Proceedings of International Conference on Heat Exchanger Fouling and Cleaning - 2013 (Peer-reviewed)
June 09 - 14, 2013, Budapest, Hungary
Editors: M.R. Malayeri, H. Müller-Steinhagen and A.P. Watkinson

Published online
www.heatexchanger-fouling.com

A SLIDING MIXED-INTEGER LINEAR PROGRAMMING APPROACH FOR THE OPTIMIZATION OF THE CLEANING SCHEDULE OF CRUDE PREHEAT TRAINS

J.C. Lemos[1], B.C.G. Assis[1,3], A. L. H. Costa[1] , E.M. Queiroz[2], F.L.P. Pessoa[2], F.S. Liporace[3] and S.G. Oliveira[3]

[1] Rio de Janeiro State University (UERJ), Rua São Francisco Xavier, 524, Rio de Janeiro, RJ, Brazil - andrehc@uerj.br
[2] Federal University of Rio de Janeiro (UFRJ), Centro de Tecnologia, Cidade Universitária, Rio de Janeiro, RJ, Brazil
[3] Petróleo Brasileiro S.A. (PETROBRAS), Research and Development Center Leopoldo Américo Miguez de Mello (CENPES), Av. Horácio Macedo, 950, Cidade Universitária. Rio de Janeiro, RJ, Brazil

ABSTRACT

The fuel consumption in the fired heaters of atmospheric distillation columns for petroleum refining usually increases during the refinery operation. This effect is consequence of the fouling in the heat exchangers of the crude preheat train. The application of a cleaning schedule during the operation of the crude preheat train can reduce the costs due to fouling. However, the adequate management of the cleaning schedule of the entire set of interconnected heat exchangers is a complex problem. Aiming to contribute to the solution of this problem, this paper presents an optimization approach based on the solution of a sequence of mixed-integer linear programming problems. Each problem indicates the set of heat exchangers that must be cleaned in a certain time instant. The structure of the crude preheat train is described using an incidence matrix, encompassing supply and demand nodes, heat exchangers, mixers, splitters and desalters. The heat exchanger equations are based on the P-NTU method. The sequence of problems is associated to a sliding horizon, where the concatenation of the set of solutions composes the complete heat exchanger cleaning schedule. Although the present approach cannot guarantee the global optimality of the solution, the linear structure avoids eventual non-convergence problems. The performance of the proposed approach is illustrated through its application in an example of crude preheat train.

INTRODUCTION

Heat exchanger fouling represents a huge problem for process industries, because it jeopardizes heat exchange by reducing the overall heat transfer coefficient and hence decreasing heat exchangers effectiveness. Therefore the heat that could not be recovered in the heat exchanger network must be compensated with extra energy consumption.

An important example of the fouling impact occurs in the petroleum refining. The first main refining step is the distillation, where the crude oil stream is fractionated in a set of streams with different boiling ranges. The crude oil must be heated to around 380ºC to be fed to the distillation column. In order to reduce the energy consumption, part of this heat load is provided by the distillation cuts and pumparounds through a heat exchanger network called crude preheat train. Unfortunately, the heat exchangers in the crude preheat train are subjected to fouling, which brings an increase of the energy consumption in the fired heater.

To diminish the energy loss due to fouling, the heat exchangers can be cleaned periodically. The identification of the best cleaning schedule is a complex problem, because it must consider the tradeoff involving the future gain with the cleaning, the costs related to the cleaning process and the increase in utility consumption while the heat exchanger is off-line.

Because of the importance of this problem, there are several studies in the literature using different mathematical techniques in order to identify optimal cleaning schedules in crude preheat trains. Smaïli et al. (2001) and Lavaja and Bagajewicz (2004) employed mathematical programming in a form of mixed-integer nonlinear programming (MINLP) and mixed-integer linear programming (MILP) problems, respectively. Stochastic optimization techniques were employed by Smaïli et al. (2002) and Rodriguez and Smith (2007), where both papers explored simulated annealing related algorithms.

An alternative to these options was proposed by Smaïli et al. (2001), where a sliding horizon approach is employed. In this approach, the determination of the heat exchanger cleanings in a certain instant is conducted through a set of simulations in order to identify the most profitable options, considering a given short-term horizon ahead. Later, Ishiyama et al. (2009) presented a modification of this algorithm, aiming to reduce computational efforts.

