On a New MILP Model for the Planning of Heat-Exchanger Network Cleaning. Part III: Multiperiod Cleaning under Uncertainty with Financial Risk Management

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This paper is a follow-up to a two-part 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, where the net present cost is minimized by carefully choosing the appropriate cleaning schedules. In the second part (Lavaja, J. H.; Bagajewicz, M. *Ind. Eng. Chem. Res.* **2005**, *44*, 8046−8056), throughput loss was added to the model, thus allowing the throughput to be reduced when convenient. Because of the high importance of financial risk in almost any industry and the presence of uncertainty in some of the parameters involved in the operation of heat exchanger networks, a stochastic version of the model was developed and applied to crude fractionation units. The model considers uncertainty not only in the future price of the natural gas expended in the furnace but also in the actual value of the fouling rates of the crudes and in the schedule of change of feedstock during the operation.

Introduction

In a previous paper (Part I),[1] we introduced a new model for optimizing the cleaning schedule of heat exchanger networks. We applied this model to crude fractionation units. In a second part,[2] we extended the model to consider throughput reduction during fractions of the time (mainly cleaning subperiods) and showed that a cleaning schedule that considers this throughput reduction can be used to increase profit. In particular, we showed how this technique can be used to increase the average throughput in units where the bottleneck for throughput is the furnace capacity. In this second part, we also introduced the extension of the model to multiperiod production, that is, the use of crudes with different fouling characteristics for different periods of time.

In this part, we extend the model to consider uncertainty and manage financial risk. We omit covering the background of the problem because it is reviewed in Part I. In addition, decision making in process operations under uncertainty is a mature field. Being such a mature field, we also omit reviewing it. In particular, the scheduling of heat exchanger network cleaning has uncertain parameters, such as the future price of the gas (or fuel) expended in the furnace, the exact time when a distillation unit would change the type of crude processed, and the fouling rate of the crude processed.

The paper is organized as follows: We present first a brief revision of the model (for completeness); then the effect in the total unit operating costs of the crude schedule variability, the variability in the fouling rate for the crude processed, and the fluctuation of the future price of the natural gas expended in the furnace are studied. In the case of the natural gas price, risk analysis was performed using the technique developed by Aseeri and Bagajewicz,[3] which is based on the two-stage stochastic programming formulation. Last, risk analysis is addressed by introducing uncertainty in the three parameters previously described, and an example illustrating the concepts is given.

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 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 is maximized. 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

$$r_{it} = \frac{1}{U_{it}} - \frac{1}{U_i^c} \tag{1}$$

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

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

The clean and actual heat transfer coefficient for each

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10.1021/ie050319y CCC: $30.25
Published on Web 09/10/2005

subperiod can be written in terms of the binary variable and the fouling factor as follows,

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

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

where a_{ikt}, b_{it}, and c_{it}^{c} are constants that are functions 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}).

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

where $d_{it} = (A_i/Fc_{it}Cc_{it})(R_{it} - 1)$. The expression can be easily linearized through standard tricks.[1] The model minimizes the expected net present value (throughout 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 man power, chemicals, and maintenance).

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

where NPC is the net present cost, Ef_t is the actual furnace's energy consumption, $\mathrm{Ef}_t^{\mathrm{cl}}$ is the furnace's energy consumption for clean condition, 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.

In the second part,[2] the model for the optimization of the cleaning schedule for a multipurpose/multiperiod HEN presented in Part I[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 under consideration, 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. The model was coded in GAMS.[4]

Effect of the Crude Schedule on the Cleaning Schedule. In this section, the effect of the variations in the crude schedule on the cleaning schedule is analyzed by changing the month in which the switch of the crude is done in the time horizon. The analysis was performed using the HEN shown in Figure 1 (data from Table 1) for two crudes, light and heavy, for a throughput of 132 Kbpd with a furnace capacity of 542 MMBtu/h and penalties β = 2 \$/bbl and γ = 92 \$/bbl. The example is the same as the one used in Part II.[2]

Table 2 shows the three cases of crude schedule considered. The light crude is processed during the first 5, 7, and 9 months of the time horizon, cases 1, 2, and 3, respectively.

Figures 2, 3, and 4 show the throughput profile for each case, respectively, and Tables 3, 4, and 5 show the cleaning schedule for each case, respectively. Table 6 contains the total costs for each case, along with the total number of cleanings corresponding to each schedule.

By comparing the results obtained, one can notice that switching crude 2 months before has a negative impact of 2% in the total operating costs, even though the total number of cleanings is the same for both cases. Since 2% of 20 million dollars is a significant number, we conclude that including the uncertainty of the switching time in the problem is important.

Effect of the Fouling Rate on the Cleaning Schedule. Different fouling models can be obtained from experimental laboratory studies,[6] on-line monitoring,[7] and data reconciliation.[8,9] But there are cases in which the predictions can depart significantly from the real value of the fouling rate. Polley et al.[10] reported cases where the models used to predict the fouling rates underpredict the values with up to 41% of deviation.

In this section, the effect of the deviation of the fouling rate from the predicted value is analyzed. The same HEN was used (Figure 1 and Table 1) for a throughput of 120 Kbpd, with a furnace capacity of 542 MMBtu/h and penalties β = 2 \$/bbl and γ = 92 \$/bbl. The analysis was performed for the heavy crude for the original fouling rate reported for each exchanger in Table 1 and for two cases where the fouling rates are all 20% below and above the original value (Table 7).

