used leaves the opportunity for the academic community to develop advanced tools with real world applicability, i.e., focus on feasible and good solutions in a short amount of time.

The pipeline scheduling problem has been addressed since the late 1990's mainly using mathematical programming models. The pioneer works by Shah [4] and Sasikumar et al. [5] proposed solution approaches to address this problem. Shah [4] developed a MILP model with discrete time representation combined with a decomposition approach that was applied to the problem of crude oil supply to a refinery, whereas Sasikumar et al. [6] used a knowledge-based heuristic search.

Magatão, Arruda and Neves [6] and Rejowski and Pinto [7] employed discrete representation approaches to model the pipelines. The former authors built an optimization structure, which makes use of decomposition techniques and origins four different components. The same scenario was solved for rough and detailed discretization approaches and the computational effort was significantly higher for the

last case. The later authors studied different scenarios for product demand on a real world problem. However, the computational effort observed was high.

Cafaro and Cerdá [8] proposed a novel continuous MILP formulation that explores a sequential spatial transportation along the pipeline. This framework proved to solve the real world scenario of the work of Rejowski and Pinto [7] with less computational effort. The main characteristic of this model is the ability to reduce the amount of variables (continuous and binary) with no loss of information. The same authors presented in [9] a new version of their work where the time horizon was extended by considering a multiperiod approach and making use of rolling horizons, so as to schedule operations in a way that the operational lag added by the pipeline does not interfere with the schedule of products, quantities and flowrates.

These works enforced the pros and cons of the different possible approaches to address pipelines planning and scheduling, but no deep emphasis has been given on origin/destination operating constraints. This problem was overcome by Relvas et al. [10], who proposed a continuous time MILP model that addresses an integrated system comprising a pipeline and the destination distribution centre. Furthermore, the complexity of this type of systems also includes a high level of uncertainty. In this sense, scheduling plans must be flexible to accommodate unforeseen situations that dictate new restrictions. Reactive scheduling procedures have been proposed for general production plants and situations, having a significant gap to be applied to pipeline systems. Within this context, Relvas et al. [11] proposed a reactive scheduling procedure for pipeline systems, tackling several specific situations that are likely to happen in such systems. Finally, these authors proposed a sequencing heuristic [12] that is used as a preprocessing step for the MILP model proposed in [10]. This heuristic

develops scenario-based pumping sequences of products. With this result, the model complexity is reduced, enabling faster solutions to be applied in real world scenarios.

This paper presents the integration of these tools to provide solutions for real world problems. The paper is organized as follows: the next section focuses on the problem definition. Section 3 describes the proposed scheduling framework, which is implemented in section 4. Conclusions and further work are outlined in section 5.

2. Problem Statement

The problem addressed considers the planning of transportation and storage activities in a system comprising a multiproduct pipeline, with single origin (refinery) and single destination (distribution centre) over a short (1 or 2 weeks) or medium (1 month) term time horizons. The integrated set of decisions includes the sequencing, sizing and timing of batches in the multiproduct pipeline and the management of the available storage capacity at the distribution centre.

The operational constraints include flowrate limits inside the pipeline as well as quality constraints translated into forbidden pairs of products that cannot be pumped sequentially. On the other hand, the sequence, size and timing of the pipeline schedule have to cope with the capacity availability at the distribution centre while fulfilling completely and on time the market demand. The distribution centre comprises sets of tanks which have a fixed product service, i.e., the same tanks always store the same product. Each tank receives product from a new batch and afterwards has to perform a product dependent settling period that guarantees quality and approving tasks. After this period, the product becomes available to fulfill daily market demands.

The integration of transportation and storage management enables an efficient and effective planning of the system, organizing the products pumping into quantities and timings that cope with demands.

The system requires a wider time horizon when compared with typical scheduling problems so as to comprise the pumping, transportation, unloading, settling and consumption of a representative set of batches and reducing the pumping of batches whose storage or consumption is not included in the problem. Additionally, longer time horizons as one month become more useful for production planning at the refinery side, especially when the pipeline represents a significant consumption of the refinery production. However, larger time horizons will lead to higher complexity and, thus, to computational consuming problems.

The representation of a multiproduct pipeline coupled with a distribution centre requires a discussion on methods and techniques. Mathematical modeling is by far, as stated in the preceding section, the most used method. It was used as base method for this problem. However, the representation of such a system requires not only an effective time representation but also a volume representation of the pipeline operation. The correct choice must be done considering not only the pipeline but also the distribution centre and above all the characteristics of the batches pumped through the pipeline. For a multiproduct pipeline with a high degree of heterogeneity of products, a continuous time representation reduces the necessary number of event points. Volume is represented using an update of the evolution of batches whenever a new batch is pumped. Figure 1 represents the problem's operating system.