In this context, the current paper proposes a sliding horizon approach using a MILP formulation. This formulation is able to identify the best set of heat exchangers to be cleaned at a determined time instant (Assis et al., 2012). The performance of the proposed approach is illustrated by its application in an example based on a crude preheat train of a Brazilian refinery.

PROBLEM OBJECTIVE

The target of the optimization is to identify the best schedule of heat exchanger cleanings during a certain time horizon. The optimal schedule must minimize all costs involved, considering energy costs associated to the fired heater and cleaning costs associated to each heat exchanger. It is important to note that the heat exchanger cleaning has two effects in the energy consumption: after the cleaning, there is a decrease of the energy consumption due to the increase of the heat exchanger effectiveness, but during the cleaning, the energy consumption increases, because of the off-line exchanger.

OPTIMIZATION SCHEME

The identification of the best set of cleanings in each instant is determined by the solution of a MILP problem referred in the next section.

The proposed cleaning schedule is composed of a concatenation of the individual MILP solutions. After each MILP solution, the values of the initial fouling resistances are updated according to the cleaning decisions. Fig. 1 presents an illustration of the proposed approach.

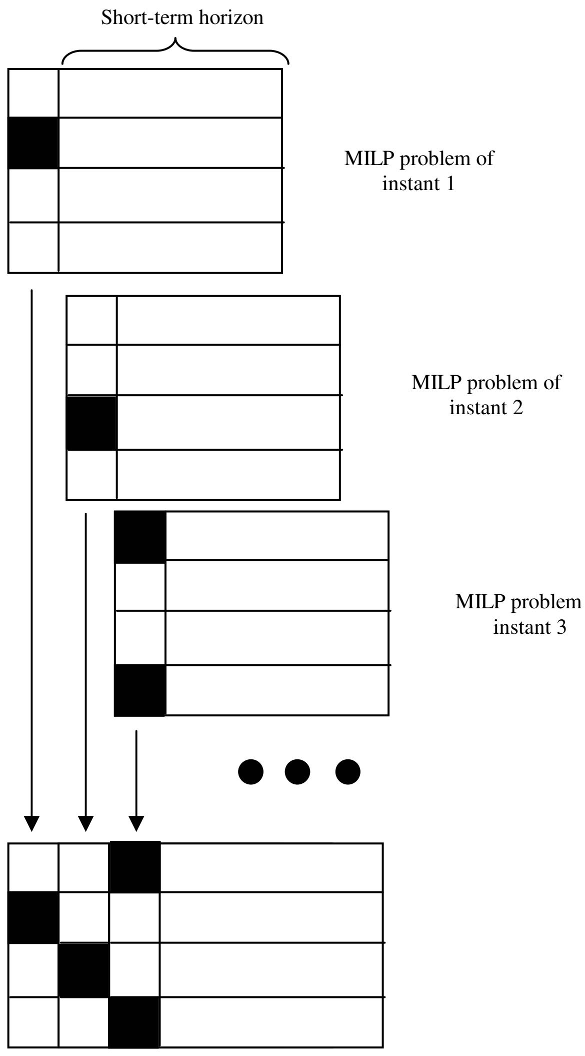

Fig. 1 Optimization scheme – Black marks indicates the cleaning actions.

MILP PROBLEM

The MILP formulation which is employed to identify the best set of heat exchanger cleanings in each time instant is based on the proposal of Assis et al. (2012). For a given time horizon, this formulation can identify the optimal set of heat exchanger cleanings in the initial time instant, excluding the possibility of further cleanings during the future time, that in this case is the short-term horizon.

Network structure

The crude preheat train is represented by a digraph, where each edge k corresponds to a process stream ($k \in STR$) and each vertex t corresponds to a network element ($t \in VET$). The process streams are divided into hot streams (*HSTR*) and cold streams (*CSTR*). The network elements are divided into heat exchangers (*HE*), mixers (*MX*), splitters (*SP*), desalters (*DS*), supply units (*PS*), and demand units (*PD*). The supply and the demand units represent the inlet and outlet streams between the crude preheat train and external equipment.

Decision variables

The decision variables involve continuous and binary variables. The continuous variables are the temperatures and heat loads and the binary variables are the indications of the heat exchangers which must be cleaned at a certain time instant. Each time instant is identified by an index τ ($\tau \in TI$).

