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Oil Refinery Heat Exchanger Network Cleaning Scheduling Strategy with Unit Cleanability Consideration

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Heat exchanger networks (HENs) play an important role in the chemical industries. Unfortunately, fouling is inevitable in heat exchangers operation. Therefore, the optimal cleaning procedure is required to restore heat exchangers' performance periodically. A systematic cleaning scheduling strategy for the heat exchanger network in an oil refinery is proposed in this work. There are 11 operating heat exchangers in an oil refinery to be reviewed. Different cleaning decision scenarios based on the overall heat transfer coefficient are explored for optimal cleaning schedule performance. The daily number of exchangers available to be cleaned i.e., the unit cleanability, is investigated while minimizing the energy consumption and the additional heat requirement due to the offline heat exchanger under cleaning procedure. The HEN performance and the energy-saving from the cleaning procedures are benchmarked with the uncleaned HEN. The results indicate that the cleaning procedure significantly increases the HEN performance and simultaneously reduces the heat requirement if compared to the untreated HEN benchmark. The possible conflicting situation is discussed when some heat exchangers are waiting to be cleaned due to the unit cleanability restriction, which allows the overall heat transfer coefficient to be below the allowed limit. Therefore, nonconflicting cleaning scheduling is also addressed in this work by relaxing the unit cleanability limit. Furthermore, the optimal cleaning schedule is also suggested for user reference. In this work, the optimum cleaning schedule with minimum energy consumption and maximum energy saving could be achieved when cleaning decision limit is set at 40% decrease of overall heat transfer coefficient. In the contrast, the lowest number of cleaning procedures is associated with 90% decrease in the overall heat transfer coefficient as the cleaning decision limit.

Keywords: Cleaning scheduling, Furnace, Heat duty, HEN, Overall heat transfer coefficient

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INTRODUCTION

The heat exchanger network (HEN) plays a vital role in the industrial energy-saving program (Angsutorn et al. 2014), which performance determines energy efficiency (Wang et al. 2015). Many researchers have studied engineering approaches and methods for energy-efficient HEN design (Varbanov et al. 2018). In a complex HEN, high energy transfer from hot streams to cold streams could be made possible in integrated processes (Macchietto et al. 2018). A well-designed HEN in a process plant is always exposed to the fouling formation continuously (Kakaç et al. 2012). Therefore, the heat transfer coefficients and the heat transfer rate of the heat exchangers will be decreased in compared to the corresponding values in a clean condition without fouling formation (Sanaye and Niroomand, 2007). Other researchers have used the exponential overall heat transfer coefficient equation and the result keeps the efficiency of HE 90% of the maximum of energy recovery (Licindo et al. 2015).

The interactive phenomena of fouling and cleaning are reciprocal (Wilson, 2005). The effectiveness of a cleaning operation determines the initial conditions for subsequent fouling, and the fouling deposit condition at the end of the run affects the dynamics of the cleaning procedure (Pogiatzis et al. 2012). A mixed-integer nonlinear programming model for optimizing of the HEN cleaning schedule subject to fouling is presented and is solved using the Outer Approximation/Extended Relaxation algorithm (Smaïli et al. 2002a). The effect of thermal and economic behavior is also studied accordingly (Diaby et al. 2016). A new mixed-integer linear model for the planning of heat-exchanger cleaning in chemical plants is also proposed (Lavaja & Bagajewicz, 2004). Mixed-integer nonlinear programming (MINLP) is mainly used to formulate the optimal cleaning scheduling problem that is subsequentially solved through deterministic optimization algorithms (Lozano Santamaria and Macchietto, 2018). All of the previous works consider cleaning schedule time interval related to energy saving or penalty cost (Rossiter and Jones, 2015). A simple heuristic optimization approach has been proposed to provide suitable solutions for the cleaning scheduling problem (Gonçalves et al. 2014). The recent stochastic optimization method i.e., the Imperialist Competitive Algorithm (ICA), is also implemented for the cleaning scheduling problem (Biyanto et al. 2015). Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Duelist Algorithm (DA) are considered for the optimization of HEN cleaning schedule by reviewing the thermal and hydraulic impacts on the energy and economics aspect in operation and maintenance of the HEN due to fouling (Biyanto et al. 2016).

Some operational constraints were considered to increase reasonable decisions or overcoming the obstacles. Some proposed formulations include limitations set of pump-around operation (Smaïli et al. 2002b), pressure drop (Smaïli et al. 2001), while both thermal and hydraulic impacts of fouling were considered (Ishiyama et al. 2009) on the cleaning scheduling problem. A comprehensive mitigation strategy should consider optimization of operating conditions such as wall temperature and flow velocity (Rodriguez and Smith, 2007), while temperature bounds on the performance of exchangers are required to be applied, for example in the case of desalter temperature control (Ishiyama et al. 2010). One hot end exchanger is allowed to be cleaned at a time as the operational constraints in the cleaning scheduling problem (Adloor et al. 2018). The disadvantages of the above studies are that there are restrictions on only one HE and are complicated for other users, which is different from what is done in this work, namely, the number of HEs that are cleaned can be more than one and the method is user-friendly because of its simplicity.

This paper aims to explore the optimal cleaning schedule based on limitations scenario of simple overall heat transfer coefficients that corresponds to the scheduling conflict of HEs unit cleanability while minimizing energy consumption. It is expected that the maintenance engineer could easily select the desired heat exchanger cleaning schedule's policy from the proposed approach.

There are several advantages of the proposed approach on a given HEN. The furnace and heater before desalter duty are addressed as the essential performance indicators. Moreover, cleaning scheduling conflict is considered when more than one HE is allowed to be cleaned, represented as the maximum HEN under cleaning, and minimum allowable overall heat transfer coefficient (*U*) for each HE. These considerations have not yet considered in previous studies.

The paper is structured as follows: In section 2, the HEN model is described, including the process scenario of the cleaning schedule and its related conditional constraints. In section 3, a case study is provided for a thorough discussion on cleaning scenario problems and the impact on the heater unit before desalter, furnace, energy-saving, and total exchanged heat within the HEN along with the corresponding literature comparison. Finally, the conclusions are made at the end of this paper.

METHOD

HEN Model

The HEN structure in a crude oil refinery (Biyanto et al. 2016) is studied in this paper (see Figure 1). The corresponding HEN design parameters, i.e., overall heat transfer coefficient in clean condition, surface area, the mass flow of hot and cold streams, the specific heat of hot and cold streams, are shown in Table 1.

