

Simultaneous Optimization of Synthesis and Scheduling of Cleaning in Flexible Heat Exchanger Networks*

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Abstract A novel methodology is presented for simultaneously optimizing synthesis and cleaning schedule of flexible heat exchanger network (HEN) by genetic/simulated annealing algorithms (GA/SA). Through taking into account the effect of fouling process on optimal network topology, a preliminary network structure possessing two-fold oversynthesis is obtained by means of pseudo-temperature enthalpy (T - H) diagram approach prior to simultaneous optimization. Thus, the computational complexity of this problem classified as NP (Non-deterministic Polynomial)-complete can be significantly reduced. The promising matches resulting from preliminary synthesis stage are further optimized in parallel with their heat exchange areas and cleaning schedule. In addition, a novel continuous time representation is introduced to subdivide the given time horizon into several variable-size intervals according to operating periods of heat exchangers, and then flexible HEN synthesis can be implemented in dynamic manner. A numerical example is provided to demonstrate that the presented strategy is feasible to decrease the total annual cost (TAC) and further improve network flexibility, but even more important, it may be applied to solve large-scale flexible HEN synthesis problems.

Keywords flexible heat exchanger network, synthesis, cleaning schedule, continuous time representation, simultaneous optimization

1 INTRODUCTION

Heat exchanger network is taken as one of the most important measures for energy saving in process industry. However, its synthesis remains in the realm of specified operating condition at present. In fact, it is necessary to maintain certain operational flexibility for grassroots design of heat exchanger network (HEN) to weaken the influence of either the disturbances of uncertain parameters involving source-stream temperature, heat capacity flowrate and overall heat transfer coefficient or the alteration of operating condition with the seasons on network performance. Since Marselle *et al.* [1] defined resilience and stated related properties, flexible HEN synthesis has been paid more attention. Some critical milestone events such as flexibility index, active set strategy and sensitivity tables have been introduced in the last century. Recently, Konukman *et al.* [2] presented a formulation to optimize flexible targeting and utility consumption simultaneously. But the model was valid only if the formulation was presumed that the feasible region in the space of uncertain input parameters was convex. Aaltola [3] proposed a simultaneous multi-period mixed integer nonlinear programming (MINLP) model based on stage-wise superstructure for minimum costs and flexibility. However, its result tended to underestimate investment cost as the equalization of heat transfer areas. The modifications to Aaltola's model by Verheyen and Zhang [4] included the appli-

cation of maximum area per period in the area cost calculation of the MINLP objective function, and the removal of slack variables and weighted parameters. Chen and Hung [5] presented an approach to decompose the complex problem to three main iterative steps: simultaneous HEN synthesis, flexibility test, and the removal of infeasible networks. Ma *et al.* [6] presented a sequential two-stage strategy to synthesize flexible multi-stream HEN, but only the disturbance of source-stream temperature was taken into account.

For cleaning schedule of HEN subject to fouling, various approaches have been proposed in previous literatures. Smaili *et al.* [7] presented an alternative approach based on the threshold accepting algorithm with backtracking variation to solve MINLP problem generated by considering HEN scheduling problem in a multi-period formulation. Georgiadis and Papageorgiou [8] considered a general mathematical framework for the optimal periodic cleaning and energy management problem in HENs. Economic trade-offs between the total number and timings of cleaning interventions, and the cost and availability of the hot utility in the plant were illustrated. In order to model cleaning intervention, the segmentation of the given time horizon in previous papers is based on discrete time representation. This method, however, may put severe limitations on rigorous mathematical model in the following three main aspects:

(1) The regular duration of sub-time interval is overlong, and usually the time span of one month is

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employed in pervious works;

(2) Cleaning intervention is only permitted to perform at the end of time interval;

(3) Change in energy consumption is often neglected during cleaning intervention.

As is known, heat exchange unit in HEN requires an extra allowance of area at initial design stage as a result of gradual deterioration of heat transfer performance subject to fouling. TEMA (Tubular Exchanger Manufacturers Association) recommended that for conventional shell and tube heat exchanger with hydraulic diameters of the tubes of about 25 mm, additional surface area reaches up to about 40%, and even more for some special process streams. Fouling deposition is in general a slow process especially for the stream featuring great asymptotic fouling resistance and long decay time of fouling formation. Thus, it is clear that the area of exchanger is in a surplus state during most period of network operation, and then the bypasses must be assembled to regulate stream outlet temperatures. It is an inevitable waste for previous synthesis approaches in steady state form. But if the synthesis and cleaning schedule of HEN are taken into account simultaneously at initial design stage, and anticipated on-line cleaning interventions are carried out at some moments of network operation so as to restore heat transfer performance, the extra area and utility consumptions may be considerably economized. For the synthesis and cleaning schedule problems their previous MINLP formulations in most of literatures were featured by high discretization, nonconvexity and nonlinearity, thus it is difficult to capture global optimal solution. Thus, a novel method used for simultaneously optimizing synthesis and cleaning schedule is introduced in this paper. Firstly, through taking into account the impact of fouling process on network topology, a twofold over-synthesis network is obtained by means of pseudo- $T-H$ diagram approach prior to simultaneous optimization, and the most promising matches are identified as match candidates of final structure. Therefore, the strategy of preliminary synthesis may powerfully eliminate a lot of binary variables from simultaneous multi-period MINLP model. To further reduce computational complexity, a novel continuous time representation is introduced at simultaneous optimization stage to subdivide the given time horizon into several sub-time intervals with unequal time durations. The match candidates resulting from preliminary synthesis are further optimized in parallel with their heat transfer areas and operating periods by GA/SA. It is interesting to note that each member of match candidates is randomly chosen by the aid of predetermined acceptance probability to construct network. The probability value of every match depends on the frequency of existing in synthesized networks of preliminary synthesis stage. As a result, the network topology can be rapidly developed in a direction favorable to objective function.

