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SPECIALREPORT

Logistics: the missing link in blend scheduling optimization

Incorporating them can yield significant improvements in efficiency and productivity

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Blending liquids of diverse quality, as defined by their composition and properties, to obtain mixtures more consistent in quality and meet specific quality requirements is well-known in the hydrocarbon processing industries (HPI), especially for crude oil, naphtha, gasoline and diesel blends. This article describes a less familiar dimension of blending known as "logistics" scheduling optimization[1,2] and emphasizes the importance of not just meeting quality but also respecting as much as possible the many, sometimes hidden logistical elements of blending.

Logistics deals with the quantity and logic details of the blendshop optimization problem. It provides the needed "coarse-tune" for the overall problem where the corresponding "quality" scheduling optimization (not described) is relegated as a "fine-tune" to readjust the quantities but keeping the logic decisions fixed. In the logistics subproblem, quantity decisions such as the lot-sizes for component and product tank inventories, charge or blend sizes for blenders and movement sizes between tanks and blenders, etc., are continuous variables in the optimization. The logic decisions are the combinatorial or discrete variables and have an exact one-to-one correspondence between the quantity sizing variables. Essentially, the logic variables are known as 0/1 or binary variables,[3,4] which are 1 if there is flow and 0 if there is no flow. If there is flow (i.e., the logic variable is 1), this flow must be between its lower and upper quantity sizing bound. Here the ratio of the upper bound over the lower bound is called its "turn-down" ratio and applies to lot, blend and movement sizing.

The most popular method to schedule the quantity, logic and quality dimensions of the blending problem is to partially use simulation. This is usually developed internally by the scheduling analyst (or handed down from the previous scheduler) in a spreadsheet, although several commercial HPI-specific simulators are available. To be more specific, these scheduling simulators really only address the quantity and quality details of the problem over some limited time horizon into the future. The logic details (i.e., operating rules or procedures) are relegated or consigned to the scheduling analyst when making quantity and quality decisions, and later to the operator charged with executing the blend production schedule. Simulators are, in fact, only sophisticated calculators that rely on the user to specify the independent variables, i.e., flows into and out of a tank over time. The simulator will calculate the dependent variables such as a tank's holdup and quality at each time interval. This type of simulator is what we call a "quality" scheduling simulator. It helps the user manage the quantity and quality details of the blendshop, but, unfortunately, it does a relatively poor job of managing the logic details, and that is the focus of this article.

In reality, it is more the norm than the exception that these scheduling simulators are really only "quantity" simulators.

