

Strategy for Synthesis of Flexible Heat Exchanger Networks Embedded with System Reliability Analysis

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Abstract System reliability can produce a strong influence on the performance of the heat exchanger network (HEN). In this paper, an optimization method with system reliability analysis for flexible HEN by genetic/simulated annealing algorithms (GA/SA) is presented. Initial flexible arrangements of HEN is received by pseudo-temperature enthalpy diagram. For determining system reliability of HEN, the connections of heat exchangers (HEXs) and independent subsystems in the HEN are analyzed by the connection sequence matrix (CSM), and the system reliability is measured by the independent subsystem including maximum number of HEXs in the HEN. As for the HEN that did not meet system reliability, HEN decoupling is applied and the independent subsystems in the HEN are changed by removing decoupling HEX, and thus the system reliability is elevated. After that, heat duty redistribution based on the relevant elements of the heat load loops and HEX areas are optimized in GA/SA. Then, the favorable network configuration, which matches both the most economical cost and system reliability criterion, is located. Moreover, particular features belonging to suitable decoupling HEX are extracted from calculations. Corresponding numerical example is presented to verify that the proposed strategy is effective to formulate optimal flexible HEN with system reliability measurement.

Keywords flexible heat exchanger network synthesis, system reliability, network decoupling, independent subsystem

1 INTRODUCTION

The heat exchanger network (HEN) synthesis is one of the most focused topics which closely relate to the cost-efficiency of process engineering although the challenging computational complexity is to formulate optimal HEN structure. Considerable researches have been conducted towards HEN synthesis and provide many insights on the efficient networks synthesis. Among them, Swaney and Grossmann [1] put forward flexibility index, Kotjabasakis and Linnhoff [2] applied sensitivity tables, Grossmann and Floudas [3] proposed active set strategy, Aaltola [4] adopted a multi-period mixed integer nonlinear programming (MINLP) model to gain flexibility and minimum costs. HEN flexibility refers to the adjusting capability of HEN for satisfying heat exchange duty, when operation shifts from one condition to another, Verheyen and Zhang [5] used maximum area per period to exclude weighted parameters and slack variables for Aaltola's model, Chen and Hung [6] developed three main iterative steps to simplify the complex problem. And Ma [7] put forward a sequential strategy with two-step to synthesize flexible multi-stream HEN.

System reliability means the probability of the system functioning normally. System reliability has been considered as one of important design measures in all industries [8, 9]. Related researches have been performed for system reliability aspect [10, 11]. A problem formulation and solution in considering the subsystems within a system for system reliability has been proposed. Genetic algorithm (GA) is adopted to search for the system with higher system reliability [8]. No matter how delicately the HEN is designed, if the

designed HEN does not have sufficient system reliability, it may be infeasible in practical operation. Thus the system reliability analysis can be featured as necessary content in HEN design.

2 HEN SYNTHESIS WITH OPERATIONAL FLEXIBILITY

Pseudo- T - H diagram approach can reasonably rearrange energy under different temperature and realize equal energy loss [12]. By optimizing the contribution of the stream heat transfer temperature difference, the reduction of total annual cost can be realized. Therefore, the approach is introduced for initial stage of design flexible HEN.

The synthesis approach proceeds as following contents:

(1) Necessary items referring to mass flow-rates, thermal capacity, start and target temperatures of corresponding stream are loaded.

(2) The value of heat transfer temperature difference contribution of each involved stream is calculated, and thus the stream pseudo temperatures can be known. Then the hot and cold composite curves are constructed through the stream pseudo temperatures.

(3) The composite curves are labeled by enthalpy intervals, then narrow enthalpy intervals are incorporated by the tolerance of minimum enthalpy interval so that corresponding enthalpy intervals are formed for the composite curves.

(4) Vertex points that can reflect the variety of the uncertain parameter sets are received on the vertices of the polyhedral scope for uncertain parameters. The HEN arrangements for total vertex operating points

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are calculated together, indicating that all possible matches in the HEN for the total vertex operating point are entirely accommodated in the initial HEN content.

