Refining Scheduling of Crude Oil Unloading, Storing, and Processing Considering Production Level Cost

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Abstract

This paper presents an integrated optimization approach for crude operations scheduling and production for refineries. The production process is composed of a pre-fractionator, crude, and vacuum distillation columns. It is modeled as an NLP. The scheduling problem is composed of unloading operations and simultaneous blending and charging of CDUs. It is modeled as a MILP. The nonlinear simulation model for the production process is used to derive individual crude costs for the two crudes considered (Dubai and Masila). This is performed using multiple linear regressions of the individual crude oil flow rates around the crude oil percentage range allowed by the production facility. These individual crude costs are then used to derive a linear cost function that is optimized in the MILP scheduling model, along with logistics costs. Results show that this integrated approach can lead to a 0.53 M$ decrease in production and logistics costs in a 15 day time horizon.

Keywords: multilevel simulation, refinery scheduling, process optimization

1. Introduction

Process industry supply chains are striving to improve efficiency (Shah, 2005). Resources can be used more efficiently by ensuring local objective functions along the supply chain are not undermining overall goals. Combining objectives is computationally burdensome so heuristics are used to narrow the solution space before integration can fine-tune the overall objective function. Along the crude oil supply chain, there exists an unloading/loading scheduling problem followed by a refinery operating problem. Modern refining has become an extremely competitive business because of the deteriorating quality of crude oil coupled with tighter product specifications and more stringent environmental regulations. Therefore, refineries today receive many different types of crude from a variety of places. Refineries frequently change a unit’s operating conditions to reduce operating expenses including environmental impact. A general description of the oil production system considered in our analysis, which consists of vessels, docks, storage tanks, and a separation train, is shown in Figure 1.
Along the oil supply chain, vessels or tankers carrying crude arrive at the docking station according to a schedule whose duration is known as the time horizon. It is then decided in what manner the crude oil is unloaded from the vessels to storage tanks during the time horizon. The crude oil in the storage tanks is transferred to a blending manifold where it enters the separation train in a desired composition ratio range determined at the production level. We identify two local objectives along the crude oil supply chain. The crude scheduling problem (CSP) receives the shipping vessel’s schedule, including arrival times, type, amounts, the CDU demand, and blend range. The scheduler of the crude loading and unloading decides which tanks to store the incoming crude oil and which tanks should feed the refinery distillation units (CDU/VDU). The scheduler does so in a fashion which minimizes logistical costs such as inventory holding, sea-waiting, and setup cost, while feeding the separation train with the proper blend of crude oil. The production unit planner manipulates unit operating conditions in order to optimize the energy integration of the fractionating section of the refinery as well as minimize environmental cost such as the burning of high sulfur fuels in furnaces.

The traditional approach to the crude scheduling problem (CSP) for a refinery is a discrete time optimization formulation where the scheduling horizon is split into time intervals of equal size and binary variables are used to indicate if an action starts or terminates during this time interval (Saharidis et al., 2009). Various mathematical models have been developed to solve the CSP. The objective functions of these solutions include cost incurred for waiting sea vessels, unloading cost, inventory cost, etc. Yet, the blend of the crude affects the refining cost even when in the operational range. The effect of combining these objectives has not yet been published.

2. Problem Statement

This section contains the specifics of a typical scenario which was analyzed in this work.

2.1 The Process: Primary Units of a Crude Oil Refinery

The separation train considered in this study consists of pre-fractionator, atmospheric, and vacuum distillation columns each with a preheat train ending with a furnace to elevate the crude feed temperature. Masila crude is blended with lighter Dubai crude for refining. This crude oil is separated by vapor pressures into fluids with differing properties including naphtha, kerosene, diesel, gas oil, etc. The crude is first heated to approximately 245°C before entering the 30 stage pre-fractionator distillation column which takes off light gas and light naphtha in order to reduce the vapor load in the distillation column. The pre-topped crude is then further heated before entering the CDU where heavy naphtha, two kerosene grades, and diesel side draws are taken off. The bottoms are put under a vacuum, heated further and separated in the VDU into another diesel stream, light vacuum gas oil, heavy vacuum gas oil, sour diesel, and vacuum residuum. Product side draws lead into steam strippers and steam is blown up though each main column. In order to recover as much heat as possible from the
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distillation units, pump around streams exist and along with the product stream, compose the preheat trains. Some separated products are finished while others must be further treated, but each can be assigned a value.

On the production level, personnel must maximize the amount of valuable product considering the environmental and utility cost of the separation train by manipulating steam to the main column, the steam to the side strippers, pump around flow rates, side cuts, as well as operating conditions such as temperature. The complex heat integration schemes and the interactive nature of the process due to the presence of pump around and side-strippers make it difficult to operate at the optimal conditions. Each product streams must meet certain specifications such as density and compositions, but side cuts of the distillation columns have room for slight manipulation while still meeting these specifications. Product draws are then stripped with steam in side strippers. The heat integration strategy recovers as much heat as possible from the distillation process by recovering heat from final products as well as pump around streams. The Decision Variables are the stripping steam mass flow rates, product flow rates, pump around flows, reflux rate, and atmospheric & vacuum furnace outlet temperatures (25 in our model). The constraints are the quality parameters, temperature of the product flows, furnace duty, and the bounds on the Decision Variables. A more detailed problem description can be found in Yela and Romagnoli (2008).

