PROCESS DESIGN AND CONTROL

On a New MILP Model for the Planning of Heat-Exchanger Network Cleaning. Part II: Throughput Loss Considerations

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This paper is a follow-up to a paper on the scheduling of heat-exchanger network cleaning. In the first part (Lavaja, J. H.; Bagajewicz, M. *Ind. Eng. Chem. Res.* **2004**, *43*, 3924−3938), a new mixed-integer linear model for the planning of heat-exchanger cleaning in chemical plants was presented. This model minimizes the net present value of the combined costs of cleaning and energy; it takes into account changes in production rates and even changes in the properties and flows of the different streams throughout time. The model is extended here to allow the consideration of throughput reduction throughout the time horizon in cases where the maximum capacity of the furnace is reached. Results show that throughput reduction may be advisable at times. Multipurpose/multiperiod operation of the network under critical conditions is also addressed.

Introduction

In all chemical industries, the energy consumption for the processes represents an important part of the operating costs, which makes the efficient use of the energy an important issue. Because of the need for heat recovery, almost every chemical industry is nowadays heat integrated by one or more networks of heat exchangers.

The presence of dissolved or suspended materials in almost any exchanging fluid and the process conditions are, in general, favorable to the growth of deposits on the heat transfer surfaces. This process not only deteriorates the heat transfer surfaces and decreases the heat transfer capacity of the equipment but also can lead to large production losses due to planned or unplanned shutdowns of a part of a unit or an entire unit.

A previous paper (Part I) presented by Lavaja and Bagajewicz[1] introduced a new model for optimizing the cleaning schedule of heat-exchanger networks. All the background material of the problem is reviewed in Part I.[1] The model minimizes the total operating costs of the network by finding the balance point of the tradeoff existing between the fouling and the cleaning costs. The current study extends the model to optimize the throughput reduction required when the maximum capacity of the furnace is reached at a certain point of the time horizon considered or when it is desired to operate the network at a higher throughput during a certain time horizon.

The paper is organized as follows: We present first the set of equations that allow simulating the operation of a multipurpose/multiperiod network capable of processing different types of crude in the given time horizon, along with the logic required to consider throughput reduction. Next, we show the results for processing heavy crude under limited conditions in terms of furnace capacity and under “over-throughput” conditions for the operation of a two-branch multipurpose/multiperiod network. Finally, results for the case of processing light and heavy crude consecutively within the time horizon are presented. The paper also addresses the heuristic that forbids throughput reduction.

Highlights of the Previous Model. The model previously presented in Part I[1] is a rigorous mixed integer linear programming (MILP) model which minimizes the expected net present value (throughout the time horizon) of the operating costs arising from the tradeoff between furnace extra fuel costs due to fouling and heat-exchanger cleaning costs (which include manpower, chemicals, and maintenance).

Consider a heat-exchanger network (HEN) of a crude distillation unit where heat is recovered from distillation column products and pump-around streams. We consider that time is discretized in interval periods (typically months), and each one of these is subdivided into a cleaning subperiod and an operation one. Thus, the objective is to determine which exchanger is to be cleaned in which period given other restrictions and resource availability so that the net present value of the cost is minimized. The solution should also take into account the possibility of changing any network flow rate and/or fluid for any operation period. The clean and actual heat transfer coefficient in period t (U_i^c and U_{it}, respectively) are related to the fouling factor (r_{it}) by

$$r_{it} = \frac{1}{U_{it}} - \frac{1}{U_i^c} \quad (1)$$

We define a binary variable that identifies *when* and *which* exchanger is cleaned as follows:

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$$Y_{it} = \begin{cases} 1 & \text{if the } i\text{th heat exchanger is cleaned in period } t \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

The clean and actual heat transfer coefficient for each subperiod can be written in terms of the binary variable and the fouling factor as follows,

$$U_{it}^{\mathrm{ecp}} = \sum_{k=0}^{t-1}\left[a_{ikt}^{c} Y_{ik}\prod_{j=k+1}^{t}(1-Y_{ij})\right] + b_{it}^{c} Y_{it} + c_{it}^{c}\prod_{p=0}^{t}(1-Y_{ip}) \qquad \forall i,t \geq 1 \quad (3)$$

$$U_{it}^{\mathrm{eop}} = \sum_{k=0}^{t-1}\left[a_{ikt}^{o} Y_{ik}\prod_{j=k+1}^{t}(1-Y_{ij})\right] + b_{it}^{o} Y_{it} + c_{it}^{o}\prod_{p=0}^{t}(1-Y_{ip}) \qquad \forall i,t \geq 1 \quad (4)$$

where a_{ikt}, b_{it}, and c_{it}^{c} are constants that are a function of the different parameters. These equations are substituted in the equations corresponding to the heat-exchanger heat balance to render an expression for the hot outlet temperature (Th_{2it}).

$$\mathrm{Th}_{2it} = \left.\begin{aligned} &\frac{(R_{it}-1)\mathrm{Th}_{1it} - R_{it}\mathrm{Tc}_{1it}}{R_{it}\, e^{d_i\left[\sum_{k=1}^{t-1}\left(a_{ikt}Y_{ik}\prod_{j=k+1}^{t}(1-Y_{ij})\right)+b_{it}Y_{it}+c_{it}\prod_{p=1}^{t}(1-Y_{ip})\right]} - 1} + \\ &\frac{R_{it}\mathrm{Tc}_{1it}\left[e^{d_i\left[\sum_{k=1}^{t-1}\left(a_{ikt}Y_{ik}\prod_{j=k+1}^{t}(1-Y_{ij})\right)+b_{it}Y_{it}+c_{it}\prod_{p=1}^{t}(1-Y_{ip})\right]}\right]}{R_{it}e^{d_i\left[\sum_{k=1}^{t-1}\left(a_{ikt}Y_{ik}\prod_{j=k+1}^{t}(1-Y_{ij})\right)+b_{it}Y_{it}+c_{it}\prod_{p=1}^{t}(1-Y_{ip})\right]} - 1} \end{aligned}\right\} \forall i,t \geq 1 \quad (5)$$

where $d_{it} = A_i/\mathrm{Fc}_{it}\mathrm{Cc}_{it}(R_{it} - 1)$. The expression can be easily linearized through standard procedures.[1] The model minimizes the expected net present value (throughout the time horizon) of the operating costs arising from the tradeoff between furnace extra fuel costs due to fouling and heat-exchanger cleaning costs (which include manpower, chemicals, and maintenance).

$$\mathrm{NPC} = \sum_t d_t \frac{(\mathrm{Ef}_t - \mathrm{Ef}_t^{\mathrm{cl}})}{\eta_{\mathrm{f}}} C_{\mathrm{Ef}} + \sum_t d_t \sum_i Y_{it} C_{\mathrm{cl}} \quad (6)$$

where NPC is the net present costs, Ef_t is the actual furnace's energy consumption, $\mathrm{Ef}_t^{\mathrm{cl}}$ is the furnace's energy consumption for clean conditions, C_{Ef} is the furnace's fuel cost, C_{cl} is the cleaning cost, η_{f} is the furnace efficiency, and d_t is the discount factor.

Although the model is MILP, it has several suboptimal solutions that are close to the overall optimum, and therefore, the computational cost using standard MILP solvers becomes prohibitive. Part I outlines an iterative solution procedure, that can provide good solutions in reasonable computational time.

