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Logistics optimization for dispositions of product distillates in oil-refineries: closing the operations scheduling and primary distribution gap

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Abstract

In the process industries with a wide variety of different quality feeds and products, especially in oil-refining and petro-chemicals, better predictions on the production allow opportunities of exploring the contract and spot market plays of finished products. From the process network up to the product distribution side, there are definitions in the assignments, allocations, amounts and properties of distillates to be dispatched downstream, problems involving logistics and quality aspects in further process-shops and blend-shops, and diverse tank farms and various modes of transportation. At the edge of this manufacturing of distillates into refined final products, the production scheduling and primary distribution gap can be reduced by optimizing production rundown switches of distillates in a mixed-integer linear model (MILP) considering time-steps of days, shifts or hours with a delivery horizon of weeks or months, all with time-varying rundown supply rates, product demands and pricing. Other strategies to the high-performance production scheduling and distribution use feedback of measured data, regressed linear formulas in surrogated blending calculation via successive substitution and hierarchical decomposition for coordination and collaboration among multiple plants. This wide optimization scope can provide key leading indicators of market opportunities (and obstacles) with sufficient lead times and modeling evidence to ultimately enable better marketing and trading collaboration for increased benefits.

Keywords: crude-oil distillates, product scheduling, rundown switches, MILP.

1. Introduction

To refine crude-oil raw materials into final products such as fuels, lubes, asphalts and petrochemical feeds, the better match between the refinery scheduling and the primary distribution of the products allows market opportunities, reduces inventory costs, and avoids fines due to non-attendance of a client. In any competitive business, both fixed contracts and variable spot markets of feeds and products compete and complement each other whilst maintaining the balance between sustainability and profit, the former via long-term contracts and the latter in terms of short-term opportunities in the spot markets. The high-performance refining of crude-oils into products can be achieved considering integrated approaches of the following subsystems: a) raw material procurement, shipping, unloading, storage, *dieting* and charging, b) combined operations of process-shops and blend-shops, c) management of intermediate and final product inventories, d) sales and distribution of refined products.

From the monthly and weekly procurement planning cycle up to the daily and hourly production scheduling from crude-oils to distilled products or distillates, an enterprise-wide optimization (EWO) strategy can feedback decisions from a lower to an upper level for a new search of a solution, updating lower level results as targets and reducing time-grids in upper level re-optimizations (Menezes et al., 2017). By reducing the procurement time-step from a month to a week in the iterative optimization steps, this can potentially avoid long storage periods of raw materials or even their premature processing to maintain the plant feed. However, there are many challenges to develop such an EWO approach from the scheduling of product process- and blend-shops to the primary distribution management that evolves from time-steps of an hour, shift, day to those found in planning considering weeks, months and quarters.

First, to efficiently maintain the production for downstream process units, tanks or any modes of transport, a wide scheduling optimization shall determine production rundown switches in days, shifts or hours (small-buckets) for a delivery horizon of weeks or months (big-buckets), yielding models with thousands of time-periods. Despite the quality aspects in the process network, which in turn can still be modified in downstream process-shops and blend-shops, a logistics optimization finds primarily the dispatching routes or dispositions of the distillates in a mixed-integer linear model (MILP). This quantity and logic programming involves variables for networked amounts of flows and holdups, assignment of dispatching routes modeled as modes of operations, constraints for running- and standing-gauge tanks of intermediate and final inventories, operations of blend-shops, multiproduct liftings via multiple mode of transport such as trucks, pipelines, ships, etc.

Moreover, there are uncertainties in quantity (amounts) and quality (properties) on the distillates or intermediate products to be stocked in running-gauge tanks (non-standing-storage mode) or directly feed a unit-operation for further processing. To reduce the quantity and quality uncertainties in the production, the feedback of measured data (Kelly and Zyngier, 2008a) incorporating on-line flow and property analyses can be modeled using corrections such as *gains* and *biases* like in the formula $y_{measured} = gain \, . \, y_{model} +$ bias. The running-gauge tanks continuously receive distillate streams and can simultaneously feed a process unit or a blender, although restriction for deadtime may be needed to guarantee quality homogenization of the mixing in the tanks. In this case, the continuous-processes should count on more than one tank.