(5) Incorporating HEN structure of each operation point totally is directed by indicating vector which refers to match determination with cold and hot streams. All vectors are presented in matrix formation.

(6) For the sake of ensuring that the designed HEN is feasible enough for every vertex operation point, the maximum heat exchanger (HEX) area are filtered for the same match. Furthermore the corresponding maximum area of heater/cooler and the maximum utilities are recognized, and thus the structure arrangement of desirable HEN can be figured out.

3 DETERMINATION OF HEN SYSTEM RELIABILITY

3.1 Description of the problem for HEN system reliability

HEN contains intense stream and energy connection. As for the HEXs related by stream and energy connections, if the failure of one or more HEXs occurs, the inlet/outlet temperature of other HEXs may change due to the failure. Furthermore the heat exchange duty of reaching target temperature for process streams, which is specified by design expectation, may not be fulfilled. Therefore, it is necessary to know coupling relationship within the HEN and to determine the connections between HEXs and process streams, so as to locate the bottleneck that limits the system reliability of HEN.

3.2 Method that responds to the problem

As for HEN, the paths in which process streams pass through the HEXs are searched, and the connection sequence matrix (CSM) is introduced to express the connections of HEN, and to measure the HEN system reliability. Example is presented in Fig.1.

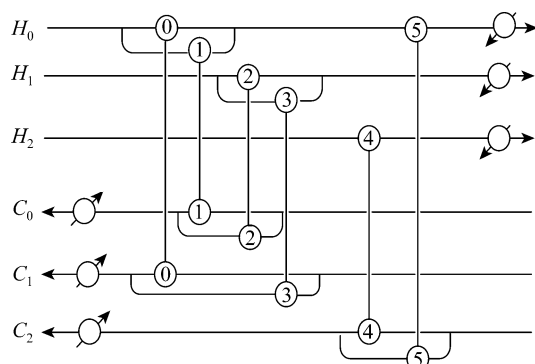


Figure 1 A network structure

The HEXs in the HEN are indicated by the rows of CSM, the process streams are denoted by the

columns of CSM, and the elements in CSM are recorded as a_{ij} , the values of a_{ij} are taken as shown in Table1.

Table 1 The values of the elements in CSM

Value	Meaning
1	the HEX i matched with process stream j
0	otherwise

Then the CSM of HEN in Fig. 1 is obtained as shown in Table 2.

Table 2 The CSM of HEN in Fig. 1

	H_0	H_1	H_2	C_0	C_1	C_2
E_0	1	0	0	0	1	0
E_1	1	0	0	1	0	0
E_2	0	1	0	1	0	0
E_3	0	1	0	0	1	0
E_4	0	0	1	0	0	1
E_5	1	0	0	0	0	1

The CSM of HEN in Fig. 1 is analyzed to find the independent subsystem. Identification process is shown in Fig. 2.

The search begins with the HEX, whose index is 0. HEX E_0 is matched with H_0 in hot stream aspect. In column H_0 , E_0 , E_1 and E_5 are observed to match with H_0 (corresponding value of these HEXs in column H_0 is 1) and thus, E_0 , E_1 and E_5 are dependent each other *via* stream H_0 . Similarly in cold stream aspect, E_0 is matched with C_1 . In column C_1 , E_0 , E_3 are observed to match with C_1 , and E_0 , and E_3 are dependent each other. E_3 and E_1 and E_5 are dependent each other *via* E_0 . E_0 , E_3 and E_1 , and E_5 constitute a subsystem. The members in this subsystem are dependent each other due to their stream connections.

Further search is located in column C_0 . Both E_1 and E_2 are connected with stream C_0 , that is reflected by the C_0 column. Therefore, E_1 and E_2 are also dependent each other. E_2 is added in this subsystem.

Next search is switched to column C_2 with the same method. E_4 is also dependent with E_5 , and dependent relationship is transferred from the subsystem to E_4 . It is found that all 6 HEX members in the HEN are dependent each other, thus, the search can be finished. It is indicated that the HEN in Fig. 1 includes 1 independent subsystem collected all 6 dependent HEXs.