2 THE APPROACH FOR SIMULTANEOUS OPTIMIZATION OF SYNTHESIS AND SCHEDULING OF CLEANING IN FLEXIBLE HENS

2.1 Preliminary synthesis of flexible HEN under fouling process

2.1.1 Division fouling process into phases

Pseudo- $T-H$ diagram approach makes energy at different temperature levels redistributed, and further brings out equal exergy loss distribution [9]. The total annual cost involving annualized investment and utility costs can be reduced by optimizing the contribution of the stream heat transfer temperature difference. In view of this, the approach is used for preliminary synthesis of flexible HEN.

For cleaning tasks carried out at some certain moments, the stream heat transfer film coefficient under fouling ought to be set according to fouling resistance prior to cleaning intervention. In addition, the differences in either fouling deposition rate or fouling formation time among process streams may result in change in synthesized network topology over time. For the purpose of monitoring the impact of fouling deposition on optimal network structure, the asymptotic fouling formation may be divided into four phases as seen in Fig. 1.

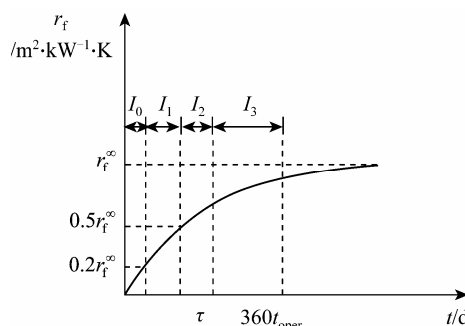


Figure 1 Divide fouling process into phases in order to monitor the impact of fouling on optimal network structure

Phase I_0 : fouling is in initial deposition condition, and the time span for this phase is defined from the startup of exchanger to the elapsed time of about 20% of fouling formation.

Phase I_1 : fouling is sufficiently developed on the surface of heat transfer unit, and the time span is equal to the elapsed time interval from 20% to 50% of fouling formation.

Phase I_2 : fouling deposition rate is gradually reduced, and the time span is equal to the elapsed time interval from 50% of fouling formation to decay time of fouling formation.

Phase I_3 : fouling approximately reaches asymptotic fouling resistance, and there is no possibility that large change will happen over time, and the time span of this phase is equal to the interval from decay time of fouling formation to final time.

2.1.2 The procedure of preliminary synthesis stage

The procedure of preliminary synthesis as seen in Fig. 2 (a) is summarized as follows:

Step 1 Divide the fouling process into phases as mentioned above by reference to the specified stream that possesses medium decay time of fouling formation among the process streams.

Step 2 Choose the intermediate time point of each phase to perform flexible HEN synthesis based on pseudo- $T-H$ diagram approach. The multiperiod HEN is obtained by merging synthesized structure per operating condition together, and every match adopts the maximum area per operating condition, thus it is

over designed for the current network requirement.

Step 3 Merge structure of each time point together, the incorporating rule is expressed by match matrix $\mathbf{M}$ in which the elements represent existing matches between hot streams and cold streams,

$$\mathbf{M}_k = \mathbf{M}_k^t \vee \mathbf{M}_k^{t+1} = \begin{bmatrix} 1 & 1 \\ & 1 \end{bmatrix} \vee \begin{bmatrix} 1 & \\ & 1 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ & 1 & 1 \end{bmatrix},$$

$k \in \text{NK}$, $t \in \text{NT}$. Thus, the resulting structure belongs to twofold over-synthesis network owing to incorporating again. Thus far, preliminary synthesis procedure has been introduced and the surviving