The fouling build-up process describes as the fouling resistance model, which is presented with Eq. (1).

$$R_{f\,(t)} = R_{f\infty}\left(1 - exp^{-\beta t}\right) \qquad (1)$$

The typical R_f profiles for each HE is shown in Figure 2. HE-10 has a significantly high final value of R_f due to the dynamic interrelation between $R_{f\infty}$ and β. Although the values of $R_{f\infty}$ and β cause these behaviors, it can be indirectly affected by the HE's operating temperature, according to Figure 1 where HE-01 has the lowest operating temperature, which leads to its lowest R_f. The fouling characteristic exhibits linear fouling models in the HE-08, HE-09, and HE-10, due to the small β values, as tabulated in Table 1.

The overall heat transfer coefficient is expressed as in Eq. (2).

$$U_{f(t)} = \frac{U_c}{1 + U_c . R_{f(t)}} \quad (2)$$

By substitution of Eq. (1) into Eq. (2).

$$U_{f(t)} = \frac{U_c}{1 + U_c . R_{f\infty}(1 - exp^{-\beta t})} \quad (3)$$

The heat duty each day of a single-pass shell and tube heat exchanger operating in counter-current mode is given by Eq. (4), based on the log-mean temperature difference method.

$$Q_{(t)}^{HE-n} = U_{f(t)} \; A \; \Delta T_{LM\,(t)} \quad (4)$$

Heater before desalter

The nature of the cleaning schedule will change the temperature dynamics of the overall HEN. Therefore, a backup heater must be installed before entering the desalter to satisfy the downstream temperature requirements. This heater works to heat the crude oil that will come into the desalter. Crude oil temperature before entering the desalter is maintained at a minimum temperature of 115°C. Penalty cost is imposed when the heater is taken into action. Therefore, less use of the heater is preferred during the cleaning schedule. The performance heater before desalter is calculated as in Eqs. (5)-(6).

$$Q_h = \sum_{t=0}^{H} m_c \, c_{pc} \, (T_{i,d} - T_{i,d\,(t)}) \Delta t \quad (5)$$

$$T_{i,d\,(t)} = T_{c,o\,(t)}^{HE-n} \quad (6)$$

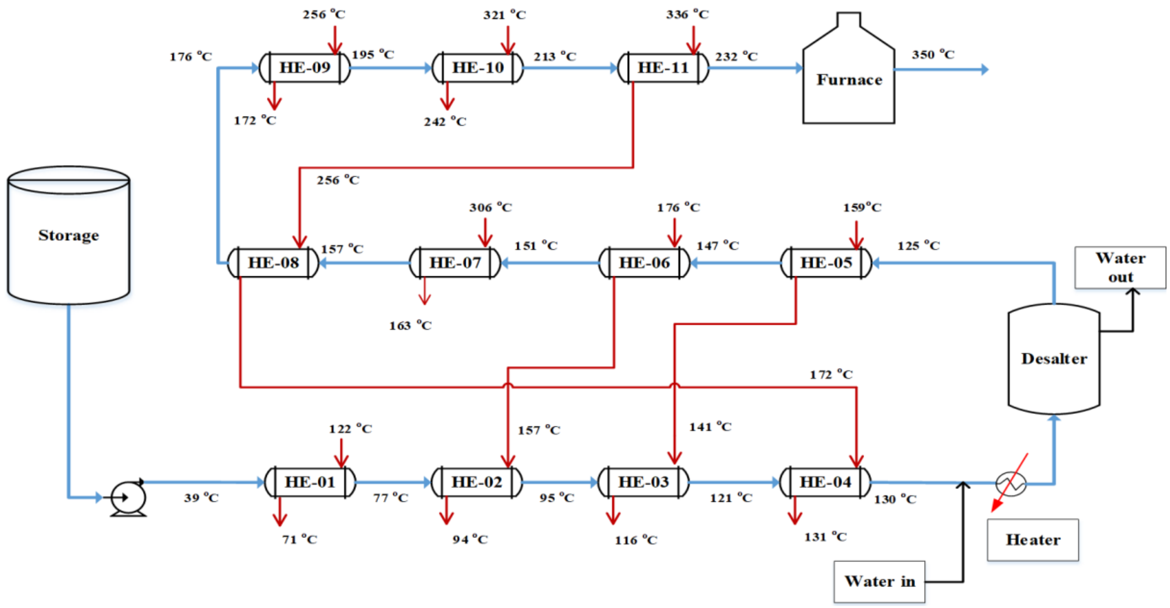

Fig. 1: Schematic diagram and typical operating conditions of the HEN in a crude oil refinery (Biyanto et al. 2016)