3.3 Determination of HEN system reliability

So far the independent subsystem of the HEN has been determined. The system reliability is affected by the reliability of component forming the system and the connection pattern among components. In order to

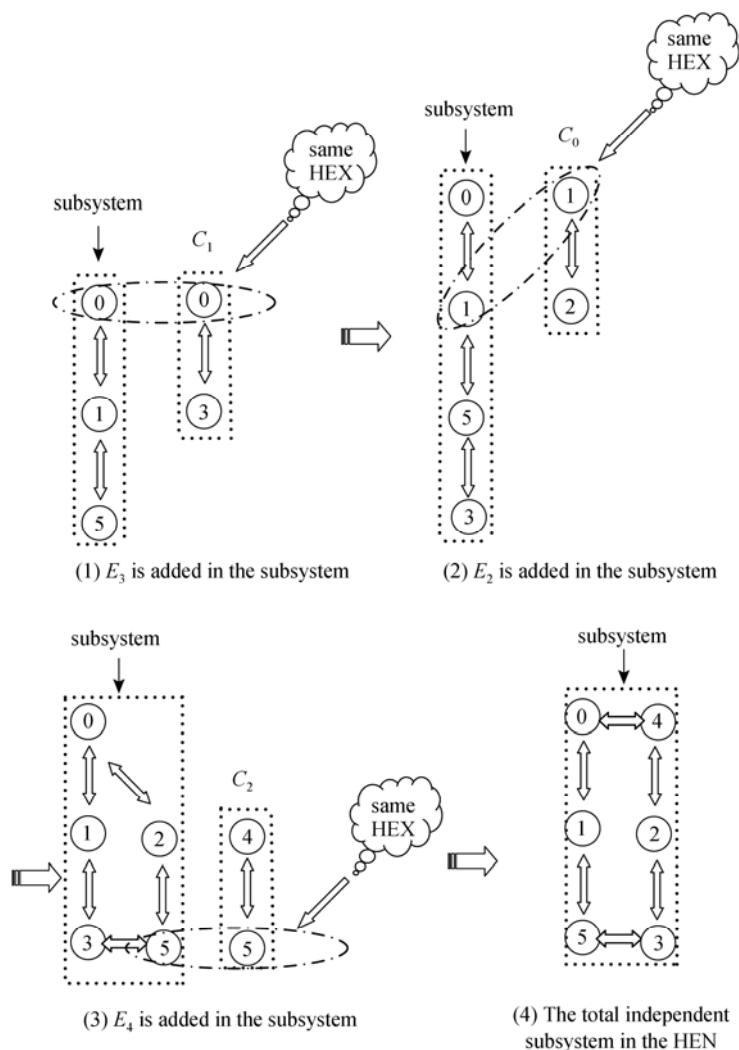


Figure 2 Identification of the independent subsystem for Fig. 1

simplify calculation, the reliability of HEX in the HEN is taken uniformly as 0.98. The independent subsystem, which includes maximum number of HEXs in the HEN, is notable and recorded as important subsystem (ISYS). Only if each HEX in the subsystem is functioned reliably, the reliability of the subsystem can be ensured. Thus the subsystem reliability is decided by the multiplication product of reliability for the components in ISYS. Because the number of HEX in this subsystem is more than other independent subsystem members, the multiplication product for reliability of ISYS is smaller than other independent subsystems. ISYS is the frailest part of the whole system. Therefore the system reliability of the whole HEN is controlled by the ISYS.

Through Section 3.2, the connection pattern is recognized. ISYS contains all 6 dependent HEXs in the HEN and the system reliability for the HEN is known as the reliability multiplication of the 6 dependent HEXs which compose the ISYS in the HEN. The system reliability of the HEN in Fig. 1 is calculated as:

$$0.98^6 = 0.8858.$$

4 NETWORK DECOUPLING FOR IMPROVING HEN SYSTEM RELIABILITY

4.1 Introduction of HEN decoupling

High system reliability is desirable. If the system reliability of the HEN is required not to be less than 0.9, it in Fig. 1 needs to be improved. Measure for increasing the system reliability is shift to adjust connection pattern among the HEXs, that means to reshape HEN structure.

