Enterprise-Wide Optimization for Operations of Crude-Oil Refineries: Closing the Procurement and Scheduling Gap

Brenno C. Menezes[a*], Ignacio E. Grossmann[a], Jeffrey D. Kelly[b]

[a]*Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh 15213, United States*
[b]*Industrial Algorithms, 15 St., Andrew Road, Toronto MIP 4C3, Canada*
brennocm@andrew.cmu.edu

Abstract

We propose a quantitative analysis of an enterprise-wide optimization for operations of crude-oil refineries considering the integration of planning and scheduling to close the decision-making gap between the procurement of raw materials or feedstocks and the operations of the production scheduling. From a month to an hour, re-planning and re-scheduling iterations can better predict the processed crude-oil basket, diet or final composition, reducing the production costs and impacts in the process and product demands with respect to the quality of the raw materials. The goal is to interface planning and scheduling decisions within a time-window of a week with the support of re-optimization steps. Then, the selection, delivery, storage and mixture of crude-oil feeds from the tactical procurement planning up to the blend scheduling operations are made more appropriately. The up-to-down sequence of solutions are integrated in a feedback iteration to both reduce time-grids and as a key performance indicator.

Keywords: Crude-oil refining, Planning and scheduling integration, Feedback iteration.

1. Introduction

The final quality composition of a crude-oil mix to be fed and processed in the distillation towers of an oil-refinery involves a multi-level and multi-entity decision-making framework with time-steps varying from a month to an hour. To reduce the gap or differences between the resulting solutions from these different levels and entities independently calculated, the key aspect is the integration of the decisions in both time and space. Given the closeness of the decision-making time-steps, more similarities between the procurement planning and the blend-scheduling operations are expected. The degree of spatial aggregation or simplification in planning will define how far it can potentially be from the scheduling. The latter considers amounts and properties of ongoing inventory of crude-oils and fuels (at their initial, intermediate and final storage stages), as well as the real topology of equipment or structures such as process units, tanks, pipelines, etc.

Efficient and integrated approaches to reduce capital and operating costs can be accomplished by hierarchical coordination and collaboration between the different levels of management over the different entities (Kelly and Zyngier, 2008). However, there can be numerous trade-offs between these levels and entities due to their interdependency. Ideally, the decisions from different scales should be made simultaneously (Papageorgiou, 2009). Although, in practice, these decisions are made independently due to limitations in the modelling and solution of such wide optimization problems, when moving different quality raw materials from sources (reservoirs, terminals) to industrial sites such as gas processing plants, oil-refineries, petro-chemical facilities, etc.

To transform crude-oil raw materials into specified products in a specific refining process network, the final composition of the charged or processed raw materials (in terms of amounts and properties of hydrocarbon compounds) is the primary way for defining quantities and qualities of fuels. Crude-oil refined products such as gasoline, kerosene, jet and diesel contain a range of light to heavy hydrocarbon molecules, and their extension yields the amounts and properties of such bulk fuels. By operational variations in physical and chemical processes of hydrocarbon streams, only slight ranges of separation and conversion of the molecules can be achieved by adjustment of pressure, temperature, catalytic activity, etc. Therefore, in refining crude-oils into fuels, any degree of integration in the crude-oil compound-property optimization from the procurement up to the scheduling of crude-oils is a paramount decision point in any fuels producing industry.

Solution methodologies for operations of crude-oil refineries must handle a multi-scale optimization of logistics and quality problems starting at the sources (producers, logistics providers) and closing in the sinks (refineries) of raw materials. There is great economic potential to connect managerial and operational decisions of procurement and scheduling as an enterprise-wide optimization (EWO) approach (Oddsdottir et al., 2013). However, no application nor theoretical view covering such matters in this industry have been addressed to close the gap or differences between the procurement and scheduling optimizations. From this assessment, one can expect reduced production costs by better match between the purchasing of crude-oils and distribution and sales of fuels, all with respect to the quality of the crude-oil raw materials.