Other improvement in this integrated production scheduling and distribution of hydrocarbon products can apply linear blending formulation in blenders using variables of factor-flows for giveaway of qualities coupled to nonlinear simulations to re-calculate surrogated/proxied blending via successive substitution. Aggregated pools may require a post disaggregation or depooling step. Decompositions to iteratively solve nonlinear programs (NLP) by fixing the MILP results (Menezes et al, 2015) as well as a pool of MILP problems for hierarchical coordination and collaboration among multiple sites/areas (Kelly and Zyngier, 2008b) may support the distillates production for the edge optimization proposed in this paper.

2. Scheduling and primary distribution of products

The flowsheet in Figure 1 shows the example of a crude-oil refinery network for production and distribution of medium to heavy distillates produced in the atmospheric distillation units ADU1 and ADU2. The distilled kerosene (KERO), light gasoil (LGO) and heavy gasoil (HGO) streams can be dispatched to feed tanks for processing in units such as hydrotreaters, dryers, blenders or directly to a final tank for commercialization. The mode of transportation of products considers pipelines, trucks, ships and other local market deliveries to supply the multiple products continuously and under precise short-term demands within days and under uncertain monthly demand.

The main objective is to effectively maintain the distillates production for unit-operation feeds, product blenders or final tanks with direct lifting. DHT-WS and DHT-GO represent the same physical hydrotreater DHT with WS and GO as modes of operation. VHT is a hydrotreating unit for HGO, the dryers of light and heavy HGO are the units DRYER and DRYER2 and the blender of HGO is the unit PL_GOBLEND1.

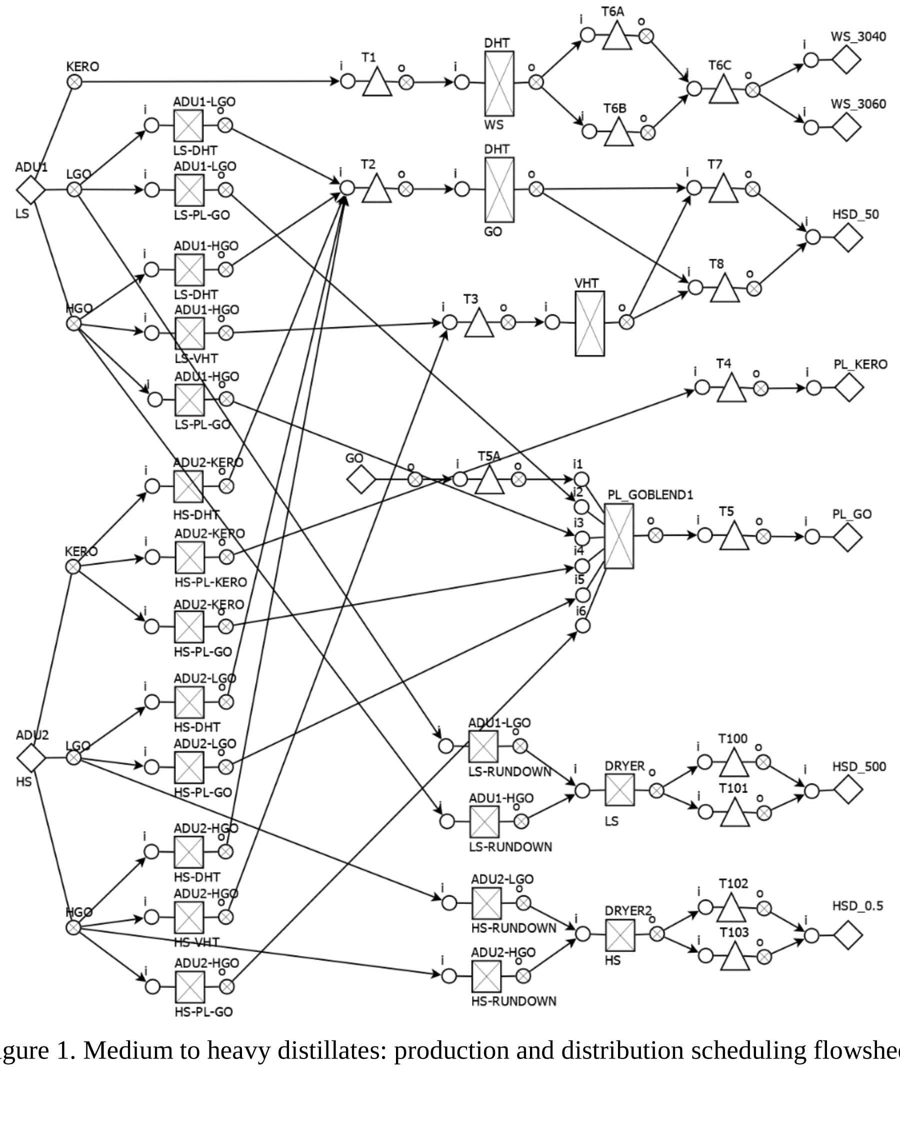

Figure 1. Medium to heavy distillates: production and distribution scheduling flowsheet.