The variable $T_{k,\tau}$ identifies the temperature of a process stream k in an instant τ. The variable $V_{t,\tau}$ identifies the network inlet/outlet temperature through a supply/demand vertex t in an instant τ. The heat load of a heat exchanger t in an instant τ is represented by $Q_{t,\tau}$. The binary variable y_t identifies if a heat exchanger t must be cleaned (=1) or not (=0).

The mass flow rates of the process streams, m_k, and the inlet/outlet network mass flow rates at the vertices, n_t, are considered previously known, i.e., they are problem parameters already established.

Objective function

The objective function encompasses the integration of the utility consumption costs, during the short-term horizon ahead of the analyzed time instant, summed with the cleaning costs:

$$fobj = \sum_{t \in PD} \sum_{\tau \in TI} p_\tau s_\tau C_{OP,t} n_t CP_t (V_{ref,t} - V_{t,\tau}) + \sum_{t \in HE} y_t C_{C,t} \tag{1}$$

where p_τ are the weights of the numerical integration procedure (e.g. Simpson rule), s_τ are the present worth factors, $C_{OP,t}$ is the utility cost associated to the outlet stream of vertex t, n_t and V_t are the flow rate and temperature associated to the outlet stream of vertex t, *ref* is a subscript associated to the specified value of the temperature downstream the final heater, and $C_{C,t}$ are the cleaning costs.

Constraints – Energy balances

The energy balances at the network vertices are given by:

$$\sum_{k\in S_t^{in}} m_k Cp_k T_{k,\tau} - \sum_{k\in S_t^{out}} m_k Cp_k T_{k,\tau} = 0 \qquad t\in(MX\cup SP), \tau\in TI \quad (2)$$

$$\sum_{k\in S_t^{in}} m_k Cp_k T_{k,\tau} - \sum_{k\in S_t^{out}} m_k Cp_k T_{k,\tau} + n_t CP_t V_{t,\tau} = 0 \qquad t\in(PS\cup PD), \tau\in TI \quad (3)$$

$$\sum_{k\in(S_t^{in}\cap HSTR)} m_k Cp_k T_{k,\tau} - \sum_{k\in(S_t^{out}\cap HSTR)} m_k Cp_k T_{k,\tau} - Q_{t,\tau} = 0 \qquad t\in HE, \tau\in TI \quad (4)$$

$$\sum_{k\in(S_t^{in}\cap CSTR)} m_k Cp_k T_{k,\tau} - \sum_{k\in(S_t^{out}\cap CSTR)} m_k Cp_k T_{k,\tau} + Q_{t,\tau} = 0 \qquad t\in HE, \tau\in TI \quad (5)$$

$$T_{k,\tau} - T_{k',\tau} = \Delta_t \qquad t\in DS, k\in S_t^{in}, k'\in S_t^{out}, \tau\in TI \quad (6)$$

$$T_{k,\tau} - T_{k',\tau} = 0 \qquad t\in SP, k\in S_t^{in}, k'\in S_t^{out}, \tau\in TI \quad (7)$$

$$V_{t,\tau} - V_{t,\tau}^{spe} = 0 \qquad t\in PS, \tau\in TI \quad (8)$$

where Cp_k is the heat capacity of the stream k, CP_t is the heat capacity of the inlet/outlet stream through the supply/demand vertex t, Δ_t is the temperature variation in the desalter t, the superscript *spe* identifies the specifications of the network inlet temperature at the supply units, and the superscripts *in* and *out* identify the set of edges S_t that is direct to/from the vertex t.

Constraints – Heat exchanger equations

Heat exchanger modeling. The steady-state behavior of a heat exchanger can be described using the P-NTU method (Shah and Sekulic, 2003). This method is based on three dimensionless groups: the effectiveness, P, the number of transfer units, NTU, and the ratio between the heat capacity flow rates, CR. Considering a heat exchanger with area A and overall heat transfer coefficient U, these groups can be described by the following equations:

$$P = (T_{h,i} - T_{h,o})/(T_{h,i} - T_{c,i}) \quad (9)$$

$$NTU = (UA)/(m_h Cp_h) \quad (10)$$

$$CR = (m_h Cp_h)/(m_c Cp_c) \quad (11)$$

According to the P-NTU method, for a given heat exchanger configuration, it is possible to establish a mathematical relation among these parameters:

$$P = P(NTU, CR) \quad (12)$$

The relation between the overall heat transfer coefficients in dirty and clean conditions can be given by:

$$U^d = \left(R_f + \frac{1}{U^c}\right)^{-1} \quad (13)$$

where R_f is the current fouling resistance in the heat exchanger.

