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The Non-Random Method of Cleaning Schedule Optimization for Heat Exchangers in a HEN

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The paper presents the method of scheduling of heat exchangers cleaning from fouling in heat exchanger networks (HEN). The objective function (F) was formulated, taking into account the savings associated with the increase of heat recovery in HEN (as a result of on-line cleaning of the heat exchangers from fouling), reduced by costs of cleaning operation of the exchangers. The decision variables are the set of p integers $\{n_1, n_2,..,n_j,..n_p\}$, expressing the number (n_j) of cleaning interventions from fouling of any j^{th} heat exchanger. F maximization belongs to the category of INLP (integer nonlinear programming) programming. F optimization methods are commonly based on random search methods.
The authors proposed a new approach to the F optimization issue, enabling plant staff to make cleaning decisions for selected heat exchangers. Namely, the authors propose to lay down the HEN schedule based on an analysis of the F 's sensitivity to the number (n_j) of cleaning interventions of any j^{th} heat exchanger.
The proposed method was used to arrange the HEN cleaning schedule for the Crude Distillation Unit (CDU), processing 800 t/h of crude oil. The analyzed HEN is composed of 26 heat exchangers serving for the heat recovery. The non-random method of the HEN scheduling was used and the resulting savings amounted to 2.33 M USD/y. For comparison, a random method (Monte Carlo method) was used to arrange the HEN cleaning schedule. and the resulting savings amounted to 2.19 M USD/y.
The proposed by the authors the non-random method of HEN scheduling enables reduction the number of cleaning interventions comparing to other methods. For the presented in the article case of CDU plant, the number of cleaning interventions amounted to 36 - for the proposed method whereas for the Monte Carlo method amounted to 49.

1. Introduction

As it is commonly known, mathematical models of industrial processes include nonlinear functions with continuous and discrete (integer) variables. The integer variables are used to model discrete decisions, such as choices among different discontinuous operations or equipment types, etc. The problem of the process optimization belongs to the category MINLP (mixed - integer nonlinear programming) optimization. From recently review paper (Kılınç and Sahinidis, 2017), MINLP applications include many areas: design and control of industrial processes, scheduling and planning, layout design, network design and energy systems. Some of the first systematic approaches to resolve MINLP problem were developed by Duran and Grossmann, (1986). Thru the last three decades, the MINLP problem has experienced an activity with contributions from engineers, mathematicians, and researchers. The problem was detailly depicted in review paper presented by Belotti et al. (2013). The MINLP problem was continued in the next review paper presented by Trespalacios et al. (2014). To reach the local and global solution of MINLP, these contributions have addressed issues of problems with convexification, computational complexity, decomposition, searching feasible solutions, development of deterministic and stochastic algorithms.
The MINLP problem requires an application of stochastic algorithms because the decision variables are integer and problem are non-convex with many local optimum. The commonly used optimization methods of HEN

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involve random search methods such as Imperialist Competitive Algorithm (Totok et al., 2015), Particle Swarm Optimization (Kennedy and Eberhart, 2007), Genetic algorithms (Goldberg, 1989), Duelist Algorithm (Totok et al., 2016).
Wang et al. (2021) proposed the original method of cleaning schedule based on graphical tool called Time vs Temperature Diagram. This diagram can be used to determine the cleaning plan over a long period.
The above-mentioned methods don't guaranty the global optimum. Moreover, the methods are based on random number generator implemented into software, yielding random arrangement of the HEN cleaning schedule by a computer program that implements the imposed algorithm by the programmer.
Because the plant staff very often is conservative and reluctant to accept the random search methods in industrial applications, the authors proposed a new approach to optimization methods, based on non-random method of the HEN scheduling, enabling plant staff to make cleaning decisions for selected heat exchangers, considering computer aided. Moreover, the proposed by the authors the non-random method of the HEN scheduling enables reduction the number of cleaning interventions comparing to other methods.