Given: a) the pipeline volume, b) maximum and minimum flowrates, c) the products to be pumped and matrix of possible sequences between consecutive products, d) the storage capacity by product and by storage tank, e) settling period by product, f) the time scheduling horizon extent, g) the maximum number of batches to be pumped, h) the initial inventory by product, and i) the daily demand forecasts; Determine: 1) the pipeline schedule and 2) the inventory management. The pipeline schedule includes products' sequence, pumping flowrates, batches' volumes, timing issues and pipeline stoppages. The inventory management includes pipeline outputs, existent inventory, settling periods and outputs by product for customers.

3. Scheduling Framework

Figure 2 represents the architecture of the scheduling framework as well as the required inputs and outputs obtained and the interaction with the MILP algorithm.

The inputs required have three origins: i) initial conditions, ii) market forecasts and iii) scenario parameters. The initial conditions connect the current time horizon to the previous. They capture the initial contents of the pipeline as well as initial inventory at each tank and for each product. The market forecasts comprise the daily amounts of each product to supply for the local market. Finally, the scenario parameters include time horizon extent, maximum number of batches to pump given the market forecasts, flowrate limits, pipeline stoppages information as well as tanks states.

From this point, the initialization heuristic [12] can be activated or not. The heuristic uses the initial conditions and market forecasts to analyze the current tank farm situation and establish parameters to develop sequences of products that aim to

replenish the products supplied to clients. For time horizons longer than two weeks, it is advisable to use the heuristic as preprocessing step.

The MILP models are run using inputs and the heuristics' results, if activated. The results of the models are used as schedules for the current time horizon. The scheduling framework includes two MILP models i) the Aggregated Tanks Formulation (ATF) and ii) the Detailed Tanks Formulation (DTF). The ATF corresponds to the model proposed by Relvas et al. [10]. This model represents the available storage capacity at the tank farm in an aggregated manner, i.e., each product is stored in a single tank which has as maximum capacity the corresponding sum of individual tanks capacity. On the other hand, the DTF model represents each tank as an individual entity, enlarging the model size. Additionally, this model decides in which tank each new batch is accommodated when being unloaded to the distribution centre. In this way, the schedule accounts for the sequence of receiving and dispatching tanks.

When a good schedule is established and the pipeline operation is working using that information, it is likely that disruptions or unforeseen situations may occur. In this case, new inputs are provided for each unpredicted situation. The reactive scheduling approach [11] can be used either before or during the time horizon period and at each usage one can include as much occurrences as needed. Additionally, the objective function now includes penalizing terms that guarantee that the new solution found has the minimum changes when compared to the previous. The reactive scheduling procedure is run to obtain the adapted schedule. The unforeseen situations considered are summarized in Table 1.

The user can select which level of detail regarding the inventory management is desired to have in the solution. This would correspond to choose between both MILP models.

The MILP models and the reactive scheduling framework are run using a suitable algorithm, such as CPLEX. Up to date, the models have been written and tested using GAMS system.

4. Case Study

The framework developed has been applied to the real world scenario of CLC – Companhia Logística de Combustíveis. This company transports six oil products (P1-P6) from Galpenergia Sines' Refinery and distributes them in the central region of Portugal. The distribution centre comprises 29 tanks, whose product service is fixed. Scheduling results were obtained for medium and short term horizons. The reactive scheduling has been used to address several occurrences types, while a sequencing heuristic provides valid pumping sequences, which are given to the model as input data.

The month of July 2007 was used as study-scenario, where several studies were made i) develop several pumping sequences using the sequencing heuristic and implement them in the ATF model, ii) the chosen sequence will be used in the pipeline schedule, giving origin to a detailed inventory management for the first week with the DTF model and iii) the reactive scheduling procedure so as to face unforeseen situations occurring during July 2007.

- When implementing the sequencing heuristic it was verified that product P2 was the one with highest priority to be pumped. In this way, pumping sequences were developed placing this product as earlier as possible in the pipeline transportation schedule. The termination criterion is to finish the monthly schedule with the pipeline filled up with P1. Five sequences were developed (Figure 3), being the final decision taken over the operational indicators results as presented in Table 2. Sequence 5, with a total of 41 batches, was the selected candidate due to fact that operational results are the most consistent with the operations management objectives (lowest medium flowrate or flexible minimum inventories by product).