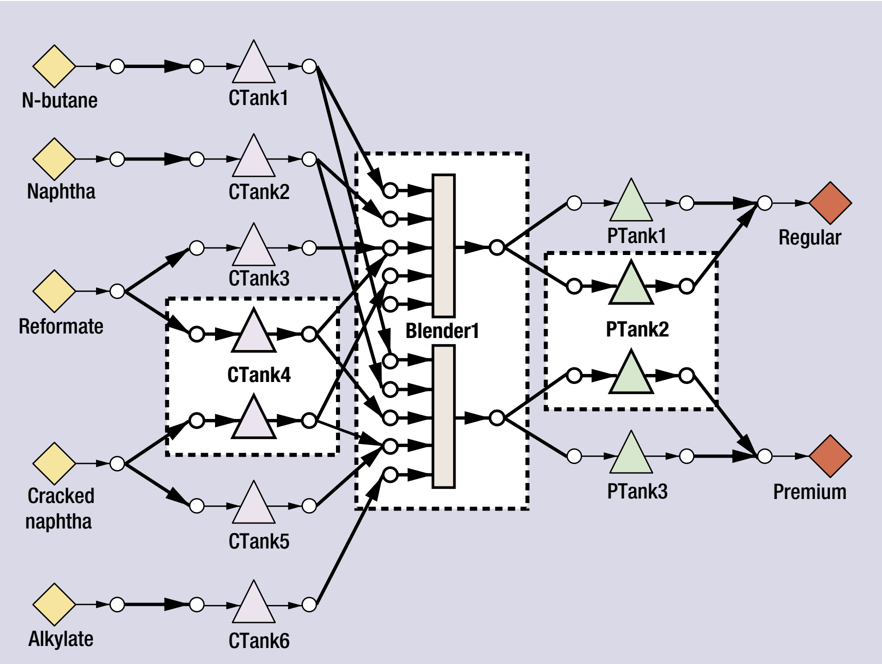

FIG. 1 An effective way to articulate the logistics details is through a small, but representative, blendshop example.

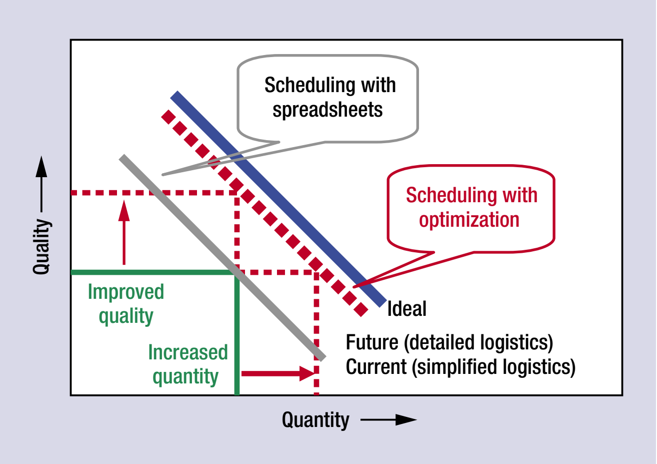

FIG. 2 Quantity-quality trade-off curve with logistics isotherms.

This means that, when scheduling blendshops in practice, schedules are considered to be complete when only the quantity constraints are feasible such as no tank over- or underflows, lower and upper flow sizes are respected, and supply and demand orders for feedstocks and product stocks are satisfied. The section to follow describes the fine points behind scheduling logistics in blendshops, which we consider to be the missing link in generating full and accurate blend production schedules.

Blending logistics detail. An effective way to articulate the logistics details is through a small but representative blendshop example (Fig. 1). Blendshop modeling is taken from our unit-operation-stock superstructure (UOSS) production modeling framework.[5,6,7] The diamonds represent supply and demand points or perimeter units where component stocks enter the blendshop and product stocks leave. The triangles are the tanks or pool units, the rectangles are the blend-headers or continuous process units (or batch process units if doing batch blending) and the circles are called port units, representing the stocks or materials. The two types of streams are internal and external. Internal streams define how ports are connected to units such as perimeters, processes and pools, and external streams define the port-to-port connectivity which are boldfaced in the figure.

A unit can be either multipurpose or dedicated. Units N-butane, Naphtha, Reformate, Cracked naphtha, Alkylate, CTank1, CTank2, CTank3, CTank5, CTank6, PTank1, PTank3, Regular and Premium are dedicated. Units CTank4, Blender1 and PTank2 are multipurpose or sometimes referred to as swing-tanks and swing-blenders. In addition, the outlet ports connected to Reformate, Cracked naphtha, CTank1, CTank2, CTank4 and Blender1 are considered to be multipurpose or multiplexed ports, given that they can split or bifurcate to two or more destinations.

Both dedicated and multipurpose units have corresponding quantity and logic variables attached that relate to the notion that all units can execute or occupy one and only one operation, activity, task or mode at any give time. A unit that can perform two or more operations is drawn or shown as a "logical" unit-operation (c.f., the units surrounded by the dotted-lined boxes). For example, the three multipurpose units are actually shown as CTank4-Reformate, CTank4-Cracked naphtha, Blender1-Regular, Blender1-Premium, PTank2-Regular and PTank2-Premium. Eventually, the production network described in Fig. 1 becomes a node arc-directed graph with unit operations as nodes and the internal and external streams as arcs where the external streams, as mentioned, are the port-to-port movements between logical unit operations.