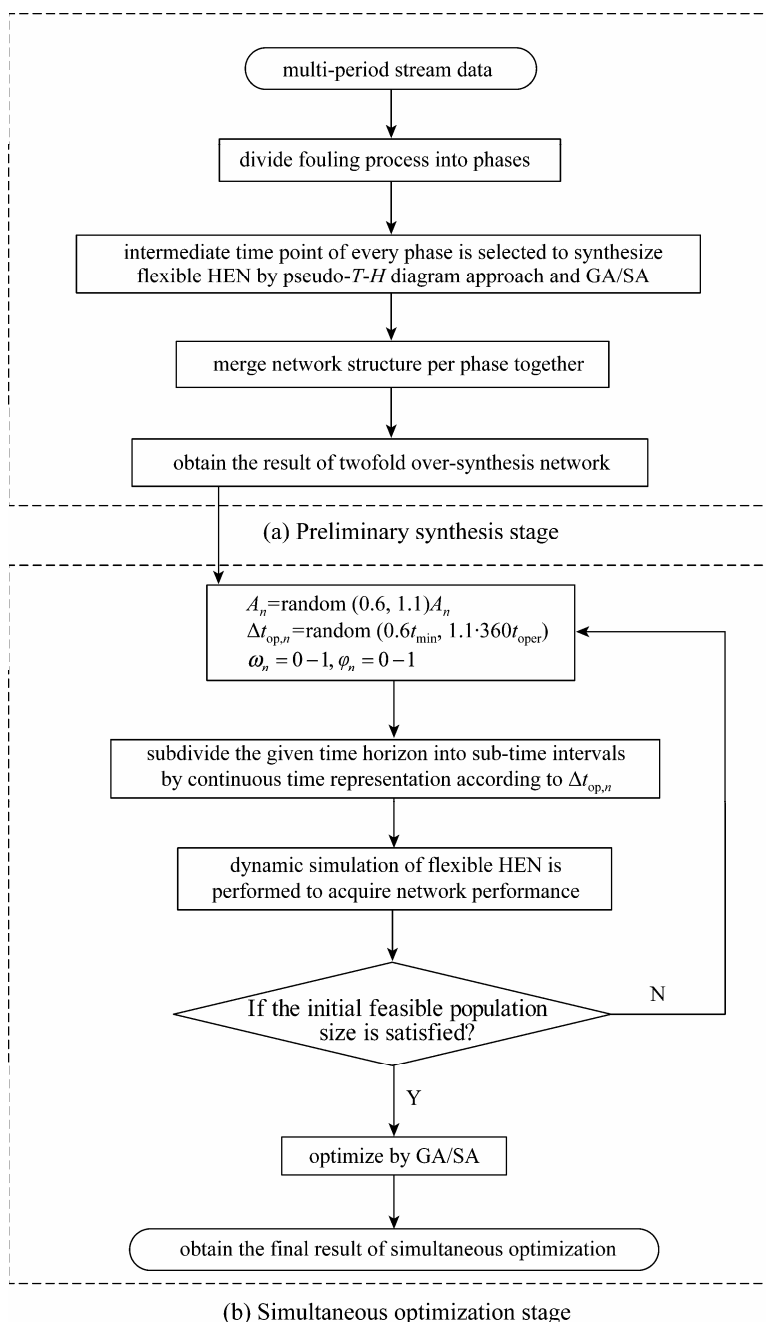


Figure 2 Flowchart of simultaneous optimization of flexible HEN synthesis and cleaning schedule

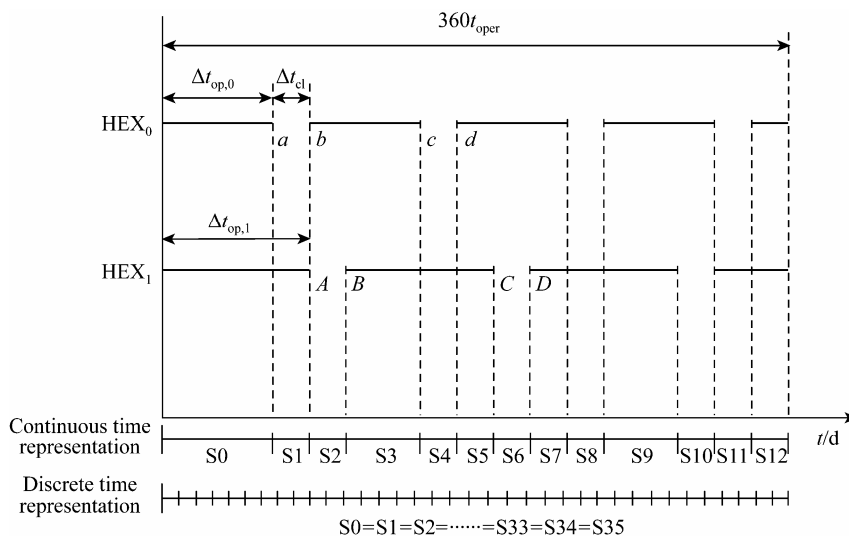


Figure 3 Subdivision of the given time duration into sub-time intervals by continuous time representation

matches will be further optimized at simultaneous optimization stage.

2.2 Simultaneous optimization of synthesis and cleaning schedule for flexible HENs

2.2.1 Continuous time representation

Continuous time representation has been used for establishing models of scheduling problems such as the scheduling of multipurpose batch process [10] and the scheduling of crude oil [11]. The method can avoid the settings of unnecessary time intervals, therefore, the model size in contrast with that of discrete time representation is reduced obviously. It only requires the initial consideration of a necessary number of event points corresponding to the initiation of a task. Thus, a novel continuous time representation as described in Fig. 3 is introduced so as to reduce computational complexity. With the aid of Fig. 3, an explanation of the proposed approach is given as follows.

For heat exchanger HEX_0 , the operating and cleaning interventions are performed in turn during period of network service so as to restore heat transfer performance of heat exchanger, thus some discrete-time intervals such as S_0 , S_1 , (S_2 , S_3) and S_4 are formed between adjacent boundary points originated from the launch or termination of events involving operating and cleaning interventions. For single heat exchanger, these boundary points and resulting time intervals can be easily identified according to Δt_{op} and Δt_{cl} . Network structure is however made up of many heat exchange units and it makes this a difficult task for discretization of the given time horizon.