- The comparison between the ATF and DTF models can be done through the model statistics presented in Table 3, where it is shown the different model sizes and computational effort when considering the first week of operation of July 2007 and the optimal solutions. For the same problem, the number of binary variables increases significantly as well as the computational effort due to the increase on the level of detail considered at the DTF model. On the other hand it is obtained a broader set of results comprising specific and detailed procedures for inventory management.

- The reactive scheduling procedure was applied in five situations during the month, where one or more situations (Table 1) can be combined in the same reschedule. CLC's schedulers developed six schedule revisions. Table 4 presents the operational results after the last revision has been undertaken using the ATF model. The model managed to return a lower medium final inventory while using a larger portion of the total time horizon to pump products. However, the balance between inputs and outputs

is higher than the one achieved by CLC's schedulers. The number of interfaces inside the pipeline when pipeline stoppages occurs it is also an important factor, because it is likely to decrease adjacent product quality.

The case study results show a similar final inventory with a higher pipeline usage, but with a reduction on the required pumping flowrate, about less 8% when comparing with the company solution.

5. Conclusions

This paper presents an integrated scheduling framework that addresses the complex problem of multiproduct pipeline systems. A single origin and single destination system was considered involving inventory management decisions at the end of pipe site. In this way, the solution returned considers capacity availability, market demand and inventory management tasks.

The architecture presented in this work was built using the optimization tools developed by the authors.

The current objective is to systematize and simplify their usage for schedulers with reduced knowledge of optimization and mathematical programming methods. In this way it will be possible to spread the software usage among oil products distribution companies. This is one focus of the current work being developed by the authors, namely an operations management user interface for this scheduling framework. The intent of this tool is to become intuitive and simple despite dealing with such complex systems (pipeline + tank farms).

Acknowledgments

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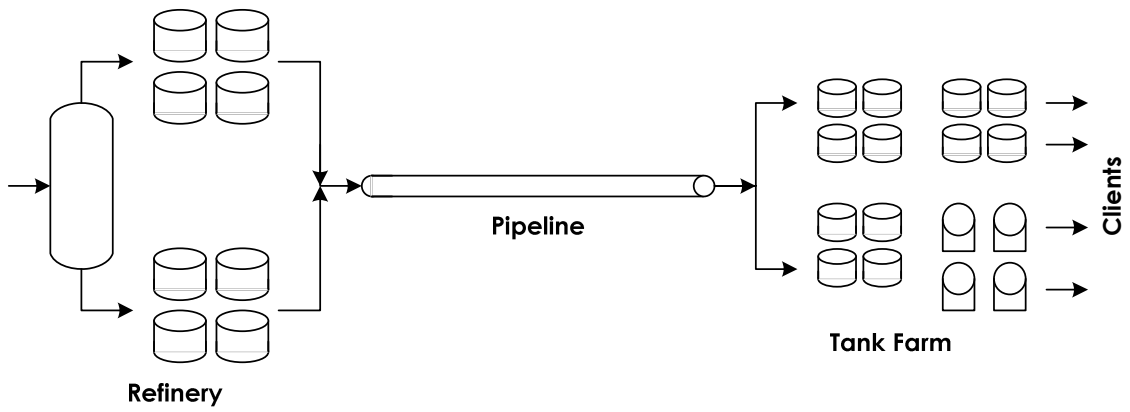