As for the HEN indicated by Fig. 1, all 6 HEXs are dependent. Coupling among the HEXs retards the system reliability. Therefore, decoupling method needs to be applied for promoting the system reliability. Certain HEX is selected to be excluded from the HEN for network decoupling consideration so that HEN is favorable to enhance system reliability after

decoupling process. Decoupling effects of each HEX for HEN in Fig. 1 are different. For example E_0 is used as decoupling HEX. After that, E_1 , E_2 , E_3 , E_4 , and E_5 (for convenience of comparison, the following all HEX indexes after decoupling are still used as those before decoupling) are dependent. CSM for the HEN after decoupling reflects that the new HEN includes only 1 independent subsystem and the subsystem gathers all 5 HEXs (E_1 – E_5). Similarly decoupling effects of other 5 HEXs in Fig. 1 are known. It is perceived that decoupling effects of E_5 is better than other 5 HEXs. For complicated HEN containing large number of HEXs, if decoupling HEX is not properly adopted, the decoupling effect is limited. Then, the system reliability cannot be satisfied, and thus a question what are the features of suitable decoupling HEX appears.

4.2 Prolongation for CSM of HEN and the preliminary determination of suitable decoupling HEX

In order to find the features of suitable decoupling HEX, CSMs of HEN are extended to new row and column. First, the CSM of HEN noted as bottom row is added a row at the bottom of CSM. The element of bottom row stores summation of element values in corresponding column within CSM. For example, b_{Mj} is one of the bottom row element, M is the index of bottom row and j is the index of certain column, then, the value of b_{Mj} is determined by Eq. (1).

$$b_{Mj} = \sum_{i=0}^{M-1} a_{ij} \quad (1)$$

The value of b_{Mj} records the HEX number that process stream j passes through.

Then a column noted as initial column is expressed at the left of CSM. As explained in Section 3.2, the row of CSM indicates the HEX in the HEN. For E_0 in the CSM of HEN in Fig. 1, E_0 connects both process stream H_0 and C_1 . The bottom row element of column H_0 is 3 and of column C_1 is 2. The element value of initial column for row E_0 is the summation of the bottom row element of column H_0 and C_1 , and then 5 is obtained for initial column value of row E_0 . According to the method, the value of initial column for each row can be known and the data of initial column implies the number of dependent HEXs due to hot/cold process stream connection. After these procedures, the CSM for Fig. 1 is renewed as shown in Table 3.

Larger element value of initial column implies that corresponding HEX holds more intense links with other HEXs. Applying this type of HEX as decoupling HEX may effectively cut down couplings in HEN, and thus can directly improve system reliability. For the CSM of Fig. 1, the initial column value (ICV) can be regarded as a referential criterion for suitable decoupling HEX. Due to the connection complexity of HEN, E_0 , E_1 , and E_5 are all with the same ICV(5), which is

Table 3 CSM of HEN in Fig. 1 with increasing elements

ICV		H_0	H_1	H_2	C_0	C_1	C_2
5	E_0	1	0	0	0	1	0
5	E_1	1	0	0	1	0	0
4	E_2	0	1	0	1	0	0
4	E_3	0	1	0	0	1	0
3	E_4	0	0	1	0	0	1
5	E_5	1	0	0	0	0	1
	b_{Mj}	3	2	1	2	2	2

the maximum in the CSM. Therefore, further measures are needed to examine which is the most suitable decoupling HEX.