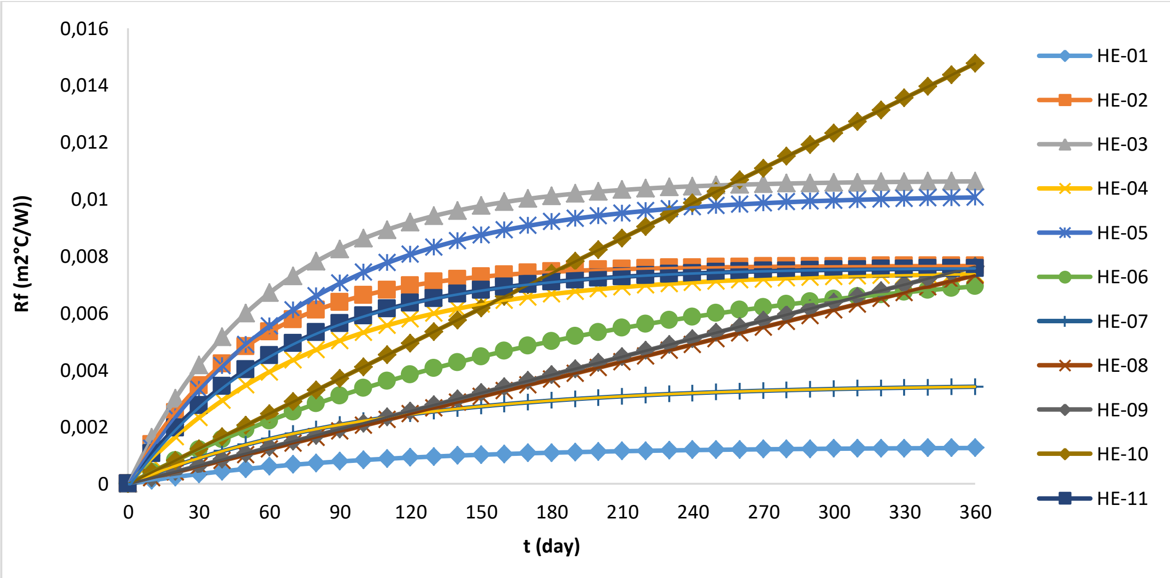

Fig. 2: Profile of R_f for each HE

Table 1. Typical design parameters of HE and R_f model result for each HE

Number HE	U_c (W/m^2.°C)	A (m^2)	m_h (kg/hr)	m_c (kg/hr)	c_{ph} (J/kg.°C)	c_{pc} (J/kg.°C)	$R_{f\infty}$ (m^2.°C/W)	β (unit/day)
HE-01	689	650	372070	420279	2600	2150	1.30E-03	1.05E-02
HE-02	533	576	99246	420279	2475	2285	7.66E-03	1.99E-02
HE-03	618	1144	377161	420279	2530	2390	1.07E-02	1.65E-02
HE-04	293	744	96001	420279	2335	2470	7.45E-03	1.25E-02
HE-05	516	1624	377161	420085	2630	2530	1.02E-02	1.31E-02
HE-06	677	238	99246	420085	2670	2580	8.14E-03	5.31E-03
HE-07	176	296	14436	420085	2930	2605	3.51E-03	9.96E-03
HE-08	415	581	96001	420085	2590	2665	3.87E-01	5.31E-05
HE-09	544	495	121864	420085	2920	2755	4.16E-01	5.14E-05
HE-10	699	243	85828	420085	3140	2845	1.90E+00	2.17E-05
HE-11	562	327	96001	420085	2920	2935	7.61E-03	1.50E-02

In this work, a 5°C decrease in temperature for a desalting process is taken into account, as the decrease is significant enough to affect the HEN's overall heat consumption. The desalting process is introduced to remove salt in crude oil by mixing the crude oil with water.

Furnace

Furnace in the form of fired heater is deployed to bring crude oil at the desired inlet temperature of the distillation column (Coletti et al. 2015). The decreasing of furnace inlet stream temperature and the increasing of furnace fuel consumption are all inevitably affected by the fouling phenomenon. To determine the furnace performance at any time as the direct implication of fouling, one can formulate the furnace's total energy consumption as in the Eq. (7) and Eq. (8).

$$Q_{fu} = \sum_{t=0}^{H} m_c\, Cp_c\left(T_{o,fu} - T_{i,fu(t)}\right)\Delta t \quad (7)$$

$$T_{i,fu\,(t)} = T_{c,o\,(t)}^{HE-n} \quad (8)$$

The upstream heat exchanger temperatures $T_{c,o\,(t)}^{HE-n}$ will reflect the fouling process of each heat exchanger at any time and directly affect the furnace total heat duty Q_{fu}.

Energy recovery

Cleaning scheduling optimization aims to maximize the energy recovery of a cleaned HE from untreated ones (Biyanto et al. 2015). There are 3 components to be considered, the total heat duty of HE with cleaning treatment, the total heat duty of HE without cleaning treatment, and the difference of prior both components in terms of energy saving. The relationship of the elements was described with Eqs. (9)-(11).

$$E_{s\,HEN} = E_{cs\,HEN} - E_{f\,HEN} \quad (9)$$

$$E_{cs\,HEN} = \sum_{n=1}^{N}\sum_{t=0}^{H} Q_{cs\,(t)}^{HE-n}\,\Delta t \quad (10)$$

$$E_{f\,HEN} = \sum_{n=1}^{N}\sum_{t=0}^{H} Q_{fouled\,(t)}^{HE-n}\,\Delta t \quad (11)$$

Cleaning schedule

A regular cleaning schedule of HEN is essential to address the fouling build-up in each HE. However, the HEN cleaning frequency and schedule will have an impact on process continuity and operating costs under an economic perspective. Therefore, we need a proper cleaning scheduling strategy that is easy to implement and provide the optimal HEN performance during the whole operating horizon.

A novel approach is proposed where the cleaning decision of HE in HEN is based on when U_f reaches a predetermined heuristic limit, and U_f follows profile over time based on the Eq. (3). It is rational to obtain an optimal cleaning schedule of HEN by following the decrease in U_f. This way, users could follow the performance of each HE and easily decide when to clean the HE. There are nine heuristic cleaning decision limits based on U_f when reaching 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% of U_c as expressed in the Eqs. (12)-(20).

$$U_{f1} = 0.9\,U_c \quad (12)$$

$$U_{f2} = 0.8\,U_c \quad (13)$$

$$U_{f3} = 0.7\,U_c \quad (14)$$

$$U_{f4} = 0.6\,U_c \quad (15)$$

$$U_{f5} = 0.5\,U_c \quad (16)$$

$$U_{f6} = 0.4\,U_c \quad (17)$$

$$U_{f7} = 0.3\,U_c \quad (18)$$

$$U_{f8} = 0.2\,U_c \quad (19)$$

$$U_{f9} = 0.1\,U_c \quad (20)$$

In the proposed cleaning scenarios, a limit of total available HE to be cleaned on the same day is imposed as a unit cleanability limit. Five days of cleaning time for each HE is assumed. Hard deposit fouling is assumed, and consequently, mechanical cleaning is considered as the cleaning procedure. A heater before desalter is introduced as a supporting unit maintains the temperature of the desalter inlet when any of the HE is under cleaning treatment. The heating capacity of the heater is determined according to the HEN cleaning schedule for the entire operating time horizon that follows Eq. (5). HE with fewer cleaning history is put into cleaning a priority if two or more HEs enter the same cleaning schedule. If two or more HEs have the same number of cleaning histories, those with higher cold inlet temperatures take precedence because of the potential higher fouling rate. When a particular HE enters the cleaning process, the corresponding HE is bypassed, and the heat duty is distributed to the other HEs in the HEN. Therefore, the operating conditions of other HEs are affected by the bypassed HE under cleaning treatment.

Cleaning scheduling conflict may arise due to the unit's cleanability limit in a day that requires HE cleaning treatment prioritization. When another HE above the unit cleanability limit enters the same cleaning schedule, the corresponding HE cleaning treatment is put on hold until there is a slot available as the cleaning treatment of the previous HE has finished. This situation may cause cleaning delays to the HE that is put on hold and allows its U_f below the heuristic cleaning decision limit. By delineating all the possible schedules, an appropriate schedule with or without conflict can be suggested to users as reference for the final decision of the cleaning schedule.

A flowchart of the cleaning scheduling for HEN is shown in Figure 3. The procedure starts from providing HE design parameters and R_f parameter. The corresponding R_f and U_f are defined with the respected Eq. (1) and (3). For each increment of the unit cleanability limit, the HEN cleaning schedule is then generated by considering the decision scenarios of Eqs. (12)-(20). The operational constraints and cleaning priorities are imposed as described in the previous paragraphs, simultaneously. The n is defined for HE unit cleanability constraint in the cleaning station. The algorithm will incrementally add the unit cleanability n up to 11. Each cleaning schedule key performance indicators, i.e., heater heat duty as defined in Eq. (5), furnace heat duty as defined in Eq. (7) and heat recovery, as defined in Eqs. (9)-(11) are calculated subsequently. Based on the total cleaning numbers of each HE and the aforementioned key performance indicators, the cleaning schedules are then analyzed for user recommendation.

