On a New MILP Model for the Planning of Heat-Exchanger Network Cleaning †

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On a New MILP Model for the Planning of Heat-Exchanger Network Cleaning†

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This paper presents a new mixed-integer linear model for the planning of heat-exchanger cleaning in chemical plants. The model maximizes the net present value based on the cost of cleaning and the cost of energy and takes into account changes in production rates and even changes in the properties and flows of the different streams throughout time. This is important for the case of petroleum distillation in refineries that process different types of crudes. The model is multiperiod and uses two different fouling models.

Introduction

For a long time, surface fouling was considered the major unresolved problem in heat transfer and continues to be considered a major industrial problem. Taborek et al.[1] was one of the first to point out its importance. In numbers, the total cost of fouling in highly industrialized nations has been projected at 0.25% of the Gross National Product, the total annual cost of fouling in the U.S. is estimated at $18 billion, and the total annual cost of shell and tube exchanger fouling in the process industries is estimated at $6 billion.[2]

Fouling is the process of material deposition on heat-exchanger surfaces by different mechanisms, which affects the equipment performance, increasing heat-transfer resistance. Fouling resistance could reach much more than 50% of the overall thermal resistance[3] and is a function of the velocity, temperature, and composition of the streams involved. In the case of the oil industry, fouling of crude preheat train's heat exchangers causes significant increases in operating costs because of increases not only in fuel consumption in furnaces and consequently in cooling utilities but also in distillate yield and throughput reduction. Thus, to ameliorate these problems, heat exchangers are cleaned between shutdowns or during operations by isolating the exchanger through bypasses.

Determining which exchanger to clean and when during operations is of paramount importance. On the 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 offline 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.

Since the early 1980s, different strategies for optimal cleaning plans have been developed for single equipments[4−7] and for heat-exchanger networks (HENs) in continuous processes.[8−13] The latest tendency is to use mixed-integer nonlinear programming (MINLP) models.[10,14,15] Some of these models are nonconvex and therefore do not guarantee a globally optimal solution. Others use the assumption of cyclic schedules, which is very much in question, as is shown in this paper. Departing from this tendency, Georgiadis et al.[11] developed a mixed-integer linear programming (MILP) model by introducing linear approximations (e.g., using arithmetic-mean temperature differences instead of log-mean averages), which could lead to erroneous conclusions.[13] While nonlinear models are more accurate, they require solutions from different initial points and often require special tuning, which makes them less robust and user-friendly. Instead, MILP models are more appealing: they can easily provide solutions with tolerable gaps, are more robust and subject to fewer crashes, and can be easily tuned to run automatically.

In this paper, a rigorous MILP cleaning schedule optimizer model applied to a typical preheat train configuration is presented. We base our model on assumptions similar to those made by Smaïli et al.[13] The model does not approximate the nonlinear equations related to heat transfer or the fouling models. Instead, it takes advantage of a special equation rearrangement to obtain linear expressions. Thus, for smaller problems, the model is capable of rendering global optimality. However, because the model exhibits some computational limitations for larger models, we propose a decomposition procedure. Finally, we compare it with other solutions and with the use of heuristics.

Model Formulation Background

Consider a simple HEN of a crude distillation unit where heat is recovered from distillation column products and pump-around streams (Figure 1). We consider that time is discretized in interval periods (typically months). 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.

Time periods, which are not necessarily equal, are divided into two subperiods: a *cleaning subperiod*, in which exchangers are bypassed for cleaning, and an *operating subperiod*, where all exchangers are function-

† To Art Westerberg, who taught by example to formulate the right model first. M.B.

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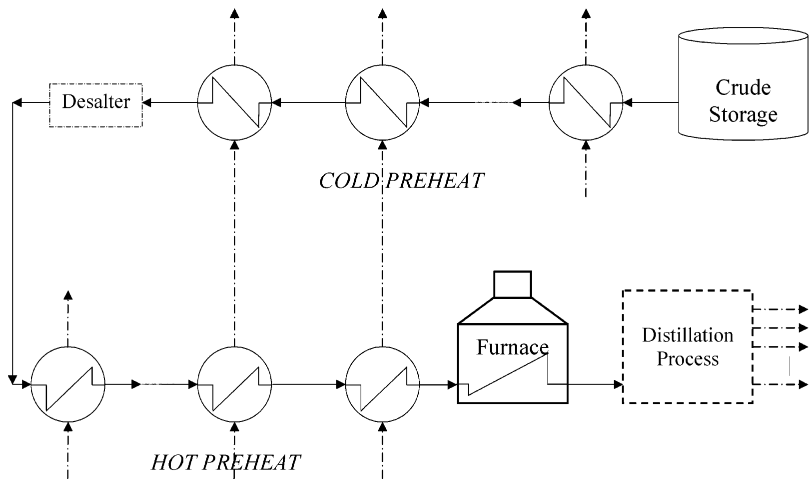

Figure 1. Crude unit HEN.

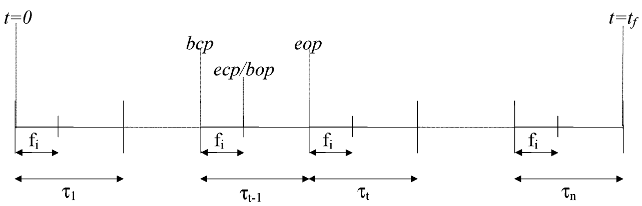

Figure 2. Time horizon discretization. τ_t: tth time period duration. f_i: duration of the ith exchanger cleaning subperiod.

ing in the same way as was done by Smaïli et al.[13] (see Figure 2). We denote the beginning and end of the cleaning subperiod by bcp and ecp, respectively, and the beginning and end of the operating subperiod by bop and eop, respectively. These are used as superscripts.

Mixed-Integer Representation of the Heat-Transfer Coefficient

Fouling in crude oil processes takes place by chemical reaction and polymerization.[1] In other processes, it takes place through other mechanisms such as crystallization, precipitation, etc., although knowledge about how this process occurs under different conditions is not thorough.[16] Different fouling models can be obtained from experimental laboratory studies,[17] from online monitoring,[18] and from data reconciliation.[12,14] Moreover, each heat exchanger of a network has different rates of fouling, depending on film temperatures and stream compositions, increasing the rate with increasing film temperature.[19] Typical fouling behaviors are linear and exponentially asymptotic, with the latter applying more to crude preheat exchangers.[3] Nevertheless, which model fits better for each case could be determined from plant data. Some authors[20,21] have considered exponential fouling. This means that the fouling rate actually increases with (or is somewhat catalyzed by) increased fouling. Nevertheless, when these rates are plotted, they end up being very similar to linear fouling in the time horizon of interest. We omit studying this type of fouling, although it can be easily incorporated into our model.

The clean and actual heat-transfer coefficient in period t ($U_i^{\rm c}$ and U_{it}, respectively) are related to the fouling factor (r_{it}) by

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

The linear fouling model is given by

$$r_{it} = \dot{r}_{it} t \tag{2}$$

whereas the exponentially asymptotic model is given by

$$r_{it} = r_{it}^{\infty}[1 - \exp(K_{it} t)] \tag{3}$$

We now proceed to express the heat-transfer coefficient for any period, both at the end of the cleaning subperiod and the end of the operating subperiod. To do this, we define a binary variable that identifies when and which each exchanger is cleaned as follows:

$$Y_{it} = \begin{cases} 1 & \text{if the } i\text{th heat exchanger is cleaned in period } t \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

Consider the first time period and the linear fouling model. The value of the heat-exchange coefficient at the end of the cleaning subperiod is given by

$$U_{i1}^{\rm ecp} = \eta_{\rm c} U_{i1}^{\rm c} Y_{i1} + \frac{1 - Y_{i1}}{\dfrac{1}{U_i^0} + \dot{r}_{i1} f_i} \tag{5}$$

In this expression, U_i^0 represents the initial value of the heat-exchanger coefficient. When $Y_{i1} = 0$, the above expression reduces to

$$U_{i1}^{\rm ecp} = \frac{1}{\dfrac{1}{U_i^0} + \dot{r}_{i1} f_i} \tag{6}$$

where f_i represents the time needed to clean the ith heat exchanger. When $Y_{i1} = 1$, the exchanger is clean at the end of the cleaning period; that is, $U_{i1}^{\rm ecp} = \eta_{\rm c} U_i^{\rm c}$, where $\eta_{\rm c}$ represents the fraction of the clean value to which the heat-transfer coefficient is restored after cleaning. In turn, for the second period, we have

$$U_{i2}^{\mathrm{ecp}} = \frac{Y_{i1}(1 - Y_{i2})}{\dfrac{1}{\eta_{\mathrm{c}} U_{i1}^{\mathrm{c}}} + \dot{r}_{i1}(\tau_1 - f_i) + \dot{r}_{i2} f_i} + \eta_{\mathrm{c}} U_{i2}^{\mathrm{c}} Y_{i2} + \frac{(1 - Y_{i1})(1 - Y_{i2})}{\dfrac{1}{U_i^0} + \dot{r}_{i1}\tau_1 + \dot{r}_{i2} f_i} \quad (7)$$

which renders $U_{i2}^{\mathrm{ecp}} = \eta_{\mathrm{c}} U_i^{\mathrm{c}}$ when $Y_{i2} = 1$ and

$$U_{i2}^{\mathrm{ecp}} = \frac{1}{\dfrac{1}{\eta_{\mathrm{c}} U_i^{\mathrm{c}}} + \dot{r}_{i1}(\tau_1 - f_i) + \dot{r}_{i2} f_i} \quad (8)$$