Finally, the outlet temperatures of a heat exchanger can be evaluated by the following system of linear equations:

$$PT_{c,i} + (1-P)T_{h,i} - T_{h,o} = 0 \quad (14)$$

$$T_{c,i} - T_{c,o} + CRT_{h,i} - CRT_{h,o} = 0 \quad (15)$$

where Eq. (14) can be derived from Eq. (9) and Eq. (15) comes from the energy balance.

Fouling dynamic behavior. In several situations, the variation of the fouling resistance with time can be satisfactorily described by empirical time functions, e.g. linear:

$$R_f(t) = R_{f,0} + ct \quad (16)$$

where $R_{f,0}$ is the fouling resistance at the beginning of the period.

Because the variation of the fouling resistance is much slower than the behavior of the operational variables, the fouling time equation can be introduced into the expression of the number of transfer units to represent the dynamic behavior of the heat exchanger:

$$NTU(t) = \left(R_f(t) + \frac{1}{U^c}\right)^{-1} \frac{A}{m_h Cp_h} \quad (17)$$

The expression of the heat exchanger effectiveness can be extended to consider an initial cleaning ($y = 1$) or not ($y = 0$):

$$P(t) = yP^{yes}(t) + (1-y)P^{no}(t) \quad (18)$$

where the superscripts *yes* and *no* indicate the values of the effectiveness considering or not the cleaning, respectively.

Considering a linear behavior, the expression for the evaluation of P^{no} is:

$$P^{no}(t) = P(\left(R_{f,0} + ct + \frac{1}{U^c}\right)^{-1} \frac{A}{m_h Cp_h}, CR) \quad (19)$$

The evaluation of P^{yes} is given by two expressions, depending on the heat exchanger being cleaned or not (the duration of the cleaning period is represented by Δt^{clean}). If $t < \Delta t^{clean}$, it means the heat exchanger is still off-line for cleaning, then:

$$P^{yes}(t) = 0 \quad (20)$$

If $t > \Delta t^{clean}$, it means the heat exchanger has returned to the operation, therefore:

$$P^{yes}(t) = P\left(\left(c(t-\Delta t^{clean}) + \frac{1}{U^c}\right)^{-1} \frac{A}{m_h Cp_h}, CR\right) \quad (21)$$

It is important to note that P^{yes} and P^{no} can be evaluated prior to the optimization, i.e., they are problem parameters which can be determined previously.

Constraint equations. The representation of the heat exchanger effectiveness in the optimization problem is based on the insertion of Eq. (18) into Eq. (14), thus yielding:

$$P^{no}_{t,\tau}(T_{c,i})_{t,\tau} + (1-P^{no}_{t,\tau})(T_{h,i})_{t,\tau} - (T_{h,o})_{t,\tau} - \\ - yh_{t,\tau}(P^{yes}_{t,\tau} - P^{no}_{t,\tau}) + yc_{t,\tau}(P^{yes}_{t,\tau} - P^{no}_{t,\tau}) = 0 \quad (22)$$

where the new variables $yh_{t,\tau}$ and $yc_{t,\tau}$ contain bilinear terms:

$$yh_{t,\tau} = y_t (T_{h,i})_{t,\tau} \quad (23)$$

$$yc_{t,\tau} = y_t (T_{c,i})_{t,\tau} \quad (24)$$

These bilinearities can be substituted by a set of linear inequalities (Floudas, 1995):

$$(T_{h,i})_{t,\tau} - UT(1-y_t) \le yh_{t,\tau} \le (T_{h,i})_{t,\tau} - LT(1-y_t) \quad (25)$$

$$(T_{c,i})_{t,\tau} - UT(1-y_t) \le yc_t \le (T_{c,i})_{k,\tau} - LT(1-y_t) \quad (26)$$

$$LTy_t \le yh_{t,\tau} \le UTy_t \quad (27)$$

$$LTy_t \le yc_{t,\tau} \le UTy_t \quad (28)$$

where LT and UT are bounds on $T_{h,i}$ and $T_{c,i}$.