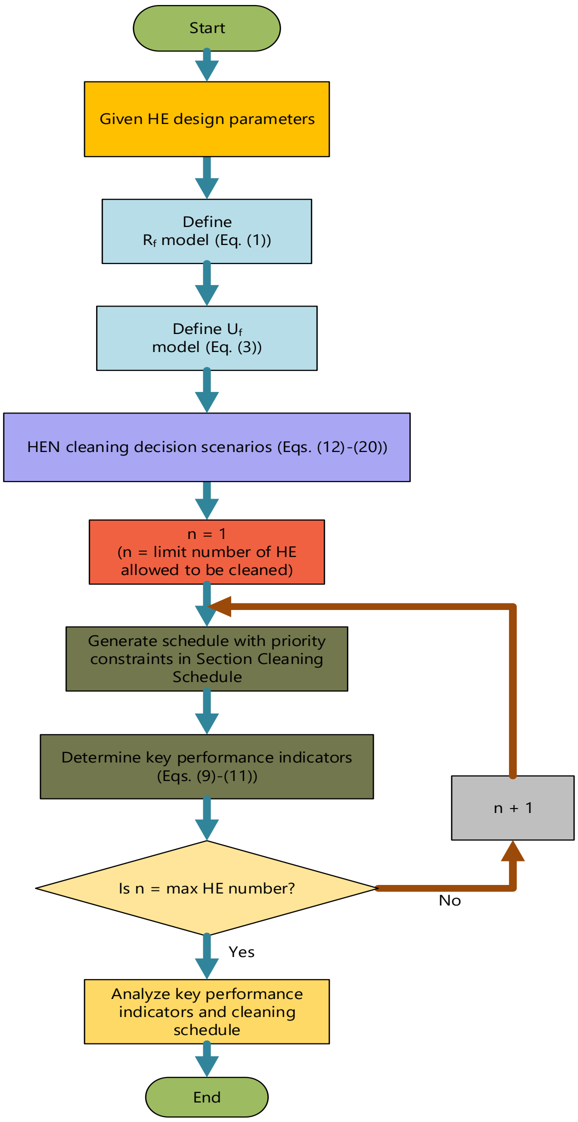

Fig. 3: Computation flowchart of cleaning scheduling for HEN

RESULTS AND DISCUSSION

Subsequent results computed according to the flowchart shown in Figure 3 are elaborated in this section. The effect of different scenarios and unit cleanability limits on the number of cleaning treatments for each HE is detailed in Table 2.

Table 2. Total number of cleaning treatment for each HE

Scenario of U	Unit cleanability limit	Total number of cleaning treatment											Total
		HE-01	HE-02	HE-03	HE-04	HE-05	HE-06	HE-07	HE-08	HE-09	HE-10	HE-11	
U_{f1}	1 HE	6	6	7	6	6	6	6	7	7	7	7	71
	2 HE	11	14	14	13	14	14	7	14	14	14	14	143
	3 HE	11	20	24	13	20	19	8	24	24	22	24	209
	4 HE	12	21	29	14	22	21	8	26	27	25	29	234
	5 HE	12	22	29	15	22	21	8	27	28	25	29	238
	6 HE	12	22	30	15	22	21	8	27	28	25	30	240
	7 HE	12	22	30	15	22	21	8	27	28	26	30	241
	8 HE	12	22	30	15	22	21	8	27	28	26	30	241
	Unconstrained	12	22	30	15	22	21	8	28	28	26	30	242
U_{f2}	1 HE	6	7	8	6	7	6	4	7	7	7	7	72
	2 HE	7	13	16	9	13	13	4	14	15	13	17	134
	3 HE	7	14	19	9	15	13	5	16	17	14	20	149
	4 HE	7	15	20	9	15	14	5	17	17	15	20	154
	5 HE	7	15	20	9	15	14	5	17	17	15	20	154
	6 HE	7	15	20	9	15	14	5	17	17	15	20	154
	Unconstrained	7	15	20	9	15	14	5	17	17	15	20	154
U_{f3}	1 HE	4	7	8	5	7	7	2	7	8	6	8	69
	2 HE	4	10	14	7	11	10	2	11	11	9	15	104
	3 HE	4	11	15	7	11	10	2	12	12	10	15	109
	4 HE	4	11	15	7	11	10	2	12	12	10	15	109
	5 HE	4	11	15	7	11	10	2	12	12	10	15	109
	Unconstrained	4	11	15	7	11	10	2	12	12	10	15	109
U_{f4}	1 HE	2	7	9	4	7	7	0	7	8	6	9	66
	2 HE	2	8	11	5	8	7	0	8	9	7	11	76
	3 HE	2	8	12	5	8	7	0	8	9	7	12	78
	4 HE	3	8	12	5	8	8	0	8	9	7	12	80
	Unconstrained	3	8	12	5	8	8	0	8	9	7	12	80
U_{f5}	1 HE	0	5	5	4	5	4	0	5	5	4	5	42
	2 HE	0	6	9	3	6	5	0	6	7	5	9	56
	3 HE	0	6	9	3	6	5	0	6	7	5	9	56
	Unconstrained	0	6	9	3	6	5	0	6	7	5	9	56
U_{f6}	1 HE	2	7	9	4	7	7	0	7	8	6	9	66
	2 HE	0	4	7	2	5	4	0	5	5	4	7	43
	Unconstrained	0	4	7	2	5	4	0	5	5	4	7	43

Scenario of U	Unit cleanability limit	Total number of cleaning treatment											Total
		HE-01	HE-02	HE-03	HE-04	HE-05	HE-06	HE-07	HE-08	HE-09	HE-10	HE-11	
U_{f7}	1 HE	0	3	5	0	3	3	0	4	4	3	5	30
	2 HE	0	3	5	0	3	3	0	4	4	3	5	30
	3 HE	0	3	5	0	3	3	0	4	4	3	5	30
	4 HE	0	3	5	0	3	3	0	4	4	3	5	30
	Unconstrained	0	3	5	0	3	3	0	4	4	3	5	30
U_{f8}	1 HE	0	1	3	0	1	1	0	3	3	2	2	16
	Unconstrained	0	1	3	0	1	1	0	3	3	2	2	16
U_{f9}	1 HE	0	0	0	0	0	0	0	2	2	1	0	5
	Unconstrained	0	0	0	0	0	0	0	2	2	1	0	5

As shown in Table 2, the different number of the cleaning treatment of each HE is affected by how fast the *U* of each HE reaches the *U* limit for each scenario. Note that the fouling rate of each HE is different, as shown in Figure 2 and Table 1 in the previous section. Consequently, a HE associated with a higher fouling rate R_f will have a higher number of cleaning treatments. The value of U_c of each HE also has some effect on the number of cleaning treatments accordingly, although not as significant as the fouling rate R_f. As the unit cleanability limit increases, the total possible number of HE to be cleaned in a year is also increased. In other words, the maintenance capacity of the HE cleaning station rises because of the total cleaned HE in a year. When the unit cleanability limit is increased to a certain point, the number of HE to be cleaned will insignificantly differ, so the daily cleaning schedule of each HE is also slightly affected. When the unit cleanability limit is removed, i.e., the HE cleaning station has the capacity to clean all the HEs that are decided to be cleaned, this unconstrained condition is also computed accordingly for each different scenario as additional user reference.