Tables 8, 9, and 10 show the cleaning schedule for each case, respectively. Table 11 contains the total costs for each case, along with the total number of cleanings associated with each schedule.

By comparing the schedules, it is observed that, in all the cases, the hottest exchangers have the same cleaning schedule. This happens because the high fouling rates of the hottest exchangers do not allow for different allocations of the cleanings, even when these values change, within the range of deviation considered. The variations in the schedules are registered basically among the exchangers belonging to the cold train, because their predicted fouling rates are not so high, allowing for different cleaning allocations for different values of the fouling rates.

The results also show that the total costs are affected by the deviation of the predicted fouling rate from the observed value. In this example, the total costs can be affected from 2 up to 6%, if we consider that it is possible to have deviations on the order of 40% or even more.

Effect of the Natural Gas Price on the Cleaning Schedule. In previous work,[11] a risk analysis was

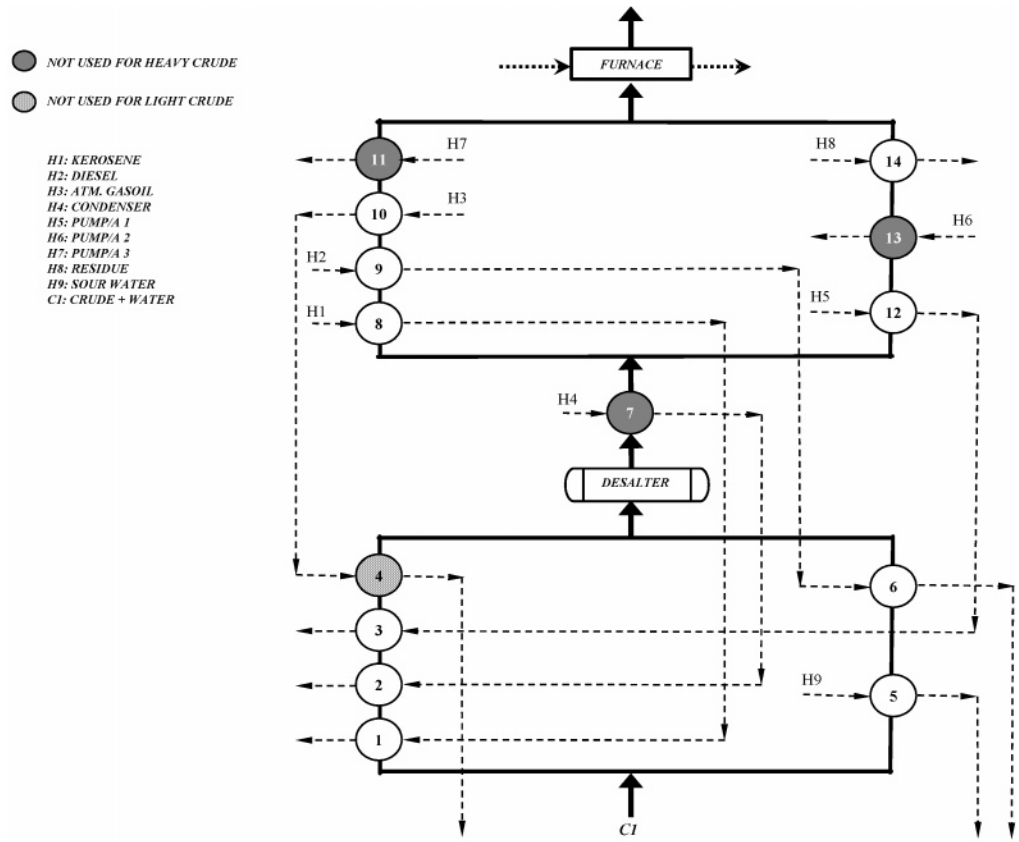

Figure 1. Two-branch multipurpose/multiperiod heat exchanger network of Bagajewicz and Soto. Reproduced with permission from ref 5. 2003 American Chemical Society.

Table 1. Data for the Network of Bagajewicz and Soto[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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Table 2. Schedule of the Crude Type Processed in the Time Horizon (Three Different Cases)

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

(month columns 1–12)

performed to see the effect of the natural gas price on the cleaning schedule and the total operating costs. The two-stage stochastic programming technique was used to build the model, considering the binary variable of cleaning the exchanger or not ($Y_{(i,t)}$) as the only first-stage decision variable, since this problem has the peculiarity that once this variable is fixed s which means that the cleaning schedule is fixed s the solution is fixed, without room for corrections by the second-stage variables.

The scenarios were constructed by sampling natural gas prices, which are assumed to follow a cyclical average trend of seasonal variations, based on U.S. Department of Energy data. Ten base curves were constructed around the average trend, with increasing deviation from it for similar months of the year as the time horizon increases (Figure 5). Then sampling around these base curves was performed assuming normal distributions and equal probability for all the scenarios.

The model was solved for the ten-exchanger network used by Lavaja and Bagajewicz,[11] for a time horizon of 18 months. It was assumed that fouling has already taken place in some exchangers at the beginning of the time horizon.