Finally, these equations assume their final form employing the indexation of the stream temperatures presented in the optimization problem:

$$P^{no}_{t,\tau} T_{k,\tau} + (1-P^{no}_{t,\tau}) T_{k',\tau} - T_{k'',\tau} - \\ - yh_{t,\tau}(P^{yes}_{t,\tau} - P^{no}_{t,\tau}) + yc_{t,\tau}(P^{yes}_{t,\tau} - P^{no}_{t,\tau}) = 0 \\ t \in HE, \tau \in TI, k \in (CSTR \cap S^{in}_t), \\ k' \in (HSTR \cap S^{in}_t), k'' \in (HSTR \cap S^{out}_t) \quad (29)$$

$$T_{k,\tau} - UT(1-y_t) \le yh_{t,\tau} \le T_{k,\tau} - LT(1-y_t) \\ t \in HE, \tau \in TI, k \in (HSTR \cap S^{in}_t) \quad (30)$$

$$T_{k,\tau} - UT(1-y_t) \le yc_{t,\tau} \le T_{k,\tau} - LT(1-y_t) \\ t \in HE, \tau \in TI, k \in (CSTR \cap S^{in}_t) \quad (31)$$

$$LTy_t \le yh_{t,\tau} \le UTy_t \qquad t \in HE, \tau \in TI \quad (32)$$

$$LTy_t \le yc_{t,\tau} \le UTy_t \qquad t \in HE, \tau \in TI \quad (33)$$

Constraints – Resource limitations

The maximum number of cleanings in a time instant is established by the following constraint:

$$\sum_{t \in HE} y_t - N_{\max} \le 0 \quad (34)$$

RESULTS

The performance of the proposed approach is illustrated through its application to an example based on a real crude preheat train from a Brazilian refinery. This train is composed of thirty five heat exchangers distributed along five branches, three upstream the desalter and two downstream the desalter. The section after the pre-flash was not analyzed because the monitoring system that gave the necessary data for the simulation was not installed in that section (Liporace and Oliveira, 2007).

Fig. 2 contains a block diagram of the crude preheat train, where the heat exchangers are numbered from 28 to 62 (the other network elements are not shown in the figure). A full representation of the process flowsheet diagram together with a complete description of the heat exchanger data can be found in Oliveira Filho et al. (2009). The stream data employed were based on Assis et al. (2012). The dynamic behavior of fouling was described using a linear model, where the fouling rates of the heat exchangers upstream and downstream the desalter were considered equal to $0.7 \cdot 10^{-11}$ m^2K/J and $1.6 \cdot 10^{-11}$ m^2K/J, respectively. All heat exchangers are clean at the beginning of the period. The time was discretized in one week intervals and the cleaning process also lasts one week.

Regarding the objective function, the reference temperature for the determination of the extra energy needed in the heater unit corresponds to the network outlet temperature at the clean condition, 271.03°C. In the investigated example, the cleaning costs were considered null and the energy cost equal to $8.46 \cdot 10^{-3}$ \$/MJ. An interest rate of 0.22% was assumed during a 105 week period. Also, only four heat exchangers can be cleaned simultaneously.

The optimization scheme was implemented using the software GAMS, where each MILP problem was solved using the solver CPLEX.

Table 1 contains the resultant objective function obtained for different lengths of the short-term horizon together with the no cleaning alternative. Additionally, this table also displays the savings attained in relation to the no cleaning solution.

The optimal solution is displayed in Fig. 3 and Fig. 4. Because of the space limitations, these figures are displaying the schedule in a transposed sketch (i.e. the exchangers are represented along the columns and the time instants along the rows). This schedule involves 65 cleaning actions during the two year horizon. Additional numerical results indicated that the insertion of cleaning costs determines schedules with a considerable lower number of cleanings.

The profile of the outlet temperature of the crude stream in the optimal solution together with the no cleaning alternative is shown in Fig. 5. This graph shows that there is a significant gain in the network outlet temperature in the optimized case, therefore showing that the proposed approach attained a cleaning schedule capable of providing considerable energy savings.