2. Optimization of on-line cleaning of heat exchangers

The mathematical model of optimal cleaning schedule of the HEN is adopted from publication written by Markowski and Urbaniec (2005).
The aim of heat exchanger cleaning from fouling is to minimise the operating cost of HEN. Therefore, there was defined the avoided loss understood as (Markowski and Urbaniec, 2005):

Avoided loss	=	*Value of energy recovered when cleaning the HEN*	-	*Value of energy recovered without HEN cleaning*	-	*Cost of HEN cleaning*	(1)

Assuming that HEN is composed of *p* heat exchangers operated during period t_e of continuous operationand the time required for cleaning each heat exchanger is negligibly short comparing with the period t_e, the avoided loss can be mathematically formulated as (Markowski and Urbaniec, 2005):

$$F = k_q \sum_{j=1}^{p} \sum_{l=1}^{n_j+1} \int_0^{t_{jl}} Q_{jl} dt - k_q \sum_{j=1}^{p} \int_0^{t_e} Q_j dt - \sum_{j=1}^{p} \sum_{l=1}^{n_j} k_{jl} \tag{2}$$

Subject to constraints time intervals t_{jl} ($l=1..n_j+1$) between successive cleaning operations must be equal for each *j*-th exchanger) (Markowski and Urbaniec, 2005):

$$\frac{t_e}{t_{jl}} = n_j + 1; \tag{3}$$

$$t_{jl} = t_{j,l+1} \quad for \;\; l = 1..n_j, \;\; j = 1..p \tag{4}$$

The objective function *F* depends on the number of cleaning intervention performed on each exchanger n_j ($j=1..p$).
The optimal scheduling of HEN cleaning can be understood as maximizing function *F* while satisfying the constraint (Eq(3), Eq(4)) imposed on time intervals between cleaning operations. The decision variables are integer (n_j) and the function is non-linear. The optimization problem belongs to INLP category.
Commonly the integer, non-linear optimization techniques are based on random search methods. The proposed by the authors non-random method is based on a sensitivity analysis of the function *F* to the number of cleaning interventions *n* for all heat exchangers, but without cleaning interventions for the selected heat exchanger *m*. For the sensitivity analysis purposes, the following equation is proposed:

$$F_m = k_q \sum_{j=1}^{m-1} \left(\sum_{l=1}^{n+1} \int_0^{t_{jl}} Q_{jl} dt - k_q \int_0^{t_e} Q_j dt - \sum_{l=1}^{n} k_{jl} \right) + k_q \sum_{m+1}^{p} \left(\sum_{l=1}^{n+1} \int_0^{t_{jl}} Q_{jl} dt - k_q \int_0^{t_e} Q_j dt - \sum_{l=1}^{n} k_{jl} \right) \tag{5}$$

with constraints:

$$\frac{t_e}{t_{jl}} = n + 1; \tag{6}$$

$$t_{jl} = t_{j,l+1} \quad for \;\; l = 1..n, \;\; j = 1..p \tag{7}$$

Assuming that the number of cleaning interventions (n) is the same for each heat exchanger belonging to HEN (except the selected heat exchanger m without cleaning) and comparing F_m with F function according to following relationship:

$\Delta F_m(n) = (F - F_m)/F \quad$ for m=1..p (8)

the value close to zero of $\Delta F_m(n)$ means that the influence of m-th exchanger cleaning on the value of avoided loss F is negligible. For that situation, in the first approximation, the number of cleaning intervention amount 0 for the m^{th} exchanger. In the second approximation, it should be tested the influence of one cleaning intervention (n=1) on the value of avoided loss F. If F value decreases, it means that finally n=0 for m-th heat exchanger. Otherwise n=1 and the above procedure is repeated for n=2, 3, etc. until finding such value of n for which F value reach maximum for m^{th} exchanger. In that way the number of cleaning intervention for m-th exchanger is determined.

Using that kind of algorithm for each heat exchanger belonging to HEN, it is possible to determine the cleaning schedule of HEN.

3. Example of optimal cleaning schedule for HEN from crude distillation unit

In Figure 1 the heat exchanger network for Crude Distillation Unit (CDU) is shown. CDU is processing 800 t/h of Ural oil. All process streams are in liquid phase. Their properties (density, viscosity, thermal conductivity, specific heat) are estimated using ASTM D86 method, commonly used in crude oil industry.