The dispatching routes, destinations or dispositions of the distillates from ADU1 and ADU2 are depicted in Figure 1 as: a single for KERO from ADU1, dispositions of ADU2-KERO and LGO (from both ADU1 and ADU2) are represented with 3 modes of operations and HGO from both distillation units with 4 modes. The network in Figure 1 is constructed in the unit-operation-port-state superstructure (UOPSS) formulation (Kelly, 2005; Zyngier and Kelly, 2012). The UOPSS objects are: a) unit-operations *m* for sources and sinks of perimeters (◇), tanks (△) and continuous-processes (⊠) and b) the connectivity involving arrows (→), in-port-states i (○) and out-port-states j (⊗). Unit-operations and arrows have binary and continuous variables (*y* and *x*, respectively).

In the mixed-integer linear (MILP) problem (P), the objective function (1) maximizes the gross margin of fuels revenues by subtracting weighted operational performance terms. Eq. (2) shows the performance constraints considering deviations on variables around a target ($\bar{x}_t$). The x_t^{LD} and x_t^{UD} are lower and upper deviation variables valid for any variable as flows of process-units $x_{m,t}$, arrows $x_{j,i,t}$, and holdups $xh_{m,t}$. The remaining logistics and quality calculations can be found in Kelly et al. (2017). Unit-operations *m* for tanks, blenders, and final products belong, respectively, to the sets M_{TK}, M_{BL}, and M_{FP}. The deviation variables are represented in the set D_{VAR}. The port-states j' and i'' represent upstream and downstream ports connected, respectively, to the in-port-states i and out-port-states j of unit-operations m. For $x \in \mathbb{R}^+$ and $y \in \{0,1\}$:

$$(P)\ \ Max\ Z = \sum_t \left(\sum_{m \in M_{FP}} price_{m,t}\, x_{m,t} - \sum_{x \in D_{VAR}} weight(x_t^{LD} + x_t^{UD}) \right)\ \ s.t. \tag{1}$$

$$x_t - \bar{x}_t + x_t^{LD} - x_t^{UD} = 0\ \ \forall\, t \tag{2}$$

$$\bar{x}_t^L\, y_t \le x_t \le \bar{x}_t^U\, y_t\ \ \forall\, t \tag{3}$$

$$\frac{1}{\bar{x}_{m,t}^U} \sum_{j'} x_{j',i,t} \le y_{m,t} \le \frac{1}{\bar{x}_{m,t}^L} \sum_{j'} x_{j',i,t}\quad \forall\, i,m,t \tag{4}$$

$$\frac{1}{\bar{x}_{m,t}^U} \sum_{i''} x_{j,i'',t} \le y_{m,t} \le \frac{1}{\bar{x}_{m,t}^L} \sum_{i''} x_{j,i'',t}\quad \forall\, j,m,t \tag{5}$$

$$xh_{m,t} = xh_{m,t-1} + \sum_{j'} x_{j',i,t} - \sum_{i''} x_{j,i'',t}\ \ \forall\, (i,m,j) \in M_{TK}, t \tag{6}$$

$$\sum_{j'} x_{j',i,t} = \sum_{i''} x_{j,i'',t}\ \ \forall\, (i,m,j) \in M_{BL}, t \tag{7}$$

$$\sum_{m \in U_m} y_{m,t} \le 1\ \ \forall\ t \tag{8}$$

The semi-continuous constraints to control the quantity-flows of the arrows $x_{j,i,t}$, the throughputs of the unit-operations $x_{m,t}$ (except tanks) and tank holdups or inventory levels $xh_{m,t}$ are given in Eq. (3). Eq (4) imposes that the sum of the arrows arriving in the inlet-ports *i* (or mixers) of unit-operation *m* ($m \notin M_{TK}$) are bounded by their throughputs (flows). Similarly, in Eq. (5) the sum of the arrows leaving from the outlet-ports *j* (or splitters) of

m ($m \notin M_{TK}$) must be between bounds of their throughputs. The quantity balance of inventory or holdup for unit-operations of tanks ($m \in M_{TK}$) in Eq. (6) considering initial inventories $xh_{m,t-1}$ and inlet and outlet streams of the tanks. Eq. (7) is a material balance in blenders M_{BL} to assure that there is no accumulation of material in these types of units. In Eq. (8), for all physical units, at most one unit-operation m (as $y_{m,t}$ for procedures, modes, dispositions or tasks) is permitted in U_m at a time t.