Scheduling for Multipurpose/Multiperiod Networks. In this section, we extend the model previously presented in Part I[1] to a multipurpose/multiperiod heat-exchanger network capable of processing different types of crude (from light up to heavy crudes) with different flow rates and different inlet and outlet temperatures during a certain time horizon.

In multipurpose/multiperiod networks, some of the exchangers are only used for light or heavy crudes, but not for both. In addition, for each exchanger, the heat transfer coefficient, the fouling rate, and other parameters might vary with the type of crude being processed. Therefore, a set of controlling parameters needs to be incorporated in the model to specify the correct value for those parameters that may change with the type of crude processed for different periods of time. These binary controlling parameters ($N_{i,\mathrm{cr}}$ and $X_{\mathrm{cr},t}$) are defined next:

$$N_{i,\mathrm{cr}} = \begin{cases} 0 & \text{if the } i\text{th heat exchanger is used for crude type cr} \\ 1 & \text{otherwise} \end{cases} \quad (7)$$

$$X_{\mathrm{cr},t} = \begin{cases} 0 & \text{if crude type cr is not being processed at the } t\text{th period of time} \\ 1 & \text{otherwise} \end{cases} \quad (8)$$

We use a logical constraint to force one and only one $X_{\mathrm{cr},t}$ to be 1 at time t, as follows:

$$\sum_{\mathrm{cr}} X_{\mathrm{cr},t} = 1 \qquad \forall t \quad (9)$$

On the basis of these parameters, the flow rates of the cold and hot stream for each exchanger at time t are

$$\mathrm{Fc}_{i,t} = \sum_{\mathrm{cr}} X_{\mathrm{cr},t}\mathrm{Fc}_{\mathrm{cr},i} \qquad \forall i,t \quad (10)$$

$$\mathrm{Fh}_{i,t} = \sum_{\mathrm{cr}} X_{\mathrm{cr},t}\mathrm{Fh}_{\mathrm{cr},i} \qquad \forall i,t \quad (11)$$

respectively. In these equations, $\mathrm{Fc}_{i,t}$ and $\mathrm{Fh}_{i,t}$ are the actual flow rates, and $\mathrm{Fc}_{\mathrm{cr},i}$ and $\mathrm{Fh}_{\mathrm{cr},i}$ are the flow rates for each type of crude that can be processed at time t. The inlet temperature of hot streams in the heat exchangers ($\mathrm{Th}_{1i,t}$) is also defined on the basis of the crude processed as follows:

$$\mathrm{Th}_{1i,t} = \sum_{\mathrm{cr}} X_{\mathrm{cr},t}\mathrm{Th}_{\mathrm{cr},i} \qquad \forall i,t \quad (12)$$

The fouling rate $r_{i,t}$ and the constant $d_i = A_i(R_i - 1)/(\mathrm{Fc}_i Cc_i)$ are now represented as a function of the crude type as follows:

$$r_{i,t} = \begin{cases} \sum_{\mathrm{cr}\neq\mathrm{cr}'} X_{\mathrm{cr},t} r_{\mathrm{cr},i} & \text{if } N_{\mathrm{cr}',i} = 1 \\ \sum_{\mathrm{cr}} X_{\mathrm{cr},t} r_{\mathrm{cr},i} & \text{if } N_{\mathrm{cr},i} = 0\ \forall \mathrm{cr} \end{cases} \quad (13)$$

$$d_{i,t} = \begin{cases} \sum_{\mathrm{cr}\neq\mathrm{cr}'} X_{\mathrm{cr},t} d_i & \text{if } N_{\mathrm{cr}',i} = 1 \\ \sum_{\mathrm{cr}} X_{\mathrm{cr},t} d_i & \text{if } N_{\mathrm{cr},i} = 0\ \forall \mathrm{cr} \end{cases} \quad (14)$$

Throughput Reduction. In this extension of the model, the maximum capacity of the furnace is incorporated into the model as a constraint. Two binary variables are incorporated to determine when the required heat load at the furnace exceeds the maximum for each period of time. The first binary variable ($Z1_t$) takes into account the need of reducing the throughput. In other words, it becomes 1 only if the maximum capacity of the furnace is reached and the throughput must be reduced. The second binary variable ($Z2_t$) becomes 1 only when $Z1_t = 1$ and the magnitude of the reduction is such that it will affect forward contracts and, therefore, will not allow the organization to keep its obligations to the customers:

$$Z1_t = \begin{cases} 0 & \text{when } G_t = G^{OP} \\ 1 & \text{when } G_t < G^{OP} \end{cases} \tag{15}$$

$$Z2_t = \begin{cases} 0 & \text{when } G_t \geq \alpha G^{OP} \\ 1 & \text{when } G_t < \alpha G^{OP} \end{cases} \tag{16}$$

In these equations, G_t is the actual throughput, G^{OP} is the throughput processed without considering reductions, and α represents the fraction of throughput reduction that the firm can incur without affecting forward contracts. When $Z1_t = 1$ but forward contracts are not affected ($Z2_t = 0$), the objective function is penalized with the loss of net profit incurred because of the reduction in the production. The binary variables can also be rewritten in terms of the furnace load, as follows,

$$Z1_t = \begin{cases} 0 & \text{when } \dfrac{Qf_t}{\eta_f} \leq Q_{max} \\ 1 & \text{when } \dfrac{Qf_t}{\eta_f} > Q_{max} \end{cases} \tag{17}$$

$$Z2_t = \begin{cases} 0 & \text{when } \dfrac{Qf_t}{\eta_f} \leq (1+\alpha) Q_{max} \\ 1 & \text{when } \dfrac{Qf_t}{\eta_f} > (1+\alpha) Qf_{max} \end{cases} \tag{18}$$

where Qf_t is the furnace load required for processing G_t and Qf_{max} is the maximum load the furnace can handle. These definitions are translated into model constraints as follows,

$$\left(\frac{Qf_t}{\eta_f} - Q_{max}\right) - \Omega Z1_t \leq 0 \tag{19}$$

$$\left(\frac{Qf_t}{\eta_f} - Q_{max}\right) + \Omega(1 - Z1_t) \geq 0 \tag{20}$$

$$\left(\frac{Qf_t}{\eta_f} - (1+\alpha) Q_{max}\right) - \Omega Z2_t \leq 0 \tag{21}$$

$$\left(\frac{Qf_t}{\eta_f} - (1+\alpha) Q_{max}\right) + \Omega Z2_t \geq 0 \tag{22}$$

where Ω is a number greater than the maximum capacity of the furnace.

In turn, the time horizon is represented by discrete periods of time, each period being split into *cleaning* and *operating* subperiods (as in the previous model). Therefore, all the previous equations are written for both subperiods. We denote the cleaning subperiod with the supra-index "cp" and the operating subperiod with the supra-index "op".