when $Y_{i2} = 0$ and $Y_{i1} = 1$, that is, when the exchanger has been cleaned in the first period but not in the second, and

$$U_{i2}^{\mathrm{ecp}} = \frac{1}{\dfrac{1}{U_i^0} + \dot{r}_{i1}\tau_1 + \dot{r}_{i2} f_i} \quad (9)$$

when $Y_{i2} = Y_{i1} = 0$, that is, when it has never been cleaned. We generalize for all periods using the following formula:

$$U_{it}^{\mathrm{ecp}} = \sum_{k=0}^{t-1} \left\{ \frac{Y_{ik} \prod_{j=k+1}^{t} (1 - Y_{ij})}{\dfrac{1}{\eta_{\mathrm{c}} U_i^{\mathrm{c}}} + \dot{r}_{ik}(\tau_k - f_i) + \sum_{s=k+1}^{t-1} \dot{r}_{is}\tau_s + \dot{r}_{it} f_i} \right\} + \eta_{\mathrm{c}} U_{it}^{\mathrm{c}} Y_{it} + \frac{1}{\dfrac{1}{U_i^0} + \sum_{s=1}^{t-1} \dot{r}_{is}\tau_s + \dot{r}_{it} f_i} \prod_{p=0}^{t} (1 - Y_{ip}) \qquad \forall\, i,\, t \geq 1 \quad (10)$$

In this formula, we use a "zero" period $t = 0$ in which $Y_{i0} = 0$ and $\tau_0 = 0$, allowing us to generalize all equations for all periods and not having to write special equations for period 1. For the end of the operation subperiod, one can derive similar formulas as follows:

$$U_{it}^{\mathrm{eop}} = \sum_{k=0}^{t-1} \left\{ \frac{Y_{ik} \prod_{j=k+1}^{t} (1 - Y_{ij})}{\dfrac{1}{\eta_{\mathrm{c}} U_i^{\mathrm{c}}} + \dot{r}_{ik}(\tau_k - f_i) + \sum_{s=k+1}^{t} \dot{r}_{is}\tau_s} \right\} + \frac{Y_{it}}{\dfrac{1}{\eta_{\mathrm{c}} U_i^{\mathrm{c}}} + \dot{r}_{it}(\tau_t - f_i)} + \frac{\prod_{p=0}^{t} (1 - Y_{ip})}{\dfrac{1}{U_i^0} + \sum_{s=1}^{t} \dot{r}_{is}\tau_s} \qquad \forall\, i,\, t \geq 1 \quad (11)$$

Thus, one can write

$$U_{it}^{\mathrm{ecp}} = \sum_{k=0}^{t-1} [a_{ikt}^{\mathrm{c-lin}} Y_{ik} \prod_{j=k+1}^{t} (1 - Y_{ij})] + b_{it}^{\mathrm{c-lin}} Y_{it} + c_{it}^{\mathrm{c-lin}} \prod_{p=0}^{t} (1 - Y_{ip}) \qquad \forall\, i,\, t \geq 1 \quad (12)$$

$$U_{it}^{\mathrm{eop}} = \sum_{k=0}^{t-1} [a_{ikt}^{\mathrm{o-lin}} Y_{ik} \prod_{j=k+1}^{t} (1 - Y_{ij})] + b_{it}^{\mathrm{o-lin}} Y_{it} + c_{it}^{\mathrm{o-lin}} \prod_{p=0}^{t} (1 - Y_{ip}) \qquad \forall\, i,\, t \geq 1 \quad (13)$$

where

$$a_{ikt}^{\mathrm{c-lin}} = \frac{1}{\dfrac{1}{\eta_{\mathrm{c}} U_i^{\mathrm{c}}} + \dot{r}_{ik}(\tau_k - f_i) + \sum_{s=k+1}^{t-1} \dot{r}_{is}\tau_s + \dot{r}_{it} f_i} \qquad \forall\, i,\, t \geq 1 \quad (14)$$

$$a_{ikt}^{\mathrm{o-lin}} = \frac{1}{\dfrac{1}{\eta_{\mathrm{c}} U_i^{\mathrm{c}}} + \dot{r}_{ik}(\tau_k - f_i) + \sum_{s=k+1}^{t} \dot{r}_{is}\tau_s} \qquad \forall\, i,\, t \quad (15)$$

$$b_{it}^{\mathrm{c-lin}} = \eta_{\mathrm{c}} U_{it}^{\mathrm{c}} \qquad \forall\, i,\, t \geq 1 \quad (16)$$

$$b_{it}^{\mathrm{o-lin}} = \frac{1}{\dfrac{1}{\eta_{\mathrm{c}} U_i^{\mathrm{c}}} + \dot{r}_{it}(\tau_t - f_i)} \qquad \forall\, i,\, t \quad (17)$$

$$c_{it}^{\mathrm{c-lin}} = \frac{1}{\dfrac{1}{U_i^0} + \sum_{s=1}^{t-1} \dot{r}_{is}\tau_s + \dot{r}_{it} f_i} \qquad \forall\, i,\, t \geq 1 \quad (18)$$

$$c_{it}^{\mathrm{o-lin}} = \frac{1}{\dfrac{1}{U_i^0} + \sum_{s=1}^{t} \dot{r}_{is}\tau_s} \qquad \forall\, i,\, t \quad (19)$$

In the case of asymptotic fouling, one can rewrite eq 3 for $t - 1$ and subtract from eq 3 to obtain

$$r_{it} = r_{i(t-1)} - (r_{it}^{\infty} - r_{i(t-1)})[1 - \exp(K_{it} t)] \quad (20)$$

Thus, at the end of the cleaning and operating subperiods, one has

$$U_{it}^{\mathrm{ecp}} = \sum_{k=0}^{t-1} [a_{ikt}^{\mathrm{c-asy}} Y_{ik} \prod_{j=k+1}^{t} (1 - Y_{ij})] + b_{it}^{\mathrm{c-asy}} Y_{it} + c_{it}^{\mathrm{c-asy}} \prod_{p=0}^{t} (1 - Y_{ip}) \qquad \forall\, i,\, t \geq 1 \quad (21)$$

$$U_{it}^{\mathrm{eop}} = \sum_{k=0}^{t-1} [a_{ikt}^{\mathrm{o-asy}} Y_{ik} \prod_{j=k+1}^{t} (1 - Y_{ij})] + b_{it}^{\mathrm{o-asy}} Y_{it} + c_{it}^{\mathrm{o-asy}} \prod_{p=0}^{t} (1 - Y_{ip}) \qquad \forall\, i,\, t \geq 1 \quad (22)$$

where

$$\frac{1}{a_{ikt}^{\mathrm{c-asy}}} = \frac{1}{\eta_{\mathrm{c}} U_{it}^{\mathrm{c}}} + r_{it}^{\infty}[1 - \exp(-K_{it} f_i)] + \sum_{j=k}^{t-1} r_{ij}^{\infty} \exp(-\sum_{s=j+1}^{t-1} K_{is}\tau_s - K_{it} f_i) - r_{ik}^{\infty} \exp[-K_{ik}(\tau_k - f_i) - \sum_{s=k+1}^{t-1} K_{is}\tau_s - K_{it} f_i] - \sum_{j=k+1}^{t-1} r_{ij}^{\infty} \exp(-\sum_{s=j+1}^{t-1} K_{is}\tau_s - K_{it} f_i) \qquad \forall\ i, t \geq 1 \quad (23)$$

$$\frac{1}{a_{ikt}^{\mathrm{o-asy}}} = \frac{1}{\eta_{\mathrm{c}} U_{it}^{\mathrm{c}}} + r_{it}^{\infty}[1 - \exp(-K_{it}\tau_t)] + \sum_{j=k}^{t-1} r_{ij}^{\infty} \exp(-\sum_{s=j+1}^{t} K_{is}\tau_s) - r_{ik}^{\infty} \exp[-K_{ik}(\tau_k - f_i) - \sum_{s=k+1}^{t} K_{is}\tau_s] - \sum_{j=k+1}^{t-1} r_{ij}^{\infty} \exp(-\sum_{s=j}^{t} K_{is}\tau_s) \qquad \forall\ i, t \quad (24)$$

$$b_{it}^{\mathrm{c-asy}} = \eta_{\mathrm{c}} U_{it}^{\mathrm{c}} \qquad \forall\ i, t \geq 1 \quad (25)$$

$$b_{it}^{\mathrm{o-asy}} = \frac{1}{\dfrac{1}{\eta_{\mathrm{c}} U_{it}^{\mathrm{c}}} + r_{it}^{\infty}\{1 - \exp[-K_{it}(\tau_t - f_i)]\}} \qquad \forall\ i, t \quad (26)$$

$$\frac{1}{c_{it}^{\mathrm{c-asy}}} = \frac{1}{U_i^0} + r_{it}^{\infty}[1 - \exp(-K_{it} f_i)] + \sum_{j=0}^{t-1} r_{ij}^{\infty} \exp(-\sum_{s=j+1}^{t-1} K_{is}\tau_s - K_{it} f_i) - \sum_{j=0}^{t-1} r_{ij}^{\infty} \exp(-\sum_{s=j}^{t-1} \dot{K}_{is}\tau_s - K_{it} f_i) \qquad \forall\ i, t \geq 1 \quad (27)$$

$$\frac{1}{c_{it}^{\mathrm{o-asy}}} = \frac{1}{U_i^0} + r_{it}^{\infty}[1 - \exp(-K_{it}\tau_t)] + \sum_{j=0}^{t-1} r_{ij}^{\infty} \exp(-\sum_{s=j+1}^{t} K_{is}\tau_s) - \sum_{j=0}^{t-1} r_{ij}^{\infty} \exp(-\sum_{s=j}^{t} \dot{K}_{is}\tau_s) \qquad \forall\ i, t \quad (28)$$

Equations 12 and 13 for the linear fouling model and eqs 21 and 22 for the asymptotic fouling model contain products of integers. However, these can be easily linearized, as is shown below.