In order to guarantee an either-or device status (in operating or in cleaning) for every heat exchanger within a certain length of time, it is necessary to redivide the whole time horizon into new sub-time intervals according to the previously identified boundary points. Firstly, all the boundary points are rearranged

in order of occurrence time, and the time span between adjacent boundary points serves as newly acquired sub-time interval, e.g. the sub-time intervals S_2 and S_3 . Then, the source object of rearranged boundary point needs to be identified by searching in order to acquire the information about which exchanger has a state transition within newfound sub-time interval. If '1' in binary code is used to indicate that either operating intervention or cleaning intervention is coming at the starting point of next sub-time interval, every element value in the defined state transition matrix M_T is obtained in terms of preceding search result. Partial element values of matrix M_T are given below.

$$M_T \Rightarrow \begin{matrix} & a & b(A) & B & c & d & \dots \\ HEX_0 & \begin{bmatrix} 1 & 1 & 0 & 1 & 1 \end{bmatrix} & \dots \\ HEX_1 & \begin{bmatrix} 0 & 1 & 1 & 0 & 0 \end{bmatrix} & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \end{matrix}$$

where the rows denote the heat exchangers of the network resulting from preliminary synthesis, the columns denote rearranged boundary points, and the elements represent true or false for event occurrences.

The device status matrix M_S , in which the rows and columns refer to heat exchangers and sub-time intervals and the elements represent device statuses, is defined. All heat exchangers are in service within sub-time interval S_0 , thus every element of the column vector M_{SS_0} is expressed by the value 1 in binary variable. The device status of each heat exchanger within sub-time interval S_1 is obtained by addition operation of binary bit between the column vector M_{SS_0} and the column vector of state transition matrix, M_{TS_1} . Similarly, every element in the column vector M_{S_s} is obtained by addition operation of binary bit between the column vector $M_{S_{s-1}}$ and the column vector M_{TS_s} .

The detailed process for identifying device statuses within sub-time intervals is demonstrated in Fig. 4.

The binary variable y as seen in Eq. (1) is defined to represent device status within each sub-time interval.

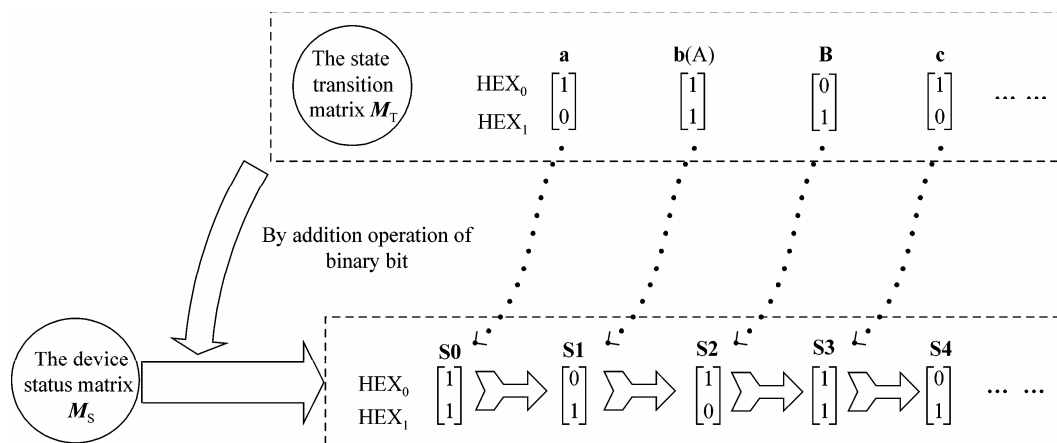


Figure 4 Identify device status of exchanger within each sub-time interval

Its value can be determined by above identification process. Based on this, the dynamic simulation can be performed to acquire detailed information of network performance.

$$y_{n,s} = \begin{cases} 1 & \text{if heat exchanger } n \text{ is working within} \\ & \text{sub-time interval } s \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

2.2.2 Objective function of simultaneous optimization stage

In previous section, the resulting preliminary network featuring twofold oversynthesis obviously deviates from the optimum. Thus, it is necessary to further optimize the network structure, heat exchanger areas and utility consumptions. Simultaneously taking into account cleaning task, the total annual cost makes a compromise among exchanger investment, utility costs and cleaning cost. The objective function described by MINLP formulation is given by

