CRUDE OIL SCHEDULING

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Abstract

This paper describes the development of a short-term crude oil scheduling model. The system under consideration is composed of a terminal, a pipeline, a refinery crude storage area and its crude units, where the pipeline is a particularly challenging component. The resulting integrated model is a Mixed Integer Linear Programming problem (MILP) which determines the key decisions related to this system, such as tank allocations, sequence and size of crude parcels to be pumped through the pipeline and timing of the operations. The model's role is to set up a feasible schedule where a minimum deviation from the planned operation of the crude units is sought, while at the same time respecting constraints on tank inventories, tanker unloading constraints and other operational rules such as tank settling times and the pipeline peak time flow regime. Results for PETROBRAS' REFAP refinery, located in Canoas, southern Brazil, are presented and future extensions for this model are also mentioned.

Keywords

Crude, Short-Term Scheduling, Terminal, Pipeline, Refinery, MILP, Continuous Time Grid.

Introduction

Fierce competition and relatively high crude oil prices have forced the downstream oil industry to operate with very slim margins. In such situations, any improvement in its supply chain management may potentially lead to significant economic benefits because the oil industry deals with very high volumes of raw materials. In this context refinery scheduling can provide strong support to overall supply chain business and operations.

In a refinery, the planning application produces a plan, where the major productions targets are set up for a specific period of time, typically one month. Planning software is usually LP – Linear Programming – based, where the economics are the key issue and feasibility is barely considered.

The purpose of the scheduling activity is to break down the production plan into feasible operations throughout time. The scheduling horizon spans from a few days to weeks, depending on information availability and uncertainty, and decisions are considered on an hourly basis. Although there are some optimization variables at the scheduling level, in this application the focus is feasibility, where economics are generally overlooked.

According to Castro (2001), in a typical refinery the major activities performed by the scheduler are:

- Crude Receipt: Definition of the best crude receipts sequence and how to blend the crude in order to get the best possible yields at the crude units;
- Process Units: Definition of the sequence of feedstocks to be processed by any process unit, its operational modes and products destination;
- Inventory Management: Inventories for raw materials, intermediate and final products must be appropriate for smooth refinery operation;
- Blending: In order to meet customer demands (orders), the scheduler must be able to define from the current and future availability of blending components

when to start a batch of blend, its volume, the best blend recipe and tanks involved in this operation.

An important feature is the diversity in the magnitude of importance of each of the scheduling sub-problems found on a refinery. For refineries with a simple refining scheme and a very unsteady crude supply, the crude allocation problem (assignment of tanks for crude receipt and to feed crude units) is usually the most important of the scheduling decisions. In refineries where the crude supply is quite steady, the challenge is to schedule the refinery towards meeting products delivery. Moreover, there are cases where the scheduling effort is driven by setting a proper sequence of operational modes for the process unit, to cope with a wide range of crudes processed in the crude units.

An enhanced scheduling activity would enable the realization of the following benefits: assets optimization, reduction of inventory levels, improvement in the responsiveness of production and the logistics processes, more flexible operation, increase in the number of marketed products, better visibility of production forecasts and better customer service, and optimization of local variables such as demurrage costs and energy usage.

In this paper a crude oil short-term scheduling problem is considered. In this system tankers unload to terminal tanks, crude is pumped from the terminal to the refinery through a pipeline, and refinery crude tank farm stores and supplies crude to the crude distillation units (CDU). A number of operational rules must be assured.

Crude Oil Scheduling Model

Although the literature is rich in scheduling references, with contributions dating back to the 1950s, the ones using mathematical programming are much more recent.

Some authors have studied crude allocation problems. Shah (1996) and Lee et al. (1996) have proposed an MILP formulation using a discrete time grid to model a crude unloading system. While the former sought to minimize the tanks heels, the latter minimizes operating costs. Both authors considered a number of operational rules such as non-simultaneity of receipt and lifting operations for the same tank and crude compatibility requirements.

