Managing Financial Risk in the Planning of Heat Exchanger Cleaning

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Abstract
In this paper we extend a recently presented mixed integer linear model for the planning of heat exchanger cleaning in chemical plants to an uncertain model. We compare the stochastic solutions to the deterministic and heuristic solutions. We also discuss the financial risk management options.

Keywords: Heat Exchanger Network Cleaning, Operations Planning.

1. 1. Introduction

Fouling mitigation and management is an important problem in industry (the total cost of fouling in highly industrialized nations has been projected at 0.25% of the GNP; the total annual cost of fouling in the U.S. is estimated at $18 billion). For this reason, determining which exchanger to clean and when during operations is of paramount importance. On one hand, cleaning results in less energy costs over the time horizon after it is cleaned, but it also implies that the exchanger needs to be put off-line during cleaning and therefore in this period of time the energy cost actually increases. Thus, while cleaning is advantageous, doing it too often may not be economically advisable after all.

Several models have been developed to determine the optimal schedule of cleaning in heat exchanger networks. Of all these the model by Smaïli et al. (2002) is the one that introduces the least simplifying assumptions, as it does not resort for example to any hypothesis of cyclic cleaning and models the exchanger through detailed and rigorous equations. We have recently developed an MILP formulation that is even more rigorous (Lavaja and Bagajewicz, 2003) and, when solved, renders global optimality, in contrast with previous models (they are non-linear). The paper also makes a literature review, which we omit here. For cases where computation time is extensive (cases where several suboptimal solutions exists), all models (linear or not) have difficulties in identifying the global optimum. For these cases, in the aforementioned paper we present a decomposition procedure that is remarkably efficient, renders better solutions than other formulations, outperforms heuristic approaches and proves that solutions based on moving horizons (a simplification arising from the need to speed up computation) are

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often not optimal. In this paper, we make the model stochastic and we discuss options to manage financial risk.

2. MILP Deterministic Model

Consider the heat exchanger network (HEN) of a crude distillation unit (Figure 1, reproduced from Smaïli et al, 2002) where heat is recovered from a distillation column products and pump-around streams. We consider that time is discretized in interval periods (typically months); and each one this is subdivided into a cleaning sub-period 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. Throughput losses due to pressure drops are beyond the scope of this project and thus they are not considered.

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:

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

Smaïli et al (2002) use a linear and exponentially asymptotic fouling model. We concentrate here on the exponentially asymptotic fouling model, given by:

$$r_{it} = r_{it}^{\infty}\left(1 - e^{K_{it}\, t}\right) \tag{2}$$

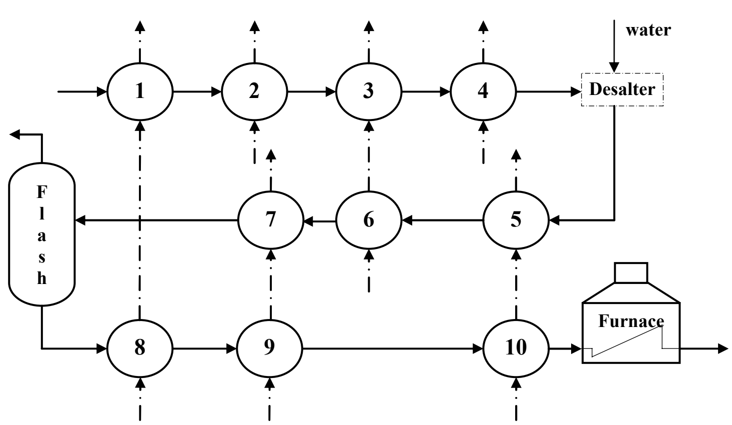

Figure 1. HEN from Smaïli et al (2002).