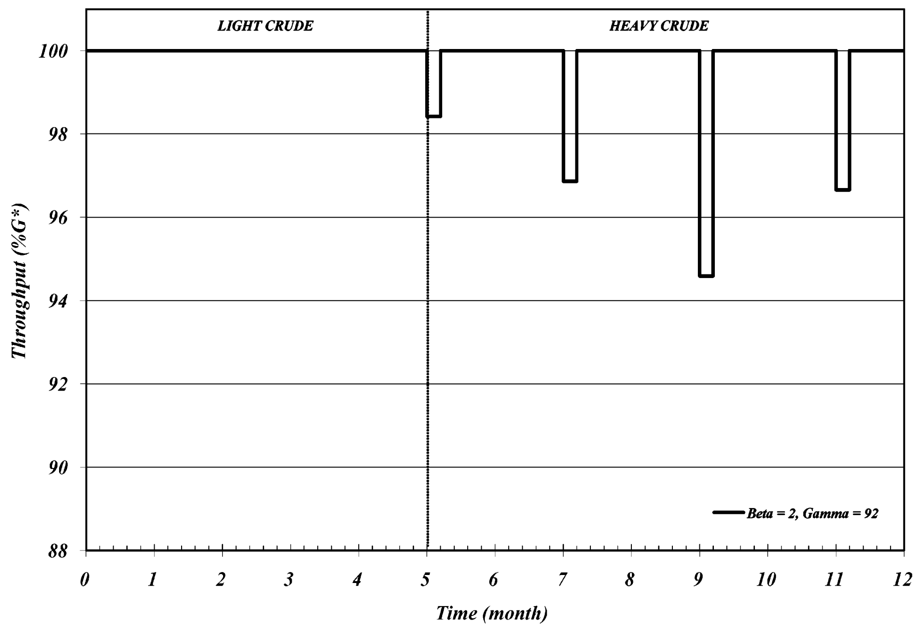

Figure 2. Throughput profile for case 1: light crude processed during the first 5 months.

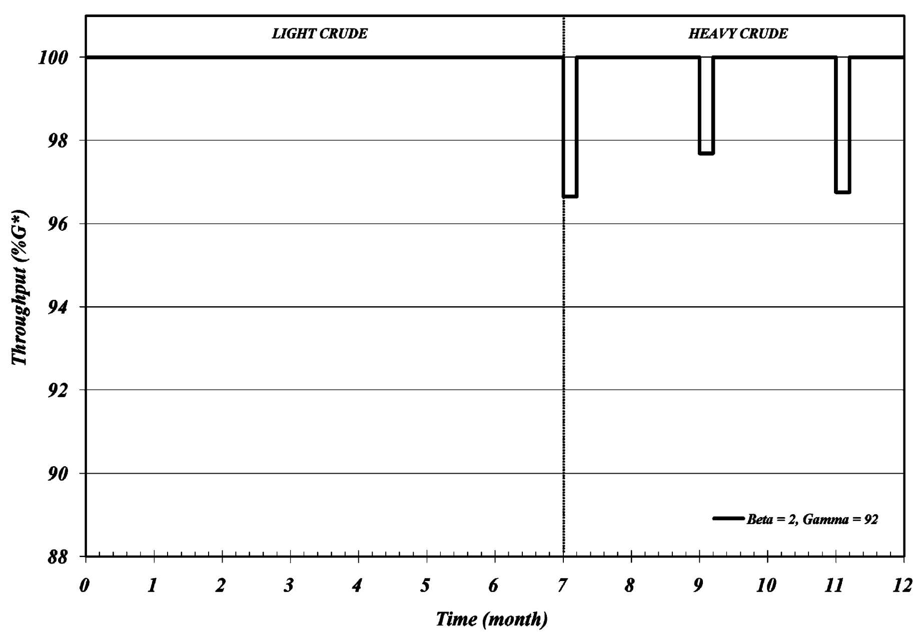

Figure 3. Throughput profile for case 2: light crude processed during the first 7 months.

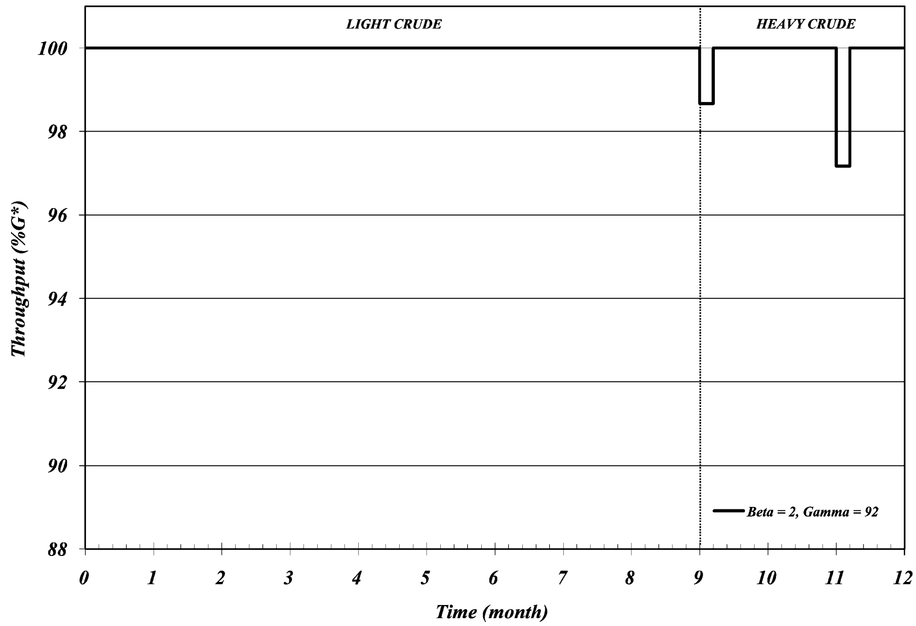

Figure 4. Throughput profile for case 3: light crude processed during the first 9 months.

