

# REAL-TIME OPTIMIZING CONTROL OF A CLASS OF CRUDE OIL BLENDING OPERATIONS

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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.  
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## 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 (Sanchez and Morales, 2003). 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 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 towards the optimum against the constraints. Two important tools in

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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 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 Forbes and Marlin (1994) is introduced the notion of a “bias update” scheme. Singh *et al.* (1997) improved the formulation with a non-linear model and including an stochastic model for perturbations. Coordination control has been also used for crude blending purposes (Chang *et al.*, 1998). Alvarez *et al.* (2002) 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 Alvarez *et al.* (2002) have been developed by Campos *et al.* (2003) and Sanchez *et al.* (2004), 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 (Campos *et al.*, 2003) and (Sanchez *et al.*, 2004), 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 heavier crude input while maintaining constant the flow rate of the lighter 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

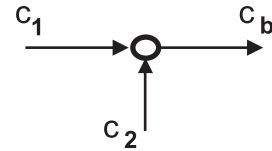


Fig. 1. A crude blending node.

A crude blending node with two input crude components is considered as shown in Figure 1. The crude components are denoted by  $C_1$  for the lighter crude and  $C_2$  corresponding to the heavier one. The properties of the crude components are measured online and present high variability due to its origin, i.e. oil well, tank. The crude components  $C_i$ , for  $i = 1, 2$ , are characterized by their minimum  $f_{i,min}$  and maximum  $f_{i,max}$  flow rate in  $[kg/hr]$ , the density  $\rho_i$  in  $[kg/m^3]$ , the percentage of water in the oil  $w_i$  in  $[\%]$ , and the salt concentration  $s_i$  in  $[kg/m^3]$ . So, each crude component can be characterized by a vector of properties given by

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

The blended crude (product) is denoted by  $C_b$  and is characterized by its density  $\rho_b$ , the percentage of water in the oil  $w_b$ , and the salt concentration  $s_b$ , thus by a vector of properties as

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

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-linear effects on the density due to excess properties and volume compression phenomena (Campos *et al.*, 2003), (Sanchez *et al.*, 2004). Therefore following thermodynamic theory (Smith and Van Ness, 2000) the density of the blended crude is modeled as

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

where  $\rho_l$  and  $\rho_{nl}$  denote the linear and non-linear 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

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

Among the properties of the blended crude (2), the density is the most important one and thus modeled in detailed by (3). The other properties are modeled only by its linear contribution and mass balance, although, if it is required the non-linear contribution of the blending process may be incorporated. The water and salinity models are given by

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

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

For completeness of the parameters of the blended crude, its flow  $f_b$  in  $[kg/hr]$  is given by

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

notice that the blended flow 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 some quality constraints related to the density, water and salinity in the oil. Nevertheless, there may be some other constraints imposed by the particular optimization functional being considered.

#### 3.1 Quality constraints and bias update

From the model of the crude blended properties (3), (7) and (8) we have that 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, and  $s_{b,max}$  the maximum salt concentration in the oil.

Notice that the RTO controller is monitoring the blended properties, through online 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 for the density property. 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 blended density quality (3) can be straightforwardly computed from measurements of the crude components. However, the non-linear contribution (5) depends on empirical coefficients that introduce lots of 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  $\eta$  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 to operators' criteria.

For the water  $w_b$  and the salt  $s_b$  on the blended crude, the models (7) and (8) do not consider non-linear contributions. Moreover, from historic data measurements of a crude blending process, the deviations between model predicted values

and measurements is so small that it 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 Optimization functionals

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

*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 by the optimization functional

$$J_1 = \min_{f_1, f_2} c_{c,1}f_1 + c_{c,2}f_2 \quad (18)$$

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

$$f_1 + f_2 = f_{b,d} \quad (19)$$

*3.2.2. Case 2* The second functional considers a constant flow of the lighter crude component  $f_1$ , so that, the goal is to maximize the injected flow of the heavier crude component  $f_2$ , this is

$$J_2 = \max f_2 \quad (20)$$

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

## 4. SIMULATION RESULTS

Simulations for the RTO controller considering both optimization functionals (18) and (20) are carried out. For both cases the same crude components  $C_1, C_2$  are considered. The properties of the crude components are listed in Table 4, while the desired blended crude quality properties are

Table 1. Crude component properties.