Moro (2000) modeled a real world crude tank farm scheduling problem. The author compares discrete and continuous time grid formulations and concludes that the former may lead to very large problems due to the huge number of binary variables to accommodate the same number of events the latter can handle with a much smaller number of binary variables, though with worse relaxation properties. The author also modeled the crude interfaces management and resting time calculations. In none of the previous works was the pipeline explicitly modeled.

Moreover, the literature is very scarce in references about pipeline modeling using optimization techniques. In one of the most recent works, Kong (2002) presented two different approaches for pipeline models. In the first a general MILP formulation was considered and in the second the author used the Resource-Task Network (RTN) framework.

Problem Definition

One of the major challenges faced by REFAP's Scheduling Group are related to the crude scheduling activity, due to difficulties resulting from bad sea and weather conditions, which hinder the moorage and therefore may impair tankers unloading at the terminal (TEDUT). This may lead the refinery to potentially run on some imbalanced positions of demand and production for some products. The refinery is connected to the terminal through the OSCAN pipeline.

The picture below provides an idea of the system under consideration:

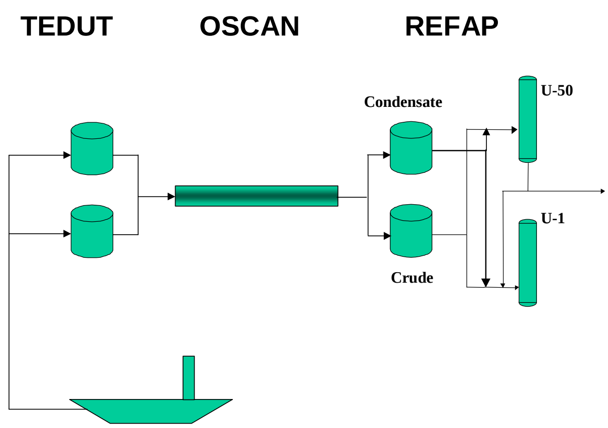

Figure 1 - Crude Allocation Problem Envelope

The crude oil scheduling problem can be summarized as follows:

Given:
- Scheduled ship arrivals;
- Terminal infrastructure (6 tanks and monobuoy);
- Refinery infrastructure (7 tanks and 2 CDUs);
- Pipeline details;
- Production requirements and planned CDU runs (throughput and operational modes).

Determine:
- Ship discharge details;
- Terminal and refinery tank allocation;
- Pipeline schedule;
- CDU schedule.

In order to:
- Minimize the deviation between the planned and scheduled throughputs at the crude units.

Subject to:
- Some operational rules;
- Material Balance

This problem was modeled as an MILP with a continuous time grid, where the main assumptions and/or operational rules regarding each of the components as illustrated in Fig.1 will be further described. For the sake of conciseness equations will not be presented extensively, but a brief description of their purpose will be given instead.

Before presenting the model it is convenient to list some definitions valid here:

1. Parcel – A volume of crude pumped from one of the terminal tanks to the pipeline.
2. Batch – A volume of crude to be unloaded from tankers to the terminal. A batch is also characterized by the crude type, the time it starts discharging and the time it finishes discharging.
3. Peak Time - This is a daily time window where the pipeline operation is performed at reduced flow. Normally it lasts from 6 to 9 p.m.

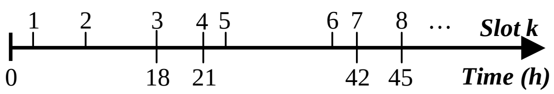

Figure 2 - Continuous Time Grid Example

Refinery

In this section the main issues regarding the refinery behavior will be presented.