Procurement planning to production scheduling of crude-oils coordinates the procured, shipped, transported, stocked, blended and charged raw materials in a broad multi-scale problem from a reduced to a detailed degree of modelling precision. An integrated optimization targeting the storage and processing residence time of a crude-oil arrival within a week, can potentially avoid long storage periods of crude-oils or even their premature processing to maintain refinery feed. Monthly procurement cycles lead to an overall inefficient refinement since this common practice neglects process demands with regards to the liftings of fuels within a week or less. In the EWO proposition of this paper, decisions from a lower level return to an upper level for a new automated search of a solution, updating lower level targets and reducing time-grids in upper level optimizations. Better performance using re-optimization steps can succeed by having closer solutions among levels and entities of the decision-making echelons.

2. Planning and scheduling time integration within a week

The enterprise-wide optimization approach calculates first several nonlinear (NLP) problems among tactical and operational planning as follows: a tactical problem defines the monthly procurement of crude-oils for 3 months ahead and the sequential operational planning determines optimal amounts of crude-oils in each week of the first month. Then, a re-planning step of the tactical problem considers the weekly optimal crude-oil amounts (found previously in the operational problem) as a key indicator of performance or target in a feedback flow of information where the tactical re-planning is in a week time-step within the first month. This feedback iteration integrates the tactical and operational problems to identify the optimized amounts of the different quality crude-oils in a week time-grid within the first month. This creates a non-uniform time-discretization in the tactical re-planning with four periods of a week and two periods of a month. Then, the following operational planning is re-done considering the tactical re-planning results on crude-oil procurement in a week basis. These planning problems are expected to be solved within minutes with a weekly frequency for the operational or even for the tactical re-planning. Additionally, small- to medium-size problems of a sole refinery may be directly solved with time-step of a week for the tactical and operational planning without iterative re-planning cycles.

These NLP planning steps guide the definitions on the procurement of crude-oil raw materials. Therefore the purchasing or allocated amounts (procurement) for the next 3 months are defined to both spot and contract orders. Time-series analytics to forecast prices for crude-oils and fuels can potentially improve these procurement definitions. Although, due to the numerous uncertainties from both exogenous and endogenous causes, pricing prediction in a 3-months horizon problem represents a minor aspect in the non-integrated sequence of optimization steps without the EWO approach of this paper. Example of integration of operational and financial strategies in procurement of crude-oils can be found in Ji et al. (2015). Their approach manages the risk in the oil procurement due to oil price fluctuation.

In the following, three different optimizations are proposed regarding the movement of crude-oils from their sources to the refinery processing units. First, the crude-oil amounts determined in the re-planning problems will guide the dispatching weeks of the crude-oil feedstocks, and the transportation is calculated day-by-day in a 30-day problem. Then, the clustering and scheduling of crude-oil feedstocks similar to components in product blending, from ships or terminal tanks to the refinery site, determine the final crude-oil or compound-property blend to be refined downstream.

3. Scheduling-related solutions

After the planning and re-planning steps, the EWO approach continues the crude-oil refinery operation by calculating 3 groups of scheduling-related solutions: the maritime shipping, the feedstock storage assignment and the refinery blend scheduling.

First, a mixed-integer linear (MILP) model calculates a daily maritime shipping in a 30-days horizon considering weeks of departure and arrival of vessel cargoes with crude-oil feedstocks. Then, an assignment design problem for feedstock storage is solved with an MILP formulation by clustering similar quality raw materials to minimize their quality variation when different quality raw materials are sharing storage (Kelly et al., 2017a). Finally, scheduling decisions are programmed in a 1 to 2 h time-step over a week using both practical logistics details and quality balances in an iterative decomposition, considering first an MILP model, by neglecting the nonlinear blending constraints, and secondly, an NLP formulation with quantity and quality variables and constraints by fixing the logic results from the MILP problem (Kelly et al., 2017b). A re-planning with scheduling feedback reduces the operational planning time-grid to a day or a shift of 8 hours for the initial days of a scheduling.