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

$$Y_{it} = \begin{cases} 1 & \text{if the ith heat exchanger is cleaned in period } t \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

The clean and actual heat transfer coefficient for each sub-period can be written in terms the binary variable and the fouling factor as follows:

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

$$U_{it}^{eop} = \sum_{k=0}^{t-1}\left[a_{ikt}^{o}\, Y_{ik} \prod_{j=k+1}^{t}\left(1-Y_{ij}\right)\right] + b_{it}^{o}\, Y_{it} + c_{it}^{o}\prod_{p=0}^{t}\left(1-Y_{ip}\right) \qquad \forall i, t \geq 1 \tag{5}$$

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 cold outlet temperature (Th_{2it}).

$$\left.\begin{aligned} Th_{2it} = {} & \frac{\left(R_{it}-1\right)Th_{1it} - R_{it}\, Tc_{1it}}{R_{it}\, e^{d_i\left[\sum_{k=1}^{t-1}\left(a_{ikt}Y_{ik}\prod_{j=k+1}^{t}\left(1-Y_{ij}\right)\right)+b_{it}Y_{it}+c_{it}\prod_{p=1}^{t}\left(1-Y_{ip}\right)\right]}-1} \quad + \\ & + \frac{R_{it}\, Tc_{1it}\left[e^{d_i\left[\sum_{k=1}^{t-1}\left(a_{ikt}Y_{ik}\prod_{j=k+1}^{t}\left(1-Y_{ij}\right)\right)+b_{it}Y_{it}+c_{it}\prod_{p=1}^{t}\left(1-Y_{ip}\right)\right]}\right]}{R_{it}\, e^{d_i\left[\sum_{k=1}^{t-1}\left(a_{ikt}Y_{ik}\prod_{j=k+1}^{t}\left(1-Y_{ij}\right)\right)+b_{it}Y_{it}+c_{it}\prod_{p=1}^{t}\left(1-Y_{ip}\right)\right]}-1} \end{aligned}\right\} \quad \forall i, t \geq 1 \tag{6}$$

where $d_{it} = \frac{A_i}{Fc_{it}\, Cc_{it}}\left(R_{it}-1\right)$. The expression can be easily linearized through standard tricks (Lavaja and Bagajewicz, 2003). The model minimizes the expected net present value (throughout time horizon) of the operating costs arising from the trade-off between furnace extra fuel costs due to fouling, and heat exchanger cleaning costs (which include man power, chemicals and maintenance).

$$NPV = \sum_{t} d_t \frac{\left(Ef_t - Ef_t^{cl}\right)}{\eta_f} C_{Ef} + \sum_{t} d_t \sum_{i} Y_{it}\, C_{cl} \tag{7}$$

where Ef_t is the actual furnace's energy consumption, Ef_t^{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.

3. New Decomposition Procedure

Our decomposition procedure is the following:

1) Solve the first exchanger schedule assuming all the rest are not cleaned.
2) Solve the next exchanger schedule assuming the rest have the same cleaning schedule as the current solution.
3) Check for convergence once all exchangers have been solved. If convergence is achieved that proceed to the next step. If not start a new iteration.
4) Pick the largest number of periods for which a moving window solution procedure would solve in a reasonable amount of time. Start with the first month and solve the problem within that horizon. Leave the scheduled cleaning outside the horizon as they were established in the last run.
5) Keep running the moving horizon until the end of the time horizon is reached.
6) Check for convergence. If no convergence is achieved, run the moving horizon again.

3. Stochastic Model

To build a stochastic model we have only considered only uncertainties in the Energy prices. Other parameters that are uncertain but have been kept deterministic are the fouling coefficients of the model, cleaning costs, plant turnaround horizons, and the processing of different crudes at different times. To build the model we considered the standard two-stage stochastic programming model. The scenarios are constructed sampling energy prices, which are assumed to follow a cyclical trend of seasonal variations, based on U.S. Department of Energy data. The sampling was done assuming normal distributions with increasing standard deviation for similar months of the year as the time horizon increases. The trend curve used and all the samples taken are depicted in Figure 2.

The model was solved for initial conditions were fouling has already taken place in some exchangers. To determine a lower bond of the stochastic solution (we are minimizing cost here), we used the technique introduced by Aseeri and Bagajewicz (2003). This technique consists of solving each scenario independently and using the net present cost (NPC) of each scenario to construct the lower bound. Then each solution is solved again with the first stage variables fixed for all the scenarios to obtain all the curves.
The above strategy was applied to generate 200 solutions. Figure 3 shows the lower bound and the five best solutions obtained. It also depicts the solution obtained by the deterministic model using the mean values of the trend. Finally, we simulated the heuristic approach of cleaning every heat exchanger that reaches 25% fouling.

