Real-Time Optimizing Control of a Class of Crude Oil Blending Operations

A. Rodriguez-Angeles   A. Morales-Diaz
Mexican Petroleum Institute
Program of Applied Mathematics and Computation
Eje Central Lazaro Cardenas 152, Mexico D.F., 07730, Mexico
arangele@imp.mx   bmorales@imp.mx
A. M. Blanco
PLAPIQUI (UNS-CONICET), Universidad Nacional del Sur, Argentina
ablanco@plapiqui.edu.ar
A. Sanchez
Dept. of Elec. Eng. and Computing, Cinvestav
Apdo. Postal 31-438, Guadalajara 45091, Jalisco, Mexico
arturo@gdl.cinvestav.mx

Abstract

A real–time optimizing (RTO) controller for the blending of crude oil is presented. The RTO controller uses a non–linear "bias-update" technique and measurements of crude component properties to provide optimal blend flows. Two typical operating scenarios are considered for the blending of two inputs. The objective of the first scenario is to keep a constant flow of blended crude with a minimum production cost. The second case considers maximizing the amount of the heavier crude input while maintaining constant the flow rate of the lighter crude input. Simulation results are compared with historic data of a real blending process, showing the convergence properties and efficiency of the RTO controller.

1 Introduction

Blending is well recognized as a common operation in the process industries (e.g. petrochemical, cement, paint) playing a key role in achieving the required quality parameters for intermediate and final products. It has been established in the petrochemical industry that proper blending of crude oils could be translated in increments of up to 0.30 USD/bbl for a type of crude oil representing 13.6% of Mexican exports [5]. Also, an optimal crude feedstock with small variability on its properties results in more stable and consistent operation of downstream processes, yielding higher value products and improving refinery and downstream processes profit margins.

Advanced automation technology plays an important role in improving product quality, optimizing processes and achieving economic benefits. Since the economic optimum of virtually all industrial processes occurs at an intersection of process constraints - that is, where multiple operating constraints are active making difficult the improvement of process economics - the objective is to locate a feasible optimum and continually push the operation of the process toward the optimum against the constraints. Two important tools in this effort are advanced process control (APC) and RTO. The role of APC is to reduce variation in controlled variables and thus allow their set–points to be placed closer to their optima. However, APC in itself is unable to identify which constraints are active and define a local economic optimum. The role of RTO, based on rigorous process models, is to identify and track the constraints that define an economic optimum, and to pass operating targets to the APC to enforce operation against these constraints. By running at regular intervals, an RTO system ensures that changes in the plant or economic environments that shift the active constraint set are tracked and that the APC is continually pushing the economically optimal constraints.

The key for APC and RTO control is the use of on-line measuring and analysis equipment that provides reliable and accurate process measurements. However, it is common that correction of crude component properties may take several hours due to the

ISBN: 970-32-2137-8

need of running laboratory tests. On–line measurement and analysis would help the optimizing control to correct, through feedforward techniques, for deviations and variations in crude component, while feedback techniques correct and optimize the blending model for regulation of variations on the blended crude. In this way the optimizing blending control will drive the crude product qualities in the specified control toward the quality limit, whilst optimizing the usage of the crude components. The aim of the optimizing controller is to yield a product that meets quality specifications during the entire operation. If that cannot be achieved (i.e. the blend is infeasible), it will instead provide an alternative feasible solution.

Because crude oil properties may vary considerably, real-time optimizing controllers have been proposed previously for calculating the optimal operating conditions. In [4] is introduced the notion of a "bias update" scheme. [7] improved the formulation with a non-lineal model and including an stochastic model for perturbations. Coordination control has been also used for crude blending purposes [3]. [1] studied the "bias update" for gasoline blends, establishing sufficient conditions for stability and convergence. They also showed that this scheme can be interpreted as a feedback linear-integral regulator acting on the modeling error. More recently, extensions to the work of [1] have been developed by [2] and [6], where centralized and decentralized models for blending processes are presented and economical optimization criteria and density quality constraints are used.

This work based on those of [2] and [6] addresses a non-linear optimization problem, making the RTO crude oil blending system capable of dealing with more realistic problems. The RTO blending control considers density, water volumes and salt contents as operational requirements. It takes into account design (max. and min. flow rates) and operation variables (raw materials availability and physical properties). The goal of the RTO blending control is to provide optimal crude component flows based on measurements of crude component quality and blended crude quality. The desired blended crude quality are established by contractual values.