	$f_{i,min}$ [bbl/hr]	$f_{i,max}$ [bbl/hr]	$\rho_i$ [°API]
$C_1$	0	6000	32.4
$C_2$	0	6000	30.0
	$w_i$ [%]	$s_i$ [lb/kbbl]	$c_{c,i}$ [USD/bbl]
$C_1$	0.2	30	24.78
$C_2$	0.7	80	24.41

Table 2. Desired blended crude quality properties.

	$\rho_i$ [°API]	$w_i$ [%]	$s_i$ [lb/kbbl]
$C_b$	32.0	0.5	50

listed in Table 4. Note that the property units are in petrochemical units, therefore a unit conversion routine, to the units considered on the models and constraints, is incorporated to the simulator. In particular for density units the °API gravity are inversely related to  $[kg/m^3]$ , it means that a lighter oil in  $[kg/m^3]$  has a higher °API value. The simulator has been programmed in SIMULINK (MATLAB). Because the optimization constraints  $J_1$  and  $J_2$  subject to (15), (16), (17) are nonlinear the routine *fmincon* is used for solution of the RTO problem. For comparison purposes the blending simulator runs 12 hrs with a conservative flow ratio guideline, that is reported on historic data from a petrochemical company. Then the simulator changes to the RTO controller and runs for 12 hrs more. Because the desired blended flow in case 1, section (3.2.1), is  $f_{b,d} = 4000$  [bbl/hr], and according to the guidelines and the historic data the flow of the crude components are  $f_1 = 3900$  and  $f_2 = 100$  [bbl/hr] for the lighter and heavier crude respectively.

Figures 2 - 6 show the results for the optimization case 1, Section 3.2.1. Note that 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 - 10. Note that when the RTO control is activated, at  $t = 12$  hrs., the flow of the heavier crude component  $f_2$  increases till achieving the density quality constraint Figure 8. This yields an economic benefit by increasing the proportion of the heavier oil, which will be commercialized as a higher value oil.

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

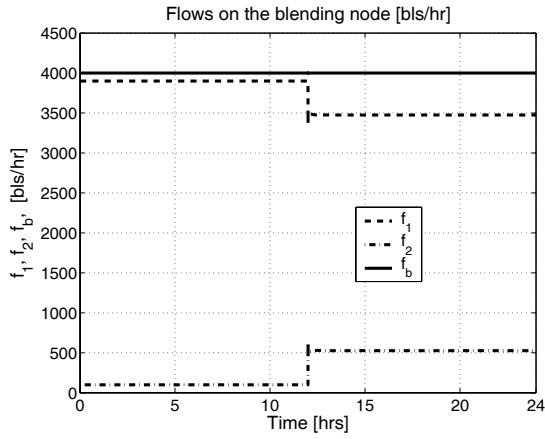


Fig. 2. Flows on the blending node, case 1 (3.2.1).

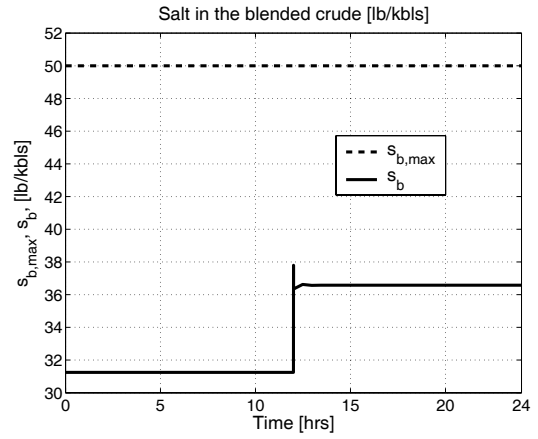


Fig. 5. Salt in the blended crude, case 1 (3.2.1).