4.3 Formation of the CSM after network decoupling

In order to know the implications of suitable decoupling HEX, the CSM after performing decoupling process needs to be expressed. The CSM before decouple can serve as useful information. For the CSM, according to the meanings of ICV in the CSM, the ICV for some HEX is unchanged as that before decoupling. It is the HEX without connection with the hot/cold stream that matches the decoupling HEX because decoupling does not affect the bottom row value for that type of HEX. For example, selecting E_0 as decoupling HEX, E_0 connects with stream H_0 and C_1 . From the CSM in Fig. 1, it can be observed that stream H_0 passes through E_0 , E_1 and E_5 , stream C_1 passes through E_0 and E_3 . Thus, after decoupling, the number of dependent HEXs for E_1 , E_3 and E_5 , reduces one. The ICVs of E_1 , E_3 , and E_5 change from 5, 4, 5 to 4, 3, 4, respectively. E_2 , and E_4 do not have direct stream link with E_0 , and thus the ICV of E_2 , and E_4 is unchanged. Table 4 presents the CSMs with different decoupling HEX respectively.

4.4 Comparison of values for parameter

$$\sum_{k=0(k \neq m)}^{M-1} (E_m)_{H_i, C_j}$$

As for the HEXs which all own the maximal ICV in the CSM for the HEN, parameter $\sum_{k=0(k \neq m)}^{M-1} (E_m)_{H_i, C_j}$

is introduced to determine the feature of suitable decoupling HEX. For $\sum_{k=0(k \neq m)}^{M-1} (E_m)_{H_i, C_j}$, k means the

index of row for CSM, M is the index of bottom row, E_m refers to decoupling HEX option of taking E_m , and H_i , and C_j mean the hot/cold stream that matches with

Table 4 The CSM of HEN in Fig. 1 after decoupling with E_0 , E_1 , E_5

ICV	HEX	H_0	H_1	H_2	C_0	C_1	C_2
(4){4}[4]	$(E_1)\{E_0\}[E_0]$	(1){1}[1]	(0){0}[0]	(0){0}[0]	(1){0}[0]	(0){1}[1]	(0){0}[0]
(4){3}[4]	$(E_2)\{E_2\}[E_1]$	(0){0}[1]	(1){1}[0]	(0){0}[0]	(1){1}[1]	(0){0}[0]	(0){0}[0]
(3){4}[4]	$(E_3)\{E_3\}[E_2]$	(0){0}[0]	(1){1}[1]	(0){0}[0]	(0){0}[1]	(1){1}[0]	(0){0}[0]
(3){3}[4]	$(E_4)\{E_4\}[E_3]$	(0){0}[0]	(0){0}[1]	(1){1}[0]	(0){0}[0]	(0){0}[1]	(1){1}[0]
(4){4}[2]	$(E_5)\{E_5\}[E_4]$	(1){1}[0]	(0){0}[0]	(0){0}[1]	(0){0}[0]	(0){0}[0]	(1){1}[1]
	b_{Mj}	(2){2}[2]	(2){2}[2]	(1){1}[1]	(2){1}[2]	(1){2}[2]	(2){2}[1]

Note: elements wrapped with () indicate the CSM elements after decoupling with E_0 , elements wrapped with { } refer to the CSM elements after decoupling with E_1 , elements wrapped with [] indicate the CSM elements after decoupling with E_5 .

$E_m \cdot \sum_{k=0(k \neq m)}^{M-1} (E_m)_{H_i, C_j}$ is obtained by the sequential

summation of ICV for elements, whose value is 1 in columns H_i and C_j (summation does not include the ICV of E_m).

For example, E_0 is responsible for the heat duty between H_0 and C_1 . Taking E_0 as an initial column, H_0 and C_1 columns of Table 3 can be collected.