- Each tank is either idle, receiving a crude parcel from the pipeline or feeding a CDU;
- One refinery tank must always be connected to the pipeline;
- A tank being filled by the pipeline can only be selected if the parcel crude type is appropriate to the tank;
- A tank feeding a CDU can only be selected if it is compatible with the CDU operational mode;
- Each CDU runs continuously with one main crude tank, in addition to the condensate tank;
- In order to separate brine from the oil, thus avoiding operational problems at the CDUs, any refinery tank must rest for at least 24 hours after receiving a parcel from the pipeline before feeding a CDU;
- Material balances on refinery tanks must be enforced, including the inbound (from the arriving parcels) and outbound (to the CDUs) flows;
- Bounds on all volumes and flows must also be respected.

The objective function is mathematically expressed as:

$$\boxed{Obj = \min \sum_{c} \sum_{k} Gap_{ck}} \qquad (1)$$

$$Gap_{ck} = \left| Q_{ck}^{plan} - Q_{ck}^{sch} \right| \qquad \forall c, k \qquad (2)$$

Q_{ck}^{plan} and Q_{ck}^{sch} are respectively the planned and the scheduled amounts for crude unit *c* over time slot *k*.

Terminal

The following is valid at the terminal side:

- Each tank is either idle, receiving a crude batch from a tanker or pumping a parcel to the pipeline;
- One terminal tank must always be connected to the pipeline;
- Any crude batch must be unloaded to an appropriate tank, at the right time, and in the right amount;
- Two consecutive parcels cannot be pumped from the same terminal tank to the pipeline;
- Material balances on terminal tanks must be enforced;
- Bounds on all volumes and flows must also be respected.

Pipeline

It will be assumed that the pipeline is a device of fixed volume through which a sequence of incompressible crude parcels can flow. The pipeline runs:

1. Continuously, with a "plug flow" type of behavior where no mixing occurs between two consecutive parcels;
2. Always one-way, flowing from the terminal to the refinery;
3. At reduced flow during peak time operation and at normal flow on the rest of the day. In each period the flow will be constant.

As a consequence of the assumptions stated above, the following rules apply to the pipeline:

- A parcel is always filling the pipeline at the terminal side;
- A parcel is always emptying the pipeline at the refinery side;
- The first parcel to flow in is the first parcel to flow out of the pipeline;
- The sum of all parcels (or fraction of parcels) flowing inside the pipeline is equal to the pipeline volume at any time.

Results and Discussion

In order to verify the suitability of the formulation presented some examples were built considering a 4 day (26 time slots) scheduling horizon. 3 crude batches and 4 crude parcels were assumed to account for the major oil movements through the system. Space restrictions preclude the detailed description of problem data.

The table below shows the main computational results from a set of 5 runs. The modeling system GAMS (Brooke et al, 1998) version 2.50 was used with the solver CPLEX 6.0 on a Sun Ultra 60 machine.

Table 1 – Computational Results

Case	Sol. Fixed	Binary Var.	Single Var.	Equations	CPU (s)
1	No	1558	4266	8767	5806
2	Yes	974	3678	8453	0.65
3	No	1263	3971	8716	153
4	No	1148	3856	8574	5607
5	No	1107	3815	8528	136

The difference among all cases is the number of binary variables fixed in advance prior to the run. This is a fairly realistic assumption since the refinery is a continuous process and by the time the scheduler has to produce a schedule some tasks are already taking place in the facilities and some time is required to change their status.

In Case 1 no binary variable was fixed in advance, which explains the longest solution time. In Case 2, a large number of binary variables are fixed. Cases 3, 4 and 5 different groups of binary variables were fixed achieving interesting results. These results suggest that there might exist a more efficient MILP formulation for the problem as a function of the binary variables fixed in advance. Further results for Case 5 are given below.