The new objective function is the following,

$$\text{NPC} = \sum_t d_t \Bigg\{ \tau_{cp} \Bigg[C_{Ef} \cdot \frac{(Qf_t^{cp})}{\eta_f}(1 - Z1_t^{cp}) + C_{Ef} Qf_{max} Z1_t^{cp} + \beta G^{OP} \left(\frac{Qf_t^{cp} Z1_t^{cp}}{\eta_f Qf_{max}} - Z1_t^{cp} \right) + \gamma G^{OP} \left(\frac{Qf_t^{cp} Z2_t^{cp}}{\eta_f (1+\alpha) Qf_{max}} - Z2_t^{cp} \right) \Bigg] + (\tau - \tau_{cp}) \times \Bigg[C_{Ef} \frac{(Qf_t^{op})}{\eta_f}(1 - Z1_t^{op}) + C_{Ef} Qf_{max} Z1_t^{op} + \beta G^{OP} \times \left(\frac{Qf_t^{op} Z1_t^{op}}{\eta_f Qf_{MAX}} - Z1_t^{op} \right) + \gamma G^{OP} \left(\frac{Qf_t^{op} Z2_t^{op}}{\eta_f (1+\alpha) Qf_{max}} - Z2_t^{op} \right) \Bigg] \Bigg\} + \sum_t d_t \sum_i Y_{it} C_{cl} \tag{23}$$

where β and γ are the penalties representing throughput loss and loss of contracts, respectively, τ represents the duration for the time period, and τ_{cp} is the duration for the cleaning subperiod. This objective function contains products of integers and continuous variables. To linearize this objective function, we resort to variable substitution and new constraints. These are standard transformations. Thus, the objective function is rewritten as follows,

$$\text{NPC} = \sum_t d_t \Bigg\{ \tau_{cp} \Bigg[\frac{C_{Ef}}{\eta_f}(Qf_t^{cp} - Q1_t^{cp}) + C_{Ef} Qf_{max} Z1_t^{cp} + \beta G_{max} \left(\frac{Q1_t^{cp}}{\eta_f Qf_{max}} - Z1_t^{cp} \right) + \gamma G_{max} \left(\frac{Q2_t^{cp}}{\eta_f (1+\alpha) Qf_{max}} - Z2_t^{cp} \right) \Bigg] + (\tau - \tau_{cp}) \times \Bigg[\frac{C_{Ef}}{\eta_f}(Qf_t^{op} - Q1_t^{op}) + C_{Ef} Qf_{max} Z1_t^{op} + \beta G_{max} \left(\frac{Q1_t^{op}}{\eta_f Qf_{max}} - Z1_t^{op} \right) + \gamma G_{max} \left(\frac{Q2_t^{op}}{\eta_f (1+\alpha) Qf_{max}} - Z2_t^{op} \right) \Bigg] \Bigg\} + \sum_t d_t \sum_i Y_{it} C_{cl} \tag{24}$$

where $Q1_t^{cp/op}$ and $Q2_t^{cp/op}$ are continuous variables

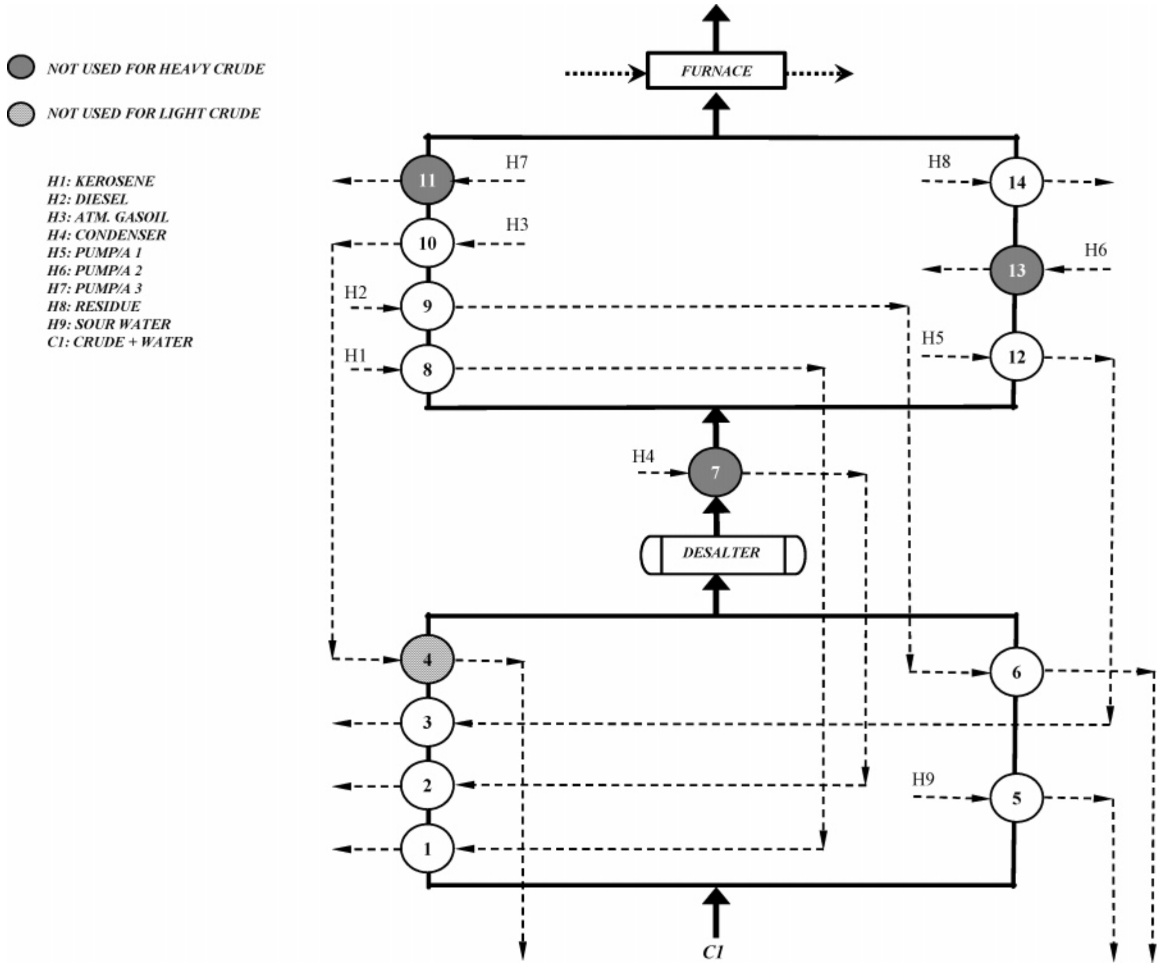

Figure 1. Two-branch heat-exchanger network. Adapted with permission from ref 2. 2003 American Chemical Society.

which substitute the nonlinear terms in eq 23. These variables are then substituted by the corresponding product of continuous and binary variables, which in turn are expressed through standard constraints.

The only value for the throughput considered by the model is the maximum throughput, entered as a constant in the model. This maximum throughput is usually given by either furnace load maximum capacity or column hydraulic limitations. When the solution is obtained, the actual throughput that must be processed for each subperiod is then calculated as follows:

$$\text{Throughput}_t^{\text{cp/op}} \text{ (as \% } G^{\text{OP}}) = \left[1 - \frac{\text{Qf}_t^{\text{cp/op}}}{\eta_\text{f}\text{Qf}_\text{max}} Z1_t + Z1_t\right] \times 100 \quad (25)$$

Results

Throughput Reduction. The following example shows how the model can be used for operating the preheating train under limited conditions—that is, when the furnace capacity reached the limited conditions—or under over-capacity conditions by adding more cleanings and reducing the throughput for short periods of time (cleaning subperiods). Figure 1 shows the network proposed by Bagajewicz and Soto[2] for multipurpose/multiperiod preheating trains. This network has two branches before and after the desalter, resulting in an intermediate network between those that have high levels of branching (which are energy efficient but are not desired in practice, i.e., because of the high level of piping involved) and those that have inefficient one-branch, linear configurations. This network has been designed to be capable of processing light, intermediate, and heavy crudes.