$$\begin{aligned} \min \text{TAC} = & \sum_k \sum_j \sum_i \left[\omega_{i,j,k} \cdot \varphi_{i,j,k} \cdot \left(C_{f,i,j,k} + \right. \right. \\ & \left. \left. C_{i,j,k} \cdot A_{i,j,k}^{B_{i,j,k}} \right) \right] + \max_p \max_s \left(C_{f,cu,i} + C_{cu,i} \cdot A_{p,s,i}^{B_{cu,i}} \right) + \\ & \max_p \max_s \left(C_{f,hu,j} + C_{hu,j} \cdot A_{p,s,j}^{B_{hu,j}} \right) + \sum_p \sum_s \left\{ \text{NOP}_p \cdot \right. \\ & \left. \left[\int_{\Delta t_s} (C_{u,cu} \cdot q_{cu,p}(t) + C_{u,hu} \cdot q_{hu,p}(t)) dt \right] / t_{\text{oper}} \right\} + \\ & \sum_k \sum_j \sum_i \left[\omega_{i,j,k} \cdot \varphi_{i,j,k} \cdot \left(C_{f,i,j,k}^{\text{cl}} + C_{i,j,k}^{\text{cl}} \cdot A_{i,j,k}^{B_{i,j,k}^{\text{cl}}} \right) \cdot \right. \\ & \left. N_{i,j,k}^{\text{cl}} \right] / t_{\text{oper}} \\ & i \in \text{NH}, j \in \text{NC}, \text{hu} \in \text{NUH}, \text{cu} \in \text{NUC}, \\ & k \in \text{NK}, p \in \text{NP}, s \in \text{NS} \end{aligned} \quad (2)$$

The binary variables ω and φ are randomly chosen by the aid of predetermined acceptance probability for every match to construct network. The probability

value for every match depends on the frequency of its existing in the preliminarily synthesized networks. As a result, less effort is spent to acquire favorable network structures. It is important to note that in above MINLP model the hot and cold utility consumptions during period of network operation are obtained by integral method, thus the proposed formulation is more rigorous in this work than in previous papers.

2.2.3 Optimization algorithm

Genetic algorithm (GA) and simulated annealing algorithm (SA) are in principle random methods generally used to solve large scale combinatorial optimization problems. Both of them can handle discontinuous, nondifferential and nonconvex functions. GA has a good performance to find the global optimal solution, and SA is used to prevent the tendency of premature convergence and escape from local optimum solution. For the purpose of improving the computational accuracy and the convergence speed of GA/SA, float coding instead of the traditional binary coding is used. Effective crowding (EC) is introduced to prevent 'genetic floating'. The orthogonal crossover (OCX) operator is adopted in GA in addition to the continuous crossover operator [12].

2.2.4 General procedure for simultaneous optimization

The main procedure of simultaneous optimization as seen in Fig. 2 (b) is summarized as follows.

Step 1 Collect desired input data. The initial value of heat exchanger area A_n for every match candidate is obtained according to the result of preliminary synthesis stage. And the initial value of operating period $\Delta t_{\text{op},n}$ for every match candidate is obtained in terms of fouling process. On this basis the uncertain regions of optimization variables including A_n and $\Delta t_{\text{op},n}$ are defined.

Step 2 Subdivide the given time horizon into sub-time intervals as mentioned previously by continuous time representation according to $\Delta t_{\text{op},n}$.

Step 3 Perform dynamic simulation of flexible HEN to acquire the outlet temperatures of process streams to further obtain the utility cost, cleaning cost

and TAC.

Step 4 Go to Step 1, and repeat the procedure if the initial feasible population size is not satisfied.

Step 5 Obtain the final result of simultaneous optimization by GA/SA.

3 NUMERICAL EXAMPLE

A large-scale 10-hot/10-cold streams problem adapted from literature [9] is used to demonstrate the efficiency of the proposed strategy. The multi-period data are listed in Table 1. The annual hot and cold utility costs per unit are 70 and 10 \$·kW⁻¹, respectively. For all exchangers, the uniform cost equation is $\text{cost} = 8000 + 800A^{0.8}$ (\$) annually. The cleaning cost is expressed by $\text{cost} = 30A^{0.7}$ (\$). In addition, the duration of each cleaning intervention is equal to the time interval of 1 day, and the whole time duration of network operation in this study is a span of 3 years.

Depending on fouling process, the hot stream 6 is chosen for division of phases. Thus, the time points including the 67th, 275th, 508th and 840th days are used to perform the preliminary flexible HEN synthesis based on pseudo-temperature enthalpy diagram approach. The match candidates that will be further optimized at simultaneous optimization stage are obtained as shown in Fig. 5. The index of heat exchanger

is signed and the figure in bracket is the probability value of match candidate presented in the preliminary network.

The results at simultaneous optimization stage are listed in Table 2.

The optimum structure of flexible HEN is shown in Fig. 6. There are approximately half as many exchangers obtained at simultaneous optimization stage as exchangers obtained at the preliminary synthesis stage, and the final acceptance rates for those match candidates given 25%, 50%, 75% and 100% probabilities of existing in optimum structure are 5/28, 8/23, 10/15 and 7/8, respectively. It shows that the approach of predetermined acceptance probability is capable of rapidly searching out favorable network structures. The annual cost in simultaneous optimization stage is 1728515.69 \$, being 4.25% less than the corresponding result obtained by the approach of the literature [6]. It is interesting to note that there is a utility exchanger at the end of each process stream. Thus, the network can tolerate greater disturbances of uncertain parameters and the flexibility is further improved.

In addition, with the aid of this example a comparison between discrete time representation and presented continuous time representation is made as follows.

(1) The number of decision variables is 1080 and 74 for discrete time representation and continuous time representation, respectively.