Two typical operating scenarios are considered for the blending of two inputs. The objective of the first scenario is to keep a constant flow of blended crude with a minimum production cost. The second case considers maximizing the amount of the heaviest crude input while maintaining constant the flow rate of the lightest crude input.

Section 2 describes the proposed model for the crude oil blending process with two inputs. The controller formulation then follows in Section 3. Dynamic simulation results are presented in Section 4 comparing the performance of the proposed RTO controller against conservative guidelines for blending processes. The paper closes with section 5 discussing practical aspects of the proposed scheme.

2 Model of a blending node

The crude blending node with two input crude components to be considered is shown in Figure 1. The crude components are denoted by C_1 and C_2, corresponding to the lighter and the heavier crudes. The properties of the crude components are measured online and may exhibit high variability due to the crude origin (e.g. oil well, tank).

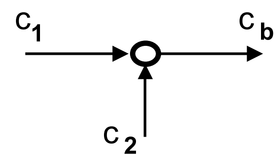

Figure 1: A crude blending node

The crude components C_i, for $i = 1, 2$, are characterized by their minimum $f_{i,min}$ and maximum $f_{i,max}$ mass flow rates in $[kg/hr]$, densities ρ_i in $[kg/m^3]$, percentage of water volume w_i in [%], and salt concentration s_i in $[kg/m^3]$. So, each crude component can be characterized by a vector of properties given by

$$C_i = \{f_{i,min}, f_{i,max}, \rho_i, w_i, s_i\} \qquad i = 1, 2 \qquad (1)$$

The blended crude (product) is denoted by C_b and is characterized by its density ρ_b, the percentage of water in the oil w_b, and the salt concentration s_b, thus by the vector

$$C_b = \{\rho_b, w_b, s_b\} \qquad (2)$$

The properties (quality) of the blended crude are determined by the blending ratio of crude component flows and their properties.

The blending process presents non-ideal effects on the density due to excess properties and volume reduction phenomena [2], [6]. Thus, the density of the blended crude can be modeled as [8]

$$\rho_b = \rho_l + \rho_{nl} \qquad (3)$$

where ρ_l and ρ_{nl} denote the linear and non-linear

ISBN: 970-32-2137-8

density contribution and are given by

$$\rho_l = \frac{\rho_1\rho_2(f_1+f_2)}{f_1\rho_2+f_2\rho_1} \quad (4)$$

$$\rho_{nl} = \frac{\pi_{1,2}\rho_1\rho_2 f_1 f_2}{(f_1\rho_2+f_2\rho_1)^2} \quad (5)$$

with f_1, f_2 the crude component flows, and $\pi_{1,2}$ an interaction coefficient between the crude components. $\pi_{1,2}$ is determined empirically through a positive adjustment parameter $\delta > 0$, and it is given by

$$\pi_{1,2} = \delta(\rho_1+\rho_2) \quad (6)$$

The water content and salinity are considered to behave linearly. They are modeled by the corresponding mass balances

$$w_b = \frac{w_1 f_1\rho_2 + w_2 f_2\rho_1}{f_1\rho_2+f_2\rho_1} \quad (7)$$

$$s_b = \frac{s_1 f_1\rho_2 + s_2 f_2\rho_1}{f_1\rho_2+f_2\rho_1} \quad (8)$$

The mass flowrate of the blended crude f_b in $[kg/hr]$ is given by

$$f_b = f_1 + f_2 \quad (9)$$

notice that the blended flow rate is not a quality parameter, but it becomes a constraint depending on the optimization functional to be considered.

3 RTO Control formulation

The RTO controller must satisfy quality constraints related to the density, water content and salinity in the oil. Nevertheless, there may be some other constraints imposed by the particular problem being considered.

3.1 Quality constraints and bias update

¿From the model of the crude blended properties (3), (7) and (8), the RTO control must satisfy the quality constraints

$$\rho_b \leq \rho_{b,max} \quad (10)$$

$$w_b \leq w_{b,max} \quad (11)$$

$$s_b \leq s_{b,max} \quad (12)$$

where $\rho_{b,max}$ denotes the maximum allowed density, $w_{b,max}$ the maximum percentage of water content, and $s_{b,max}$ the maximum salt concentration in the oil.

Notice that the RTO controller is monitoring the blended properties, through on-line measurements, to ensure that they satisfy the constraints given by (10) - (12). The differences between the measurements and the model predicted values are used to compute a "bias update" term. The "bias update" compensates for the deviation errors and improves the convergence of the RTO controller and increases its robustness.