Mixed-Integer Representation of the Temperature Relations in a Heat Exchanger

We consider at this point single-pass countercurrent shell and tube heat exchangers, with bypasses for both streams required to put the exchanger offline during operation. The equations that represent the relationship between the inlet and outlet temperatures of the ith heat exchanger (Figure 3) with the heat exchanged are

$$Q_{it} = \mathrm{Fc}_{it}\mathrm{Cc}_{it}(\mathrm{Tc}_{2it} - \mathrm{Tc}_{1it}) \quad (29)$$

$$Q_{it} = \mathrm{Fh}_{it}\mathrm{Ch}_{it}(\mathrm{Th}_{1it} - \mathrm{Th}_{2it}) \quad (30)$$

$$Q_{it} = U_{it}\mathrm{FT}_{it}A_{it}\frac{(\mathrm{Th}_{1it} - \mathrm{Tc}_{2it}) - (\mathrm{Th}_{2it} - \mathrm{Tc}_{1it})}{\ln\left[\dfrac{(\mathrm{Th}_{1it} - \mathrm{Tc}_{2it})}{(\mathrm{Th}_{2it} - \mathrm{Tc}_{1it})}\right]} \quad (31)$$

In the case of single-pass exchangers, we have $\mathrm{FT}_{it} = 1$, whereas for the case of multiple-pass configurations, FT_{it} can be estimated using a range of possible values of temperatures involved. However, there are ways of modeling multipass exchangers using linear models, work that is left for the future. Rearranging these equations, one can write[22]

$$\mathrm{Th}_{2it} = \frac{(R_{it} - 1)\mathrm{Th}_{1it} + \left\{\exp\left[\dfrac{U_{it}A_i}{\mathrm{Fc}_{it}\mathrm{Cc}_{it}}(R_{it} - 1)\right] - 1\right\}R_{it}\mathrm{Tc}_{1it}}{R_{it}\exp\left[\dfrac{U_{it}A_i}{\mathrm{Fc}_{it}\mathrm{Cc}_{it}}(R_{it} - 1)\right] - 1} \quad (32)$$

where

$$R_{it} = \frac{\mathrm{Fc}_{it}\mathrm{Cc}_{it}}{\mathrm{Fh}_{it}\mathrm{Ch}_{it}} = \frac{\mathrm{Th}_{1it} - \mathrm{Th}_{2it}}{\mathrm{Tc}_{2it} - \mathrm{Tc}_{1it}} \quad (33)$$

Now substituting the value of U_{it} as a function of the integers given by eqs 12 and 13 or eqs 21 and 22, one obtains

$$\mathrm{Th}_{2it} = \frac{(R_{it} - 1)\mathrm{Th}_{1it} - R_{it}\mathrm{Tc}_{1it}}{R_{it}\exp\{d_i[\sum_{k=1}^{t-1}[a_{ikt}Y_{ik}\prod_{j=k+1}^{t}(1 - Y_{ij})] + b_{it}Y_{it} + c_{it}\prod_{p=1}^{t}(1 - Y_{ip})]\} - 1} + \frac{R_{it}\mathrm{Tc}_{1it}[\exp\{d_i[\sum_{k=1}^{t-1}[a_{ikt}Y_{ik}\prod_{j=k+1}^{t}(1 - Y_{ij})] + b_{it}Y_{it} + c_{it}\prod_{p=1}^{t}(1 - Y_{ip})]\}]}{R_{it}\exp\{d_i[\sum_{k=1}^{t-1}[a_{ikt}Y_{ik}\prod_{j=k+1}^{t}(1 - Y_{ij})] + b_{it}Y_{it} + c_{it}\prod_{p=1}^{t}(1 - Y_{ip})]\} - 1} \qquad \forall\ i, t \geq 1 \quad (34)$$

where

$$d_{it} = \frac{A_i}{\mathrm{Fc}_{it}\mathrm{Cc}_{it}}(R_{it} - 1) \quad (35)$$

Because *one and only one* of the terms inside of every power of the exponentials in eq 34 can be different from zero, it is possible to transform eq 34 into

$$\mathrm{Th}_{2it} = (R_{it}-1)\mathrm{Th}_{1it} \times \left[\sum_{k=0}^{t-1}\frac{(Y_{ik}\prod_{j=k+1}^{t}(1-Y_{ij}))}{R_{it}h_{ikt}^{a}-1} + \frac{Y_{it}}{R_i h_{it}^{b}-1} + \frac{\prod_{p=0}^{t}(1-Y_{ip})}{R_{it}h_{it}^{c}-1}\right] - R_{it}\mathrm{Tc}_{1it}\left[\sum_{k=0}^{t-1}\frac{(Y_{ik}\prod_{j=k+1}^{t}(1-Y_{ij}))}{R_{it}h_{ikt}^{a}-1} + \frac{Y_{it}}{R_{it}h_{it}^{b}-1} + \frac{\prod_{p=0}^{t}(1-Y_{ip})}{R_{it}h_{it}^{c}-1}\right] + R_{it}\mathrm{Tc}_{1it}\left[\frac{h_{ikt}^{a}\sum_{k=0}^{t-1}(Y_{ik}\prod_{j=k+1}^{t}(1-Y_{ij}))}{R_{it}h_{ikt}^{a}-1} + \frac{h_{it}^{b}Y_{it}}{R_{it}h_{it}^{b}-1} + \frac{h_{it}^{c}\prod_{p=0}^{t}(1-Y_{ip})}{R_{it}h_{it}^{c}-1}\right] \quad \forall\, i,\, t \geq 1 \quad (36)$$

where $h_{ikt}^{a} = \exp\{d_{it}a_{ikt}\}$, $h_{it}^{b} = \exp\{d_{it}b_{it}\}$, and $h_{it}^{c} = \exp\{d_{it}c_{it}\}$. These last three parameters will become $h_{ikt}^{a-\mathrm{ecp}}$, $h_{it}^{b-\mathrm{ecp}}$, and $h_{it}^{c-\mathrm{ecp}}$ in the case where the evaluation is done at the end of the cleaning period. The nonlinearities in eq 36 consist of products of integers, which can be easily linearized by adding new continuous variables. Thus, this model takes into account the fouling effect throughout time without doing any kind of approximation. This is in contrast with earlier works, which had to introduce approximations to the models. For example, Georgiadis et al.[11] used the arithmetic-mean temperature difference instead of the log-mean average, and Smaïli et al.[13] linearized the asymptotic fouling curve and considered constant-temperature profiles throughout each subperiod.

We now distinguish two cases: a single exchanger and an exchanger in a network. In the case of a single heat exchanger, Th_{1it} and Tc_{1it} are parameters and one can directly relate the temperature at the end of one subperiod with the one at the beginning of the next. To illustrate this, we consider the case where no cleaning takes place in period $t-1$ and cleaning takes place in period t. The outlet cold temperature profile for asymptotic fouling is shown in Figure 4.

Clearly, if the exchanger is cleaned in period t, the outlet hot temperature at the beginning of the cleaning subperiod is equal to the inlet temperature, whereas if it is not cleaned, it is equal to the temperature at the end of the operating subperiod of the previous period ($\mathrm{Th}_{2i,t-1}^{\mathrm{eop}}$). Thus, one can write

$$\mathrm{Th}_{2it}^{\mathrm{bcp}} = \mathrm{Th}_{1it}Y_{it} + \mathrm{Th}_{2i,t-1}^{\mathrm{eop}}(1-Y_{it}) \quad \forall\, i,\, t \geq 1 \quad (37)$$

At the end of the cleaning period, either the hot outlet temperature is equal to the hot inlet one or it would be a function of the U and Tc_1 at that point:

$$\mathrm{Th}_{2it}^{\mathrm{ecp}} = \mathrm{Th}_{1it}Y_{it} + H_{it}(1-Y_{it}) \quad \forall\, i,\, t \geq 1 \quad (38)$$

Similar relations can be written for the beginning and end of the operating subperiods, as follows:

$$\mathrm{Th}_{2it}^{\mathrm{bop}} = L_{it}Y_{it} + \mathrm{Th}_{2it}^{\mathrm{ecp}}(1-Y_{it}) \quad \forall\, i,\, t \geq 1 \quad (39)$$

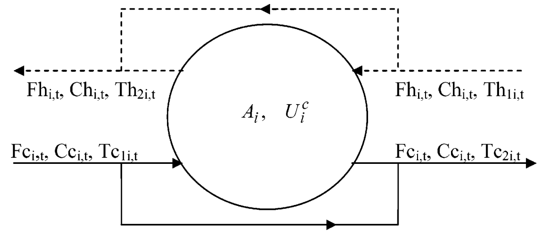

Figure 3. Single-heat-exchanger representation.