Table 1 Multi-period stream data

Stream	T_{in}/K	T_{out}/K	$FC_p/kW \cdot K^{-1}$	$h/kW \cdot m^{-2} \cdot K^{-1}$	$r_t^{\infty}/m^2 \cdot kW^{-1} \cdot K$	τ/d
cold stream 0	313.15	503.15	20	1.5	0.19	330
cold stream 1	393.15	533.15	35	2.0	0.33	480
cold stream 2	313.15	463.15	35	1.5	0.09	210
cold stream 3	[313.15, 333.15]	463.15	30	2.0	0.47	570
cold stream 4	323.15	523.15	20	2.0	0.44	630
cold stream 5	313.15	423.15	10	0.06	0.37	360
cold stream 6	313.15	423.15	20	0.4	0.16	180
cold stream 7	393.15	483.15	35	1.5	0.17	180
cold stream 8	313.15	403.15	35	1.0	0.26	300
cold stream 9	333.15	393.15	15	0.7	0.40	450
cold utility	298.15	313.15	–	2.0	0.22	600
hot stream 0	453.15	348.15	30	2.0	0.41	650
hot stream 1	553.15	393.15	15	0.6	0.25	410
hot stream 2	453.15	348.15	30	0.3	0.13	200
hot stream 3	413.15	318.15	30	2.0	0.32	740
hot stream 4	493.15	393.15	25	0.08	0.26	550
hot stream 5	453.15	328.15	10	0.02	0.18	150
hot stream 6	443.15	318.15	[25, 35]	2.0	0.45	600
hot stream 7	453.15	323.15	30	1.5	0.36	440
hot stream 8	553.15	363.15	15	1.0	0.50	510
hot stream 9	453.15	333.15	30	2.0	0.22	800
hot utility	598.15	598.15	–	1.0	0.10	600