3.1. Maritime shipping

Typically known as maritime industrial shipping (MIS) or maritime inventory routing problem (MIR), this logistics optimization involves ship assignment to the berths or docks as well as inventory management of both immobile (tanks) and mobile (ships) elements (Christiansen et al., 2007 and Goel et al., 2012). The ships can have different possible routes each with varying size and number of cargoes (compartments or holds) to store crude-oils destined for one or more processing sites. The different routes can relate to different shipping channels (requiring different amounts of travel or hauling-time) where the order or sequence of delivery (unloading) i.e., crude-oil A then B or C then D, is fundamentally set by the crude-oil clustering/segregation rules or systematic algorithms to store similar quality crude-oils as in sub-section 3.2.

Given that the deliveries of crude-oils can be unloaded to tanks or the inventory buffer is not known, for these types of demand points there are two options for their unloading configuration: contiguous and non-contiguous. Contiguous use is similar to a pipeline connection where the flows must be within lower and upper bounds for each time-period as specified by the demand order and its flowrate. Non-contiguous relaxes this restriction by defining a release- and due-date or time-window and a holdup lower and upper bound. To not incur an infeasibility, the solution must ensure that within the time-periods defined by the time-interval, the aggregated, accumulated or summed flow (equal to the holdup) must be within bounds.

3.2. Feedstock storage assignment

Kelly et al. (2017a) present a novel storage assignment problem to allocate or segregate raw materials to a definite place in an orderly system. The MILP model minimizes the overall crude-oil quality deviation in the storage tanks when a larger number of feedstocks from marine vessels or ships are transferred to a smaller number of storage tanks in the plant, known as the Pigeonhole Principle. Rather than segregations on light-to-heavy specific gravity and low-to-high sulfur concentration, yields of naphtha and diesel or properties such as nickel and carbon residue contents are considered in the clustering optimization. This pre-defining storage assignment reduces the binary search space in further down-stream blend scheduling programs, and allows the solution of discrete-time formulations with hundreds of time-periods using 1h to 2h time-steps in highly complex process plants as seen in the next sub-section.

3.3. Refinery blend scheduling

Kelly et al. (2017b) developed an industrial-sized example of the refinery blend scheduling including 5 crude-oil distillation units (CDU) in 9 modes of operations and around 35 tanks among storage and feed tanks. The model decomposes the mixed-integer nonlinear (MINLP) optimization into an MILP and NLP problems. First, the MILP approach finds the binary operations and assignments in the refinery site considering detailed logistics as fill-draw-delay, uptime use, filling-full and drawing-empty relationships (Zyngier and Kelly, 2009). This stage neglects nonlinearities from blending constraints and CDU processing transformations (Kelly and Zyngier, 2017). Then, binary solutions from both local and global MILP results of the *logistics* model are solved in the NLP programs of the *quality* sub-problems, and ad-hoc criteria select to continue those among a score of the MILP+NLP pairs of solutions. Iteratively, CDU yields of the final compound-property crude-oil (found in the *quality* calculation) are updated in the following *logistics* problem until their convergence is achieved (Menezes et al., 2015).

4. Examples

Table 1 compares examples of the tactical and operational planning plus the crude-oil blend scheduling involving crude-oil supply, storage and feed tank operations, and the

CDU production. Figure 1 shows an illustrative example with full topology of 6 marine vessels or feedstock tanks (CR1 to CR6) supplying a crude-oil refinery with different quality raw materials to produce the main CDU distillates: fuel gas (FG), liquid petroleum gas (LPG), light naphtha (LN), heavy naphtha (HN), kerosene (K), light diesel (LD), heavy diesel (HD) and atmospheric residue (AR). Storage tanks (S1 to S4) are connected to the feed tanks (F1 to F3) using a crude-oil blender (COB), as the best practice to reduce crude-oil composition disturbances in further real-time optimization and model predictive control. For the planning cases, their partial topology excludes the blender and feed tanks, so the storage tanks are connected direct to the CDU. An industrial-sized case of a crude-oil blend scheduling with 5 CDUs, 20 storage tanks and 10 feed tanks is also included in Table 1.