We extend the model presented in part I[1] by adding parallel flow configuration. Appendix A describes the equations added to the previous model, along with the new operational constraints. Table 1 contains the network data, along with the data for the two different crudes processed, light and heavy, indicating which exchangers are off-line for each type of crude ($N_{i,\text{cr}}$). The price of the gas expended in the furnace (C_{Ef}) is shown in Figure 2 and is based on the U.S. natural gas industrial price determined by the U.S. Department of Energy.[3] The cleaning costs of the exchangers vary between \$10 000 and \$15 000 depending on the size.[4]

Case I. No Throughput Reduction Allowed. For any existing network, the furnace has a certain limited capacity, and there exists a set of operational and physical constraints that limits the amount of cleanings that can be done at the same time. It can also occur that the limitations stem from hydraulic limits in the column; we do not consider this case here. Because of these limitations, along with the fact that the exchangers may have a history of fouling at the beginning of the time horizon, the network might reach a certain point of fouling beyond which it is not possible to meet the specifications (column inlet temperature). To simulate this situation, for the network described in Figure 1, we look for the minimum furnace capacity for which

Table 1. Data for the HE Network[a]

exchanger No.	crude type	$N_{i,cr}$	A (ft^2)	Fc × Cpc [Btu/(h °F)]	Fh × Cph [Btu/(h °F)]	U^c [Btu/(ft^2 h °F)]	U^o [Btu/(ft^2 h °F)]	r [(ft^2 °F)/Btu]	Thin (°F)
1	light	1	2 899	808 437	136 680	30	9	1.15E-05	
	heavy	1		709 072	47 520			1.64E-05	
2	light	1	4 177	808 437	835 240	35	21	8.61E-06	
	heavy	1		709 072	246 540			1.23E-05	
3	light	1	2 035	808 437	620 410	30	12	1.15E-05	
	heavy	1		709 072	640 600			1.64E-05	
4	light	0	20 220	808 437	135 800	30	30	1.29E-05	
	heavy	1		709 072	30 960			1.84E-05	
5	light	1	23 550	76 258	178 000	40	12	9.45E-06	220
	heavy	1		240 718	178 700			1.35E-05	220
6	light	1	12 282	76 258	73 750	30	15	1.20E-05	
	heavy	1		240 718	73 130			1.72E-05	
7	light	1	5 118	778 910	835 240	31	31	2.29E-05	293.9
	heavy	0		853 661	246 540			3.27E-05	293.9
8	light	1	4 460	257 429	136 680	41	41	2.42E-05	371.5
	heavy	1		107 502	47 520			3.45E-05	454.3
9	light	1	13 874	275 101	73 750	30	30	2.46E-05	501.3
	heavy	1		118 977	73 130			3.51E-05	557.6
10	light	1	27 632	324 752	135 800	30	30	2.58E-05	612.6
	heavy	1		118 977	30 960			3.68E-05	538
11	light	1	31 212	351 181	215 670	30	30	2.58E-05	589.1
	heavy	0		118 977	215 670			3.68E-05	587
12	light	1	87 874	567 751	620 410	30	30	2.42E-05	342.5
	heavy	1		746 159	640 600			3.45E-05	340.2
13	light	1	10 594	694 746	711 240	30	30	2.46E-05	492.6
	heavy	0		746 159	73 750			3.51E-05	490
14	light	1	18 692	791 694	293 600	30	30	2.63E-05	661.4
	heavy	1		795 285	842 360			3.75E-05	660
Tcin (°F)	light	70							
	heavy	70							
Tcout (°F)	light	679							
	heavy	670							
fr (month)	0.2								
η_f	0.75								
η_c									

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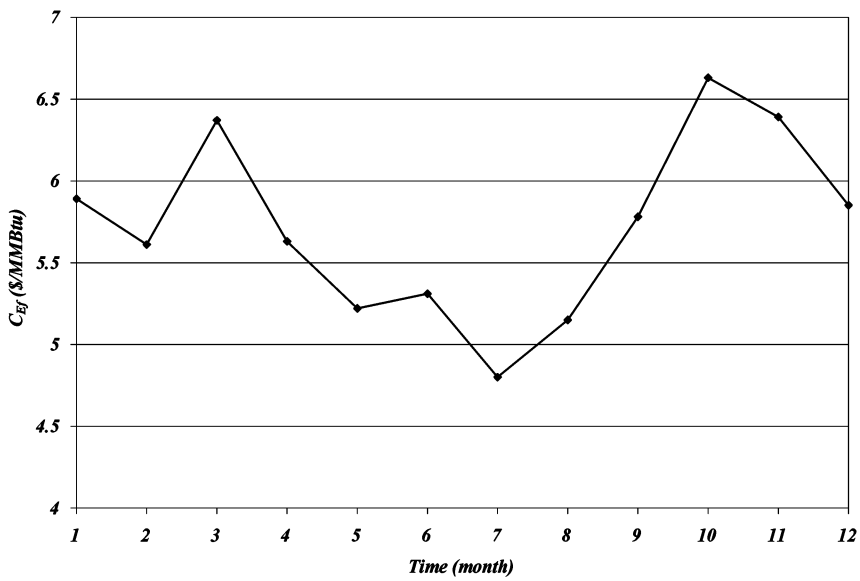

Figure 2. Price of the gas expended in the furnace (C_{Ef})[3].

there exists a feasible solution (Qf_{max}^{min}). Thus, if the capacity of the furnace is $<Qf_{max}^{min}$, it is not possible to achieve, for the throughput considered, the specified column inlet temperature. For the case of a throughput of 120 000 bpd (G^{OP}) of heavy crude throughout a time horizon of 12 months, the value of Qf_{max}^{min} is 542 MMBtu/h. Figure 3 shows the energy load profile for the furnace along the time horizon, and Table 2 shows the cleaning schedule.

Case II. Throughput Reduction Allowed. For the same problem, we then introduced the logic for throughput reduction outlined above. We solve for different values of penalties. We first consider $\gamma = 92$ $/bbl, which corresponds to the market price of product equivalent to a barrel of crude processed. If the furnace capacity is $\geq Qf_{max}^{min}$, the throughput is never reduced, as is commonly practiced in industry, where the throughput is only reduced (to zero) in the case of planned or un-

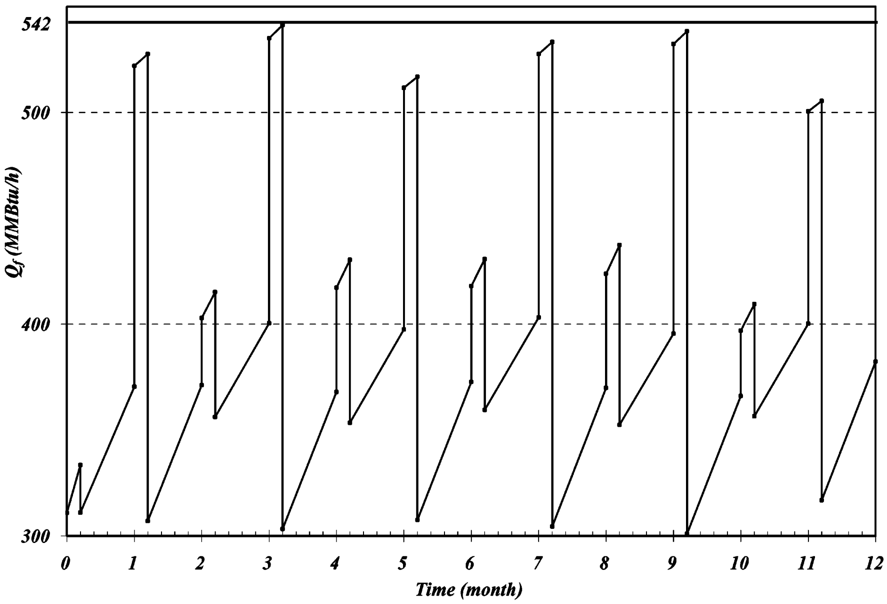

Figure 3. Furnace load for Qf_{max}^{min} = 542 MMBtu/h (no throughput reduction allowed).