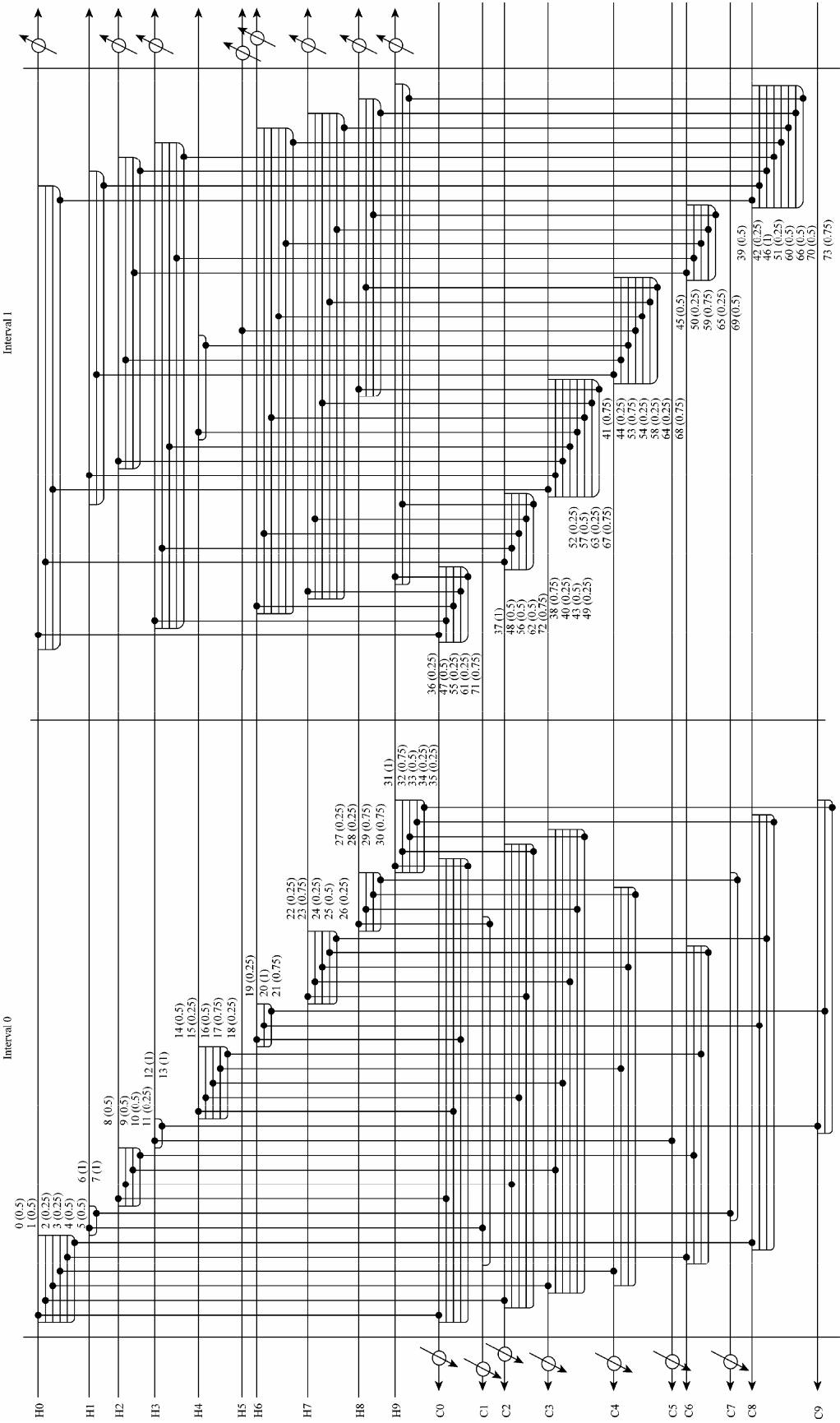


Figure 5 HEN structure obtained at preliminary synthesis stage

Table 2 Results of simultaneous optimization stage

Interval 0			Interval 1		
Exchanger index	Area/m ²	Operating period/day	Exchanger index	Area/m ²	Operating period/day
0	99.41	269	17	7.07	545
1	95.48	243	18	13.20	339
2	24.79	575	19	53.69	443
3	193.11	395	20	4.17	207
4	41.56	565	21	16.18	407
5	54.61	503	22	25.93	334
6	51.84	556	23	21.40	402
7	113.04	492	24	21.47	256
8	343.22	509	25	1.24	256
9	69.10	482	26	5.42	511
10	20.92	566	27	6.85	421
11	86.24	527	28	12.39	597
12	29.65	324	29	6.30	275
13	26.99	202			
14	33.22	535			
15	79.85	231			
16	27.55	313			

(2) Similarly, the number of sub-time intervals is 1080 and 138, respectively.

(3) A feasible solution can be obtained in 1683 and 152 CPU seconds on a Pentium PC for discrete time representation and continuous time representation, respectively.

It proves that the presented continuous time representation has more advantageous in reducing com-

putational complexity than discrete time representation due to less decision variables and sub-time intervals.

The optimum cleaning schedule of HEN is shown in Fig. 7.

It is observed from Fig. 7 that there are not cleaning interventions during the first six months because heat exchangers are in clean state. But few cleaning actions are carried out in the last month. This shows that although 'end effects' [8] are weakened, yet they are still in existence.

4 CONCLUSIONS

A novel approach is presented in this paper to optimize flexible HEN synthesis and cleaning schedule simultaneously by GA/SA. Through taking into account scheduling of cleaning at the initial design stage, the heat exchanger areas and utility consumptions can be decreased significantly. In order to reduce computational complexity some effective strategies are introduced as follows: (a) Pseudo *T-H* diagram approach is used to simplify the multiperiod synthesis of HEN; (b) By preliminary network synthesis, the most promising matches can be identified prior to simultaneous optimization. In addition, by means of predetermining acceptance probabilities of match candidates, the favorable network topology can be rapidly developed; (c) A novel continuous time representation is offered to subdivide the given time horizon into less sub-time intervals. Some limitations of discrete time representation such as overlong discrete-time interval, too many unnecessary sub-time intervals and non-strict mathematical model may be overcome in some extent. In the last section the result of numerical example shows that the TAC has a 4.25% drop, and thus the simultaneous consideration of flexible HEN synthesis

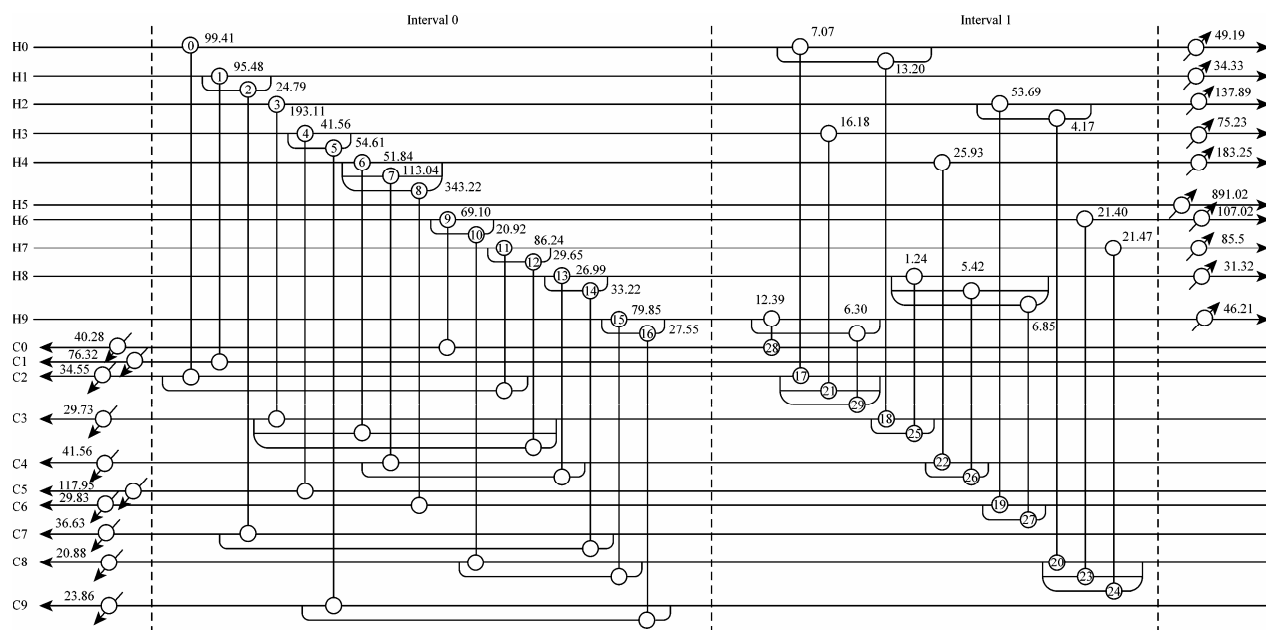


Figure 6 Optimal structure of flexible HEN obtained at simultaneous optimization stage