Transformations in the hydrotreaters DHT and VHT are not represented, although a reduction on the yields of the medium distillates are expected by the replacement of heteroatoms and metals by hydrogen and secondary carbon chain cracking. The intermediate tanks for each inlet of the blender are skipped for simplification.

3. To the edge of smart refinery scheduling and distribution

The prescriptive analytics or optimization involving the processing, supply chain and marketing evaluate choices of production and transportation considering the commercialization cycle with regards to the client deliveries in a monthly horizon with time-steps around an hour or a shift. Two are the challenges to the edge of the smart production and distribution inside the refinery industry:

3.1. Multi-level supply chain optimization

Efficient modeling and solving capabilities of multi-level supply chains yield highly responsive and competitive environment that make excellent decisions (Brunaud and Grossmann, 2017) considering multiple grids of time covering several production and distribution sites. The challenges are in standardization of supply chain models, coordination and collaboration among sites, uncertainties on the refinery production and client demands and flexibility for the short-term deliveries.

3.2. Refinery manufacturing toward Industry 4.0

The information age evolution towards a universal accessibility of data (through wireless networks and cloud computing) can achieve better performance in manufacturing considering the potentials of the decision automation and data analytics bodies. Efficient scheduling solutions in discrete time-step of an hour working in a near on-line fashion are becoming reality by the virtue of all advances in decision-making modeling, heuristic algorithms and computer-aided resources in terms of faster CPU clock speeds and higher solvability limits of solvers. The major challenge now is to integrate proper or correct data (in timeliness and quality) to the decision automation core (Joly et al., 2017).

4. Example

The example in Figure 1 is performed in the structural-based UOPSS framework found in the semantic-oriented modeling and solving platform IMPL (Industrial Modeling and Programming Language) from Industrial Algorithms Limited using Intel Core i7 machine at 3.41 GHz (in 8 threads) with 64GB of RAM. The logistics optimization for the proposed MILP for a 31 day time-horizon with 1 hour as the time-step (744 time-periods) is solved in 24.07 minutes (with Gurobi 7.5.1). There are 326,870 constraints (105,321 equality) for 144,781 continuous variables and 29,088 binary variables with 68,548 degrees-of-freedom. Figure 2 shows an example of the ADU1-HGO stream destinations.

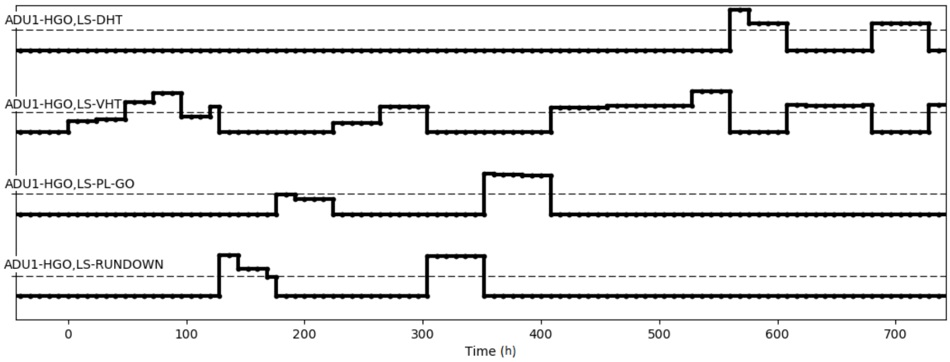

Figure 2. ADU1-HGO Gantt chart of destinations.

5. Conclusions

The logistics optimization of the oil-refinery production and demand chains creates the necessary mapping of flows, inventories and movements of intermediate and final products. This is demanded in the operations and commercialization teams for their month to day-by-day business with the clients in both contract and spot markets. The advances in the infrastructure of cyber-physical systems (CPS) for a digital twin of reality demands the integration of computational algorithms and physical assets to enable capability, adaptability, scalability, resiliency, reliability, safety, security, and usability of the production and distribution sides among all parts of the entire system of producers, distributors and clients.

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