Table 2. Cleaning Schedule for Qf_{max}^{min} = 542 MMBtu/h (No Throughput Reduction Allowed)

heat exchanger no.	month												no. cleanings/ exchanger
	1	2	3	4	5	6	7	8	9	10	11	12	
1			X				X						2
2		X			X				X				3
3	X			X				X		X			4
4						X							1
5	X			X			X			X			4
6		X				X			X				3
7													0
8				X		X			X		X		4
9			X		X			X		X			4
10							X						1
11													0
12			X		X		X		X		X		5
13													0
14		X		X		X		X		X		X	6
							total no. cleanings						37

Table 3. Total Costs and Number of Cleanings for Qf_{max}^{*} = 488 MMBtu/h

penalties ($/bbl)	total costs (MM$)	total no. cleanings
$\beta = 0, \gamma = 0$	18.825	39
$\beta = 2, \gamma = 92$	19.450	33
$\beta = 4, \gamma = 92$	19.734	31

planned shutdowns. This is, of course, true, because there is a feasible solution in the form of a cleaning schedule for that capacity of the furnace; the natural conclusion is that, in such cases, it is better not to clean more and thus avoid throughput reduction. But if the capacity of the furnace is not capable of handling the required load for the system, for certain initial conditions (i.e., some exchangers initially too dirty), the only way to meet the specifications is by reducing the throughput. We illustrate this idea by solving for $Qf_{max}^{*} < Qf_{max}^{min}$ = 542 MMBtu/h. Figures 4 and 5 show the throughput and the furnace load profile, respectively, for different values of penalties β (0, 2, and 4 $/bbl) and γ (0 and 92 $/bbl), when the furnace capacity is Qf_{max}^{*}= 488 MMBtu/h. Table 3 shows the costs and total number of cleanings for the different cases. The case of no penalties is ideal, but it is used to show the effect of the penalties on the total operating costs.

The results show that the only possibility for operating the network under critical conditions is by reducing the throughput during short periods of time like the cleaning subperiods, when some of the exchangers must be put off-line to be cleaned and the furnace cannot handle the required load. Reducing the throughput in small percentages (<10%) during short periods of time allows for more cleanings and for recovering the performance of the network. If the conditions are even more critical, it might be possible that the reduction extends into the operating subperiod. As the penalties for throughput reduction increase, the optimal total number of cleanings becomes smaller, that is, it is better to clean less to be able to maintain the throughput (Table 3). At some point there is a balance, because the reduction in cleaning leads to higher energy costs.

Case III. Increased Cleaning Schedule to Increase Throughput. The procedure can also be applied to the case of processing a higher-than-normal throughput. In this case, the furnace might be insufficient at certain points, and therefore, throughput reduction must be addressed. To illustrate this, we solve the problem for a 10% higher throughput (132 000 bpd). Figure 6 shows the throughput profile obtained for different penalties ($\beta = 0$ and 2 $/bbl, $\gamma = 92$ $/bbl), and Table 4 contains the costs and total number of cleanings for the different cases.

The profiles show that reducing the throughput during the cleaning subperiods allows for the performing of more cleanings and the meeting of the specifications. As the penalties increase, the compromise solution is higher, and the margin for throughput reduction narrows. In all cases, it is better to reduce less, but more frequently, than to incur nonperformance penalties.

Comparison with Heuristic Strategies. In this section, we compare the use of the model with heuristic strategies, for the same network presented in the previous section, for the cases of no furnace limit and the case of Qf_{max}^{*}= 488 MMBtu/h. Searching for heuristic strategies that provide cleaning schedules with a total number of cleanings close to the optimal schedule

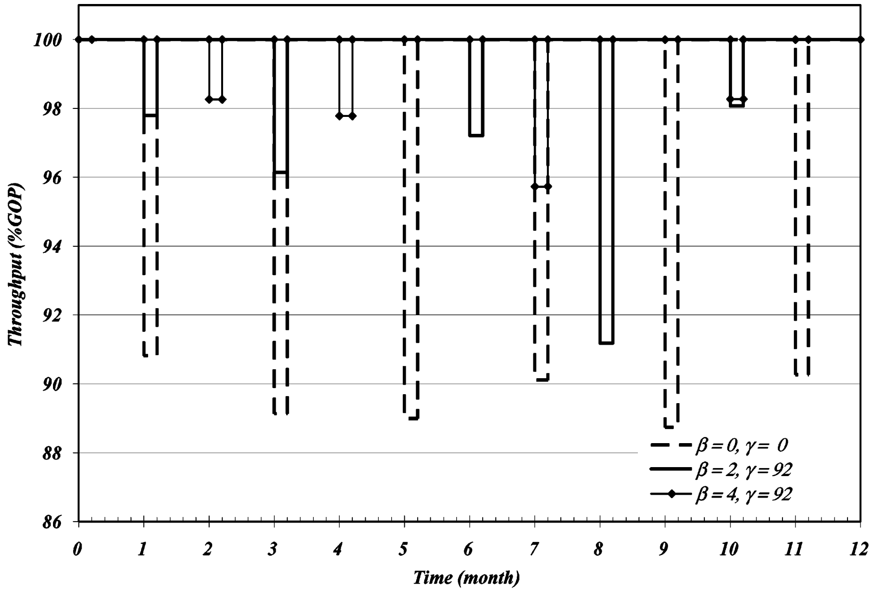

Figure 4. Throughput profile for different penalties, at Qf^{*}_{max}= 488 MMBtu/h.

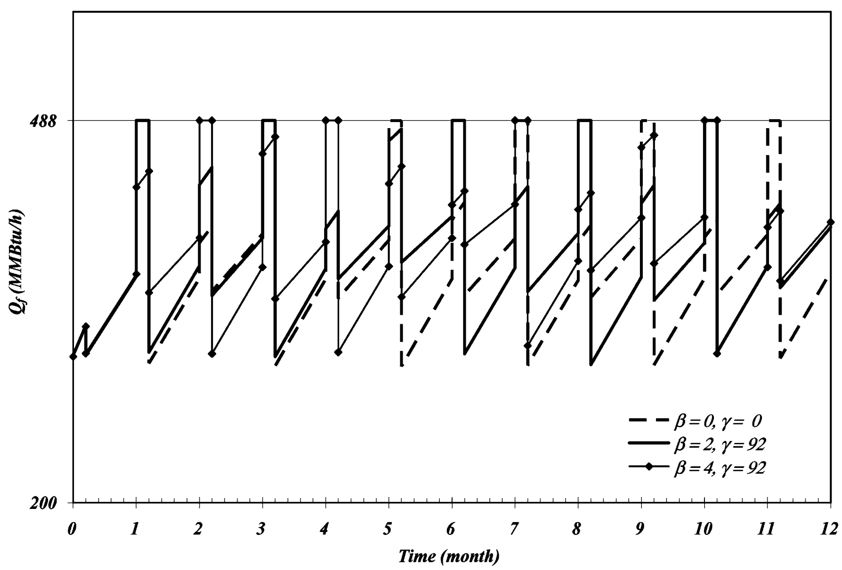

Figure 5. Actual furnace load profile for different penalties, at Qf^{*}_{max}= 488 MMBtu/h.