$$\mathrm{Th}_{2it}^{\mathrm{eop}} = G_{it} \quad \forall\, i,\, t \geq 1 \quad (40)$$

where

$$H_{it} = (R_{it}-1)\mathrm{Th}_{1it} \times \left[\sum_{k=0}^{t-1}\frac{(Y_{ik}\prod_{j=k+1}^{t}(1-Y_{ij}))}{R_{it}h_{ikt}^{a-c}-1} + \frac{Y_{it}}{R_i h_{it}^{b-c}-1} + \frac{\prod_{p=0}^{t}(1-Y_{ip})}{R_{it}h_{it}^{c-c}-1}\right] - R_{it}\mathrm{Tc}_{1it}\left[\sum_{k=0}^{t-1}\frac{(Y_{ik}\prod_{j=k+1}^{t}(1-Y_{ij}))}{R_{it}h_{ikt}^{a-c}-1} + \frac{Y_{it}}{R_{it}h_{it}^{b-c}-1} + \frac{\prod_{p=0}^{t}(1-Y_{ip})}{R_{it}h_{it}^{c-c}-1}\right] + R_{it}\mathrm{Tc}_{1it}\left[\frac{h_{ikt}^{a-c}\sum_{k=0}^{t-1}(Y_{ik}\prod_{j=k+1}^{t}(1-Y_{ij}))}{R_{it}h_{ikt}^{a-c}-1} + \frac{h_{it}^{b-c}Y_{it}}{R_{it}h_{it}^{b-c}-1} + \frac{h_{it}^{c-c}\prod_{p=0}^{t}(1-Y_{ip})}{R_{it}h_{it}^{c-c}-1}\right] \quad \forall\, i,\, t \geq 1 \quad (41)$$

$$L_{it} = \frac{(R_{it}-1)\mathrm{Th}_{1it} + [\exp(\eta_{\mathrm{c}}U_i^{\mathrm{c}}d_{it})-1]R_{it}\mathrm{Tc}_{1it}}{R_{it}\exp(\eta_{\mathrm{c}}U_i^{\mathrm{c}}d_{it})-1} \quad \forall\, i,\, t \geq 1 \quad (42)$$

$$G_{it} = (R_{it}-1)\mathrm{Th}_{1it} \times \left[\sum_{k=0}^{t-1}\frac{(Y_{ik}\prod_{j=k+1}^{t}(1-Y_{ij}))}{R_{it}h_{ikt}^{a-\mathrm{o}}-1} + \frac{Y_{it}}{R_i h_{it}^{b-\mathrm{o}}-1} + \frac{\prod_{p=0}^{t}(1-Y_{ip})}{R_{it}h_{it}^{c-\mathrm{o}}-1}\right] - R_{it}\mathrm{Tc}_{1it}\left[\sum_{k=0}^{t-1}\frac{(Y_{ik}\prod_{j=k+1}^{t}(1-Y_{ij}))}{R_{it}h_{ikt}^{a-\mathrm{o}}-1} + \frac{Y_{it}}{R_{it}h_{it}^{b-\mathrm{o}}-1} + \frac{\prod_{p=0}^{t}(1-Y_{ip})}{R_{it}h_{ikt}^{c-\mathrm{o}}-1}\right] + R_{it}\mathrm{Tc}_{1it}\left[\frac{h_{ikt}^{a-\mathrm{o}}\sum_{k=0}^{t-1}(Y_{ik}\prod_{j=k+1}^{t}(1-Y_{ij}))}{R_{it}h_{ikt}^{a-\mathrm{o}}-1} + \frac{h_{it}^{b-\mathrm{o}}Y_{it}}{R_{it}h_{it}^{b-\mathrm{o}}-1} + \frac{h_{it}^{c-\mathrm{o}}\prod_{p=0}^{t}(1-Y_{ip})}{R_{it}h_{it}^{c-\mathrm{o}}-1}\right] \quad \forall\, i,\, t \geq 1 \quad (43)$$

These equations, as will be shown next, are simpler than those one has to write for the general case. Indeed, when there are many exchangers, the inlet temperatures of each exchanger are no longer constant, but rather they are functions of the cleaning history of the upstream exchangers. Figure 5 shows how two consecutive heat exchangers interact. In this case, the qth heat exchanger is not cleaned during period $t-1$ but is cleaned in period t. The opposite occurs with the downstream $(q+1)$th heat exchanger; that is, it is cleaned in period $t-1$ and not cleaned in period t.

We also consider that exchanger q is fed by a constant-temperature stream. For this reason, its profile looks like the one in Figure 4. Now, consider exchanger $q+1$. During the cleaning subperiod in period $t-1$, the outlet temperature is equal to the outlet temperature of exchanger q and, therefore, not constant.

Thus, the outlet temperatures of the hot streams are given by

$$\mathrm{Th}^{\mathrm{bcp}}_{2it} = \mathrm{Th}^{\mathrm{bcp}}_{1it} Y_{it} + J_{it}(1 - Y_{it}) \qquad \forall\ i,\ t \geq 1 \quad (44)$$

$$\mathrm{Th}^{\mathrm{ecp}}_{2it} = \mathrm{Th}^{\mathrm{ecp}}_{1it} Y_{it} + K_{it}(1 - Y_{it}) \qquad \forall\ i,\ t \geq 1 \quad (45)$$

$$\mathrm{Th}^{\mathrm{bop}}_{2it} = M_{it} Y_{it} + N_{it}(1 - Y_{it}) \qquad \forall\ i,\ t \geq 1 \quad (46)$$

$$\mathrm{Th}^{\mathrm{eop}}_{2it} = P_{it} \qquad \forall\ i,\ t \geq 1 \quad (47)$$

where

$$J_{it} = (R_{it} - 1)\mathrm{Th}^{\mathrm{bcp}}_{1it} \times \left[\sum_{k=0}^{t-2} \frac{(Y_{ik} \prod_{j=k+1}^{t-1} (1 - Y_{ij}))}{R_{it} h^{a-\mathrm{o}}_{ik,t-1} - 1} + \frac{Y_{it}}{R_i h^{b-\mathrm{o}}_{i,t-1} - 1} + \frac{\prod_{p=0}^{t-1}(1 - Y_{ip})}{R_{it} h^{c-\mathrm{o}}_{i,t-1} - 1}\right] - R_{it}\mathrm{Tc}^{\mathrm{bcp}}_{1it}\left[\sum_{k=0}^{t-2} \frac{(Y_{ik} \prod_{j=k+1}^{t-1} (1 - Y_{ij}))}{R_{it} h^{a-\mathrm{o}}_{ik,t-1} - 1} + \frac{Y_{it}}{R_{it} h^{b-\mathrm{o}}_{i,t-1} - 1} + \frac{\prod_{p=0}^{t-1}(1 - Y_{ip})}{R_{it} h^{c-\mathrm{o}}_{i,t-1} - 1}\right] + R_{it}\mathrm{Tc}^{\mathrm{bcp}}_{1it}\left[\frac{h^{a-\mathrm{o}}_{ik,t-1}\sum_{k=0}^{t-2}(Y_{ik} \prod_{j=k+1}^{t-1} (1 - Y_{ij}))}{R_{it} h^{a-\mathrm{o}}_{ik,t-1} - 1} + \frac{h^{b-\mathrm{o}}_{i,t-1} Y_{it}}{R_{it} h^{b-\mathrm{o}}_{i,t-1} - 1} + \frac{h^{c-\mathrm{o}}_{i,t-1}\prod_{p=0}^{t-1}(1 - Y_{ip})}{R_{it} h^{c-\mathrm{o}}_{i,t-1} - 1}\right] \qquad \forall\ i,\ t \geq 1 \quad (48)$$

$$K_{it} = (R_{it} - 1)\mathrm{Th}^{\mathrm{ecp}}_{1it} \times \left[\sum_{k=0}^{t-1} \frac{(Y_{ik} \prod_{j=k+1}^{t} (1 - Y_{ij}))}{R_{it} h^{a-c}_{ik,t-1} - 1} + \frac{Y_{it}}{R_{it} h^{b-c}_{i,t-1} - 1} + \frac{\prod_{p=0}^{t}(1 - Y_{ip})}{R_{it} h^{c-c}_{i,t-1} - 1}\right] - R_{it}\mathrm{Tc}^{\mathrm{ecp}}_{1it}\left[\sum_{k=0}^{t-2} \frac{(Y_{ik} \prod_{j=k+1}^{t} (1 - Y_{ij}))}{R_{it} h^{a-c}_{ik,t-1} - 1} + \frac{Y_{it}}{R_{it} h^{b-c}_{i,t-1} - 1} + \frac{\prod_{p=0}^{t}(1 - Y_{ip})}{R_{it} h^{c-c}_{i,t-1} - 1}\right] + R_{it}\mathrm{Tc}^{\mathrm{ecp}}_{1it}\left[\frac{h^{a-c}_{ik,t-1}\sum_{k=0}^{t-2}(Y_{ik} \prod_{j=k+1}^{t} (1 - Y_{ij}))}{R_{it} h^{a-c}_{ik,t-1} - 1} + \frac{h^{b-c}_{i,t-1} Y_{it}}{R_{it} h^{b-c}_{i,t-1} - 1} + \frac{h^{c-c}_{i,t-1}\prod_{p=0}^{t-1}(1 - Y_{ip})}{R_{it} h^{c-c}_{i,t-1} - 1}\right] \qquad \forall\ i,\ t \geq 1 \quad (49)$$