Table 3. Cleaning Schedule for Case 1: Light Crude Processed During the First Five Months

heat exchanger no.	month 1	2	3	4	5	6	7	8	9	10	11	12	no. cleanings/ exchanger
1			X					X					2
2		X					X				X		3
3	X				X				X				3
4										X			1
5					X				X				2
6				X			X			X			3
7				X									1
8					X		X			X			3
9						X			X		X		3
10			X										1
11		X		X									2
12					X		X		X		X		4
13			X										1
14		X		X		X		X		X		X	6
								total no. cleanings					35

Table 4. Cleaning Schedule for Case 2: Light Crude Processed During the First Seven Months

heat exchanger no.	month 1	2	3	4	5	6	7	8	9	10	11	12	no. cleanings/ exchanger
1		X								X			2
2			X				X				X		3
3	X					X			X				3
4													0
5							X		X				2
6		X						X			X		3
7				X		X							2
8								X			X		2
9							X		X				2
10			X		X								2
11		X		X		X							3
12							X		X		X		3
13			X		X								2
14		X		X		X		X		X		X	6
								total no. cleanings					35

By using 10 trend curves, 200 solutions were obtained based on the 200 scenarios generated. Figure 6 shows all the solutions obtained. In this chart, the cumulative

Table 5. Cleaning Schedule for Case 3: Light Crude Processed During the First Nine Months

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

Table 6. Total Costs and Number of Cleanings for the Three Cases in Multiperiod Operation

case	NPC (MM$)	total no. cleanings
1	20.502	35
2	20.070	35
3	19.554	37

probability is plotted against the 200 solutions, where each of the solutions contains 200 results sorted in descending order of NPC as the cumulative probability increases. Figure 6 also depicts the solution obtained by the deterministic model using the mean values of the trend. The heuristic approach of cleaning every heat exchanger that reaches 15%, 20%, and 25% fouling was also simulated.

On one hand, the results show that the fluctuations around every trend do not affect the results significantly; that is, all the curves obtained by sampling around the same trend are very close. For example, for trend 1, the difference in the expected net present cost (ENPC) between the best and worst solutions is only 0.6%. On the other hand, there are two clear groups of

Table 7. Fouling Rates for the Three Different Cases (Heavy Crude)

	hex no.													
deviation (%)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
−20	1.37	1.03	1.37	1.53	1.13	1.43	2.73	2.88	2.93	3.07	3.07	2.88	2.93	3.13
0	1.64	1.23	1.64	1.84	1.35	1.72	3.27	3.45	3.51	3.68	3.68	3.45	3.51	3.75
+20	1.97	1.48	1.97	2.21	1.62	2.06	3.92	4.14	4.21	4.42	4.42	4.14	4.21	4.50

Table 8. Cleaning Schedule for Case 1: −20% of Deviation in the Fouling Rate

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		X		X			5
4									X				1
5	X				X				X				3
6		X		X			X			X			4
7													0
8				X			X			X			3
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					35

Table 9. Cleaning Schedule for Case 2: 0% of Deviation in the Fouling Rate

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			3
6		X			X			X			X		4
7													0
8					X			X			X		3
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					36

solutions, depending on which trend is associated with the solution.

Figure 6 shows how the heuristic solutions are far away from those predicted by modeling. Noticeably, even in the case when the same number of cleanings is used, modeling suggests better solutions. For example, compare the deterministic solution obtained using the overall mean trend with the heuristic for 80% U^c: both use 28 cleanings, but the ENPC of the heuristic strategy is 20.5% higher (see Tables 12 and 13).

Figure 6 also shows that one group of curves and the deterministic curve are close. This is because the trends and the overall mean are relatively close. However, for the trends that depart significantly from the mean (especially those that do not cross the mean too many times), the results group in another set of curves. Thus, if risk is of concern, then one should choose the solution corresponding to a curve exhibiting lower costs at low cumulative probabilities, instead of the optimal, which

Table 10. Cleaning Schedule for Case 3: +20% of Deviation in the Fouling Rate

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							X						1
5	X			X		X			X				4
6		X			X			X		X			4
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					38

Table 11. Total Costs and Number of Cleanings for the Three Cases with Different Fouling Rates

case	% deviation	NPC (MM$)	total # cleanings
1	−20	18.634	35
2	0	19.062	36
3	+20	19.752	38

in this case is close to the deterministic solution (trends 1 and 6−10).