There are several uncleaned HEs for the entire horizon, as shown in Table 2. For example, in the U_{f4} scenario, the HE-07 appears uncleaned for the whole of the horizon because the cleaning decision limit has not met as its fouling rate is very low.

By observing Table 2, which focuses more on the number of cleaning procedures, the minimum total number of cleaning in a year is associated with U_{f9} due to its significant cleaning decision limit on U_f to be 90% of U_c.

When analyzing the cleaning schedule, one phenomenon occurs when there is a conflicted or delayed cleaning treatment due to the limiting capacity of the HE cleaning station. For discussion purposes, scenario U_{f4} is chosen since there is HE, i.e., HE-07 first appears untreated for the whole horizon. Figure 4a is shown for U_{f4} and unit cleanability limit of 4 for day 111 to 129. For HE-08, it should enter the cleaning phase on day 118. Unfortunately, the cleaning station is already at full capacity for cleaning HE-01, HE-03, HE-09, and HE-11. Therefore, the cleaning schedule of HE-08 is postponed until day 120 (yellow color for the delay).

Consequently, the UF of HE-08 is

slightly lower than U_{f4}. If this condition is acceptable, i.e., HE's $U_{f(120)}$ to be smaller than the U_f limit, then the user can proceed with this schedule. Otherwise, the user should follow the schedule shown in Figure 4, which has no conflict whatsoever.