$$M_{it} = \left[\frac{(R_{it} - 1)\mathrm{Th}^{\mathrm{bop}}_{1it} + [\exp(\eta_{\mathrm{c}} U^{\mathrm{c}}_{i} d_{it}) - 1)R_{it}\mathrm{Tc}^{\mathrm{bop}}_{1it}}{R_{it} \exp(\eta_{\mathrm{c}} U^{\mathrm{c}}_{i} d_{it}) - 1}\right] \qquad \forall\ i,\ t \geq 1 \quad (50)$$

$$N_{it} = (R_{it} - 1)\mathrm{Th}^{\mathrm{bop}}_{1it} \times \left[\sum_{k=0}^{t-1} \frac{(Y_{ik} \prod_{j=k+1}^{t} (1 - Y_{ij}))}{R_{it} h^{a-c}_{ikt} - 1} + \frac{Y_{it}}{R_i h^{b-c}_{it} - 1} + \frac{\prod_{p=0}^{t}(1 - Y_{ip})}{R_{it} h^{c-c}_{it} - 1}\right] - R_{it}\mathrm{Tc}^{\mathrm{bop}}_{1it}\left[\sum_{k=0}^{t-1} \frac{(Y_{ik} \prod_{j=k+1}^{t} (1 - Y_{ij}))}{R_{it} h^{a-c}_{ikt} - 1} + \frac{Y_{it}}{R_{it} h^{b-c}_{it} - 1} + \frac{\prod_{p=0}^{t}(1 - Y_{ip})}{R_{it} h^{c-c}_{it} - 1}\right] + R_{it}\mathrm{Tc}^{\mathrm{bop}}_{1it}\left[\frac{h^{a-c}_{ikt}\sum_{k=0}^{t-1}(Y_{ik} \prod_{j=k+1}^{t} (1 - Y_{ij}))}{R_{it} h^{a-c}_{ikt} - 1} + \frac{h^{b-c}_{it} Y_{it}}{R_{it} h^{b-c}_{it} - 1} + \frac{h^{c-c}_{it}\prod_{p=0}^{t}(1 - Y_{ip})}{R_{it} h^{c-c}_{it} - 1}\right] \qquad \forall\ i,\ t \geq 1 \quad (51)$$

$$P_{it} = (R_{it} - 1)\mathrm{Th}_{1it}^{\mathrm{bop}} \times \left[\sum_{k=0}^{t-1}\frac{(Y_{ik}\prod_{j=k+1}^{t}(1 - Y_{ij}))}{R_{it}h_{ikt}^{a-\mathrm{o}} - 1} + \frac{Y_{it}}{R_i h_{it}^{b-\mathrm{o}} - 1} + \frac{\prod_{p=0}^{t}(1 - Y_{ip})}{R_{it}h_{it}^{c-\mathrm{o}} - 1}\right] - R_{it}\mathrm{Tc}_{1it}^{\mathrm{bop}}\left[\sum_{k=0}^{t-1}\frac{(Y_{ik}\prod_{j=k+1}^{t}(1 - Y_{ij}))}{R_{it}h_{ikt}^{a-\mathrm{o}} - 1} + \frac{Y_{it}}{R_{it}h_{it}^{b-\mathrm{o}} - 1} + \frac{\prod_{p=0}^{t}(1 - Y_{ip})}{R_{it}h_{it}^{c-\mathrm{o}} - 1}\right] + R_{it}\mathrm{Tc}_{1it}^{\mathrm{bop}}\left[\frac{h_{ikt}^{a-\mathrm{eop}}\sum_{k=0}^{t-1}(Y_{ik}\prod_{j=k+1}^{t}(1 - Y_{ij}))}{R_{it}h_{ikt}^{a-\mathrm{eop}} - 1} + \frac{h_{it}^{b-\mathrm{o}}Y_{it}}{R_{it}h_{it}^{b-\mathrm{o}} - 1} + \frac{h_{it}^{c-\mathrm{o}}\prod_{p=0}^{t}(1 - Y_{ip})}{R_{it}h_{it}^{c-\mathrm{o}} - 1}\right] \quad \forall\, i, t \geq 1 \quad (52)$$

To linearize all of these expressions, we resort to variable substitution and new constraints. For example, we write

$$\alpha_{ikt}^{*} = \mathrm{Th}_{1it}^{*} Y_{ik} \prod_{j=k+1}^{t}(1 - Y_{ij}) \qquad \forall\, i, t \geq 1 \qquad (53)$$

where * can be substituted for bcp, ecp, bop, or eop. This means that

$$\alpha_{ikt}^{*} = \begin{cases} 0 & \text{if } Y_{ik} = 0 \text{ or at least one } Y_{ij} = 1 \\ \mathrm{Th}_{1it}^{*} & \text{if } Y_{ik} = 1 \text{ and } \sum_{j=k+1}^{t} Y_{ij} = 0 \end{cases} \qquad (54)$$

which can be obtained through the following set of equations:

$$\alpha_{ikt}^{*} - Y_{ik}\Omega h_i \leq 0 \qquad \forall\, i, t \geq 1, k \leq t \qquad (55)$$

$$\alpha_{ikt}^{*} - (1 - Y_{ij})\Omega h_i \leq 0 \qquad \forall\, i, t \geq 1, k \leq t, j = k + 1, ..., t \quad (56)$$

$$\alpha_{ikt}^{*} \geq 0 \qquad \forall\, i, t \geq 1, k \leq t \qquad (57)$$

$$(\mathrm{Th}_{1it}^{*} - \alpha_{ikt}^{*}) - (1 + \sum_{j=k+1}^{t} Y_{ij} - Y_{ik})\Omega h_i \leq 0 \qquad \forall\, i, t \geq 1, k \leq t \quad (58)$$

$$\mathrm{Th}_{1it}^{*} - \alpha_{ikt}^{*} \geq 0 \qquad \forall\, i, t \geq 1 \qquad (59)$$

where Ωh_i is a large number. The same can be done for several other products of the same type. We omit the details because they are standard transformations.

Equations relating inlet temperatures with outlet temperatures need to be added. They are

$$\mathrm{Tc}_{2it}^{*} = \mathrm{Tc}_{1it}^{*} + \frac{\mathrm{Th}_{1it}^{*} - \mathrm{Th}_{2it}^{*}}{R_{it}} \qquad (60)$$

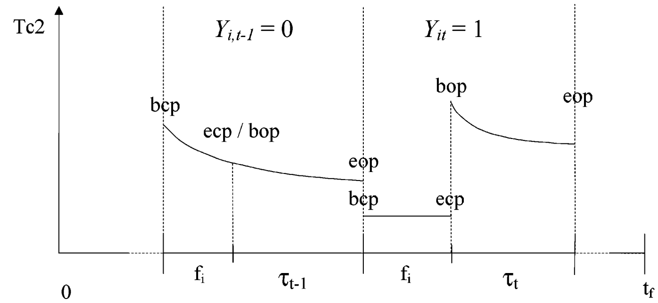

Figure 4. Outlet temperature of a cold stream for a single exchanger being cleaned in period t. Asymptotic fouling.

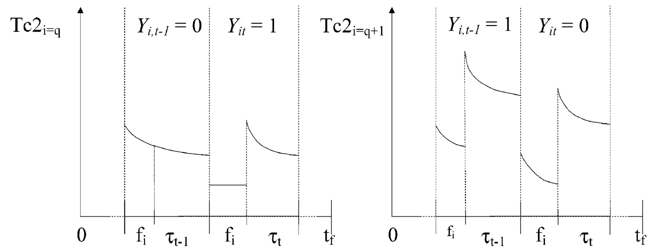

Figure 5. Outlet temperature of the cold stream for two consecutive exchangers being cleaned in period t.

Similar expressions can be written for the outlet hot temperatures Th_{2it}^{*}. Similarly, equations relating inlet temperatures with outlet temperatures of other exchangers are included in the model. In the case of exchangers in series, as in Figure 1, one can write

$$\mathrm{Tc}_{1it}^{*} = \mathrm{Tc}_{2i-1,t}^{*} \qquad \forall\, i \neq 1, \forall\, t \qquad (61)$$

$$\mathrm{Tc}_{1i=1,t}^{*} = \mathrm{Tc}_{\mathrm{in}} \qquad \forall\, i = 1, \forall\, t \qquad (62)$$

where $\mathrm{Tc}_{\mathrm{in}}$ is the temperature of the feed of the first exchanger. Other relations can be written for more complicated networks, including equations relating hot inlet temperatures with outlet hot temperatures of other exchangers.

Other Constraints

Logical Constraints. All continuous variables involved in this problem are nonnegative ones. In addition, the outlet cold temperature of each heat exchanger must be greater than or equal than the inlet cold one:

$$\mathrm{Tc}_{2it}^{*} \geq \mathrm{Tc}_{1it}^{*} \qquad \forall\, i, \forall\, t \qquad (63)$$

There are also restrictions in minimum or maximum values that certain temperatures can reach:

$$\mathrm{Tc}_{2i,t}^{*} \geq T_{2i}^{\min} \qquad \forall\, i, \forall\, t \qquad (64)$$

The value of $T_{2i}^{\min}$ is a lower bound determined by process considerations.