Risk Analysis on the HEN Cleaning Schedule. On the basis of the results of the previous three sections, risk analysis was performed by introducing uncertainty into the three parameters previously mentioned: crude schedule (X_{cr}), fouling rate (r), and natural gas price (C_{Ef}). The analysis was performed using the same multipurpose/multiperiod HEN shown in Figure 1 (data from Table 1), along with the same two crudes, for a throughput of 120 Kbpd with a furnace capacity of 500 MMBtu/h and penalties $\beta = 2$ \$/bbl and $\gamma = 92$ \$/bbl.

For the case of uncertainty in the crude schedule, three different scenarios were considered, with different probabilities associated. Table 14 shows the three scenarios of crude schedule considered, along with their corresponding probabilities. The heavy crude is processed during the first 5, 7, and 9 months of the time horizon, scenarios 1, 2, and 3, respectively.

For the uncertainty in the fouling rate, three different scenarios per each type of crude were considered, with different probabilities associated. Table 15 shows the scenarios for the fouling rates, along with their corresponding probabilities.

In the case of the natural gas price, five scenarios were considered, with each one conforming to a trend for the future price of the utility. Only the base trends were used based on the results from Lavaja and Bagajewicz;[11] fluctuations around the trends do not affect the schedule significantly. Figure 7 shows the five trends corresponding to the five scenarios and their probabilities.

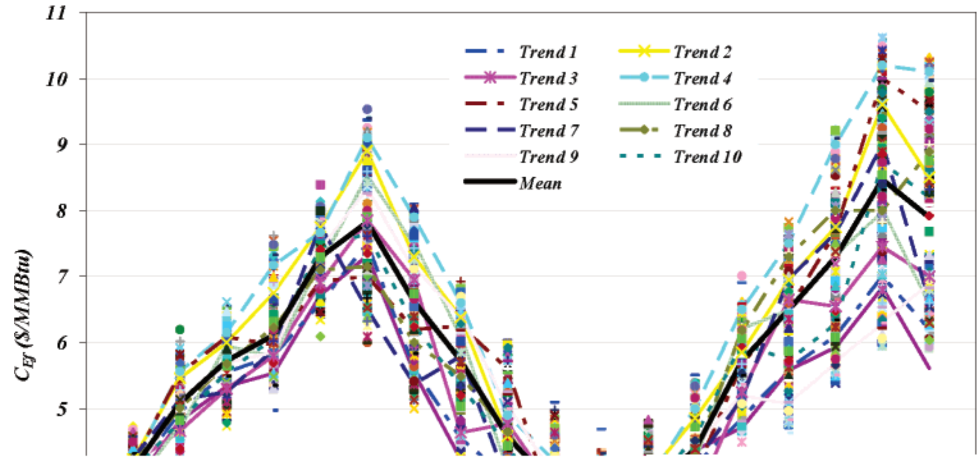

Figure 5. Trends and 200-scenario sampling for the natural gas price. Reproduced with permission from ref 2. 2005 American Chemical Society.

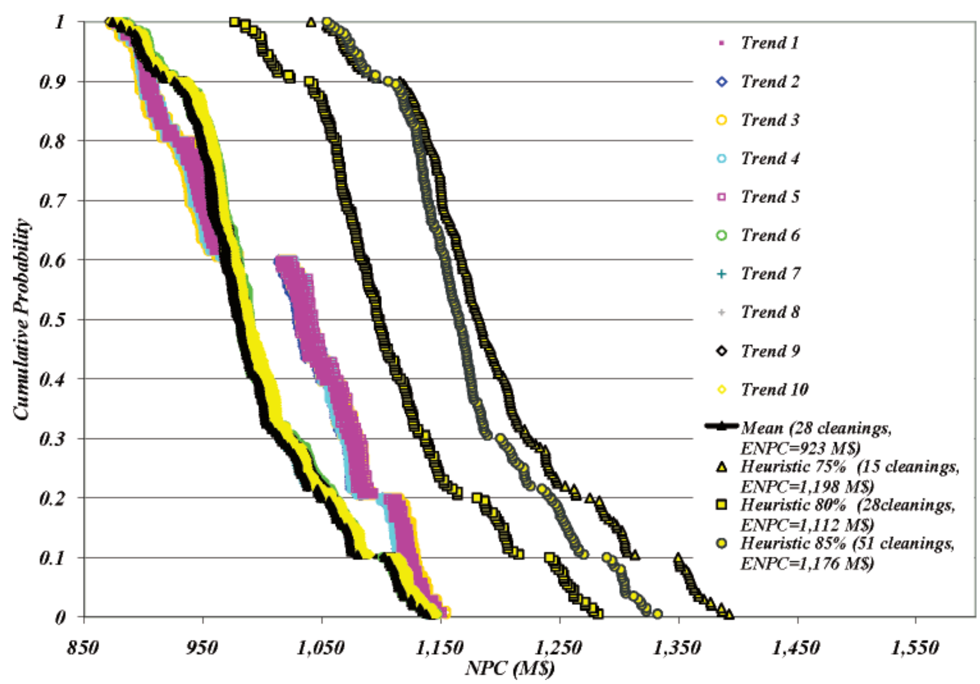

Figure 6. Risk curves for the case of uncertainty in the natural gas price.