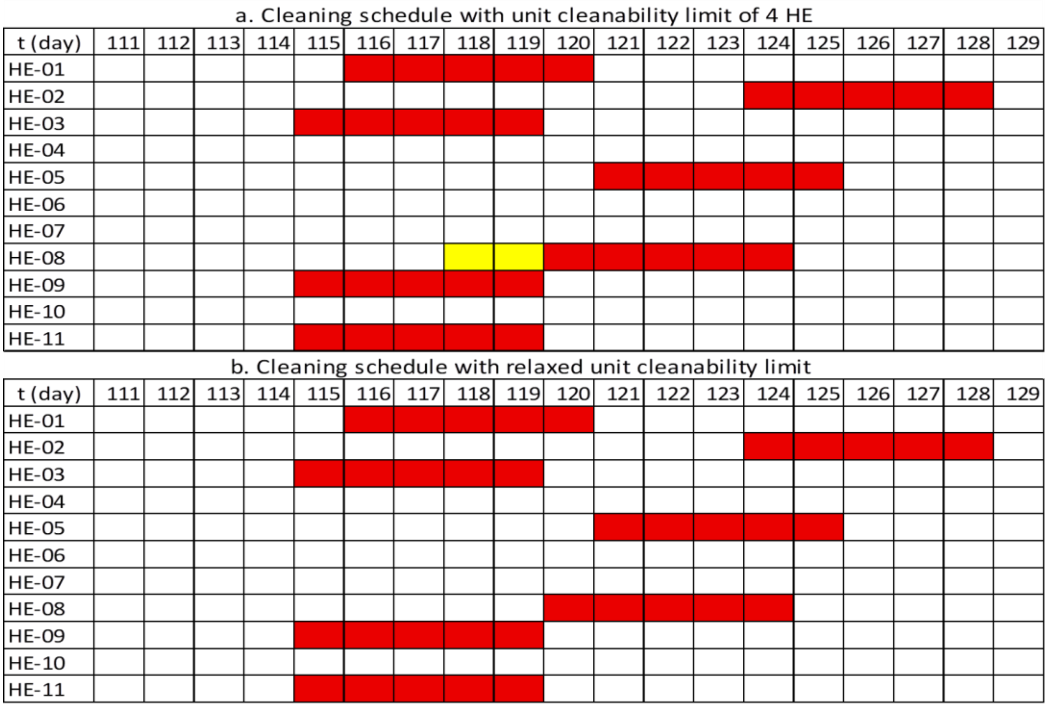

Fig. 4: Cleaning schedule for scenario U_{f4} from day 111 to 129

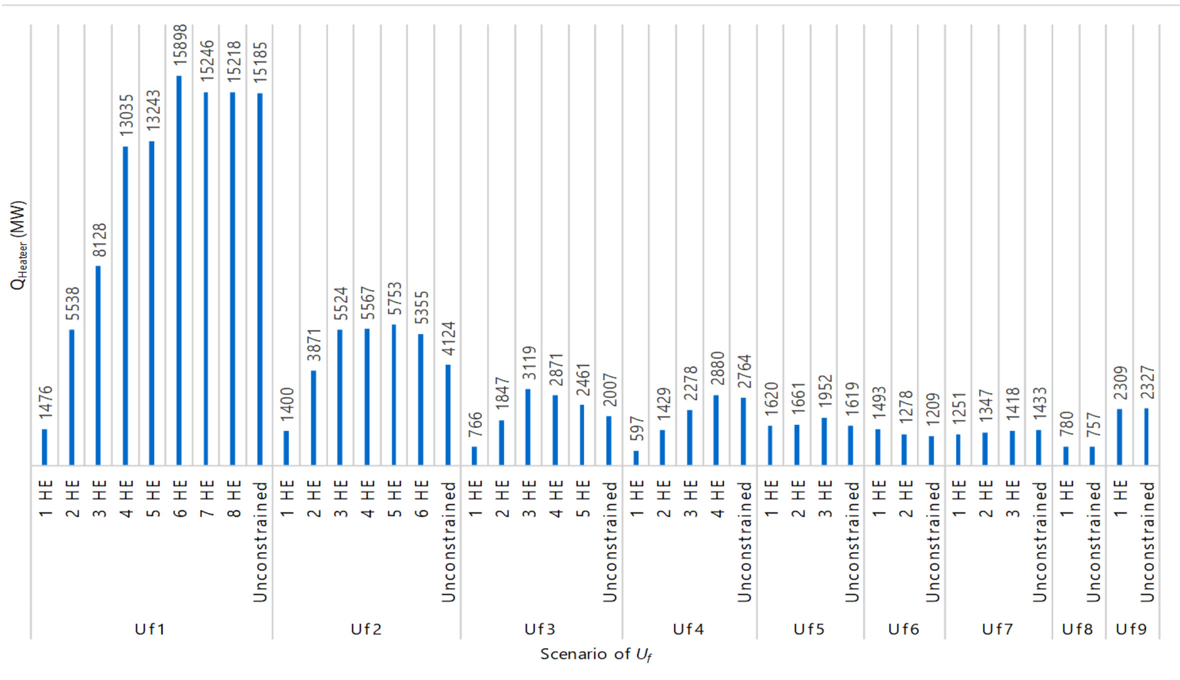

Fig. 5: Heat duty of the heater before desalter in one year

The HEN in this study is equipped with a supporting heater before the desalter unit. For a detailed analysis of the corresponding heater, Figure 5 is drawn to show the heater's energy consumption to support and replace the duty of the bypassed heat exchangers, which enter the cleaning treatment. *U* scenarios with more frequent cleanings will have higher additional energy consumption on the heater before desalter. As a matter of choice, the U_{f4} scenario and unit cleanability limit of 1 will result in the least heater energy consumption. Although the heater energy consumption is at its lowest, the high cleaning cost may be significant because the total number of cleaning in U_{f4} scenarios is more frequent than the $U_{f5\text{-}9}$ scenarios.

As the final unit of the HEN, the performance of the furnace is depicted in Figure 6. Similar to the previous analysis for the heater before desalter, the schedule with the U_{f4} scenario of the unit cleanability limit of 1 has a minimum energy consumption of the furnace but has a significant total number of cleaning in a year.

The breakdown of the HEN energy recovery as described in Eqs. (9)-(11) for different scenarios, and the unit cleanability limit is shown in Figure 7. With the cleaning schedule in place, the magnitude of the HEN energy recovery depends on the scenario of *U* and the unit cleanability limit. The highest energy recovery among the result candidate is provided at U_{f4} and cleanability unit 1. Figure 7 shows the aftermath of the corresponding cleaning decision limit, and the unit cleanability limit along with the heat duties shown in Figure 5 and Figure 6. By observing the results from Figure 5-7 and taking into account the total number of cleaning in Table 2, users can compute the tradeoff between the saved cost of energy recovery and the cleaning cost from the total number of cleaning using their cost model.

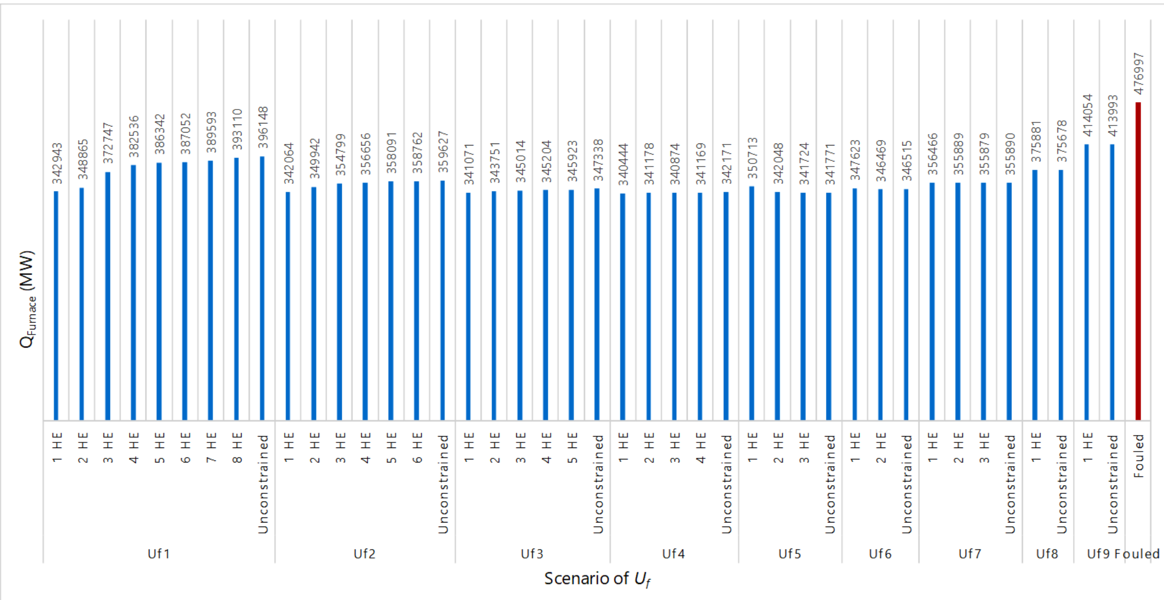

Fig. 6: Heat duty of the furnace in one year

Model comparison

In this section, the data and solution reported by Smaïli et al. (2002a) and Lavaja & Bagajewicz (2004) for a HEN case of 10 HEs are adopted for comparison purposes. The whole time horizon with 18 periods of 30 days is assumed. Table 3 showed that literature solutions are compared in terms of the total number of cleaning treatments for each HE because the results from the literature do not emphasize on the energy recovery and heat duty of each HE.

In this comparison, the heuristic method based on the cleaning decision limit based on U_f shows an advantage than those reported in the literature at higher U_fs, i.e., U_{f7-9}. The total number of cleaning of U_{f1-6} from Lavaja & Bagajewicz (2004) and U_{f1-5} from Smaïli et al. (2002a) shows less in comparison with the proposed heuristic approach.

Therefore, to obtain less number of cleaning, higher U_fs is preferable. Still, the users should keep in mind that the corresponding energy recovery and heat duty may not be optimal at high U_fs, as discussed in the previous section.