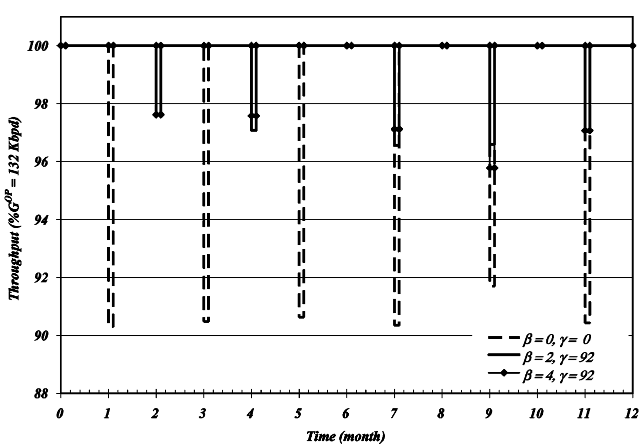

Figure 6. Throughput profile for different penalties when operating the unit at 132 Kbpd, at Qf^{min}_{max} = 542 MMBtu/h.

found with the model, we found that the strategies of cleaning each exchanger every time that its overall heat transfer coefficient reaches 30% and 40% of its clean value render schedules with total numbers of cleanings that are around the optimal number. We also show the strategy of cleaning at 50%.

Table 4. Total Costs and Number of Cleanings When Operating the Unit at 132 Kbpd (Qf^{min}_{max} = 542 MMBtu/h)

penalties ($/bbl)	total costs (MM$)	total no. cleanings
$\beta = 0, \gamma = 92$	21.433	38
$\beta = 2, \gamma = 92$	22.082	36
$\beta = 4, \gamma = 92$	22.360	34

Figure 7 shows the furnace profile for the three heuristic cases and Table 5 shows their economics along with that for the optimal solution found by applying the model. The feasible strategy of cleaning when the overall heat transfer reaches 50% provides the schedule with the lowest operating costs associated. However, it is more expensive than the optimal and requires more cleanings. Tables 6−8 show the schedules for the optimal and the cases of 40% and 50%, respectively.

The results show that the heuristics solutions show schedules with costs that are close to the optimum one. However, these heuristics are only good because the

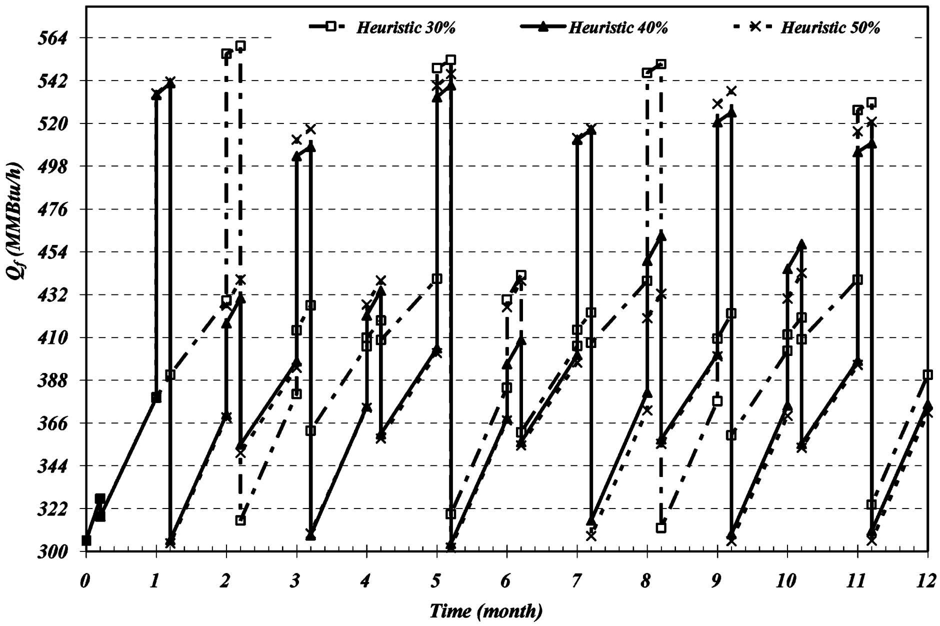

Figure 7. Furnace energy load for the case of no furnace limit, for the three heuristic cases.

Table 5. Economics for the Three Heuristic Cases and the Optimal Case, for the Case of No Furnace Limit

strategy	total costs (MM$)	total no. cleanings
modeling	19.043	37
heuristic, 30%	19.822	27
heuristic, 40%	19.189	39
heuristic, 50%	19.179	46

Table 6. Cleaning Schedule for the Optimal Solution Using Our Model and Table 3

heat exchanger no.	month												no. cleanings/ exchanger
	1	2	3	4	5	6	7	8	9	10	11	12	
1			X				X						2
2		X			X				X				3
3	X			X				X		X			4
4						X							1
5	X			X			X			X			4
6		X				X			X				3
7													0
8				X		X			X		X		4
9			X		X			X		X			4
10							X						1
11													0
12			X		X		X		X		X		5
13													0
14		X		X		X		X		X		X	6
								total no. cleanings					37

level at which cleaning is performed (30%, 40%, or 50%) was chosen knowing what number of cleanings is targeted, which is only known from our model. Clearly, practitioners choosing heuristic strategies do not know what is the appropriate value to use. The physical and operational constraints described in Appendix A do not allow for allocating many more cleanings. For example, for the heuristic strategy of 80%, the total number of cleanings is 47, just one more than that for the case of 50%.

For the case of Qf^*_{max}= 488 MMBtu/h, we applied the same strategies but allowed throughput reduction. Figure 8 and Table 9 show the throughput profile and the economics respectively, for the three cases when the penalties are $\beta = 4$ \$/bbl and $\gamma = 92$ \$/bbl. Again, the three heuristic strategies are more expensive, and they

Table 7. Cleaning Schedule for Heuristic 40%

heat exchanger no.	month												no. cleanings/ exchanger
	1	2	3	4	5	6	7	8	9	10	11	12	
1	X				X					X			3
2			X						X				2
3		X				X					X		3
4				X				X				X	3
5	X				X				X				3
6		X				X				X			3
7													0
8			X			X			X			X	4
9				X			X			X			3
10		X			X			X			X		4
11													0
12			X		X		X		X		X		5
13													0
14		X		X		X		X		X		X	6
								total no. cleanings					39

Table 8. Cleaning Schedule for Heuristic 50%

heat exchanger no.	month												no. cleanings/ exchanger
	1	2	3	4	5	6	7	8	9	10	11	12	
1	X				X				X				3
2			X				X				X		3
3		X				X				X			3
4				X				X				X	3
5	X		X		X		X		X		X		6
6		X		X		X		X		X		X	6
7													0
8		X			X			X			X		4
9			X			X			X			X	4
10				X			X			X			3
11													0
12			X		X		X		X		X		5
13													0
14		X		X		X		X		X		X	6
								total no. cleanings					46

incurred nonperformance penalties which are never desirable (compared with the optimal solution from Figure 5 and Table 3). In percentage, the differences between the associated costs of the heuristics and the optimal solution are higher, because the heuristics do not take into account the penalization incurred when throughput reduction occurs.