On the basis of all the above scenarios for each variable, we made combinations and generated 135 scenarios. Then, the stochastic model was generated, applying the technique introduced by Aseeri and Bagajewicz.[3] This technique consists of solving each scenario independently. Then each solution is solved again with the first-stage variables fixed for all the scenarios to obtain all the risk curves for the rest of the scenarios. As a result, 135 risk curves were obtained, each one conformed by the 135 values of NPC resulting from simulations for each scenario, fixing the deterministic solution obtained from 1 of the 135 scenarios.

From the deterministic point of view and based on the results obtained in the previous three sections, the worst-case scenarios are those in which the fouling rates are the highest (H+20 and L+20) (or at least the highest for the heavy crude), the schedule for the change of the crude is heavy crude the first nine months (H9-L3), and the trends for the gas price have the highest averages. Because of the high fouling rates in these scenarios, more cleanings are required in order to ameliorate the effects of the fouling process. In contrast, the best-case scenarios are those in which the fouling rates are the lowest (H-20 and L-20), the switch from heavy to light

Table 12. Cleaning Schedule for Heuristic 80% U^c (ENPC = 1112 M$)

hex no.	month 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	no. clean./hex
1																			0
2				X															1
3																			0
4					X														1
5		X					X					X					X		4
6			X																1
7	X					X					X					X			4
8	X				X				X				X				X		5
9	X			X			X			X			X			X			6
10	X			X			X			X			X			X			6
																		total no. cleanings	28

Table 13. Cleaning Schedule for Deterministic Case (ENPC = 923 M$)

hex no.	month 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	no. clean./hex
1	X																		1
2				X										X					2
3		X									X								2
4			X										X						2
5			X											X					2
6	X											X							2
7		X				X				X					X				4
8		X				X								X					3
9	X				X				X				X			X			5
10	X			X				X				X			X				5
																		total no. cleanings	28

Table 14. Three Different Scenarios for the Schedule of the Crude Type Processed in the Time Horizon

scenario	prob. (%)		month 1	2	3	4	5	6	7	8	9	10	11	12
1 (H5-L7)	60	X_{cr}, cr = light	0	0	0	0	0	1	1	1	1	1	1	1
		X_{cr}, cr = heavy	1	1	1	1	1	0	0	0	0	0	0	0
2 (H7-L5)	30	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
3 (H9-L3)	10	X_{cr}, cr = light	0	0	0	0	0	0	0	0	0	1	1	1
		X_{cr}, cr = heavy	1	1	1	1	1	1	1	1	1	0	0	0

Table 15. Three Different Scenarios for the Fouling Rates per Type of Crude

scenario	probability (%)	crude type	deviation (%)	hex no. 1	2	3	4	5	6	7	8	9	10	11	12	13	14
1 (H−20)	25	heavy	−20	1.4	1.0	1.4	1.5	1.1	1.4	2.7	2.9	2.9	3.1	3.1	2.9	2.9	3.1
2 (H 0)	50		0	1.6	1.2	1.6	1.8	1.4	1.7	3.3	3.5	3.5	3.7	3.7	3.5	3.5	3.8
3 (H+20)	25		+20	2.0	1.5	2.0	2.2	1.6	2.1	3.9	4.1	4.2	4.4	4.4	4.1	4.2	4.5
4 (L−20)	25	light	−20	1.0	0.7	1.0	1.1	0.8	1.0	1.9	2.0	2.1	2.2	2.2	2.0	2.1	2.2
5 (L 0)	50		0	1.2	0.9	1.2	1.3	1.0	1.2	2.3	2.4	2.5	2.6	2.6	2.4	2.5	2.6
6 (L+20)	25		+20	1.4	1.0	1.4	1.6	1.1	1.4	2.8	2.9	3.0	3.1	3.1	2.9	3.0	3.2

crude occurs at the fifth month (H5-L7), and the trends for the gas price have the lowest averages. Because of the low fouling rates in these scenarios, less cleanings are required in order to ameliorate the effects of the fouling process. Intermediate-case scenarios would be those in which the values of the three parameters are intermediates or those in which the good-case and bad-case scenarios for individual parameters compensate each other when they are combined.

Figure 8 shows the 135 curves obtained. It is observed that all the solutions converge to a common region at high cumulative probabilities and low costs, but when the cumulative probability decreases, they separate into two different groups. In one of the groups, which contains more curves and has lower costs, all the curves remain together, following the trend of high cumulative probabilities. In contrast, the second group is conformed by curves that start departing from the trend at a cumulative probability equal to 0.7 to give shape to a triangular envelope that reaches its widest part at the lowest cumulative probabilities, with higher costs.

Figure 9 shows only five curves belonging to each group, the five with the lowest ENPC and the five with the highest NPC out of the 135 curves, plus the lower-bound curve. Table 16 shows the corresponding scenarios and their probability of occurrence for each of the 10 solutions shown in Figure 9.