Number of Cleanings. Because of limitations in cleaning device resources, it is not possible to clean at the same period more than a certain maximum number of heat exchangers.

$$\sum_{i=1}^{n} Y_{it} \leq \mathrm{Ncl}_{\max} \qquad \forall\, t \qquad (65)$$

Other constraints limiting the number of cleanings that

Table 1. Data for a Single Exchanger (Taken from Smaïli et al.[13])

parameter	value
Tc_{in} [°F]	347
Th_1 [°F]	631.4
Fh [lb/h]	207 940
Fc [lb/h]	649 217
Ch [Btu/(lb °F)]	0.67
Cc [Btu/(lb °F)]	0.57
U^c [Btu/(h ft^2 °F)]	88.1
U^o [Btu/(h ft^2 °F)]	88.1
A [ft^2]	1257.2
$\dot{r}$(linear fouling) [(ft^2 °F)/Btu]	3.88×10^{-7}
r^∞(asymptotic fouling) [(h ft^2 °F)/Btu]	6.73×10^{-3}
K(asymptotic fouling) [month^{-1}]	0.25
τ [month]	1
f	0.20
η_f	0.75

each exchanger can be cleaned throughout the operation horizon can also be added. These reduce considerably the feasible space.

Overall Energy Consumption

To find the total furnace energy consumption, we calculate the furnace duty during each subperiod as follows:

$$Qf_t^{bcp} = Fc_t Cc_t (Tc_{out} - Tc_{2nt}^{bcp}) \quad (66)$$

$$Qf_t^{ecp} = Fc_t Cc_t (Tc_{out} - Tc_{2nt}^{ecp}) \quad (67)$$

$$Qf_t^{bop} = Fc_t Cc_t (Tc_{out} - Tc_{2nt}^{bop}) \quad (68)$$

$$Qf_t^{eop} = Fc_t Cc_t (Tc_{out} - Tc_{2nt}^{eop}) \quad (69)$$

where Tc_{out} is the furnace's outlet temperature. Because the cleaning period f_i can be different for different exchangers, we approximate the energy consumption using the following expression:

$$Ef_t = \frac{Q_t^{bcp} + Q_t^{ecp}}{2}\bar{f} + \frac{Q_t^{bop} + Q_t^{eop}}{2}(\tau_t - \bar{f}) \quad (70)$$

where

$$\bar{f} = \sum_i f_i/n \quad (71)$$

The expression approximates the energy consumption in each subperiod using a linear approximation.

Objective Function

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 man power, chemicals, and maintenance).

$$\mathrm{NPC} = \sum_t d_t \frac{(Ef_t - Ef_t^{cl})}{\eta_f} C_{Ef} + \sum_t d_t \sum_i Y_{it} C_{cl} \quad (72)$$

where 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.

Table 2. Comparative Solutions for the Single-Heat-Exchanger Case (Linear Fouling)

	Smaïli et al.[13]		this model	
	no. of cleanings	NPC	no. of cleanings	NPC
no cleaning	0	202 600	0	202 600
$C_{cl} = 0$	4	90 200	4	90 000
$C_{cl} = 4000$	3	not reported	3	10 200

Numerical Difficulties and Solution Methods

The model was coded in GAMS.[23] In many cases, the solution procedure involves overcoming gaps that are very large. In addition, the problem seems to have a lot of suboptimal solutions that are very close to the global optimum. This makes the MILP procedure explore a large and prohibitive number of nodes.

To ameliorate these difficulties, one can, of course, give up linearity and construct an MINLP model, which will be nonconvex. We rather kept linearity because we think there are better chances to capture the global optimum and we decided to explore how far we can get by means of decomposition procedures when the linear model exhibits solution times that are prohibitive.

First, we solved the single-heat-exchanger model, compared it with the results obtained by Smaïli et al.,[13] and discovered that our model renders better answers. We next introduce a new decomposition procedure that, compared to the MINLP method used by Smaïli et al.,[13] renders better solutions. Next, we tried the concept of moving horizon proposed for this problem by Wilson and Vassiliadis[19] to conclude that this is not a good approach. We finally make some comparisons with heuristic rules.

Results Using the Full Model without Decomposition. The model was solved for the same single-heat-exchanger case study proposed by Smaïli et al.[13] All of the parameters used are the same as those used by Smaïli et al.[13] and given in Table 1. Constant flows and properties throughout the horizon were assumed, and no discount factors for future costs were employed. Two different cleaning costs were used: 0 and 4000, which are the costs used by Smaïli et al.[13] The case of no cleaning cost represents the case of the energy maximization problem.

We first notice that different net present costs are obtained (Tables 2 and 3), especially for the case of asymptotic fouling. The values for Smaïli et al.'s[13] column were obtained by imposing their schedule to our model. As an illustration, the outlet cold temperature profiles for the case of zero cleaning cost and asymptotic fouling are shown in Figure 6.

From Tables 2 and 3, it can be observed that, in the case of the linear fouling, both solutions are very close but the schedules are different. These differences should be mainly attributed to the fact that the models are different. For example, in the case of the model by Smaïli et al.,[13] the temperature of each subperiod is evaluated only at the beginning of each subperiod and considered as the temperature for the whole subperiod instead of evaluating the temperature at the beginning and at the end as in the present model. However, despite theses differences, these solutions are similar in total cost. On the other hand, for the asymptotic fouling case, the solutions are not as close, and the

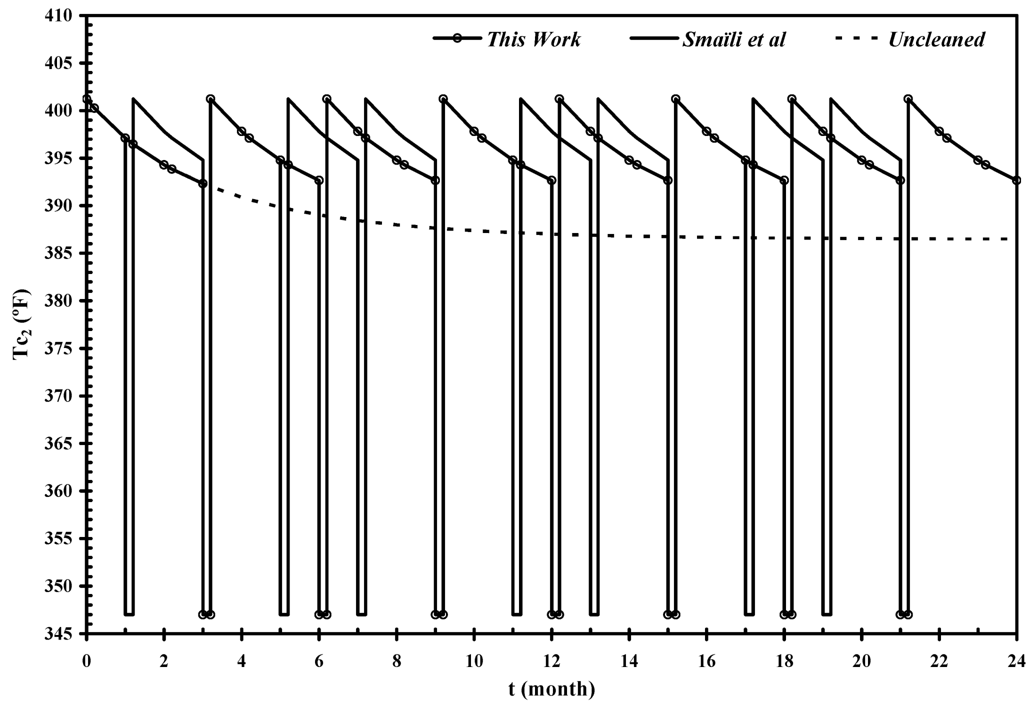

Figure 6. Comparison of outlet cold temperature profiles: zero cleaning cost; asymptotic fouling. Smaïli et al.'s[13] solution obtained by imposing their schedule.

Table 3. Comparative Solutions for the Single-Heat-Exchanger Case (Asymptotic Fouling)

	Smaïli et al.[13]		this model	
	no. of cleanings	NPC	no. of cleanings	NPC
no cleaning	0	315 900	0	315 900
$C_{cl} = 0$	11	206 900	7	196 400
$C_{cl} = 4000$	6	not reported	5	224 700

number of cleanings is different (Figure 6). This is caused by the difference in the representation of asymptotic fouling in the models. Indeed, Smaïli et al.[13] introduced some approximations that we did not use.

It is observed that all of the solutions for a single-heat-exchanger case are cyclic (Tables 4–6). This means that the heat exchanger is cleaned every time the fouling reaches a certain value, which is the strategy typically applied in practice without using any optimization tool (heuristic approaches). We will see later that this type of practice is not correct when more exchangers are involved.

The resource usage for the full model version for this one exchanger and 24 months varies significantly depending on the cleaning cost and the fouling type: for linear fouling and 0 cleaning cost, 730.1 CPU s; for linear fouling and 4000 cleaning cost, 1109.4 s; for asymptotic fouling and 0 cleaning cost, 1572.7 s; for asymptotic fouling and 4000 cleaning cost, 10 378.1 s (on a Pentium 4, 2.0 GHz, running under Red Hat Linux 7.3).

Clearly, when one tries to use this full model for a complete network, the time is impractical. Thus, to decrease the computational time, a decomposition procedure was developed, as is explained in the following section.

Decomposition Procedure. In investigating some of the properties of the model, we discovered that the schedule of each exchanger is mildly affected by the schedule of others. This prompted us to propose the following procedure:

(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. This means that at least two passes are needed. At the beginning of each pass, one solves the first heat exchanger, with the cleaning schedule for the rest of the exchangers is fixed to the value obtained in the last run.

(4) If convergence is achieved, then proceed to the next step. If not, start a new iteration.

(5) Establish the largest number of periods for which a moving window solution procedure would be solved in a reasonable amount of time. Start with the first month, and solve the problem within that window. Leave the scheduled cleaning outside the window as they were established in the last run.