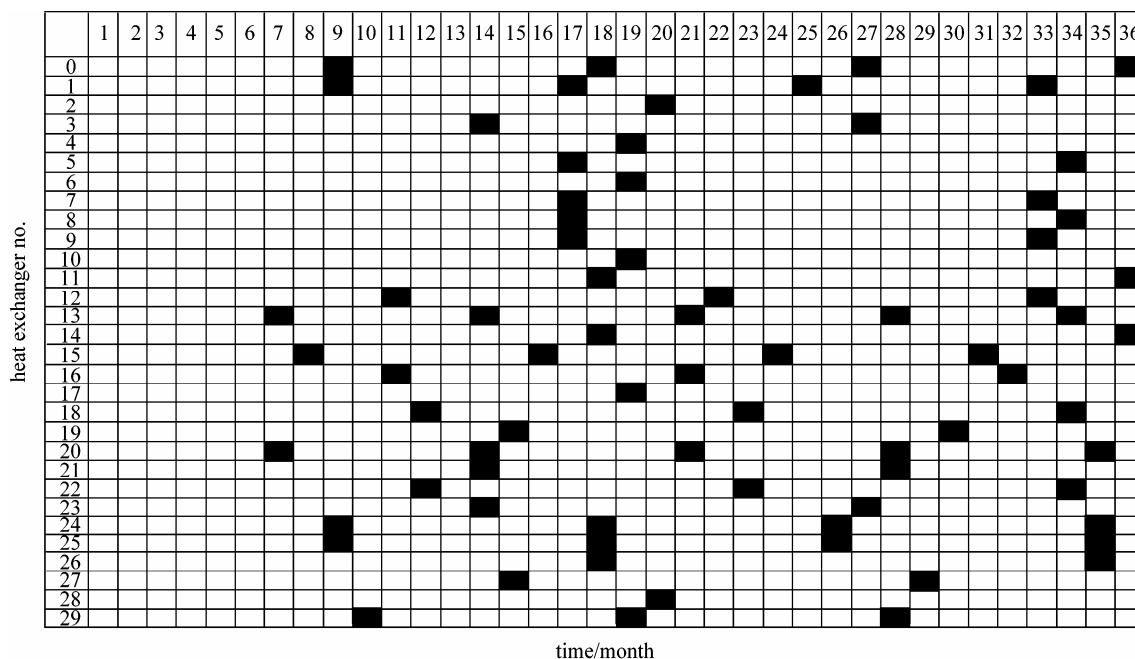


Figure 7 Optimal cleaning schedule of flexible HEN

■ indicate that cleaning intervention having regular period of 1 day is carried out in specified month

and cleaning schedule is advantageous to reduce TAC and improve network flexibility at the same time. In particular, the method is also effective for the large-scale flexible HEN synthesis problems.

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NOMENCLATURE

A	heat transfer area, m^2
B	exponential factor of area cost
B^{cl}	exponential factor of cleaning cost
C	pre-exponential factor of area cost
C_f	annual fixed cost of exchanger, \$
C_f^{cl}	annual fixed cost of cleaning intervention, \$
C_u	per unit cost for utility, $\text{\$/kW}^{-1}$
C^{cl}	pre-exponential factor of cleaning cost
F_{C_p}	stream heat capacity flowrate, $\text{kW}\cdot\text{K}^{-1}$
h	stream heat transfer film coefficient, $\text{kW}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$
M	match matrix
M_S	device status matrix
M_T	state transition matrix
N^{cl}	number of cleaning interventions for an exchanger during the time horizon
NC	cold streams
NH	hot streams
NK	enthalpy intervals
NOP	fraction of duration of operation for each operating condition

NP	operating conditions
NS	sub-time intervals
NT	time points
NUC	cold utility
NUH	hot utility
$q(t)$	utility duty at time t , kW
r_f^∞	asymptotic fouling resistance, $\text{m}^2\cdot\text{kW}^{-1}\cdot\text{K}$
T	temperature, K
$t_{\min}$	the shortest time interval of fouling formation among process streams, day
t_{oper}	the whole duration of network operation, year
y	binary variable representing device status within each sub-time interval
Δt_{cl}	regular cleaning period of heat exchanger, day
Δt_{op}	regular operating period of heat exchanger, day

Subscripts

cu	cold utility
hu	hot utility
i	index of hot stream
in	inlet
j	index of cold stream
k	index of enthalpy interval
n	index of heat exchanger
out	outlet
p	index of operating condition
s	index of sub-time interval
τ	decay time of fouling formation, day
ϕ	binary variable representing existence/absence of 'small heat exchanger'
ω	binary variable representing existence/absence of match

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