		H_0	C_1
5	E_0	①	①
●5	E_1	①	0
4	E_2	0	0
4●	E_3	0	①
3	E_4	0	0
●5	E_5	①	0

For E_0 , $\sum_{k=0(k \neq m)}^{M-1} (E_0)_{H_0, C_1} = 5 + 5 + 4 = 14$

Similarly other results can be received. They are

$$\sum_{k=0(k \neq m)}^{M-1} (E_1)_{H_0, C_0} = 5 + 5 + 4 = 14$$

and

$$\sum_{k=0(k \neq m)}^{M-1} (E_5)_{H_0, C_2} = 5 + 5 + 3 = 13.$$

It is manifested that $\sum_{k=0(k \neq m)}^{M-1} (E_5)_{H_0, C_2}$ is the small-

est among the three $\sum_{k=0(k \neq m)}^{M-1} (E_m)_{H_i, C_j}$ values. The value

of parameter $\sum_{k=0(k \neq m)}^{M-1} (E_m)_{H_i, C_j}$ implies the number of subordinate HEXs that relate with E_m . After applying

the HEX with smaller value of $\sum_{k=0(k \neq m)}^{M-1} (E_m)_{H_i, C_j}$ as

decoupling HEX, the number of HEXs, that process stream related with the decoupling HEX passes through, is less than other decoupling options. It is more easily available for newly formed independent subsystems. This feature and other features will be further examined in case study in Section 7.

4.5 Comparison of values for parameter $E_m^{\text{ICV}_{\max}}$ and $E_m^{\text{ICV}_{\min}}$

Based on the CSM, the next feature that distinguishes the most suitable decoupling HEX from other HEXs can also be found in this stage. Parameter $E_m^{\text{ICV}_{\max}}$ is applied to analyze the feature of suitable decoupling HEX. In the parameter, E_m also refers to decoupling HEX option, the maximum of ICV is written as $\text{ICV}_{\max}$, the type of HEX whose ICV is $\text{ICV}_{\max}$ is selected, and the number of this type of HEX is noted as $E_m^{\text{ICV}_{\max}}$.

$E_m^{\text{ICV}_{\max}}$, together with $E_m^{\text{ICV}_{\min}}$, imply distribution of the independent subsystems in HEN. It is shown that $E_5^{\text{ICV}_{\min}}$ is the largest among the three $E_m^{\text{ICV}_{\max}}$ values. Detailed information is presented in Table 5.

Another feature that makes difference between the most suitable decoupling HEX and other HEXs can also be collected from the CSM at the same time. Parameter $E_m^{\text{ICV}_{\min}}$ is used to extract the feature of suitable decoupling HEX. E_m still expresses decoupling HEX option. Minimum of initial column is recorded as $\text{ICV}_{\min}$. The number of HEX whose ICV is $\text{ICV}_{\min}$ is indicated as $E_m^{\text{ICV}_{\min}}$. Detailed information are shown in Table 5.

From Table 5, it can be found $\text{ICV}_{\min}$ is held by E_4 after decoupling with E_5 . Moreover E_4 after decoupling with E_5 is the only HEX in new independent

Table 5 Detailed information for determination of $E_m^{ICV_{max}}$ and $E_m^{ICV_{min}}$

ICV _{max} or ICV _{min}	HEXs whose ICV is ICV _{max} or ICV _{min} after decoupling with E_0	HEXs whose ICV is ICV _{max} or ICV _{min} after decoupling with E_1	HEXs whose ICV is ICV _{max} or ICV _{min} after decoupling with E_5
4	E_1, E_2, E_5	E_0, E_3, E_5	E_0, E_1, E_2, E_3
2	none	none	E_4

Decoupling HEX→	E_0	E_1	E_5
$E_m^{ICV_{max}}$	3	3	4
$E_m^{ICV_{min}}$	0	0	1

subsystem decoupling from Fig. 1. The other two decoupling options do not make new independent subsystem, and no HEX catches ICV_{min} in Table 5. Correspondingly decoupling effect with E_0, E_1 is inferior than that with E_5 , and the value of $E_m^{ICV_{min}}$ after decoupling with E_0 and E_1 is smaller than the value of $E_m^{ICV_{min}}$ after decoupling with E_5 . After applying the HEX with larger value of $E_m^{ICV_{max}}$ and $E_m^{ICV_{min}}$ as decoupling HEX, the reduction of network couple and simplification of network are brought as the result of newly formed independent subsystems. The HEX in new subsystem, such as E_4 after decoupling with E_5 , contributes the larger value for $E_m^{ICV_{max}}$ and $E_m^{ICV_{min}}$.