(6) Keep running the moving window until the end of the time horizon is reached.

(7) Check for convergence. If no convergence is achieved, run the moving window again.

In many cases that we could verify, this procedure rendered the global solution. In the cases in which we observed that the global solution was not reached, the difference between the solution found and the global solution was less than 1%. This fact reinforces the idea that there exist a large number of suboptimal solutions that are very close to the global. The time required by the decomposition procedure is much lower than that required to solve the full model. For example, for the case of four heat exchangers and 12 months, the time required for the full model was 218 460 s, and for the decomposed model, it was only 203.9 s.

Comparison of Models. The solutions reported by Smaïli et al.[13] for a HEN case of 10 heat exchangers reproduced in Figure 7 (data given in Table 7) were

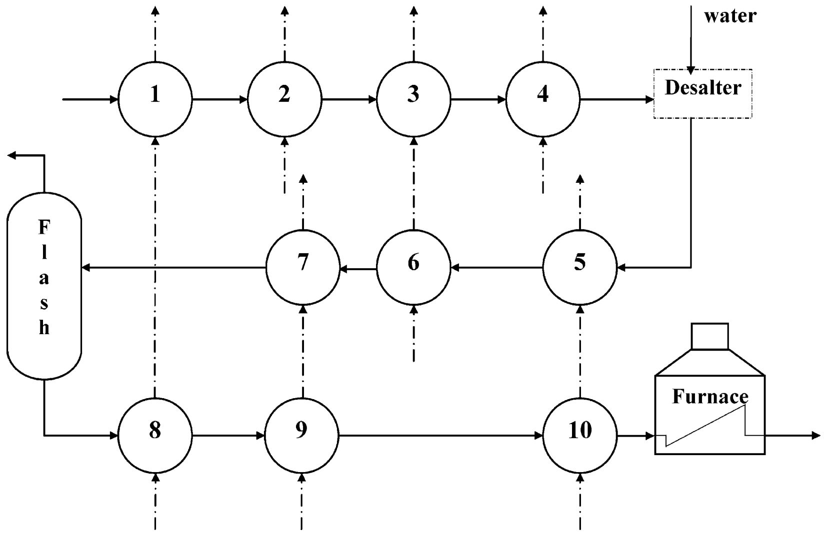

Figure 7. HEN from Smaïli et al.[13]

Table 4. Cleaning Schedule for the Single-Heat-Exchanger Case (Linear Fouling, Cleaning Cost = 0)

	month																								
author	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	no. of cleanings
Smaïli et al.[13]		•		•		•		•		•		•		•		•		•		•		•			11
this work				•			•			•			•			•			•			•			7

Table 5. Cleaning Schedule for the Single-Heat-Exchanger Case (Asymptotic Fouling, Cleaning Cost = 0)

	month																								
author	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	no. of cleanings
Smaïli et al.[13]						•					•					•					•				4
this work					•					•					•					•					4

Table 6. Cleaning Schedule for the Single-Heat-Exchanger Case (This Work Only; Cleaning Cost = 4000)

	month																								
fouling	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	no. of cleanings
linear							•						•						•						3
asymptotic					•				•				•				•				•				5

Table 7. Data for the HEN Case (Reproduced from Smaïli et al.[13])

	heat exchanger									
	1	2	3	4	5	6	7	8	9	10
Th_1 [°F]		563		457		428		513	536	631
Fh [lb/h]	141 272	73 811	423 023	428 579	207 940	423 023	210 321	141 272	282 544	207 940
Fc [lb/h]	721 441	721 441	721 441	721 441	721 441	721 441	721 441	649 217	649 217	649 217
Ch [Btu/(lb °F)]	0.67	0.70	0.62	0.62	0.67	0.62	0.69	0.67	0.69	0.67
Cc [Btu/(lb °F)]	0.46	0.46	0.46	0.46	0.55	0.55	0.55	0.57	0.57	0.57
U^c [Btu/(h ft^2 °F)]	88.1	88.1	88.1	88.1	88.1	88.1	88.1	88.1	88.1	88.1
U^0 [Btu/(h ft^2 °F)]	88.1	88.1	88.1	88.1	88.1	88.1	88.1	88.1	88.1	88.1
A [ft^2]	465	287.4	1191.6	1487.6	183.0	545.7	491.9	437.0	884.8	1257.2
$\dot{r}$ ($\times 10^7$) [ft^2 °F/Btu]	1.23	1.84	1.23	1.64	3.07	2.25	3.07	3.27	3.68	3.88
r^∞ ($\times 10^3$) [h ft^2 °F/Btu]	1.61	2.41	1.61	2.14	4.02	2.95	4.02	4.29	4.82	5.09
K [month^{-1}]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
f	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Tc_{in} [°F]					68					
τ					1.00					
η_f					0.75					

compared with those found in this work by using our decomposition strategy. The solutions are compared in the schedules shown in Tables 8−11. In this comparison, we fixed the solutions obtained by Smaïli et al.[13] and evaluated them using our model. We also compared solutions using Smaïli et al.'s[13] model. Table 12 shows the economic comparison.

The time required for each step of this strategy varies from less than 60 s for the coldest heat exchangers to around 300 s for the hottest exchangers. Similar times were required in the case of the horizontal passes depending on the position of the month evaluated.

First, comparing the results for the case of no cleaning and linear fouling, it can be observed how Smaïli et al.'s[13] model underestimates the cost. This is due to the fact that they do not take into account the decay of the heat-transfer coefficient in each subperiod (they consider it constant and equal to the initial value, and they

Table 8. Optimal Cleaning Schedules for Zero Cleaning Costs and Linear Fouling for Both Models[a]

heat exchanger	month 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	no. of cleanings X	O
1								X		O									1	1
2						⊗						X	O						2	2
3											⊗								1	1
4					O					X		O							1	2
5					⊗					X			O	X					3	2
6								⊗				⊗							2	2
7						X	O			O	X				X	O			3	3
8						X	O			X			O		X				3	2
9					X	O			X		O			X	O				3	3
10				O			X		O				X	O					2	3
																		total no. of cleanings	21	21

[a] O: Smaïli et al.[13] cleaning action. X: this work action. ⊗: common action.

Table 9. Optimal Cleaning Schedules for Zero Cleaning Costs and Asymptotic Fouling for Both Models[a]

heat exchanger	month 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	no. of cleanings X	O
1							O		X					O					1	2
2				O			X		O				X		O				2	3
3					O						X	O							1	2
4						O		X					O	X					2	2
5		O	X		O			O	X	O		X	O		O	X			4	6
6				O		X	O			X	O			O	X				3	4
7			O		X	O		X	O		X	O		X		O	X		5	5
8				O	X	O		X	O		X	O		X	O		X		5	5
9		O	X		O	X		O	X	O		X	O		X	O			5	6
10			O	X			⊗			X	O		X	O		X	O		5	5
																		total no. of cleanings	33	40

[a] O: Smaïli et al.[13] cleaning action. X: this work action. ⊗: common action.

Table 10. Optimal Cleaning Schedules for 4000 Cleaning Costs and Linear Fouling for Both Models[a]

heat exchanger	month 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	no. of cleanings X	O
1																			–	–
2										O									–	1
3									⊗										1	1
4								O			X								1	1
5									X	O									1	1
6								⊗											1	1
7							O			X									1	1
8										⊗									1	1
9						O	X					O	X						2	2
10					O	X					O	X							2	2
																		total no. of cleanings	10	11

[a] O: Smaïli et al.[13] cleaning action. X: this work action. ⊗: common action.

Table 11. Optimal Cleaning Schedules for 4000 Cleaning Costs and Asymptotic Fouling for Both Models

heat exchanger	month 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	no. of cleanings X	O
1																			–	–
2																			–	–
3																			–	–
4								O				X							1	1
5												O							–	1
6						O													–	1
7						X	O					X	O						2	2
8							X					O	X						2	1
9			O	X		O			X	O				⊗					3	4
10				O	X		O			X	O				⊗				3	4
																		total no. of cleanings	11	14

[a] O: Smaïli et al.[13] cleaning action. X: this work action. ⊗: common action.

Table 12. Comparison Chart for the HEN Case

	this work's model		Smaïli et al.'s[13] model	
case	this work's solution (NPC)	Smaïli et al.'s[13] solution (NPC)	this work's solution (NPC)	Smaïli et al.'s[13] solution (NPC)
no cleaning, linear fouling	361 060	361 060	347 990	347 990
no cleaning, asymptotic fouling	554 270	554 270	679 030	679 030
cleaning cost = 0 and linear fouling	203 600	207 210	189 280	192 840
cleaning cost = 0 and asymptotic fouling	405 770	401 230	394 000	389 940
cleaning cost = 4000 and linear fouling	257 700	262 500	243 550	248 360
cleaning cost = 4000 and asymptotic fouling	481 710	487 530	516 010	507 600

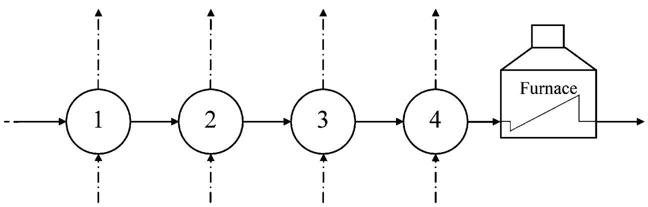

Figure 8. Four-heat-exchanger case.