The purpose of the logistics scheduling optimizer is to maximize profit and performance, and to minimize penalties[1] subject to quantity, logic and mixed quantity and logic constraints and bounds using the quantity and logic variables. The time horizon is discretized into relatively small time buckets or periods of either fractions or multiples of an hour. Solving these types of multiple time-period problems requires commercial-strength mixed-integer linear programming (MILP) solvers. A list of the quantity and logic constraints required to effectively and accurately model industrial-scaled blendshops found in oil refineries and petrochemical complexes are:

- Semicontinuous restrictions to model the fact that a flow must be 0 or between its lower and upper bounds. These constraints are for blend and movement sizes. Semicontinuousness is the simplest form of logistics.
- Single-use limits on units to model the requirement that a unit can be in only one mode or material service at a time.
- Multi-use lower and upper limits on ports to model the requirement that an inlet or outlet port must have a minimum and/or maximum number of flows in or out.
- Fill-draw-delay lower and upper bounds on the time required between the last fill (move in) and the last draw (move out). The lower delay value is useful to model a mixing delay on a tank before a draw suboperation can occur. The upper bound stipulation is useful to handle perishable stocks, whereby a draw suboperation must occur before the upper delay value. There can also be a draw-fill-delay that models the situation where a fill cannot occur until a certain amount of time after a draw. A fill-draw-delay of zero time will establish that a tank is in standing-gauge (dead-tank) as opposed to a running-gauge (live-tank), which is a common logic constraint used in blendshops to model the situation of "tank swinging" (using one tank then the other).
- Fill-to-full quantity is handy when a pool unit in a particular operation or material service must keep filling until it is greater than or equal to the quantity specified; there is a symmetrical draw-to-empty quantity.
- Shut-down-when-empty quantity is a useful constraint on pool unit operations to specify that if a particular unit operation shuts down (i.e., switches to a new material service) then the holdup in the tank must be less than or equal to the quantity specified; there are also other symmetrical logistics such as start-up-when-empty, startup-when-full and shut-down-when-full.
- Up-time lower and upper bounds allow a campaign or minimum and maximum run-length specification for a mode or move. They can also be used to model the cycle or processing time of a batch process. A down-time lower and upper bound can be specified as well.
- Equal-flow constraints ensure that, when there are consecutive operations across several time periods on a unit or move between the same source and destination, the quantity sizings are the same in each time period. Another approach to equal-flow is to use flow-smoothing that minimizes, in the performance term of the objective function, the absolute values of the

deviation between one time period to the next. This is similar to the "move-suppression" found in popular model-predictive controllers.

• Sequence-dependent switchovers offer the ability to accommodate transition management when switching between one mode or grade to the next on a blender or tank. This can be used to handle product wheels—where only a certain order of from-operations to to-operations can occur. For example, you can switch the material service on a tank from reformulated to conventional gasoline but not visa versa due to contamination issues. Sequence-independent switchovers will enforce a certain amount of downtime (or nonproductive time) on a unit to proxy the repetitive/routine maintenance such as cleaning or retooling.

• Noncontiguous order fulfillment constraints attached to ports on perimeters are useful to model the arrival and departure times of marine vessels or what we call parcel units. Any time before the arrival time or after the departure time, material cannot be loaded (or unloaded). Any time in between, material can flow. It is not required that flow be contiguous or consecutive, only that the supply or demand quantity is met. The complement is contiguous order fulfillment that is used to model delivery or lifting from or to a pipeline unit. Flow between the start and end times must occur contiguously within the specified time window (i.e., start time to end time).