4.6 Summary of general procedures of network decoupling and features for suitable decoupling HEX

General procedures of network decoupling are conducted as the following steps:

(1) Identifications of the independent subnetworks are processed and ISYS is found.

(2) Network decoupling is applied for ISYS. As for Step (2), it includes 3 substeps:

① Based on the CSM of HEN, the ICVs of ISYS are calculated.

② The HEX with larger ICV includes more links with other HEXs, and thus the HEXs with larger ICV are taken as decoupling HEX.

③ The desirable network decoupling scenarios as equipartition of ISYS is realized. ISYS is equally divided into two independent subsystems. The number of HEXs in both subsystems is equal or almost equal. If such scenarios occur with the decoupling HEX, then the HEX is the most suitable decoupling HEX.

(3) Network decoupling is run until the specified system reliability is reached.

From above presentation, typical features of suitable decoupling HEX can be extracted.

(1) The HEX with larger ICV implying this HEX contains more wide links with other HEX companions. Choosing this kind of HEX can effectively change the

subsystem distribution. The HEX embedded with larger ICV is preferable to realize the target of promoting system reliability.

Complexity of HEN makes the HEX with maximum ICV not to be unique, then the extension for CSM is applied as presented in Section 4.2. Three features are found as following Part 2–4.

(2) Parameter $\sum_{k=0(k \neq m)}^{M-1} (E_m)_{H_i, C_j}$ that implies the

number of subordinate HEX is calculated. For each decoupling HEX option, the HEX with less

$\sum_{k=0(k \neq m)}^{M-1} (E_m)_{H_i, C_j}$ value can play a better role in ele-

vating system reliability of network because the number of HEXs for the ISYS reduces more than other decoupling option after network decoupling with that type of HEX. Therefore system reliability of HEN is substantial increased.

(3) Parameter $E_m^{ICV_{max}}$ implies distribution of the independent subsystems in HEN. From Section 4.5, it can be seen that after applying the HEX with larger value of $E_m^{ICV_{max}}$ as decoupling HEX, the new independent subsystem contributes both the reduction of network couple and simplification of network. The HEX number in the ISYS decreases more than other decoupling options, and thus system reliability of HEN is more effectively elevated.

(4) On the other aspect, $E_m^{ICV_{min}}$ serves as the parameter to record distribution of the independent subsystems in HEN. The network decoupling effect of HEX tied with larger $E_m^{ICV_{min}}$ value is better than other decoupling option. Also from Section 4.5, it is shown that as the result of the reduction of network couple and simplification of network, the HEX in new independent subsystem holds ICV_{min}, however no HEX is bound with ICV_{min} for other decoupling options. Thus, the reason makes $E_m^{ICV_{min}}$ of suitable decoupling HEX larger than inferior decoupling options.