Figure 1 – Multiproduct Pipeline Operating System

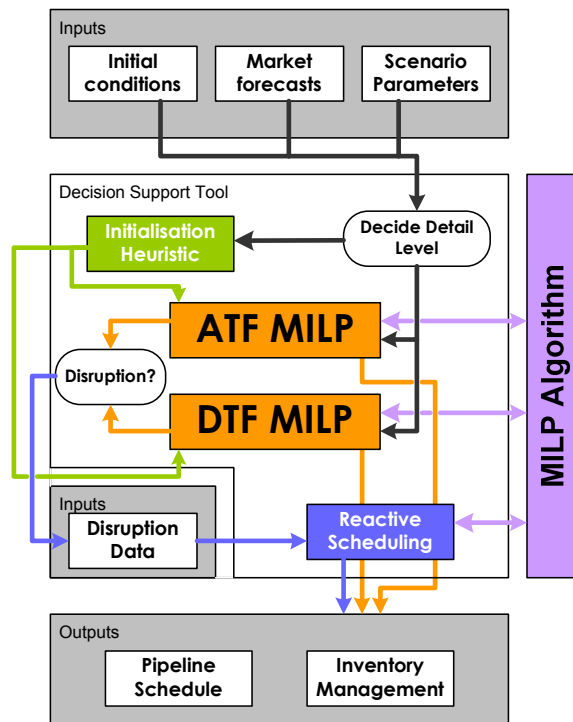


Figure 2 – Scheduling Framework Architecture

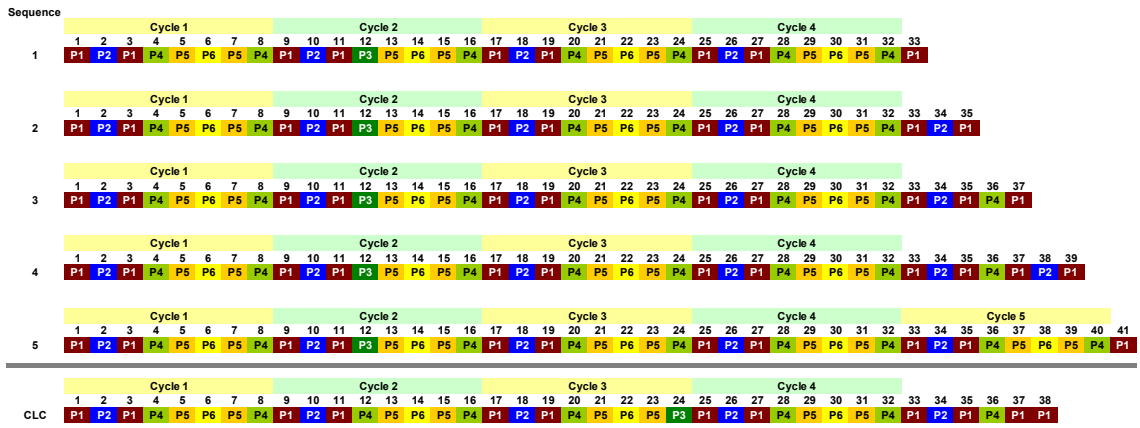


Figure 3 – Sequences of products obtained from the initialization heuristic for July 2007 and from CLC’s

Table 1 – Rescheduling situations

Situation		Description
S1	Clients' demands	Adjustments on demands on a periodic basis, e.g. weekly.
S2	Imposition on products' sequence	Due to inventory management reasons (at the refinery or tank farm).
S3	Unpredicted pipeline stoppages	Due to product shortage at the refinery or operational conditions (at the refinery or tank farm).
S4	Lots' volumes changes	Mainly due to refinery imposition (e.g. product shortage).
S5	Flowrate adjustments	Mainly due to answering quickly to an unexpected client demand.
S6	Variation on maximum storage capacity	Due to tanks' maintenance, which take place when the tank is empty.

Table 2 – Operational indicators by sequence candidate

Sequence	2	3	4	5	CLC
Medium Flowrate (vu/h)*	510.63	511.04	511.04	510.49	557.59
Δ Inventory (vu)*	+380	+680	+680	+280	+19580
Pipeline Usage (%)	98.66	98.66	98.66	98.66	94.97
Total Final Inventory (%)	55.34	55.50	55.50	55.29	65.46
Minimum global inventory (% product)	16.40 (P3)	18.44 (P3)	18.80 (P3)	21.19 (P3)	5.31 (P3)
Minimum Final Inventory (% product)	51.67 (P1)	52.53 (P1)	52.53 (P1)	52.53 (P1)	20.51 (P3)
Time of computation (min)	8.7	120.5	120.5	120.5	-

vu – volumetric units

Table 3 – Model statistics

Model	DTF	ATF
# Continuous Variables	3112	3190
# Binary Variables	2199	890
# Equations	11474	7273
# Nodes	3533	0
Time of computation (s)	310.875	0.312

Table 4 – Reactive scheduling results

Approach	Revision 5 (ATF)	Revision 6 (CLC)
Medium Flowrate (vu/h)	508.32	518.17
Δ Inventário (vu)	+8899	+3477
Pipeline Usage (%)	96.91	93.66
Total Final Inventory (%)	59.85	56.98
Minimum global inventory (%, product)	23.63 (P6)	10.09 (P6)
Minimum Final Inventory (%, product)	28.21 (P3)	31.97 (P4)
# Interfaces while pipeline is stopped	1	2