Unfortunately, all of the logistics constraints are basically being ignored in the quality scheduling simulation approach. Another important quantity modeling constraint is the bill-of-resources or materials required for continuous and batch processes. These are commonly referred to as "blend recipes," where it is perfectly acceptable to have the logistics scheduling optimizer choose between several different "favorite" recipes for the same grade of product stock blended as is described in reference 8. Each inlet port on a logical unit operation will have what we call an "inverse yield," fraction, intensity or proportion amount that specifies the intensive amount of component stock required to prepare the blend. When multiplied by the blend size at each time period, it will determine the quantity required from each component tank over time and is considered to be a proxy or substitute constraint for quality. Together with the 10-plus logistics constraints defined previously and the usual quantity or material balance constraints for each logical unit operation, a comprehensive set of logistics equalities and inequalities for the typical HPI blendshop is defined.

Blending logistics performance. Anyone familiar with blending performance as it relates to quality has heard about quality giveaway and quality nonattainment for, say, road octane and Reid vapor pressure (Rvp), which are metrics to quantify the amount of over- or under-specification. But, what about the other types of giveaway/nonattainment relating to quantity and logic (logistics)?

Quantity giveaway is trivial to quantify when either too much or too little product stock is produced and demand lifting orders must be shorted or longed; it becomes less apparent when tank inventories overflow or underflow due to too much or too little supply of component stocks. The more interesting set of metrics are around logic that can quantify the amount of "misoperation." Several types of logic giveaways/nonattainments can be described as follows, though this is by no means an exhaustive enumeration:

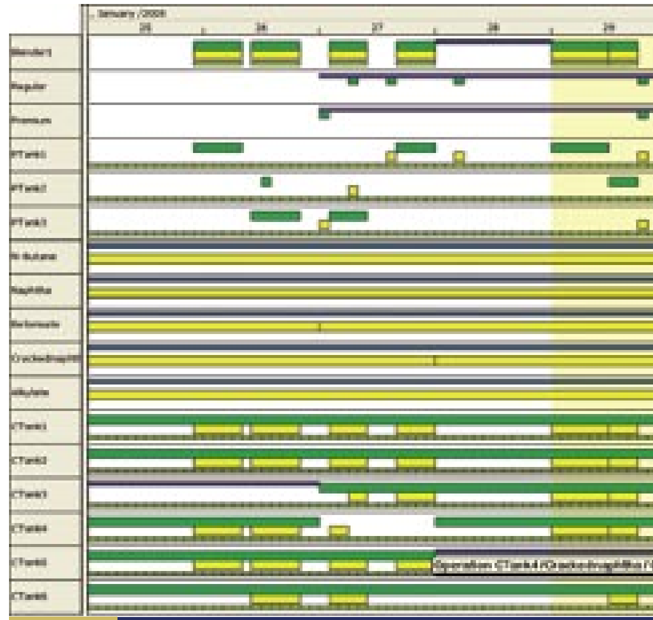

FIG. 3 Gantt chart for the blendshop example displays the logic details.

• A marine vessel has significantly delayed its departure from the berth and a demurrage is levied. This is an example of a timing or logic nonattainment relating to the end-time of a noncontiguous order fulfillment.

• A multiproduct or swing tank was switched over to a different material service, but the inventory in the tank was significantly above the shut-down-when-empty quantity, signaling another logic nonattainment. Also, it was observed that the from-material was conventional and the to-material is reformulated gasoline incurring a sequence-dependent switchover violation that could result in significant off-specification product stock.

• A blending operation for a particular grade of product stock was supposed to last for at least 6 hr of continuous operation but was shut down after only 3.5 hr. This is a lower up-time logic nonattainment misoperation and could impact the blendstock quality when not enough time has elapsed to bring the blend on specification given the available closed-loop dynamics of the blend property controller. A lower up-time is also useful to help operations balance startup/shutdown (fixed) costs versus switch-over-to-itself (variable) costs. Why make two small blends when you can do it with one larger blend?