Table 1 – Objective function values and savings

Horizon size	Objective function ($)	Number of cleans	Saving (%)
-	820251	0	0
1 – 5	550694	23	32.86
1 – 8	522460	60	36.30
1 – 9	507554	65	38.12
1 – 10	609118	78	25.74

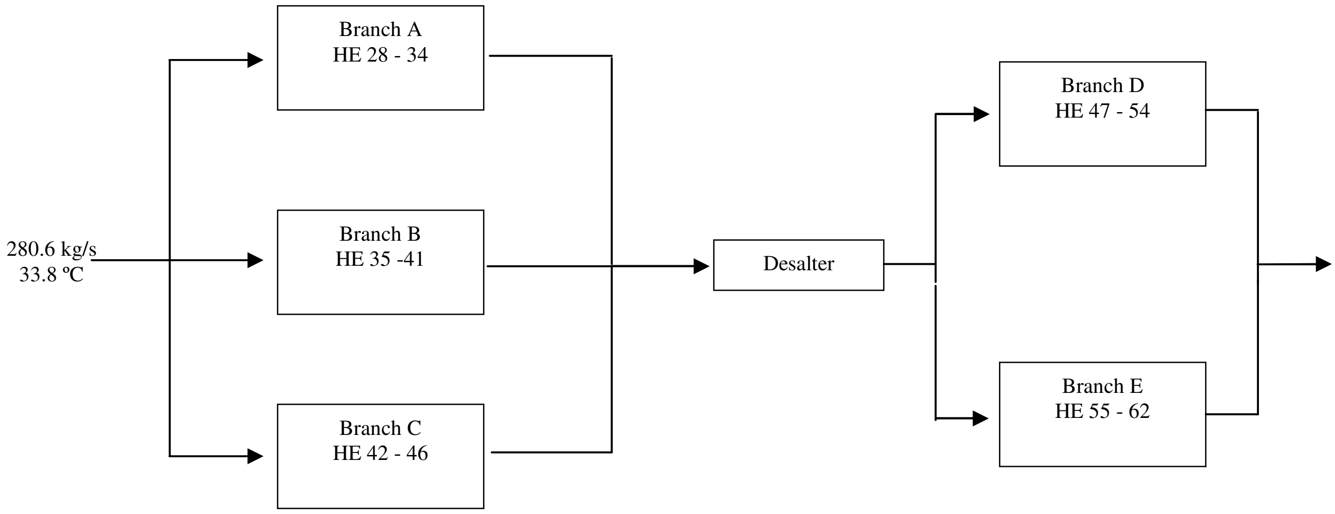

Fig. 2 Crude preheat train schematic representation

Unit Period	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	Cleans /period
39				■																1
43			■																	1
53		■																		1
55	■																			1
57					■															1
61									■											1
62								■												1
65											■				■					2
66										■										1
71																■				1
73																		■		1
74																	■			1
76						■														1
78				■																1
85												■								1
86			■																	1
94																			■	1
96													■							1
Cleanings	1	1	2	2	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	19

Fig. 3 Optimal cleaning schedule upstream the desalter

Unit Period	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	Cleans /period
17	■																1
18			■														1
19									■	■							2
21											■						1
28				■													1
29					■												1
31												■					1
32								■									1
33													■				1
34	■																1
35																■	1
36			■														1
38									■	■							2
42											■						1
45		■															1
51				■		■	■										3
52	■																1
54			■														1
57					■				■	■							3
58												■		■	■		3
63											■						1
64								■									1
66													■				1
69	■																1
70																■	1
72			■														1
76									■	■							2
79				■													1
84											■						1
85	■	■															2
87					■												1
89												■					1
90			■														1
95								■	■	■							3
Cleaning s	5	2	5	3	3	1	1	3	5	5	4	3	2	1	1	2	46

Fig. 4 Optimal cleaning schedule downstream the desalter

.