The linear contribution (4) on the blend density (3) can be computed using measurements of the crude components. However, the non-linear contribution (5) depends on empirical coefficients introducing significant uncertainty. Assuming that the deviations between measurements and model predicted values are due to the non-linear contribution, a modification to (3) is introduced as follows

$$\hat{\rho}_b = \rho_l + \eta \quad (13)$$

where η is a bias update term given by

$$\eta = \rho_{b,m} - \frac{f_1\bar{\rho}_1 + f_2\bar{\rho}_2}{f_2+f_3} \quad (14)$$

with $\rho_{b,m}$ the blended crude density measurement, and $\bar{\rho}_1, \bar{\rho}_2$ the average crude component density, which may be obtained from historic data or assigned by operators criteria.

For water content w_b and salt percentage s_b of the blended crude, the models (7) and (8) do not considered non-linear contributions. Moreover, from historic data measurements of a real crude blending process, the deviations between model predicted values and measurements are so small that can be neglected. Therefore, such models are considered for monitoring the crude blended properties. Thus, by considering (7),(8), (4), (13) and (14), the quality constraints to be satisfied by the RTO controller are given by

$$\hat{\rho}_b = \rho_l + \eta \leq \rho_{b,max} \quad (15)$$

$$w_b \leq w_{b,max} \quad (16)$$

$$s_b \leq s_{b,max} \quad (17)$$

3.2 Objective functions

For a complete formulation of the RTO control, the optimization criteria must be defined. According to the manipulated variables in the crude blending operations, that is crude component flows and actual blending policies. two objective functions are introduced.

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3.2.1 Case 1

If the flows f_1, f_2 can be manipulated by the RTO controller and costs $c_{c,1}, c_{c,2}$ are associated to each of the crude components, then the optimization goal can be stated as to keep a constant flow of blended crude with a minimum production cost. This goal is formulated as

$$J_1 = \min_{f1,f2} \quad c_{c,1}f_1 + c_{c,2}f_2 \tag{18}$$

Because the flow of the blended crude f_b must be kept constant and equal to a desired value $f_{b,d}$, then a constraint is added to those given by (15), (16) and (17). Therefore, the goal is to achieve J_1 subject to (15), (16), (17) and

$$f_1 + f_2 = f_{b,d} \tag{19}$$

3.2.2 Case 2

The second objective function considers a constant flow of the lighter crude component f_1. The goal is to maximize the injected flow of the heavier crude component f_2

$$J_2 = \max f_2 \tag{20}$$

subject to (15), (16) and (17).

4 Simulation results

Simulations for the RTO controller considering both objective functions (18) and (20) were carried out with SIMULINK (MATLAB). For both cases the same crude components C_1, C_2 are considered. The properties of the crude components are listed in Table 1, while the desired blended crude quality properties are listed in Table 2. Note that petrochemical units are used. For density units, ^{o}API are inversely related to $[kg/m^3]$, it means that a lighter oil in $[kg/m^3]$ has a higher ^{o}API value and viceversa. Because J_1 and J_2 subject to (15), (16), (17) are nonlinear optimization problems, the routine *fmincon* is used to solve the RTO problem.

For comparison purposes, 12 hours of operation were simulated using a conservative flow ratio guideline taken from real historic data from PEMEX (Petroleos Mexicanos). Then, the RTO controller is activated for the 12 hours more. Applying case 1 of section (3.2.1), the value of the blended crude oil is $f_{b,d}$ = 4000 [bbls/hr]. Following the guidelines and the historic data, the obtained flow of the crude components are $f_1 = 3900$ and $f_2 = 100$ [bbls/hr] for the lighter and heavier crude respectively.

	$f_{i,min}$ [bbls/hr]	$f_{i,max}$ [bbls/hr]	ρ_i [^{o}API]
C_1	0	6000	32.4
C_2	0	6000	30.0
	w_i [%]	s_i [lb/kbbls]	$c_{c,i}$ [USD/bl]
C_1	0.2	30	24.78
C_2	0.7	80	24.41

Table 1: Crude component properties.

	ρ_i [^{o}API]	w_i [%]	s_i [lb/kbbls]
C_b	32.0	0.5	50

Table 2: Desired blended crude quality properties.

Figures 2 to 6 show the results for the optimization case 1, Section 3.2.1.When the RTO control is activated, at $t = 12$ hrs., the flow of the heavier crude component f_2 increases, while f_1 decreases to keep a constant crude blended flow, constraint (19). The increasing in f_2 implies an economical benefit by using a heavier crude component, therefore achieving a lower production cost, Figure 6.