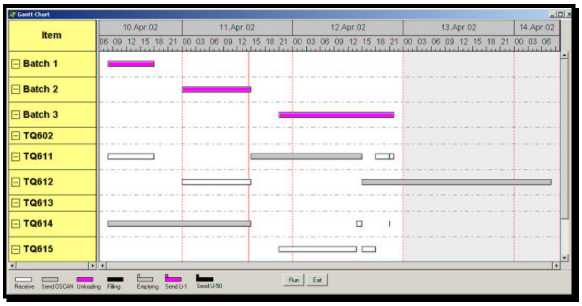

Figure 3 – Terminal Operations Gantt Chart

This chart indicates that Batch 1 was unloaded to TQ611. Batch 2 was unloaded to TQ612, since this is the only tank possible to store that type of crude. Finally, Batch 3 is scheduled to be spread between tanks TQ611, TQ614 and TQ615, which store the compatible crude. This outcome (Batch 3 unloading to 3 tanks with several switches) clearly indicates that the model needs improvement to produce schedules fully implementable in the field by the operational staff. Parcels 2, 3 and 4 are lifted from tanks TQ614, TQ611 and TQ612, respectively.

The plots below provide the inventory profiles for the terminal tanks and confirm the schedule shown on Figure 3. Also the peak-time occurrences are evident from the change in slope for the tanks pumping to the pipeline.

In all cases the resulting objective function values (optimization gap) are zero, thus indicating that the proposed schedules perfectly meet the planning targets. This was only possible due to the particular set of input data used, as this result is not always possible.

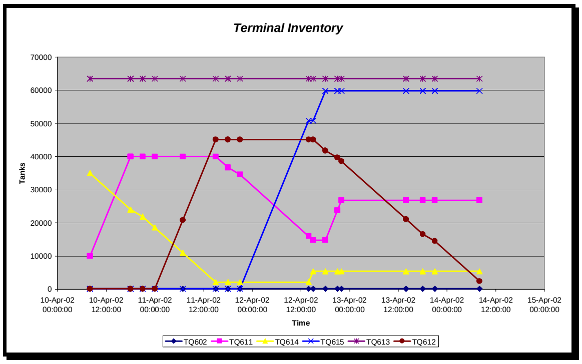

Figure 4 – Terminal Tanks Inventory Plot

A pre-processing algorithm was adopted for the unloading of crude batches. The purpose of this algorithm is to reduce the full assignment of batch unloading variables and time slots matches, thus limiting the possible search domain. This procedure is based on the previous knowledge of the peak time occurrences and the times when a batch starts/ends discharging.

Current research work undergoes in order to provide better adherence to the actual environment (e.g. demurrage costs) and increase the scheduling horizon.

Conclusions

A crude oil scheduling problem has been discussed in this paper. The system includes a terminal, a pipeline and a refinery, where a novel approach to the pipeline component was adopted. The problem was modeled as a single MILP with a continuous time formulation, minimizing the deviation from the planning targets. A number of operational rules and material balances are modeled. Areas for enhancement are to address adherence to the operating environment.

References

Brooke, A., Kendrick, D., Meeraus, A., Ramesh, R. (1998), GAMS A User's Guide; GAMS Development Corporation.

Castro, H.P. (2001), Utilização de Algoritmos Genéticos para Solução de Problema de Programação de Produção de uma Refinaria de Petróleo, MSc Logistics Thesis, Universidade Federal de Santa Catarina.

Kong, M.-T. (2002), Downstream Oil Products Supply Chain Optimisation, PhD Thesis, University of London.

Lee, H., Pinto, J.M., Grossmann, I.E. and Park, S. (1996), Mixed-Integer Linear Programming Model for Refinery Short-Term Scheduling of Crude Oil Unloading with Inventory Management. Industrial & Engineering Chemistry Research, 35(5):1630.

Moro, L.F.L. (2000), Técnicas de Otimização Mista Inteira para o Planejamento e Programação de Produção em Refinarias de Petróleo, PhD Thesis, Univ. São Paulo.

Shah, N. (1996), Mathematical programming techniques for crude oil scheduling, Computers & Chemical Engineering, Vol. 20, pp. S1227-S1232.