The first five solutions in Figure 9 belong to the lowest-cost group and are the result of fixing the schedule obtained as deterministic solutions of inter-

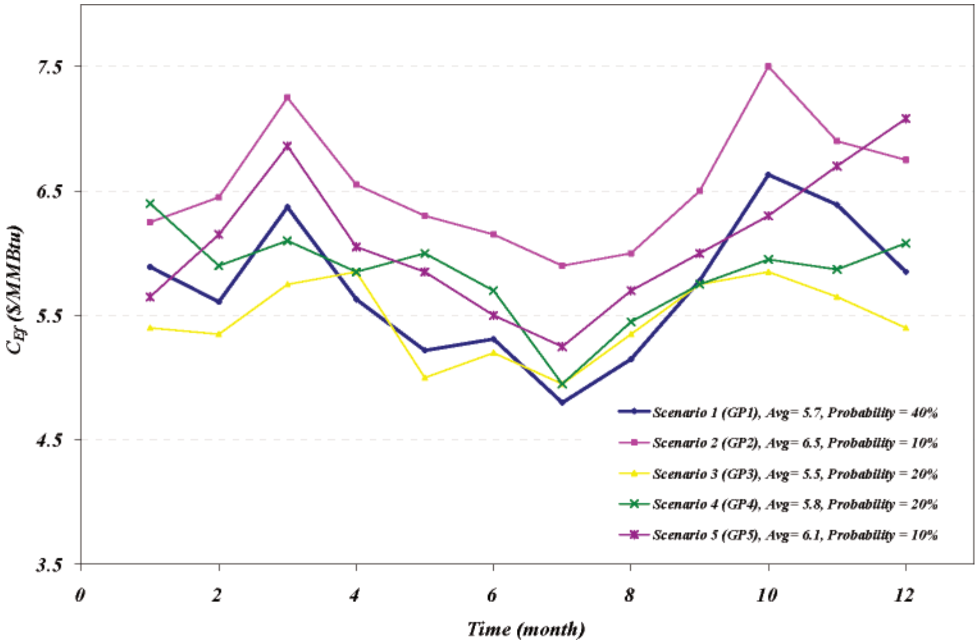

Figure 7.

mediate-case scenarios. These solutions are almost stuck to the lower-bound s which is the “ideal” solution s which implies that they are very good strategies. The difference in the ENPC between the lower-bound and Solution 1 is 0.4% (see Figure 9’s legend).

The second five solutions belong to the highest-cost group and are the result of fixing the schedule obtained as deterministic solutions of best-case scenarios. They depart from the lower-bound in almost the whole range, and the difference in the ENPC between Solution 10 and the lower-bound is 6.7% (see Figure 9’s legend).

Noticeably, the schedule in the change of the crude seems to rule the level of aggressiveness of the scenario since, for both groups, the following is observed: (1) the combination of the individual scenarios for the fouling rates for both crudes does not follow a pattern and (2) the gas price scenarios are almost the same for both groups, but for all the best solutions, the switch occurs at the seventh month (which is an intermediate scenario for that parameter), while for all the worst solutions,

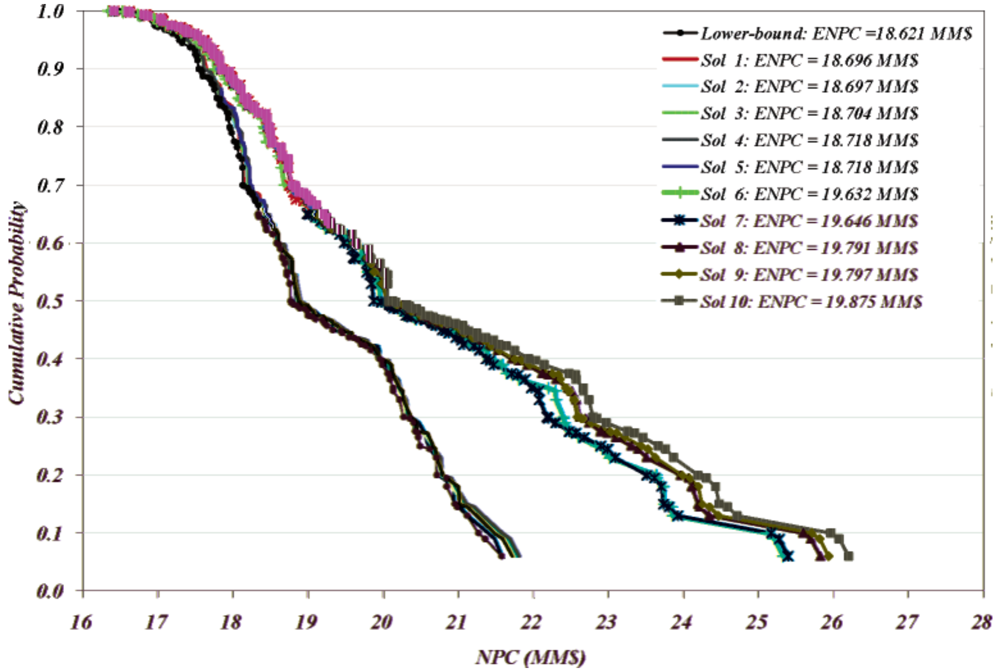

Figure 9. Ten risk curves selected from Figure 8: five with the highest ENPC and five with the lowest ENPC.