The network in Figure 1 is constructed using the unit-operation-port-state superstructure (UOPSS) formulation (Kelly, 2005; Zyngier and Kelly, 2012) composed by the following objects: a) unit-operations m for continuous-processes (⊠) and tanks (Δ), and b) their connectivity involving arrows (→), in-ports *i* (◯) and out-ports j (⊗). In this flowsheet superstructure, binary *y* and continuous variables *x* are defined for unit-operations and arrows, and the ports hold the states for the relationships among the objects, adding more continuous variables if necessary by the semantic and meaningfully configuration of the programs.

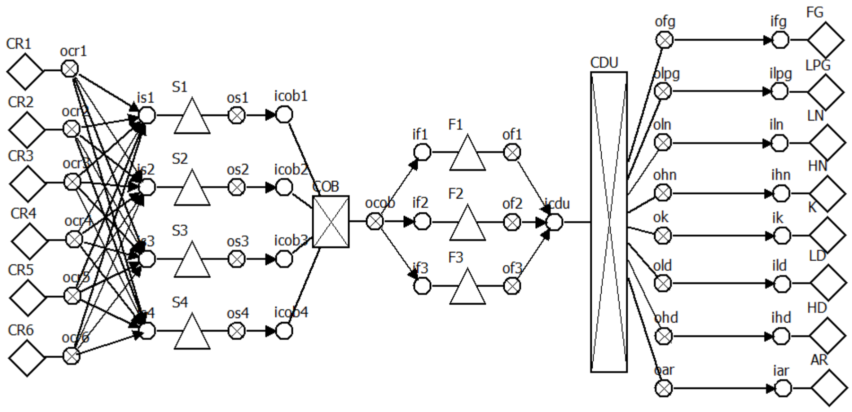

Figure 1. Illustrative example of the crude-oil blend scheduling (full topology).

Table 1. Tactical and operational planning and scheduling examples.

	Horizon	Time-Step	Nº Periods	Model (constraints; continuous/binary variables)	CPU (s)
Tactical	84 days	1 week	12	NLP (1.5 k; 1.8 k)	30.1
Operational	20 days	1 day	20	NLP (3.7 k; 4.5 k)	13.8
Scheduling	14 days	2 hours	168	MILP (19.8 k; 8.3 k/3.5 k)	176.0
				NLP (15.6 k; 19.4 k)	16.8
(industrial-sized case)	5 days	1 hour	120	MILP (81.9 k; 45.7 k/28.5 k)	170.0
				NLP (99.6 k; 121.4 k)	933.0

5. Conclusions

Instead of a time-grid of one month (as usual in procurement of crude-oil raw materials of fuels), the interfacing of planning and scheduling within a week plays a significant role for more efficient management, procurement and processing of crude-oils. Despite the fact that the calculation of the echelons of decisions is made in a sequence of solutions - instead of simultaneously - such complex EWO-like methodology still demands very powerful memory, modelling and solution capabilities. For planning, multi-period NLP problems are iteratively re-calculated and a pool of solutions can be executed in parallel by randomizing the initial points of the variables. In scheduling, problems with hundreds of periods can occur when modelling time-steps around an hour.

Optimized solutions can be integrated by similar time-steps at their boundaries as well as cascading targets from a lower to an upper level in a feedback key indicator of performance. The crude-oil refinery operations in the scheduling horizon of a week combined with the purchasing/allocation of crude-oils, can potentially improve the decision-making among the raw materials-to-products echelons as the quality of the crude-oil raw materials heavily defines the refinery operations as well as the overall amount of fuels.

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