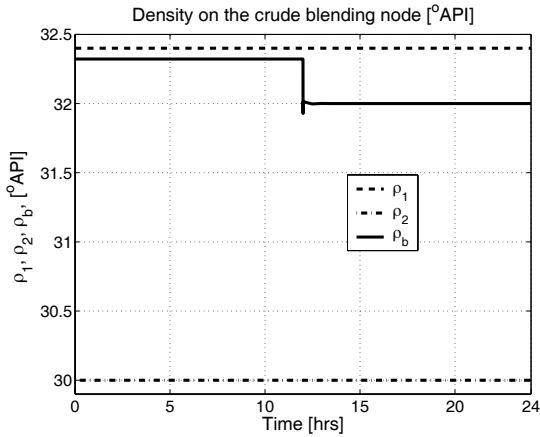


Fig. 3. Density on the blending node, case 1 (3.2.1).

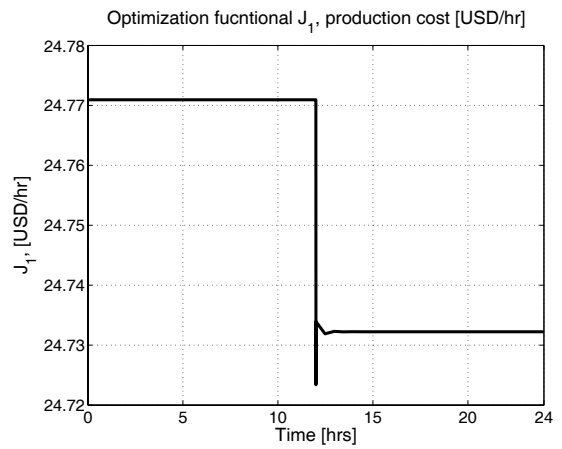


Fig. 6. Optimization functional  $J_1$ , case 1 (3.2.1).

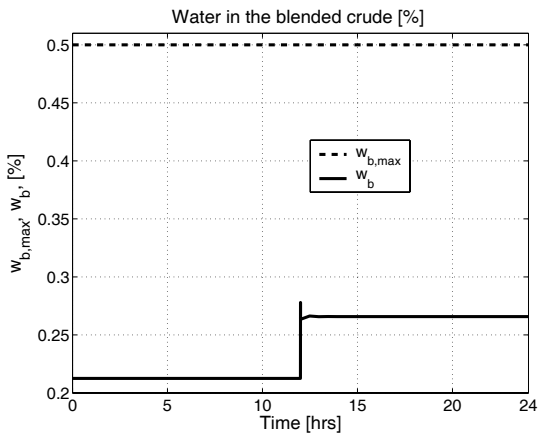


Fig. 4. Water in the blended crude, case 1 (3.2.1).

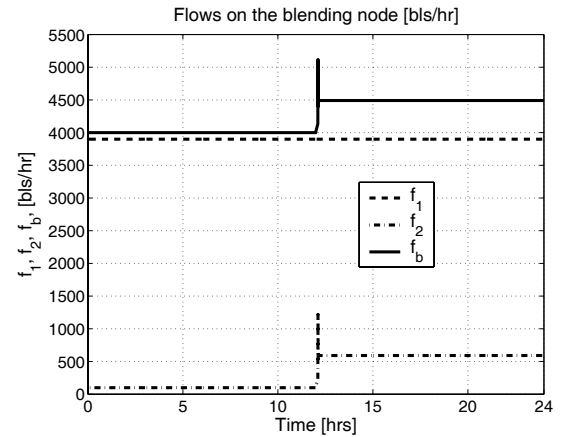


Fig. 7. Flows on the blending node, case 2 (3.2.2).

## 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 compensates for variations on the crude properties and deviations between the model predicted properties and online measurements, due to the bias update.

It may be possible that an optimal solution is not feasible, in such cases the RTO controller provides an alternative feasible solution. The performance of the RTO controller is limited by the measuring equipment resolution.