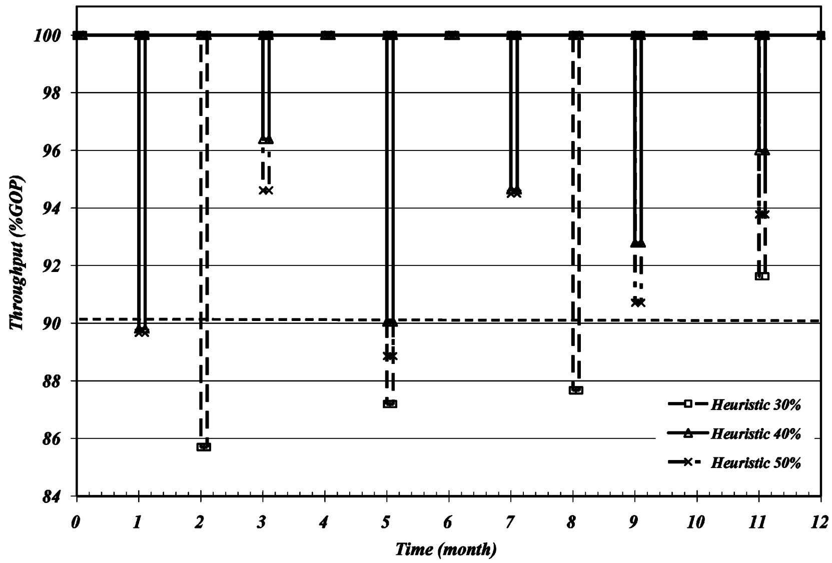

Figure 8. Throughput profile for the three heuristic strategies, for penalties of $\beta = 4$ \$/bbl and $\gamma = 92$ \$/bbl, at $Qf^*_{max} = 488$ MMBtu/h.

Table 9. Economics for the Three Heuristic Strategies and the Optimal Solution, for Penalties of $\beta = 4$ \$/bbl and $\gamma = 92$ \$/Bbl at $Qf^*_{max} = 488$ MMBtu/h

strategy	total costs (MM\$)	total no. cleanings
modeling	19.734	31
heuristic, 30%	26.688	27
heuristic, 40%	20.302	39
heuristic, 50%	21.254	46

Table 10. Schedule for the Crude Type Processed in the Time Horizon for Two Different Cases

		month											
		1	2	3	4	5	6	7	8	9	10	11	12
case 1	X_{cr}, cr = light	0	0	0	0	0	0	0	1	1	1	1	1
	X_{cr}, cr = heavy	1	1	1	1	1	1	1	0	0	0	0	0
case 2	X_{cr}, cr = light	1	1	1	1	1	0	0	0	0	0	0	0
	X_{cr}, cr = heavy	0	0	0	0	0	1	1	1	1	1	1	1

It is interesting to point out that, in this case, the best heuristic strategy to apply is the case of 40% instead of 50%. This fact shows that, if at a certain point the furnace capacity is not enough to handle the required load, the heuristic strategies must be changed in order to keep relatively good solutions; however, the number of possible combinations that must be tried in order to achieve such solutions puts this strategy far from the use of the model, which is a one-step procedure that is easy to implement.

Multipurpose/Multiperiod Operation. In this section, we show the throughput reduction modeling applied to a multipurpose network. In this case, light and heavy crudes are processed in the time horizon considered. We use the same network as in the previous example, which, by design,[2] has some exchangers offline depending on which crude is being processed. Table 10 shows the value of $X_{cr,t}$ for each crude type, for each period of time.

In this case, it is desired to operate the distillation unit at a throughput G^*, 10% greater than the designed operating throughput (G^{OP}). Penalty γ is activated when the throughput is <90% of G^*, strongly penalizing any reduction that could make the throughput less than the designed operating throughput.

Figures 9 and 10 show the throughput profile at two different penalties, and Table 11 contains the total costs

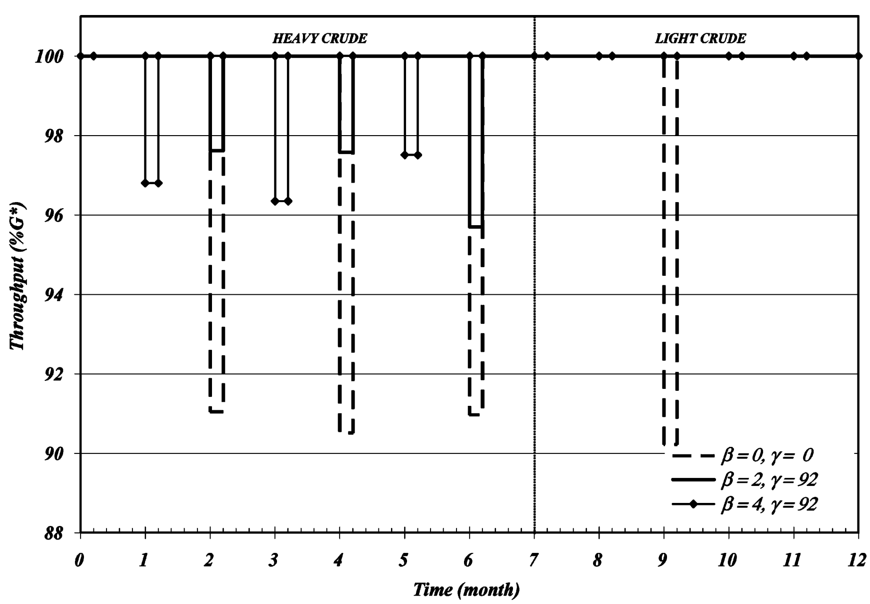

Figure 9. Throughput profile at two different penalties for case 1 (*heavy* crude first).

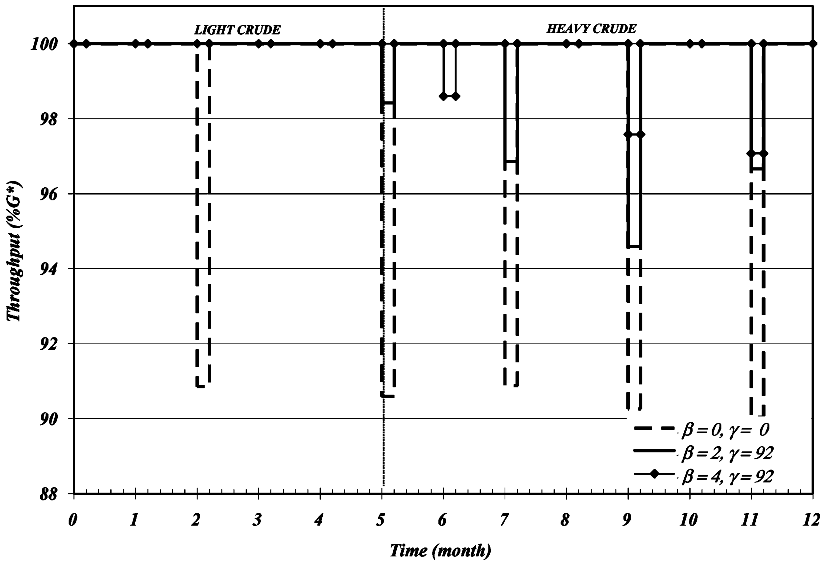

Figure 10. Throughput profile at two different penalties for case 2 (*light* crude first).