2.2 Short Term Refinery Scheduling problem

In our case study, one dock is used to feed one refinery CDU with six tanks as intermediate storage. Tanks 1, 3, and 6 initially contain 90,000 m$^3$ Dubai, 40,000 m$^3$ Masila, and 99,000 m$^3$ Masila respectively. The Masila crude is blended with lighter Dubai crude for refining. The time horizon is 15 days with discrete time intervals of 1 hour. A 90,000 m$^3$ shipment of Dubai is scheduled to arrive in the first time interval and will continuously unload for 36 hours. Similarly, a ship is scheduled to arrive on the 51st time interval and unload an addition 90,000 m$^3$ of Masila. The demand for the CDU is 765 m$^3$/hr throughout the duration of the time horizon, and the flow rate from the tanks to blender CDU has a limitation of 600 m$^3$. The setup of a pipeline is a lengthy procedure including filling the pipeline and sampling its contents, so the setup cost plus penalty are accessed at $5,000. The CDU component concentration ranges between 32.5 vol%-37.5vol% Dubai.

The following assumptions can be made for our problem: the amount of crude oil remaining in the pipeline is neglected; due to their small value in comparison with the scheduling horizon change over times are neglected; it is also assumed that there is perfect mixing in the blending manifold tanks and any additional mixing time is neglected in this model.

The decision variables that are determined at this level are: flow rates from vessel to storage tank for each vessel; flow rates from storage tank to CDUs for each storage tank; crude oil inventory levels in storage tanks for each time interval; series of crude oil blends to be charged in each CDUs under optimum costs; periods where connections are established (or setups) or broken.
3. Refinery Simulation/optimization and MILP scheduling model

This section presents models and objective functions used in the solution approach to solving the presented problem.

3.1 Production Level Model/Optimization

Objective Function: The goal in the production planning level is maximizing revenue. The objective function used includes the cost associated with the feed, products, utilities, and environmental effects. Due to the rising concerns on global warming and with implementation of emissions trading programs (“cap and trade”), the triple bottom line objective function was used (Yela & Romagnoli, 2008).

\[
\text{TripleBottomLine} = \text{ProfitFunction} - \text{EnvironmentalCosts} + \text{SustainableCredits} \quad (1)
\]

\[
\text{ProfitFunction} = \text{RevenueofProducts} - \text{UtilityCosts} \quad (2)
\]

*In Eq. (1) Environmental Costs is the cost required to comply with environmental regulations including permits, monitoring emissions, fines, etc; Sustainable credits represents the credits given to the processes that consume CO\textsubscript{2}. In this study, sulphur dioxide (SO\textsubscript{2}), carbon dioxide (CO\textsubscript{2}), and nitrogen oxides (NO\textsubscript{x}) are chosen as Environmental Load.

The modelling equations include thermodynamic relationships, mass balances, and energy balances obtained using Hysys software. The NLP optimization model is solved with Frontline Systems’ Premium Solver Platform, and a bridge code is programmed in Visual Basic Application allowing the user to import and export selected variables between the HYSYS model and Excel worksheet.

3.2 Scheduling Solution Approach

The objective function consists of logistical costs such as loading/unloading and refining costs of the blend entering the separation train. In our scenario sea-waiting times and inventory costs are negligible making setup the only the logistical cost.

Model equations are constructed by combining material balances for the vessel, storage tanks, and operation rules for arrival and departure of vessels as well as for crude oil charging. GAMS optimization software with CPLEX solver was used for the bilinear mixed integer linear loading/unloading scheduling problem. The complete model can be found in Saharidis et al. (2009) using flexible recipe blending in manifold model.

3.3 Integration of the two models

To account for the operational cost of crude oil blend entering the CDU, a linear relationship between individual crude flow rates and total refining cost was embedded into the MILP’s objective function. For several crude flow rates Eq. (1) is maximized and the associated total costs are tabulated. The refining cost from the separation optimization is calculated for the desired range of operation set for the production level and a cost equation as a function of the individual crude feed flow rates, \(Y_n\), is created:

\[
\text{Cost}(Y_1, Y_2, \ldots, Y_n) = \prod_{n=1}^{N} a_n Y_n
\]
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The coefficients, $a_i$, of Eq. 3 are determined by multiple linear regressions around the range allowable for the production facility. This refining cost function is then embedded into the scheduling and planning MILP objective function. The optimization process first takes the variables of the triple bottom line objective function from the Hysys library for the production layer model. The VBA bridge code then embeds them into an Excel spreadsheet where Frontline chooses the next set of variables to insert into the Hysys model. In each of the iterations, the total cost of the refinery operations is embedded into the Excel spreadsheet. After the decision variables have reached a maximum, the cost of the profit optimized refinery are tabulated over the production level range.