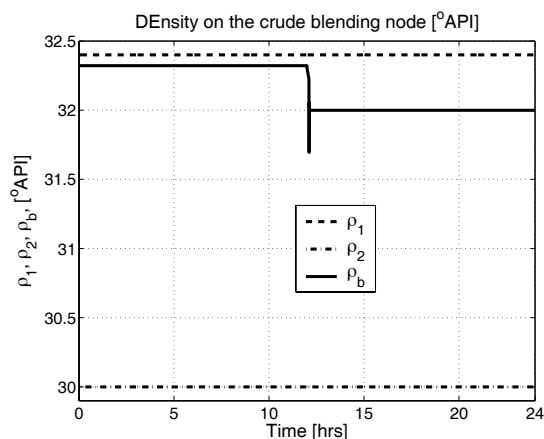


Fig. 8. Density on the blending node, case 2 (3.2.2).

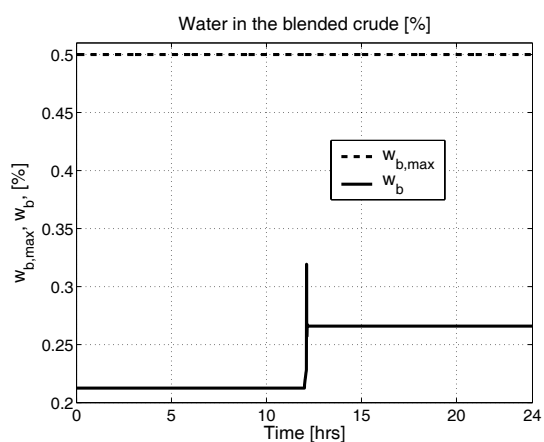


Fig. 9. Water in the blended crude, case 2 (3.2.2).

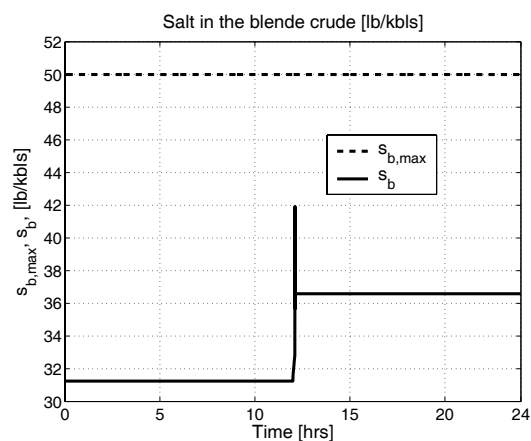


Fig. 10. Salt in the blended crude, case 2 (3.2.2).

## REFERENCES

- Alvarez, J., A. Morales and R. Suarez (2002). Robustness of a class of bias update controllers for blending systems. *Industrial Engineering Chemistry Research*, **41**, 4786–4793.
- Campos, N., A. Morales and A. Sanchez (2003). Aplicacion de un sistema de control optimizante para mezclado de petroleo crudo. In: *CD Proceedings AMCA '03*.
- Chang, D.M., C.C. Yu and I.L. Chieng (1998). Coordinated control of blending systems. *IEEE Transactions on Control Systems Technology*, **6**(4), 495–506.
- Forbes, J.F. and T.E. Marlin (1994). Model accuracy for economic optimizing controllers: the bias update case. *Industrial Engineering Chemistry Research*, **33**(8), 1919–1929.
- Sanchez, A. and A. Morales (2003). Estimacion del beneficio economico por mejoras en la administracion y control del mezclado de crudo de exportacion en TMBD. Technical report. Mexican Petroleum Institute, Program of Applied Mathematics and Computation. Mexico D.F., Mexico.
- Sanchez, A., N. Campos and A. Morales (2004). An optimizing controller for crude oil blending operations. In: *CD Proceedings ESCAPE' 04*.
- Singh, A., J.F. Forbes, P.J. Vermeer and S.S. Woo (1997). Model updating in the presence of stochastic feedstock disturbances fro real-time optimization of blending operations. In: *Proceedings of the ACC' 97*. pp. 2966–2971.
- Smith, J. and H. Van Ness (2000). *Introduction to chemical engineering thermodynamics*. McGrawHill.