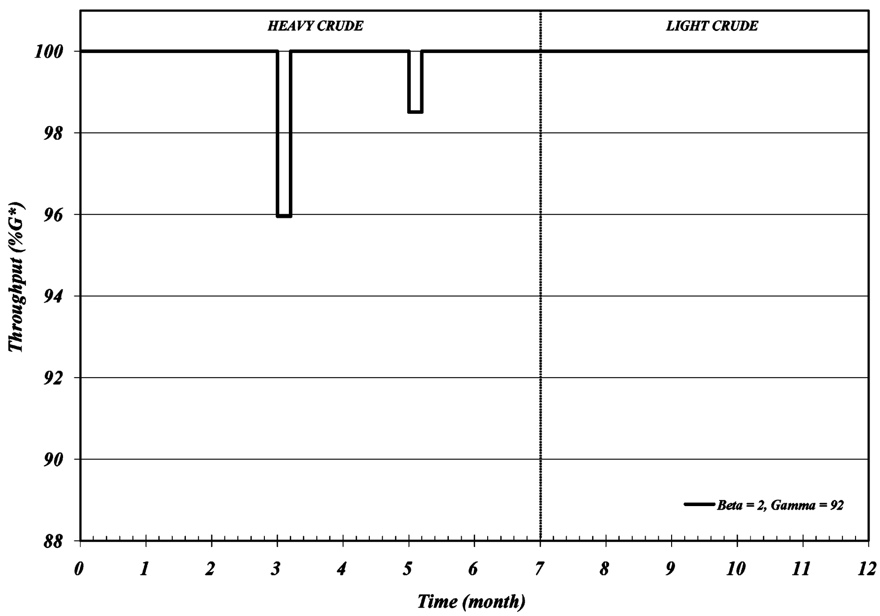

Figure 10. Throughput profile obtained from the deterministic results for Solution 1.

the switch occurs at the fifth month (which is the best-case scenario for that parameter). This fact implies that, when different parameters are considered under uncertainty simultaneously, the influence of the scenarios on the solution might be governed by one of the parameters strongly, even though all the parameters considered uncertain have similar effects when they are considered individually, as in the previous sections.

Figure 10 and Table 17 show the throughput profile and the cleaning schedule obtained for Solution 1, and Figure 11 and Table 18 do the same for Solution 10.

The deterministic schedules and total costs reaffirm what was claimed previously: intermediate-case scenarios capture better solutions than best-case scenarios, by performing more cleanings, when uncertainty is considered. While this is true in this particular case, it is not necessarily a conclusion one would generalize.

Table 17. Cleaning Schedule Obtained from the Deterministic Results for Solution 1

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

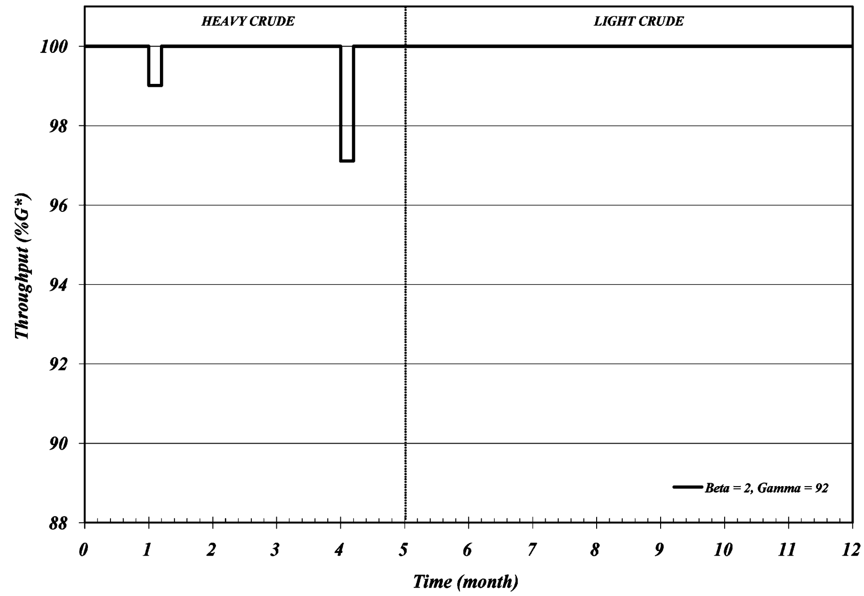

Figure 11. Throughput profile obtained from the deterministic results for Solution 10.

Table 18. Cleaning Schedule Obtained from the Deterministic Results for Solution 10

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				3
4													0
5	X		X										2
6				X									1
7								X			X		2
8				X			X					X	3
9			X		X						X		3
10						X			X				2
11								X		X			2
12			X			X						X	3
13								X		X			2
14		X			X		X		X		X		5
								total no. cleanings					32

From the previous analysis, it can be claimed that, when risk is involved, the schedules resulting from the intermediate-case scenarios provide the best strategies.

Conclusions

The model developed considers uncertainty not only in the future price of the natural gas expended in the furnace but also in the actual value of the fouling rates of the crudes and in the schedule of change of feedstock during the operation. The results show how the optimal strategies can vary when different parameters are considered uncertain simultaneously and how the model helps determine the best strategies to apply when risk is involved.

In addition, the model facilitates the decision making coordination between process and planning engineers by evaluating upfront the best strategy (cleaning scheduling and throughput reduction) to apply under multiple scenarios that are driven by different future uncertain parameters.

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Received for review March 6, 2005
Revised manuscript received July 18, 2005
Accepted August 1, 2005

IE050319Y