For scheduling the cleaning interventions, the following data is assumed:

- cost of each cleaning operation: 10,000 USD,
- lower calorific value of fuel oil: 40,000 kJ/kg,
- specific cost of fuel oil 0.5 USD/kg,
- duration of the production period: 1 y.

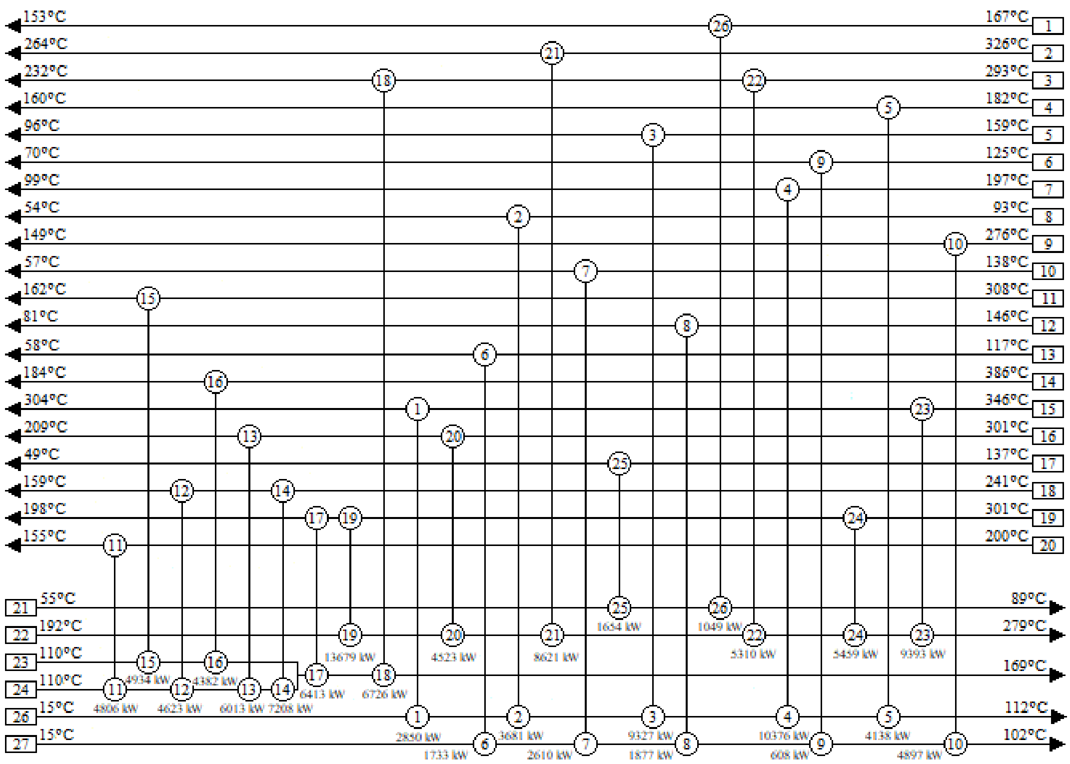

Figure 1: Scheme of the heat exchanger network for CDU.

To asses the most frequent number of cleaning intervention n for each heat exchanger belonging to HEN, Figure 2 shows dependency of the objective function F on number of cleaning intervention. As it can be seen, most of the heat exchangers should be cleaned twice the time (n=2) during the period of HEN operation to maximize the objective function F.

Taking into account that the most of the heat exchangers should be cleaned twice the time, Figure 3 shows a chart for $\Delta F_m(n=2)$ function.
From Figure 3 states that the lack of cleaning interventions for the exchangers no. 1, 6, 7, 8, 9, 16, 20, 22, 25, 26 has very small impact on the value of the objective function F. Secondly, supposedly $\Delta F_m(n=2)$ posses some kind of linearity, especially for abovelisted heat exchangers for which the $\Delta F_m(n=2)$ value approaches to zero. For example, it can be quantitively proved for arbitrary selected exchangers: 2, 11, 12, 15, 24. Namely:

$\Delta F_{2,11,12,15,24,}(2) = 8.75\%$

$\Delta F_2(2) + \Delta F_{11}(2) + \Delta F_{12}(2) + \Delta F_{15}(2) + \Delta F_{24}(2) = 8.70\ \%$

then

$\Delta F_{2,11,12,15,24,}(2) \approx \Delta F_2(2) + \Delta F_{11}(2) + \Delta F_{12}(2) + \Delta F_{15}(2) + \Delta F_{24}(2)$.