• When viewing the inventory trends for components and product tanks, supposedly under standing gauge restriction (i.e., with fill-draw-delay of zero), the classic "sawtooth" profiles were not observed. This sawtooth behavior implies a distinctive fill followed by a distinctive draw and so on. It also usually requires fill-to-full and draw-to-empty quantities to be fairly close to their upper and lower holdup capacity bounds, respectively, so that fill-then-draw chatter is not present. Sawtooth inventory trends can indicate a high-performance blendshop in that a limited number of movements are required.

• A one-flow-out restriction (multi-use upper bound on an outlet port) is required on all logical unit operations on blenders to ensure that a blend operation for a particular product stock can only go to one product tank. However, it was noticed that the output of the blender was sent to two tanks simulta-

TABLE 1. Tank and blender sizing

Unit	Operation	Lower	Upper
CTank1	N-butane	0 kbbl	10 kbbl
CTank2	Naphtha	0 kbbl	30 kbbl
CTank3	Reformate	0 kbbl	25 kbbl
CTank4	Reformate	0 kbbl	50 kbbl
CTank4	Cracked naphtha	0 kbbl	50 kbbl
CTank5	Cracked naphtha	0 kbbl	35 kbbl
CTank6	Alkylate	0 kbbl	10 kbbl
Blender1	Regular	4 kbbl/hr	5 kbbl/hr
Blender1	Premium	4 kbbl/hr	5 kbbl/hr
PTank1	Regular	0 kbbl	50 kbbl
PTank2	Regular	0 kbbl	75 kbbl
PTank2	Premium	0 kbbl	75 kbbl
PTank3	Premium	0 kbbl	50 kbbl

TABLE 2. Supply and demand order sizing and timing

Unit	Operation	Start time	End time	Lower	Upper
N-butane	N-butane	Jan. 25, 2005 00:00	Jan. 30, 2005 00:00	20 kbbl	20 kbbl
Naphtha	Naphtha	Jan. 25, 2005 00:00	Jan. 30, 2005 00:00	50 kbbl	50 kbbl
Reformate	Reformate	Jan. 25, 2005 00:00	Jan. 30, 2005 00:00	90 kbbl	90 kbbl
Cracked naphtha	Cracked naphtha	Jan. 25, 2005 00:00	Jan. 30, 2005 00:00	110 kbbl	110 kbbl
Alkylate	Alkylate	Jan. 25, 2005 00:00	Jan. 30, 2005 00:00	20 kbbl	20 kbbl
Regular	Regular	Jan. 27, 2005 00:00	Jan. 30, 2005 00:00	110 kbbl	110 kbbl
Premium	Premium	Jan. 27, 2005 00:00	Jan. 30, 2005 00:00	135 kbbl	135 kbbl

TABLE 3. Blend recipes or inverse yields

Unit	Operation	Port/Stock	Lower	Upper
Blender1	Regular	N-butane	0.050	0.075
Blender1	Regular	Naphtha	0.150	0.175
Blender1	Regular	Reformate	0.300	0.325
Blender1	Regular	Cracked naphtha	0.350	0.450
Blender1	Regular	Alkylate	0	0
Blender1	Premium	N-butane	0.050	0.075
Blender1	Premium	Naphtha	0.150	0.175
Blender1	Premium	Reformate	0.300	0.325
Blender1	Premium	Cracked naphtha	0.350	0.450
Blender1	Premium	Alkylate	0.075	0.090

neously and not sequentially. This type of misoperation can result in significant off-specification product stock given that the blend property controller would be set up to fill a specific product tank (i.e., the tank heel properties are included in the controller setup).

These examples are intended to help the reader understand the particulars of what we mean behind blending logistics performance and to contrast them briefly with blending quality performance. However, similar to quality giveaway/nonattainment, logic giveaway/nonattainment may be unavoidable and can indicate a higher-level imbalance that may be due to poor quality planning optimization or simply due to the omnipresent uncertainty found in all manufacturing environments.