4. Results and Discussion

Table 1 illustrates an optimal production unit operation conditions for particular feed flow rates.

<table>
<thead>
<tr>
<th>Decision Variables</th>
<th>Optimal value</th>
<th>Constraints (Min)</th>
<th>Constraints (Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LN rate, m³/hr</td>
<td>12.05</td>
<td>10.00</td>
<td>14.00</td>
</tr>
<tr>
<td>HN rate, m³/hr</td>
<td>27.51</td>
<td>26.00</td>
<td>30.00</td>
</tr>
<tr>
<td>Kerosene-1 rate, m³/hr</td>
<td>98.57</td>
<td>95.00</td>
<td>99.00</td>
</tr>
<tr>
<td>Kerosene-2 rate, m³/hr</td>
<td>46.12</td>
<td>44.00</td>
<td>49.00</td>
</tr>
<tr>
<td>Diesel rate, m³/hr</td>
<td>106.03</td>
<td>102.00</td>
<td>107.00</td>
</tr>
<tr>
<td>ADU feed Temp., degC</td>
<td>372.00</td>
<td>372.00</td>
<td>373.00</td>
</tr>
<tr>
<td>VDU feed Temp. degC</td>
<td>398.00</td>
<td>398.00</td>
<td>400.00</td>
</tr>
</tbody>
</table>

The refining cost for the maximized profit (Eq. 1) is tabulated for each of the twelve Dubai-Masila flow rate sets, each whose sum is 756 m³/hr and whose ratio is within the production allowable range. Table 2 shows data points created using the production optimization/simulation to determine the relationship between the crude blends, refining cost, revenue, and predicted values from that fitting function.

Table 2 describes some of the key process (decision) variables and the product flows at a specific feed flow rate of Masila and Dhubei.

*Note difficult conditions to change such as temperature are tightly constrained.

<table>
<thead>
<tr>
<th>Dubai Flow (m³/hr)</th>
<th>Masila Flow (m³/hr)</th>
<th>vol%</th>
<th>Refining cost</th>
<th>Predicted cost</th>
<th>Residuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>286.6</td>
<td>478.6</td>
<td>0.371</td>
<td>33981.81</td>
<td>33928.5</td>
<td>53.31315</td>
</tr>
<tr>
<td>283.8</td>
<td>481.5</td>
<td>0.370</td>
<td>34240.47</td>
<td>33954</td>
<td>286.4732</td>
</tr>
<tr>
<td>278</td>
<td>487.3</td>
<td>0.363</td>
<td>34096.08</td>
<td>33997.06</td>
<td>99.02241</td>
</tr>
<tr>
<td>275.2</td>
<td>490.1</td>
<td>0.359</td>
<td>33621.26</td>
<td>34017.85</td>
<td>-396.586</td>
</tr>
<tr>
<td>269.4</td>
<td>495.9</td>
<td>0.352</td>
<td>33654.13</td>
<td>34060.91</td>
<td>-406.776</td>
</tr>
<tr>
<td>260.8</td>
<td>504.6</td>
<td>0.340737</td>
<td>34288.87</td>
<td>34129.47</td>
<td>159.4029</td>
</tr>
<tr>
<td>258</td>
<td>507.4</td>
<td>0.337</td>
<td>33794.59</td>
<td>34150.26</td>
<td>-355.665</td>
</tr>
</tbody>
</table>
The residuals from the total cost function were randomly distributed within the blend range. The linear Regression provides the following equations used for predicting cost on the scheduling level:

$$Total\ Cost = 39.7\$/m^3 \times Y_{Dubai} + 47.1\$/m^3 \times Y_{Masila}$$  \hspace{1cm} (4)

Table 3 demonstrates the result of the scheduler adding the operational cost to the MILP’s objective function. A tabulation of the number of setups comprises the first row’s entries when the scheduler minimizes the logistical costs (setup cost in our scenario), while still abiding by the production level blend specifications.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Setup</th>
<th>Total cost (M$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min(setup cost)</td>
<td>4</td>
<td>4.52</td>
</tr>
<tr>
<td>Min(total cost)</td>
<td>4</td>
<td>3.99</td>
</tr>
<tr>
<td>Benefit</td>
<td>0</td>
<td>.53</td>
</tr>
</tbody>
</table>

The returned total cost was then calculated. It was found even when the setup was the same, i.e. the logistical costs were similar, the operational cost could be minimized further. In other words, there exists a solution space for the general objective function. Therefore adding the cost function picks a particular solution with the lowest refining cost. The second row indicates the results from minimizing the sum of refining and setup costs which gave the minimal total cost. Although there are many solutions to one problem, this particular solution can lead to a total cost of 4.52M$. Therefore, there is a potential reduction in cost of $530,000 by combining the different levels.

5. Conclusions

An optimization approach was presented, integrating the optimal schedule for the short-term refinery loading, unloading, and production problems. Production optimization and production level costs were considered in the tactical scheduling problem of a refinery. The strategy proposed accounts for these costs in a simple yet effective manner. The results show a significant decrease in the total operational cost for the refinery.

References