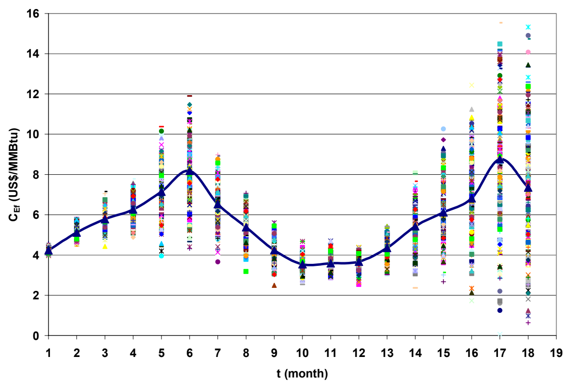

Figure 2. Energy Prices trends and samples.

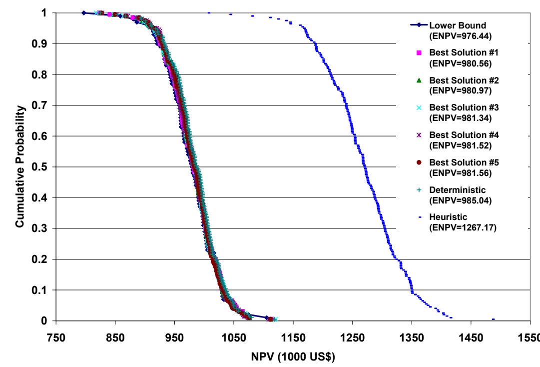

Figure 3. Risk Curves-Lower bound and 5 best solutions.

The results indicate that in this problem, the best solution is very close to the lower bound (0.42 % difference) and that the schedule obtained by this solution should be adopted. In addition, the deterministic solution seems to be also a very good choice (it ca barely be distinguished from the others). But of course, this is not always guaranteed, that is, one does not know this until the whole exercise is performed. The corresponding schedules are shown in Figures 4 and 5.

t / HEx	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	# of cleanings X	# of cleanings O
1	X	O																	1	1
2				⊗									X	O					2	2
3	O	X								X	O								2	2
4			⊗									X	O						2	2
5			X	O									X	O					2	2
6	X	O										⊗							2	2
7	O	X			O	X				O				X	O				3	4
8		X	O			X				O			X		O				3	3
9	X	O			X	O			⊗				⊗			⊗			5	5
10	⊗			X	O			⊗				⊗			X	O			5	5
Total # of cleanings																			27	28

"O": Deterministic cleaning action; "X": best stochastic cleaning action; "⊗": action in both schedules.

Figure 4. Schedules corresponding to the deterministic and the best stochastic solution.

4. Risk Management

It is obvious from the results of figure 3 that when energy prices are considered as the only uncertain parameters, risk management is not possible. This stems from the fact that the difference between the best solution and the lower bound is very small throughout the whole range. In future work, we will incorporate other uncertainties.

Month / Heat exchanger	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	# cleanings /Heat exchanger
1																			**0**
2																			**0**
3																			**0**
4																			**0**
5										■									**1**
6																			**0**
7									■										**1**
8						■								■					**2**
9				■						■						■			**3**
10			■					■					■						**3**
																		Total # of cleanings	**10**

Figure 5. Schedule corresponding to a heuristic solution ($U \leq 75\% \, U^c$).

6. Conclusions

In this paper we introduced the use of lower bounds risk curves to identify the best stochastic solutions. We determined that for uncertainties in energy prices, it seems that no there is no room for financial risk management.

7. Acknowledgements

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8. Nomenclature

r_{it}^{∞} : asymptotic fouling value [(h ft^2 ^{o}F) / Btu]
K_{it}: exponential constant (month^{-1})
U^{ecp}: actual heat transfer coefficient at the end of the cleaning period [Btu / (h ft^2 ^{o}F)]
U^{eop}: actual heat transfer coefficient at the end of the cleaning period [Btu / (h ft^2 ^{o}F)]
Th_{1it}: hot inlet temperature (^{o}F)
Tc_{1it}: cold inlet temperature (^{o}F)
R_{it}: temperature range ratio
A_i: heat exchanger area (ft^2)
Fc_{it}: cold mass flow (lb/h)
Cc_{it}: cold heat capacity [Btu / (lb ^{o}F)]

7. References

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