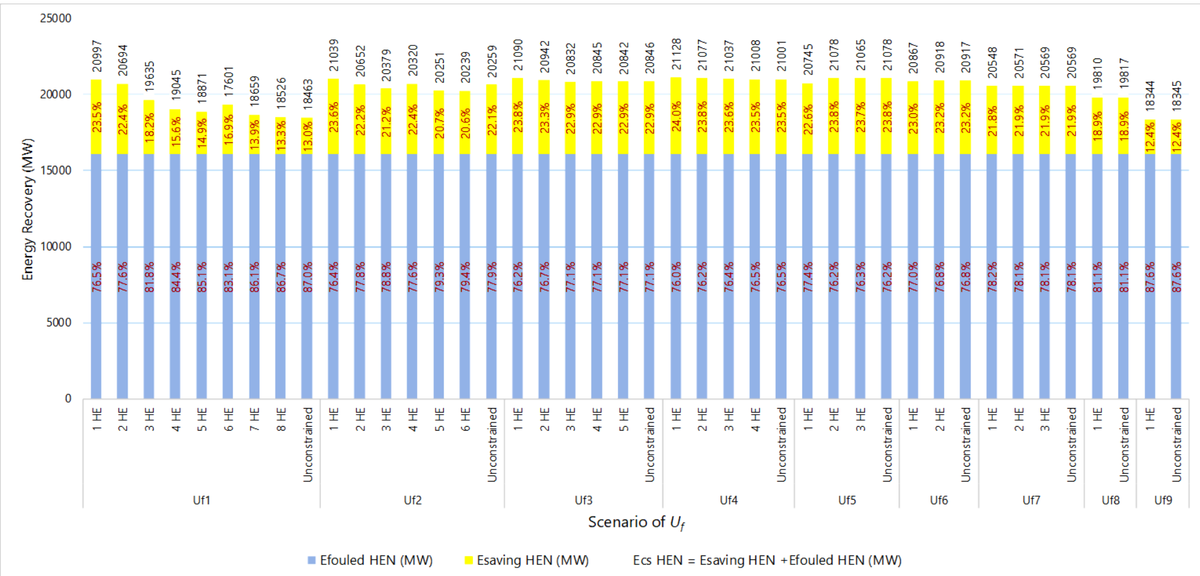

Fig. 7: HEN energy recovery in one year

Table 3. Total number of cleaning treatment for each HE

Scenario of U	Unit cleanability limit	Total number of cleaning treatment										Total
		HE-01	HE-02	HE-03	HE-04	HE-05	HE-06	HE-07	HE-08	HE-09	HE-10	
U_{f1}	1 HE	10	10	10	10	11	11	11	11	11	11	106
	2 HE	21	21	21	21	21	21	21	21	22	22	212
	3 HE	26	26	26	26	27	27	27	27	27	27	266
	4 HE	29	29	30	30	30	30	30	30	30	30	298
	5 HE	30	30	30	30	30	30	30	30	30	30	300
	6 HE	30	30	30	30	30	30	30	30	30	30	300
	7 HE	30	30	30	30	30	30	30	30	30	30	300
	8 HE	30	30	30	30	30	30	30	30	30	30	300

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Scenario of U	Unit cleanability limit	Total number of cleaning treatment										Total
		HE-01	HE-02	HE-03	HE-04	HE-05	HE-06	HE-07	HE-08	HE-09	HE-10	
	9 HE	30	30	30	30	30	30	30	30	30	30	300
	Unconstrained	30	30	30	30	30	30	30	30	30	30	300
U_{f2}	1 HE	10	10	10	10	10	10	10	10	10	10	100
	2 HE	16	16	16	16	16	16	16	16	17	17	162
	3 HE	16	16	16	16	16	16	16	17	17	17	163
	4 HE	16	16	16	16	16	16	17	17	17	17	164
	5 HE	16	16	16	16	16	17	17	17	17	17	165
	6 HE	16	16	16	16	17	17	17	17	17	17	166
	7 HE	16	16	16	17	17	17	17	17	17	17	167
	8 HE	16	16	17	17	17	17	17	17	17	17	168
	9 HE	16	17	17	17	17	17	17	17	17	17	169
	Unconstrained	17	17	17	17	17	17	17	17	17	17	170
U_{f3}	1 HE	10	10	10	10	10	10	10	10	10	10	100
	2 HE	10	10	11	11	11	11	11	11	11	11	108
	3 HE	10	11	11	11	11	11	11	11	11	11	109
	4 HE	11	11	11	11	11	11	11	11	11	11	110
	5 HE	11	11	11	11	11	11	11	11	11	11	110
	6 HE	11	11	11	11	11	11	11	11	11	11	110
	7 HE	11	11	11	11	11	11	11	11	11	11	110
	8 HE	11	11	11	11	11	11	11	11	11	11	110
	9 HE	11	11	11	11	11	11	11	11	11	11	110
	Unconstrained	11	11	11	11	11	11	11	11	11	11	110
U_{f4}	1 HE	7	7	7	7	7	7	7	7	8	8	72
	2 HE	7	7	7	7	7	7	8	8	8	8	74
	3 HE	7	7	7	7	8	8	8	8	8	8	76
	4 HE	7	7	8	8	8	8	8	8	8	8	78
	5 HE	8	8	8	8	8	8	8	8	8	8	80
	6 HE	8	8	8	8	8	8	8	8	8	8	80
	7 HE	8	8	8	8	8	8	8	8	8	8	80
	8 HE	8	8	8	8	8	8	8	8	8	8	80
	9 HE	8	8	8	8	8	8	8	8	8	8	80
	Unconstrained	8	8	8	8	8	8	8	8	8	8	80
U_{f5}	1 HE	5	5	5	5	5	5	5	6	6	6	53
	2 HE	5	5	5	5	6	6	6	6	6	6	56
	3 HE	5	6	6	6	6	6	6	6	6	6	59
	4 HE	6	6	6	6	6	6	6	6	6	6	60
	5 HE	6	6	6	6	6	6	6	6	6	6	60
	6 HE	6	6	6	6	6	6	6	6	6	6	60
	7 HE	6	6	6	6	6	6	6	6	6	6	60
	8 HE	6	6	6	6	6	6	6	6	6	6	60
	9 HE	6	6	6	6	6	6	6	6	6	6	60
	Unconstrained	6	6	6	6	6	6	6	6	6	6	60