From the perspective of assessing the benefits of explicitly scheduling with knowledge of logistics, we can provide some qualitative guidance. Fig. 2 displays a trade-off curve with quantity as the x-axis and quality as the y-axis. There are three "logistics isotherms" shown as three negative sloped diagonal lines. The gray solid line is the base case or the current situation with what we call "simplified logistics," meaning that most of the detailed logistics are ignored or only rudimentarily addressed, and only simulation is performed.

Whenever a certain quality level is required, only a certain amount of quantity can be produced at that quality and that specifies the trade-off of quantity versus quality. To make a step-change in profit and performance for the blendshop, some injection of technology is required, and we will assume that this is achieved with logistics scheduling optimization. The red dotted line shows this new isotherm where we can see an increase in quantity for the same quality and an increase in quality for the same quantity. The blue solid line shows the ideal or best-logistics isotherm that is most likely unattainable. The notion of moving your plant's logistics isotherm by employing smarter scheduling machinery can prove to be economical, effective and efficient with the exact benefits only being reached once a successful implementation has been realized.

Blending example. Here we briefly describe a gasoline blendshop solution based on the problem found in Fig. 1. The scheduling time horizon is set at 5 days and is discretized into 2-hr small time buckets. To make the problem interesting, we have added several preventive/corrective maintenance orders to the problem where it should be recognized that production is the tight integration of process, operations and maintenance. The logistics scheduling optimization was run on a laptop computer running software with penalty-free solutions (i.e., optimized and feasible) being generated in 30 seconds or less. To achieve this level of solution speed, proprietary MILP heuristics were employed.[9,10,11] Table 1 provides the lower and upper lot and charge-size bounds for the tanks and blenders where the opening inventories at the start of schedule for all tanks are 0 kbbl. The supply and demand order details are found in Table 2, with no room for profit optimization given that the lower and upper quantities are the same.

The blend recipes or inverse yields in volume fractions have lower and upper bounds that allow for limited uncertainty in the component stock quality variation from the upstream oil refinery process units. The logistics scheduling optimizer can use this flexibility to meet the fixed order sizing and timing, though the other approach is to add extra blender unit operations for the same grade (i.e., Blender1-Premium-Recipe1, etc.).

Some of the logistics details used are shut-down-when-empty for the multiproduct tanks CTank4 and PTank2, up-time lower bounds on Blender1 itself of 6 hr including any movements out of the blender, equal-flow on the charge-size of the blender, fill-draw-delay of 4 hr on the product tanks to allow for preparing certificate of analyses and noncontiguous order fulfillment for regular and premium perimeter units.

Fig. 3 presents an overview of the blendshop production that displays only the logic details; the quantity details are not shown due to space restrictions. The blue horizontal bars are supply, demand and maintenance orders; the yellow bars indicate movements out of the unit; the green bars indicate movements into the units; the thin light green bars under the tanks and blender indicate the material service or mode of the unit; and the red bars (not shown) indicate quantity and logic penalties or infeasibilities. As is evident from the Gantt chart, there are six distinct blends lasting for at least 6 hr that have been scheduled respecting the planned maintenance order on Blender1.

On the three product tanks, we see green bars followed by shorter yellow bars respecting the lower fill-draw-delay of 4 hr. These yellow bars or movements out of the tanks correspond to green bars on the regular and premium perimeter units. In addition, we can observe that PTank2 switched material service from regular to premium, which is valid given that it is a multiproduct tank. For component tanks CTank3 and CTank5, we added maintenance orders to force the use of CTank4 in either reformate or cracked naphtha material service where required. The hyper-text or tool-tips was activated when we moused over the thinner light green bar for CTank4 to confirm that the holdup was zero when the material service was switched (c.f. "/ 0," which indicates a lot-size value of zero kbbl).

Clearly, an appreciation for blending logistics is required to schedule blendshops effectively. The quantity and logic details described here can be found in most of the world's blendshops. Incorporating them into scheduling optimization can yield significant improvements in efficiency and productivity. Commercial software is available to assist with the modeling and solving the logistics details discussed. **HP**

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