Table 13. Data for the Four-Heat-Exchanger Case

	heat exchanger			
	1	2	3	4
Th_1 [°F]	428	513	536	631
Fh [lb/h]	141 272	73 811	423 023	428 579
Fc [lb/h]	721 441	721 441	721 441	721 441
Ch [Btu/(lb °F)]	0.67	0.70	0.62	0.62
Cc [Btu/(lb °F)]	0.46	0.46	0.46	0.46
U^c [Btu/(h ft^2 °F)]	88.1	88.1	88.1	88.1
U^0 [Btu/(h ft^2 °F)]	88.1	88.1	88.1	88.1
A [ft^2]	465	287.4	1191.6	1487.6
$\dot{r}$(linear, $\times 10^7$) [(ft^2 °F)/Btu]	3.07	3.27	3.68	3.88
f [month]	0.20	0.20	0.20	0.20
Tc_{in} [°F]	270			
τ [month]	1			
η_f	0.75			

Table 14. Four-Heat-Exchanger Case with a 4-month Moving-Horizon Solution (Total of 12 months, Linear Fouling, Cleaning Cost = 4000)

heat exchanger	1	2	3	4	5	6	7	8	9	10	11	12	no. of cleanings
1													–
2													–
3							•						1
4						•							1
												total no. of cleanings	2
												NPC	106 430

Table 15. Four-Heat-Exchanger Case with a 6-month Moving-Horizon Solution (Total of 12 months, Linear Fouling, Cleaning Cost = 4000)

heat exchanger	1	2	3	4	5	6	7	8	9	10	11	12	no. of cleanings
1													–
2													–
3					•								1
4						•							1
												total no. of cleanings	2
												NPC	108 410

assume a constant temperature throughout the period). The effect is even more severe in the case of asymptotic fouling.

A cost comparison between models only makes sense for the linear fouling case, where the only difference is the way the objective function is calculated. In the asymptotic case, the estimations of the heat-transfer coefficient are different. Thus we observe that our model outperforms Smaïli et al.'s model[13] for the linear fouling case. We also show the comparative results for the asymptotic fouling case, although we warn again that the optimization procedure in both cases is based on a different way of calculation fouling.

Table 16. Four-Heat-Exchanger Case with a Global Solution (Total of 12 months, Linear Fouling, Cleaning Cost = 4000)

heat exchanger	1	2	3	4	5	6	7	8	9	10	11	12	no. of cleanings
1													–
2													–
3						•							1
4							•						1
												total no. of cleanings	2
												NPC	106 050

We also point out that no cyclic cleaning takes place, which is a difference with a single-exchanger case where good schedules can be predictive without the need of optimization tools. This difference occurs because of the interrelations between the heat exchangers by the cold and hot streams. This result shows that the imposition of cyclic schedules (Georgiadis et al.[11] and Alle et al.[15]) can render solutions that are far from the optimal ones.

Results for a Moving-Horizon Strategy. The moving-horizon technique proposed by Wilson et al.[19] was also tested. This moving-horizon strategy consists of taking a window of a certain number of periods and solving the problem for that window, assuming that the cleanings ahead of the window do not exist and assuming that the cleanings in past periods are those obtained in previous runs. We implemented this moving-horizon strategy for the four heat exchangers shown in Figure 8 with the data of Table 13 and for the HEN case of Figure 7 and Table 7.

The four-heat-exchanger case of Figure 8 was solved by applying a moving horizon of 4 and 6 months of length. We also run it for full 12 and 18 month horizons to determine the global solutions. The solutions are shown in Tables 14−19.

For the HEN case of 10 exchangers over 18 months, a moving horizon was applied using a length of 4 months for the case of linear fouling and cleaning costs of 4000. The solution found was even worse than that found by Smaïli et al.[13] (see Tables 20 and 21).

As can be concluded from the results, this technique is not really effective. Moreover, making larger moving-horizon windows does not guarantee improved solutions, as can be concluded from the four-exchanger case, where the result found using a moving-horizon length of 6 months is even worse than that found using one of 4 months.

Comparison with Heuristic Strategies. Our next step was to compare our solutions with those obtained with heuristic strategies. Such strategies consist of simply cleaning the exchangers that reach a certain

Table 17. Four-Heat-Exchanger Case with a 4-month Moving-Horizon Solution (Total of 18 months, Linear Fouling, Cleaning Cost = 4000)

heat exchanger	month																	no. of cleanings
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1																			–
2																			–
3							•						•						2
4						•					•								2
																		total no. of cleanings	4
																		NPC	184 810

Table 18. Four-Heat-Exchanger Case with a 6-month Moving-Horizon Solution (Total of 18 months, Linear Fouling, Cleaning Cost = 4000)

heat exchanger	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	no. of cleanings
1											•								−1
2											•								1−
3					•					•									4
4						•						•							4
																		total no. of cleanings	6
																		NPC	182 500

Table 19. Four-Heat-Exchanger Case with a Global Solution (Total of 18 months, Linear Fouling, Cleaning Cost = 4000)

heat exchanger	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	no. of cleanings
1											•								1
2											•								1
3					•					•									4
4						•						•							4
																		total no. of cleanings	6
																		NPC	182 500

Table 20. Ten-Heat-Exchanger Case with a 4-month Moving-Horizon Solution (Total of 18 months, Linear Fouling, Cleaning Cost = 4000)

heat exchanger	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	no. of cleanings
1																			–
2																			–
3																			–
4																			–
5																			–
6																			–
7								•											1
8								•											1
9							•							•					2
10						•						•							2
																		total no. of cleanings	6

(In Tables 18–20 the column headings 1–18 are months.)

Table 21. Comparison Chart for Moving-Horizon Solutions: Ten-Heat-Exchanger Case (Total of 18 months, Linear Fouling, Cleaning Cost = 4000)

	this work's model		Smaïli et al.'s[13] model	
case	this work's solution (NPC)	Smaïli et al.[13]'s solution (NPC)	this work's solution (NPC)	Smaïli et al.'s[13] solution (NPC)
global solution	257 700	262 500	243 550	248 360
moving horizon	266 280		259 770	

level of fouling. We therefore considered different levels of the heat-exchanger heat-transfer coefficient (90% and 75% of their respective clean value) and assumed that a practitioner would decide to clean the exchangers when these values are reached. Because we used Smaïli et al.'s[13] problem, we imposed the same restrictions on cleaning certain exchangers at the same time as they did. The results were found using Smaïli et al.'s[13] and this work's models and are shown in Tables 22 and 23. The economics are compared in Table 24, where the heuristics were applied using the different models. As can be seen from the results, the heuristics results in expensive schedules, with some of them being even more expensive than no cleaning schedule at all.

Conclusions

In this paper, we have presented an MILP model to determine the cleaning schedule of HENs. We have looked at different approximating solution strategies for

Table 22. Results for Heuristic Strategy, Using Smaïli et al.'s[13] and This Work's Models, and Cleaning When $U \leq 75\%\ U^c$ (Linear Fouling)[a]

heat exchanger	month 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	no. of cleanings X	O
1																			–	–
2																			–	–
3																			–	–
4																			–	–
5																			–	–
6																			–	–
7																			–	–
8																	⊗		1	1
9															X	O			1	1
10																	⊗		1	1
																		total no. of cleanings	3	3

[a] O: Smaïli et al.[13] cleaning action. X: this work action. ⊗: common action.

Table 23. Results for Heuristic Strategy, Using Smaïli et al.'s[13] and This Work's Models, and Cleaning When $U \leq 90\%\ U^c$ (Linear Fouling)[a]

heat exchanger	month 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	no. of cleanings X	O
1													X			O			1	1
2											⊗								1	1
3												X				O			1	1
4											X	O							1	1
5						X	O				X		O			X			3	2
6								X	O				X				O		2	2
7					X		O			X			O		X				3	2
8						X		O		X			O		X				3	2
9					X		O		X			O	X				⊗		4	3
10					X	O			X		O		X			O	X		4	3
																		total no. of cleanings	23	18

[a] O: Smaïli et al.[13] cleaning action. X: this work action. ⊗: common action.

Table 24. Comparison with Heuristic Strategies (Linear Fouling, Cleaning Cost = 4000)

	this work's model		Smaïli et al.'s[13] model	
technique applied	this work's solution (NPC)	Smaïli et al.'s[13] solution (NPC)	this work's solution (NPC)	Smaïli et al.'s[13] solution (NPC)
modeling	257 700 (10 cleanings)	262 500 (11 cleanings)	243 550 (10 cleanings)	248 360 (11 cleanings)
heuristic, cleaning when $U \leq 75\%\ U^c$	341 620 (3 cleanings)		315 270 (3 cleanings)	
heuristic, cleaning when $U \leq 90\%\ U^c$	315 180 (23 cleanings)		278 760 (18 cleanings)	

problems that exceed the computational capacity and proposed a new decomposition procedure to solve the problem. In doing so, we have found better solutions than those proposed by the MINLP model proposed by Smaïli et al.[13] This is, we believe, the right way of approaching the problem, as Arthur Westerberg would have taught us, that is, construct the right model first and then worry about how to solve it. It is a strategy that has worked for him and to which we adhere wholeheartedly.

The results show that moving-horizon strategies are not effective in solving this kind of problem, that cyclic schedules imposed to the models are clearly not applicable either, and that heuristic strategies can derive into really bad solutions.

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Note Addd after ASAP Posting. This article was released ASAP on 5/4/04. Some values have been changed in column 2 of Table 24, and the corrected version was posted on 5/7/04.

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