The results for the optimization case 2, Section 3.2.2 are shown in Figures 7 to 10. Note that when the RTO control is activated, at $t = 12$ hrs., the flow of the heavier crude component f_2 increases until achieving the density quality constraint as shown in Figure 8. This yields an increasing on the produced volume to about 4500 [bbls/hr], and implies an economical benefit because of using a major proportion of a heavier oil, which will be commercialized on the price of a higher value oil.

Notice that in both optimization cases all the quality constraints are satisfied and the active constraint corresponds to the density 15.

5 Conclusions

The proposed RTO control achieves the production quality requirements, whilst optimizing the crude component flows. Because several quality constraints are imposed, this opens the door for interesting trade-off considerations in establishing contractual conditions. With the proposed RTO control changes in crude components and blended crude properties can be managed more efficiently. The RTO control is robust to variations on the crude properties due to the bias update, that compensates deviations between the model predicted properties and online measurements.

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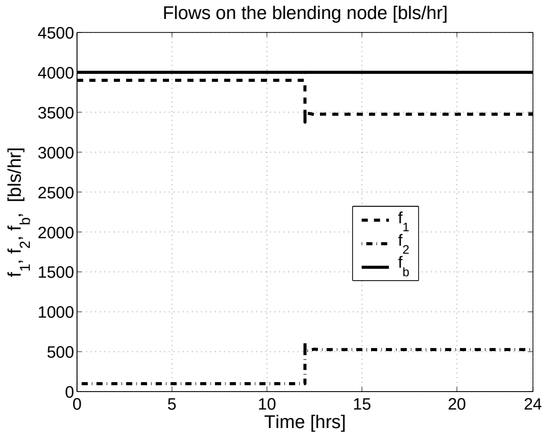

Figure 2: Flows on the blending node, case 1 (3.2.1).

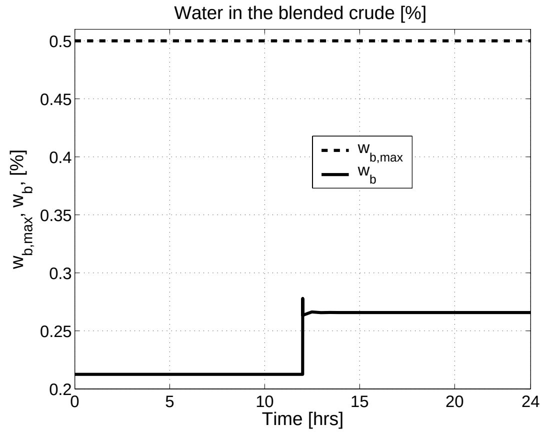

Figure 4: Water in the blended crude, case 1 (3.2.1).

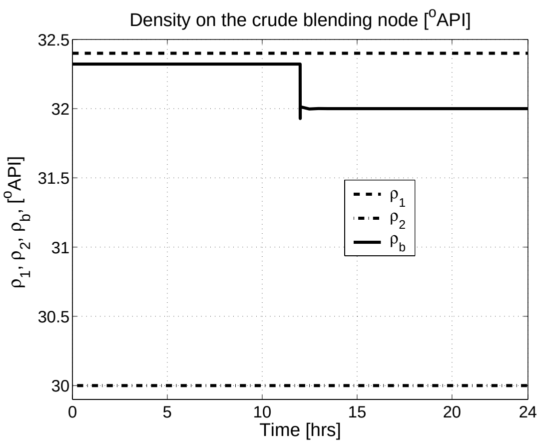

Figure 3: Density on the blending node, case 1 (3.2.1).

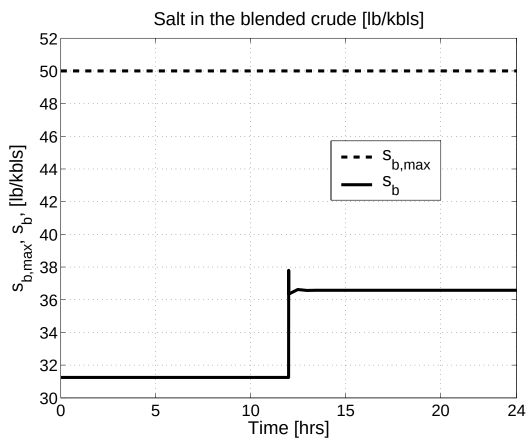

Figure 5: Salt in the blended crude, case 1 (3.2.1).