Table 11. Total Costs and Number of Cleanings for the Two Cases in a Multipurpose Operation

case	penalties ($/bbl)	total costs (mm$)	total no. cleanings
1	$\beta = 0, \gamma = 92$	20.137	36
	$\beta = 2, \gamma = 92$	20.397	33
	$\beta = 4, \gamma = 92$	20.603	29
2	$\beta = 0, \gamma = 92$	20.156	36
	$\beta = 2, \gamma = 92$	20.502	35
	$\beta = 4, \gamma = 92$	20.904	34

Table 12. Cleaning Schedule for Penalties $\beta = 0$ $/bbl and $\gamma = 92$ $/bbl. Case 2: *Heavy* Crude Processed First

heat exchanger no.	month												no. cleanings/ exchanger
	1	2	3	4	5	6	7	8	9	10	11	12	
1				X					X				2
2		X				X				X			3
3	X		X		X		X				X		5
4													0
5	X		X										2
6		X			X					X			3
7										X			1
8		X				X			X				3
9				X			X						2
10								X			X		2
11										X		X	2
12		X		X		X		X				X	5
13										X			1
14			X		X		X		X		X		5
								total no. cleanings					36

Table 13. Cleaning Schedule for Penalties $\beta = 0$ $/bbl and $\gamma = 92$ $/bbl. Case 2: *Light* Crude Processed First

heat exchanger no.	month												no. cleanings/ exchanger
	1	2	3	4	5	6	7	8	9	10	11	12	
1		X							X				2
2				X				X					2
3	X		X			X				X		X	5
4													0
5						X			X				2
6			X				X			X			3
7			X										1
8					X			X				X	3
9						X			X		X		3
10			X							X			2
11		X		X									2
12					X		X		X		X		4
13			X										1
14		X		X		X		X		X		X	6
								total no. cleanings					36

Table 14. Cleaning Schedule for Penalties $\beta = 4$ $/bbl and $\gamma = 92$ $/bbl. Case 2: *Heavy* Crude Processed First

heat exchanger no.	month												no. cleanings/ exchanger
	1	2	3	4	5	6	7	8	9	10	11	12	
1				X									1
2			X						X				2
3	X				X			X					3
4													0
5			X										1
6	X				X			X					3
7											X		1
8					X				X				2
9			X				X						2
10								X			X		2
11										X		X	2
12			X		X		X					X	4
13										X			1
14		X		X		X			X		X		5
								total no. cleanings					29

and number of cleanings, all for the two cases shown in Table 10. The results from the figures show that the throughput modeling gives flexibility to the unit to process heavy crude (which, in general, has higher fouling rates than light crude)[5] before or after light crude, reducing the throughput during the cleaning subperiod, allowing more cleanings when the heavy crude is being processed.

From the results in Table 11, it can be said that, as the penalties increase, the flexibility of reducing the throughput decreases and the optimal operating costs increase. Regardless of the penalties, in all the cases, it is more convenient to process first the heavy crude.

Tables 12 and 13 show the schedules for both cases with penalties $\beta = 0$ $/bbl and $\gamma = 92$ $/bbl, and Tables 14 and 15 show the schedules for both cases with penalties $\beta = 4$ $/bbl and $\gamma = 92$ $/bbl. The exchangers that are not used are not cleaned when they are off-line. The schedule is more affected by the order in which the crudes are processed than in the case where the penalties increase.

Table 15. Cleaning Schedule for Penalties $\beta = 4$ \$/bbl and $\gamma = 92$ \$/bbl. Case 2: *Light* Crude Processed First

heat exchanger no.	month												no. cleanings/ exchanger
	1	2	3	4	5	6	7	8	9	10	11	12	
1			X										1
2		X			X				X				3
3	X			X		X		X			X		5
4													0
5					X			X			X		3
6	X					X			X				3
7			X										1
8						X		X			X		3
9					X				X				2
10			X										1
11		X		X									2
12			X			X			X		X		4
13		X			X								2
14				X			X			X		X	4
								total no. cleanings					34

Conclusions

In this article, a previous model presented by Lavaja and Bagajewicz[1] was extended to optimize the throughput reduction required for the operation of heat-exchanger networks when the maximum capacity of the furnace is reached at a certain point of the time horizon considered or when it is desired to operate the networks at a higher throughput during a certain time horizon. The model gives the flexibility to operate the network under tight energy conditions, by reducing the throughput for short periods of time, allowing for more cleanings and recovering the performance of the unit. The model also provides optimal cleaning schedules for the operation of multipurpose/multiperiod heat-exchanger networks, also allowing for throughput reduction when it is required.

APPENDIX A

Structural and Operational Constraints for Parallel HEN. The following equations were added to the model presented in Part I[1] to simulate the operation of the two-branch HEN described in Figure 1.

Cold Stream Inlet Temperature.

$$c^*_{1i,t} = \mathrm{Tc}_{\mathrm{in}} \qquad i \in I_1 = \{1,5\}, \quad \forall t \tag{A.1}$$

$$\mathrm{Tc}^*_{1i,t} = \mathrm{Tc}_{1i=1} \qquad i \in I_2 = \{2,3,4,6,8,9,10,11,13,14\}, \quad \forall t \tag{A.2}$$

$$\mathrm{Tc}^*_{1i=7,t} = \frac{\mathrm{Fc}_{i=4,t}\,\mathrm{Tc}^*_{2i=4,t} + \mathrm{Fc}_{i=6,t}\,\mathrm{Tc}^*_{2i=6,t}}{\mathrm{Fc}_{i=4,t} + \mathrm{Fc}_{i=6,t}} \quad \forall t \tag{A.3}$$

$$\mathrm{Tc}^*_{1i=12,t} = \mathrm{Tc}_{1i=7,t} \quad \forall t \tag{A.4}$$

Hot Stream Inlet Temperature.

$$\mathrm{Th}_{1i,t} = \sum_{\mathrm{cr}} X_{\mathrm{cr},t}\mathrm{Th}_{\mathrm{cr},t} \qquad i \in I_3 = \{5, 7, 8, 9, 10, 11, 12, 13, 14\}, \quad \forall t \tag{A.5}$$

$$\mathrm{Th}_{1i=1,t} = \mathrm{Th}_{2i=8,t} \quad \forall t \tag{A.6}$$

$$\mathrm{Th}_{1i=2,t} = \mathrm{Th}_{2i=7,t} \quad \forall t \tag{A.7}$$

$$\mathrm{Th}_{1i=3,t} = \mathrm{Th}_{2i=12,t} \quad \forall t \tag{A.8}$$

$$\mathrm{Th}_{1i=4,t} = \mathrm{Th}_{2i=10,t} \quad \forall t \tag{A.9}$$

$$\mathrm{Th}_{1i=6,t} = \mathrm{Th}_{2i=9,t} \quad \forall t \tag{A.10}$$

$$\mathrm{Tf}^*_{\mathrm{in}} = \frac{\mathrm{Fc}_{i=11,t}\mathrm{Tc}^*_{2i=11,t} + \mathrm{Fc}_{i=14,t}\mathrm{Tc}^*_{2i=14,t}}{\mathrm{Fc}_{i=11,t} + \mathrm{Fc}_{i=14,t}} \quad \forall t \tag{A.11}$$

Physical and Operational Constraints.

$$Y_{1,t} + Y_{2,t} + Y_{3,t} + Y_{4,t} \le 1 \quad \forall t \tag{A.12}$$

$$Y_{5,t} + Y_{6,t} \le 1 \quad \forall t \tag{A.13}$$

$$Y_{8,t} + Y_{8,t} + Y_{10,t} + Y_{11,t} \le 1 \quad \forall t \tag{A.14}$$

$$Y_{12,t} + Y_{13,t} + Y_{14,t} \le 1 \quad \forall t \tag{A.15}$$

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