Scenario of U	Unit cleanability limit	Total number of cleaning treatment										Total
		HE-01	HE-02	HE-03	HE-04	HE-05	HE-06	HE-07	HE-08	HE-09	HE-10	
U_{f6}	1 HE	4	4	4	4	4	4	4	4	4	4	40
	2 HE	4	4	4	4	4	4	4	4	4	4	40
	3 HE	4	4	4	4	4	4	4	4	4	4	40
	4 HE	4	4	4	4	4	4	4	4	4	4	40
	5 HE	4	4	4	4	4	4	4	4	4	4	40
	6 HE	4	4	4	4	4	4	4	4	4	4	40
	7 HE	4	4	4	4	4	4	4	4	4	4	40
	8 HE	4	4	4	4	4	4	4	4	4	4	40
	9 HE	4	4	4	4	4	4	4	4	4	4	40
	Unconstrained	4	4	4	4	4	4	4	4	4	4	40
U_{f7}	1 HE	3	3	3	3	3	3	3	3	3	3	30
	2 HE	3	3	3	3	3	3	3	3	3	3	30
	3 HE	3	3	3	3	3	3	3	3	3	3	30
	4 HE	3	3	3	3	3	3	3	3	3	3	30
	5 HE	3	3	3	3	3	3	3	3	3	3	30
	6 HE	3	3	3	3	3	3	3	3	3	3	30
	7 HE	3	3	3	3	3	3	3	3	3	3	30
	8 HE	3	3	3	3	3	3	3	3	3	3	30
	9 HE	3	3	3	3	3	3	3	3	3	3	30
	Unconstrained	3	3	3	3	3	3	3	3	3	3	30
U_{f8}	1 HE	2	2	2	2	2	2	2	2	2	2	20
	2 HE	2	2	2	2	2	2	2	2	2	2	20
	3 HE	2	2	2	2	2	2	2	2	2	2	20
	4 HE	2	2	2	2	2	2	2	2	2	2	20
	5 HE	2	2	2	2	2	2	2	2	2	2	20
	6 HE	2	2	2	2	2	2	2	2	2	2	20
	7 HE	2	2	2	2	2	2	2	2	2	2	20
	8 HE	2	2	2	2	2	2	2	2	2	2	20
	9 HE	2	2	2	2	2	2	2	2	2	2	20
	Unconstrained	2	2	2	2	2	2	2	2	2	2	20
U_{f9}	1 HE	1	1	1	1	1	1	1	1	1	1	10
	2 HE	1	1	1	1	1	1	1	1	1	1	10
	3 HE	1	1	1	1	1	1	1	1	1	1	10
	4 HE	1	1	1	1	1	1	1	1	1	1	10
	5 HE	1	1	1	1	1	1	1	1	1	1	10
	6 HE	1	1	1	1	1	1	1	1	1	1	10
	7 HE	1	1	1	1	1	1	1	1	1	1	10
	8 HE	1	1	1	1	1	1	1	1	1	1	10
	9 HE	1	1	1	1	1	1	1	1	1	1	10
	Unconstrained	1	1	1	1	1	1	1	1	1	1	10
Lavaja & Bagajewicz, (2004)		1	2	1	2	4	3	5	5	5	5	33
Smaïli et al. (2002a)		2	3	2	2	6	4	5	5	6	5	40

CONCLUSIONS

This study has computed and explored numerous cleaning schedule candidates based on several indicators for a given HEN. The simple overall heat transfer coefficients cleaning decision limit separates the schedule results of HEs with or without cleaning treatment. The unit cleanability limit is also further categorized schedules with or without cleaning delays. The maintenance engineer could quickly analyze and decide on the desired and acceptable cleaning schedules based on the key performance indicators, as shown in this study.

The proposed method shows an advantage to the previous literature in terms of the total number of cleaning procedures when the cleaning decision limit is set at $U_{f7\text{-}9}$. Moreover, the novel concept of unit cleanability shows insight into how the cleaning station capacity impacts the heater's energy consumption before desalter and the furnace. The minimum energy consumption of heater before desalter and the furnace is achieved based on decision limit U_{f4} with unit cleanability of 1. Consequentially, the maximum energy saving is also achieved with the same decision limit and unit cleanability. On the other hand, the minimum number of cleaning procedure is reached when the decision limit U_{f9} with no significant effect from unit cleanability limit. It is due to the number of cleaning procedures being so low for the entire year that the cleaning station's minimal capacity is adequate for the corresponding schedule. The user can evaluate their optimum cleaning scheduling strategy by incorporating the results from this work into their cost model accordingly.

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NOMENCLATURE

R_f	:	fouling resistance [m^2 °C W^{-1}]
$R_{f\infty}$	:	asymptotic fouling resistance [m^2 °C W^{-1}]
β	:	fouling time constant, [unit day^{-1}]
t	:	time [day]
U_c	:	overall heat transfer coefficient on clean condition [W m^{-2} °C^{-1}]
U_{f1}	:	cleaning decision limits based on U_f when reaching 10%, [W m^{-2} °C^{-1}]
U_{f2}	:	cleaning decision limits based on U_f when reaching 20%, [W m^{-2} °C^{-1}]
U_{f3}	:	cleaning decision limits based on U_f when reaching 30%, [W m^{-2} °C^{-1}]
U_{f4}	:	cleaning decision limits based

		on U_f when reaching 40%, [W m^{-2} °C^{-1}]
U_{f5}	:	cleaning decision limits based on U_f when reaching 50%, [W m^{-2} °C^{-1}]
U_{f6}	:	cleaning decision limits based on U_f when reaching 60%, [W m^{-2} °C^{-1}]
U_{f7}	:	cleaning decision limits based on U_f when reaching 70%, [W m^{-2} °C^{-1}]
U_{f8}	:	cleaning decision limits based on U_f when reaching 80%, [W m^{-2} °C^{-1}]
U_{f9}	:	cleaning decision limits based on U_f when reaching 90%, [W m^{-2} °C^{-1}]
A	:	surface area [m^2]
ΔT_{LM}	:	the logarithmic mean temperature difference [°C]
H	:	operating horizon defined in 360 days
m_c	:	cold stream mass flow rate [kg hr^{-1}]
m_h	:	hot stream mass flow rate [kg hr^{-1}]
c_{pc}	:	cold stream heat capacity [J kg^{-1} °C^{-1}]
c_{pc}	:	cold stream heat capacity [J kg^{-1} °C^{-1}]
$T_{i,d}$		desired desalter inlet temperature 115 [°C]
$T_{i,d\,(t)}$	:	current (t) inlet temperature desalter [°C]
$T_{c,o\,(t)}^{HE-n}$	:	cold stream outlet temperature of HE [°C] and n for HE 1, 2, 3 and 4 in Eq. (6)
$T_{c,o\,(t)}^{HE-n}$	:	cold stream outlet temperature of HE [°C] and n for HE 5, 6, 7, 8, 9, 10, 11 and desalter in Eq. (8)
$T_{o,fu}$	:	desired furnace outlet temperature 350 [°C]
$T_{i,fu\,(t)}$	:	current (t) inlet temperature furnace [°C]
$E_{s\,HEN}$	:	total energy saving [MW]
$E_{cs\,HEN}$	:	total HEN heat duty under cleaning schedule [MW]
$E_{f\,HEN}$	:	total HEN heat duty without cleaning treatment [MW]
Q^{HE-n}	:	heat duty of the nth HE (MW) and n for HE 1, 2, ..., 11
Q_h	:	heater heat duty [MW]
Q_{cs}^{HE-n}	:	heat duty of the nth HE in Eq. (4) with $U_{f\,(t)}$ follows the cleaning schedule profile [MW] and n for HE 1, 2, ..., 11
Q_f^{HE-n}	:	heat duty of the nth HE Eq. (4) with $U_{f\,(t)}$ follows fouled condition without cleaning [MW] and n for HE 1, 2, ..., 11
N	:	total number of HEs in HEN

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