It means that the effects of cleaning interventions are additive.

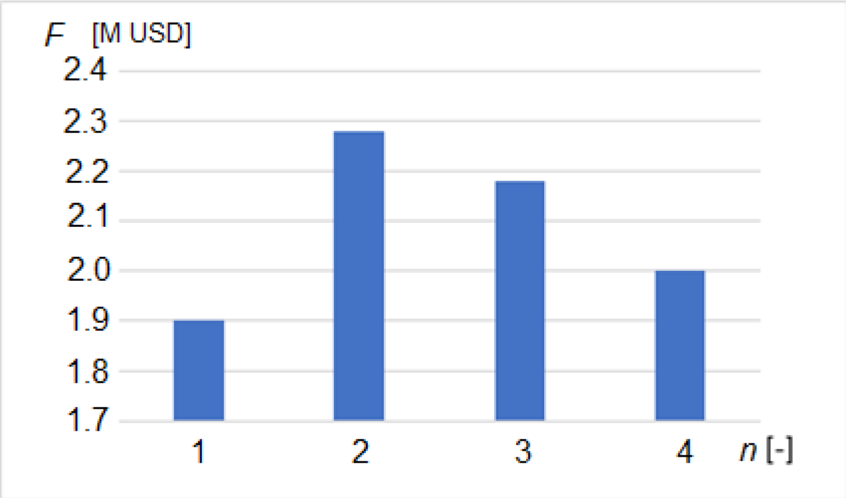

Figure 2: A bar graph for the avoided loss (F) vs. the number of cleaning interventions (n).

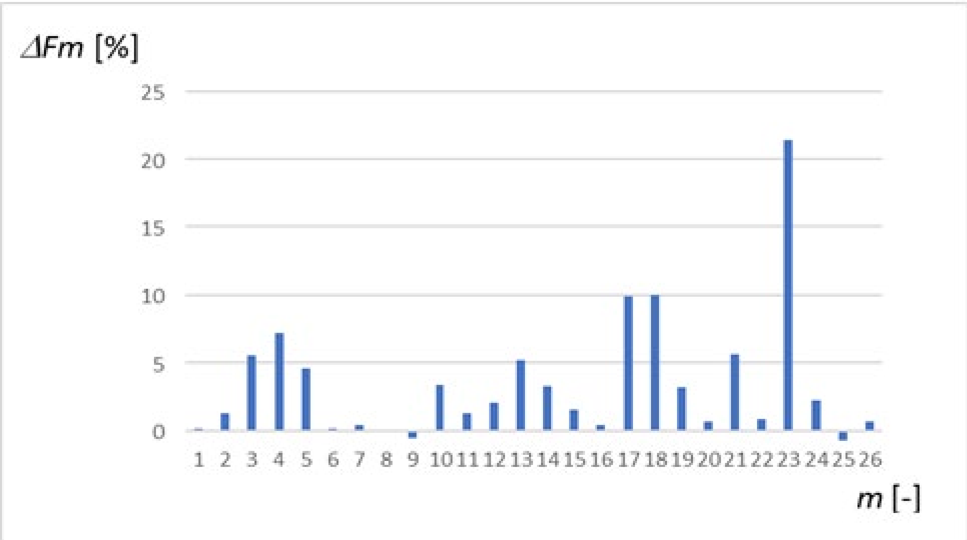

Figure 3: A bar graph for $\Delta F_m(n)$ function assuming number of cleaning interventions n=2 in each heat exchanger belonging to HEN (except the heat exchanger *m* without cleaning).