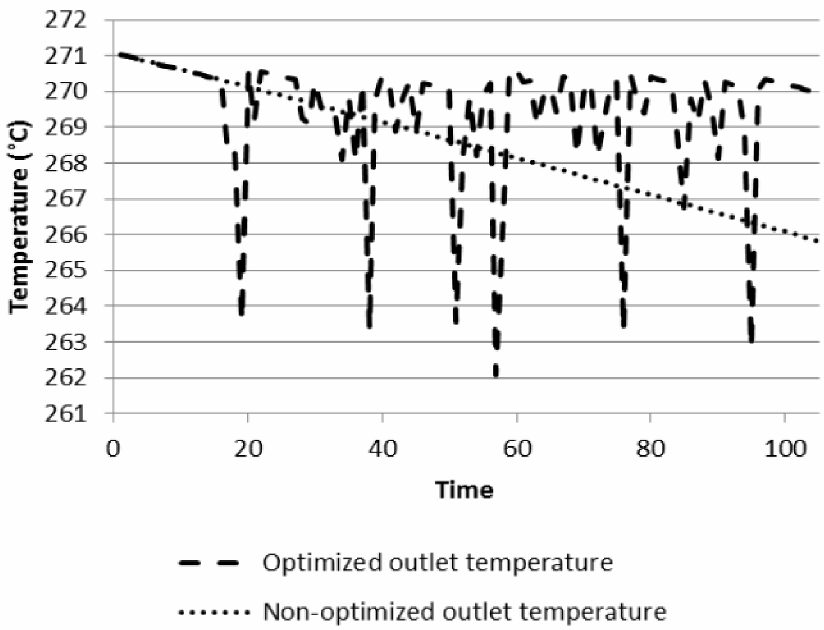

Fig. 5 Outlet temperature behaviour

DISCUSSION

The optimal solution found is associated to a reduction of about 40% of the costs compared to the non-optimized case. For example, there is a difference of almost 5 ºC in the outlet temperature of the crude at the final of the period between the optimal and non-optimal alternatives. These potential gains are relevant, considering the large throughput of petroleum refineries.

The crude preheat train is composed of 35 heat exchangers, 19 heat exchangers are located upstream the desalter and 16 heat exchangers are located downstream the desalter. However, the optimal cleaning actions were not distributed proportionally. There were more than twice cleanings in the heat exchangers located downstream the desalter than those located upstream the desalter. This pattern can be explained by the fact that the downstream fouling rate is more than two times bigger than the one upstream the desalter. Besides, there is an advantage on cleaning the heat exchangers closer to the end of the network, because there is an enlargement of the approach in the final exchangers in this case than if the cleaning were applied closer to the inlet, which partially compensates the heat that could not be recovered before.

The solution also presents some typical features already identified in previous approaches. There are no heat exchanger cleanings near the beginning or the end of the period. The absence of cleanings at the beginning can be explained by the clean status of the heat exchangers at the start, i.e., there are no economic rewards of cleaning without a relevant accumulation of deposits. The absence of cleaning near the end of the period is justified by the lack of time to recover energy in these cases to compensate the extra costs associated to the cleaning itself.

It is also important to note that increasing the size of the sliding horizon results in more cleaning decisions and the opposite if it is decreased. In this case, is important to find a good balance between too many cleanings, that provides unsatisfactory objective function, and too few cleanings, that will also provide unsatisfactory objective function. This tradeoff may be tuned applying the procedure for different horizon sizes, but the utilization of a constant value adequately selected is also effective. The reason of this pattern is that larger sliding horizons allow more time to recover energy and to compensate the costs associated with a cleaning decision, which favors a larger number of cleanings.

CONCLUSIONS

The extra energy consumption associated to the petroleum distillation to compensate fouling effects may be significant (Costa et al., 2011). A possible alternative to mitigate this problem is to promote periodical heat exchanger cleanings.

Because of the complexity of the problem to identify the optimal cleaning schedules, previous attempts in the literature for its solution using mathematical programming had presented some drawbacks: MINLP formulations resulted in nonconvex structures with several local optima (Smaïli et al., 2001) and the application of MILP formulations was limited due to the problem dimension (Lavaja and Bagajewicz, 2004).

In this context, the current paper presented a sliding mixed-integer linear programming approach to identify the optimal cleaning schedule for crude preheat trains. The heat exchangers that must be cleaned at each instant are determined through the solution of a single MILP problem. In this problem, the costs are minimized considering a short-term horizon ahead without further cleanings. The resultant cleaning schedule for the entire period is composed of the concatenation of the individual MILP solutions.

Despite this approach does not guarantee global optimality, numerical results of the analysis of an example based on real crude preheat train indicated a good performance in relation to financial savings.