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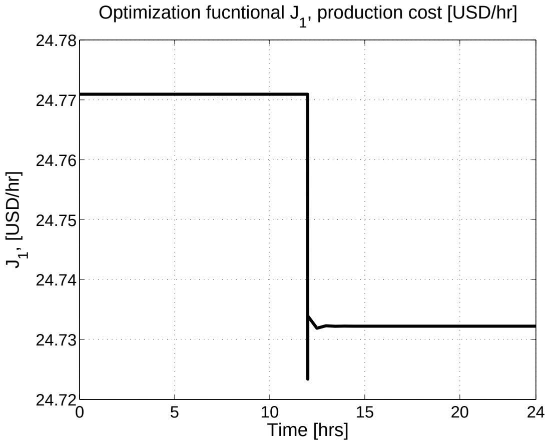

Figure 6: Optimization functional J_1, case 1 (3.2.1).

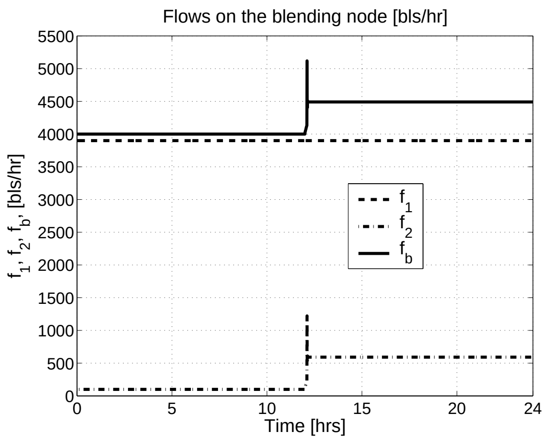

Figure 7: Flows on the blending node, case 2 (3.2.2).

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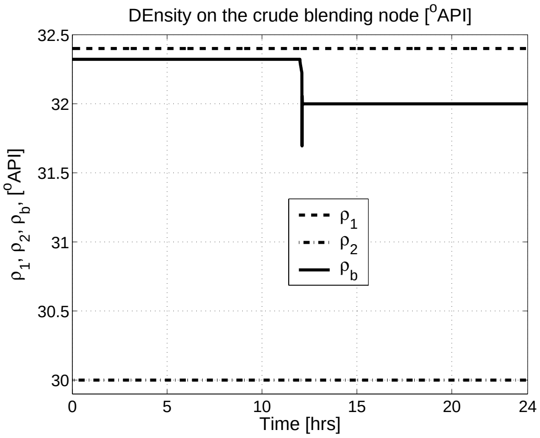

Figure 8: Density on the blending node, case 2 (3.2.2).

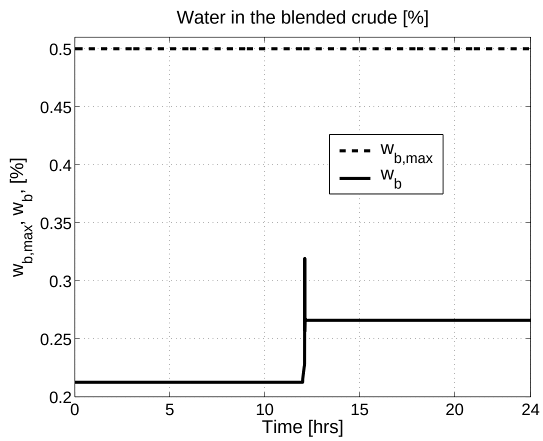

Figure 9: Water in the blended crude, case 2 (3.2.2).

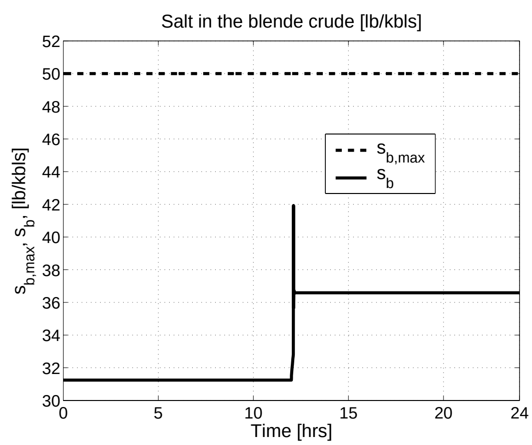

Figure 10: Salt in the blended crude, case 2 (3.2.2).

ISBN: 970-32-2137-8