Taking into account the above conclusions, the task to determinate the optimal cleaning schedule could be conducted using non-random methods. Namely, using the bar graph for $\Delta F_m(n)$ function from Figure 3, it can be created the initial cleaning schedule for HEN in the following way:

- exchangers No. 1, 6, 7, 8, 9, 16, 20, 22, 25, 26: $n = 0$
- exchangers No. 2, 11, 12, 15, 24: $n = 1$

- exchangers No. 3, 4, 5, 10, 13, 14, 17, 18, 19, 21: $n = 2$
- exchanger No. 23: $n = 3$

For the above data the avoided loss F is calculated. In the second approximation, any exchanger from the HEN is arbitrary selected. After that, step by step the cleaning intervention n is increased (or decreased) by one in the selected heat exchanger. If F value increases comparing with initially calculated, it means that n should be increased (or decreased) by one, comparing with initial value. Otherwise n doesn't change.
Repeating that kind of algorithm to each arbitrary selected exchanger, it is possible to determinate the optimal cleaning schedule of HEN (see Table 1).

Table 1: The optimal cleaning schedule for HEN – non-random method

Exchanger No.	Number of cleaning interventions	Time intervals between cleaning interventions [mon]
1, 6, 8, 9, 25	0	0
2, 7, 11, 12, 15, 16, 20, 22, 24, 26	1	6
3, 4, 5, 10, 13, 14, 19, 21	2	4
17, 18	3	3
23	4	2.4

For the data listed in Table 1, the value of the avoided loss is F=2.33 M USD/y. The total number of cleaning interventions amounted to 36.
For the other hand, using the Monte Carlo method, Table 2 presents the results of Eq(2) maximization.

Table 2: The cleaning schedule for HEN – random method

Exchanger No.	Number of cleaning interventions	Time intervals between cleaning interventions [mon]
2, 9, 16, 19	0	0
8, 11, 20	1	6
1,3,5,6,7,12,13,14, 15, 17, 18, 21, 22, 24, 26	2	4
4, 10, 23, 25	4	2.4

For the data listed in Table 2, the value of the avoided loss is F = 2.19 M USD/y. The total number of cleaning interventions amounted to 49.
Taking into account the data listed in Table 1, the consumption of fuel oil decreases by 5.38 M kg/y. It corresponds to reduction of heat consumption at the level of 215,200 GJ/y.
Assuming the following emission factors for hazardous pollutants (Krajowy Ośrodek Bilansowania i Zarządzania Emisjami, 2021):
- CO_2: 3.2 kg/kg,
- NO_x: 0.002395 kg/kg,
- SO_2: 0.000814 kg/kg,
- dust: 0.00041 kg/kg,
- benzopyrene: 0.00001 kg/kg,

the emissions of pollutants to the environment decrease by:

- CO_2: 17.2 M kg/y,
- NO_x: 12,885 kg/y,
- SO_2: 4,379 kg/y,
- dust: 2,206 kg/y,
- benzopyrene: 54 kg/y.

4. Conclusions

The model of the optimal cleaning schedule of HEN is presented. The model was applied to the industrial heat exchanger network composed of 26 heat exchangers, belonging to CDU unit processing 800 t/h of crude oil. Optimization of the objective function (F) was carried out using non-random method. The obtained in this way HEN scheduling enables savings amounted to 2.33 M USD/y whereas the total number of cleaning interventions amounted to 36. For comparison the Monte Carlo method was used to arrange the HEN cleaning schedule. For this case the savings amounted to 2.19 M USD/y whereas the total number of cleaning interventions amounted to 49. For the analysed CDU plant, the proposed method enables the reduction of pollutants to environment by: CO_2: 17.2 M kg/y; NO_x: 12,885 kg/y; SO_2: 4,379 kg/y; dust: 2,206 kg/y; benzopyrene: 54 kg/y.

Nomenclature

dt – differential of time, s
k_{jl} - cost of cleaning j^{th} exchanger after l^{th} period of continuous operation, USD
k_q - specific cost of heat, USD/GJ
n_j - number of cleaning interventions in j^{th} exchanger during the production period
p - number of heat exchangers in the HEN
Q - heating capacity, W: Q_j - j^{th} exchanger if operated without periodic cleaning; Q_{jl} - j^{th} exchanger in l^{th} period of continuous operation
t_e - duration of the production period, s
t_{jl} - duration of l^{th} period of continuous operation of j^{th} exchanger, s

Indexes

Multiple indices should be interpreted in the same order as they are listed below:
j - j^{th} heat exchanger
l - l^{th} period between cleaning interventions

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