NOMENCLATURE

A	heat exchanger area (m^2)
c	fouling rate of the linear model (m^2K/J)
C_C	cleaning costs ($)
Cop	utility costs ($/J)
Cp	stream heat capacity (J/(kgK))
CP	network inlet/outlet stream heat capacity (J/(kgK))
CR	ratio between heat capacity flow rates
$CSTR$	subset of cold streams
DS	subset of desalters
$fobj$	objective function ($)
HE	subset of heat exchangers
$HSTR$	subset of hot streams
LT	lower bound on the stream temperatures (ºC)
m	stream mass flow rate (kg/s)
MX	subset of mixers
n	network inlet/outlet mass flow rate (kg/s)
N_{max}	maximum allowable number of cleanings
NTU	number of transfer units (dimensionless)
p	weights of the numerical integration procedure
P	effectiveness (dimensionless)
PD	subset of demand units
PS	subset of supply units
Q	heat load (W)
R_f	fouling resistance (m^2K/W)
$R_{f,0}$	initial valur of the fouling resistance (m^2K/W)
s	present worth factor
S	subset of streams
SP	subset of splitters
STR	set of edges
t	time (s)
T	stream temperature (ºC)
TI	set of time instants
U	overall heat transfer coefficient ($W/(m^2K)$)
UT	upper bound on the stream temperatures (ºC)
V	network inlet/outlet temperature (ºC)
VET	set of vertices
y	binary variable for cleaning indication

Greek symbols

Δ	temperature difference in the desalter (ºC)
Δt^{clean}	duration of the cleaning (s)

Subscript

c	cold stream
h	hot stream
i	inlet
o	outlet
in	edges into a vertex
out	edges from a vertex
ref	temperature reference
k	index of the edges (process streams)
k´	alias of index k
k´´	alias of index k
t	index of the vertices (network elements)
τ	index of time instants

Superscripts

spe	specification
c	clean
d	dirty
yes	cleaning
no	no cleaning

REFERENCES

Assis, B. C. G., Lemos, J. C., Queiroz, E. M., Pessoa, F. L. P., Liporace, F. S., Oliveira, S. G., Costa, A. L. H., 2012, Optimal allocation of cleanings in heat exchanger networks, *App. Therm. Eng.*, submitted to publication.

Costa, A. L. H., Tavares, V. B. G., Queiroz., E. M., Pessoa, F. L. P., Lipoarce, F. S., Oliveira, S. G., Borges, J. L., 2011, Analysis of the environmental and economic impact of fouling in crude preheat trains for petroleum distillation, *Proceedings of International Conference of Heat Exchanger Fouling and Cleaning*, Crete.

Floudas, C. A., 1995, *Nonlinear and mixed-integer optimization – Fundamentals and applications*, Oxford University Press, New York, New York.

Ishiyama, E. M., Paterson, W. R., Wilson, D. I., 2009, Platform for techno-economic analysis of fouling mitigation options in refinery preheat trains, *Energy & Fuels*, Vol. 23, pp. 1323-1337.

Lavaja J. H., Bagajewicz M. J., 2004, On a new MILP model for the planning of heat exchanger network cleaning, *Ind. Eng. Chem. Res.,* vol. 43, pp. 3924-3938.

Oliveira Filho, L. O., Liporace, F. S., Queiroz, E. M., Costa, A. L. H., 2009, Investigation of an alternative operating procedure for fouling management in refinery crude preheat trains, *Appl. Therm. Eng.*, Vol. 29, pp. 3073-3080.

Rodriguez, C., Smith, R., 2007, Optimization of operating conditions for mitigating fouling in heat exchanger networks, *Chem. Eng. Res. Des.,* Vol. 85, pp. 839-851.

Shah, R. K., Sekulic, D. P., 2003, *Fundamentals of heat exchanger design,* John Wiley and Sons, Hoboken, New Jersey.

Smaïli, F., Vassiliadis, V. S., Wilson, D. I., 2001, Mitigation of fouling in refinery heat exchanger networks by optimal management of cleaning, *Energy & Fuels*, Vol. 15, pp. 1038-1056.

Smaïli F., Vassiliadis V. S., Wilson D.I., 2002, Long-term scheduling of cleaning of heat exchanger networks - Comparison of outer approximation-based solutions with a backtracking threshold accepting algorithm, 2002, *Chem. Eng. Res. Des.,* vol. 80, pp. 561-578.