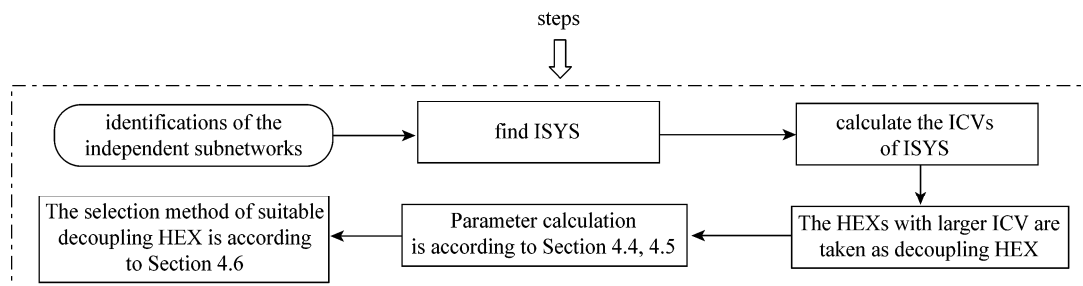


Figure 3 Selection of the suitable decoupling HEX

Selection of the suitable decoupling HEX is described in Fig. 3

5 THE SEQUENTIAL APPROACH AFTER NETWORK DECOUPLING

After network decoupling with the removal of decoupling HEX, the heat exchange relations is also changed correspondingly. The heat load loops within the HEN are searched. The previous methods for recognition and break of heat load loops are used [13]. As for the HEX that is in odd sequence in the heat load loop string, the heat duty of the HEX is taken from the subtraction between the original heat duty and the heat duty of the decoupling HEX. While for the HEX that is in even sequence in the heat load loop string, the heat duty of the HEX is inputted from the summation between the original heat duty and the heat duty of the decoupling HEX.

After adjustment of the heat duty of HEX in the HEN, the value of heat duty needs to be examined. If the HEX with negative heat duty is observed, the merging of HEX should be given up. Furthermore the heat transfer temperature difference also needs to be examined. If the heat transfer temperature difference of certain HEX exceeds the minimum tolerance of heat transfer temperature difference, the merging of HEX is also infeasible.

Due to the change of HEN structure for improving system reliability consideration, flexibility of HEN is required to be checked. The HEN structure that meets system reliability criterion needs to make the process hot/cold streams *via* the heat exchange provided by the HEN to reach specified temperature within the variation range of streams temperature. Otherwise, if the HEN structure is disqualified the heat exchange task to realize specified temperature for stream, the HEX areas are recalculated on the basis of HEN simulations until the heat exchange task is fulfilled. The objective of this arrangement is to guarantee that the HEN structure not only strengthens to the designed system reliability tolerance, but also satisfies flexibility specification.

Final HEN structure should own three contents:

(1) HEN structure is qualified with the specification of system reliability.

(2) HEN structure also meets flexibility requirement simultaneously. For all operating points within the variation range of streams temperature, the HEN can fulfill heat exchange task to reach target temperatures of streams.

(3) The total cost of HEN is the most thermoeconomical.

6 PROCESS SUMMARY OF HEN SYNTHESIS WITH FLEXIBILITY AND SYSTEM RELIABILITY

6.1 Mathematical expression of HEN synthesis

Objective function of HEN synthesis with flexibility and system reliability is targeted with cost, which contains trade off for exchanger budget and utility expenditure. The objective function mathematically modeled by MINLP strategy is shown in Eq. (2).

$$\begin{aligned}
 \min_{\text{total}}^{\text{annual}}(\text{cost}) = & \sum_i F_{ci}^{\text{UC}} + \sum_j F_{cj}^{\text{UH}} + \sum_k \sum_i \sum_j F_{cijk} + \\
 & \sum_p \text{NOP}_p \cdot \left(\sum_i F_{ci}^{\text{UC}} \cdot q_{i,p}^{\text{UC}} + \sum_j F_{cj}^{\text{UH}} \cdot q_{j,p}^{\text{UH}} \right) + \\
 & \sum_i C_{UCi} \cdot \max_p(A_{UCi}^{\alpha_{UCi}}) + \sum_j C_{UHj} \cdot \max_p(A_{UHj}^{\alpha_{UHj}}) + \\
 & \sum_k \sum_i \sum_j C_{ijk} \cdot \max_p(A_{ijk}^{\alpha_{ijk}})
 \end{aligned} \quad (2)$$

Constraint contents include operational flexibility and system reliability of HEN is not less than 0.9.

6.2 Algorithm of HEN synthesis

Both genetic algorithm (GA) and simulated annealing algorithm (SA) can deal with for the optimization of nonconvex, discontinuous, and nondifferential problem. GA functions remarkably determine global optimum arrangement. SA can avoid the scenarios of premature convergence and jump from local optimal value. Both algorithms are substantially belonged to mathematically random searching methods. Satisfactory results can be received by GA/SA as shown in the literatures [14–16]. In view of above contents, the combined

algorithm of GA and SA is applied in the HEN synthesis to facilitate the optimization process. In order to accelerate the convergence of HEN design, not only crossover and mutation operators, but also effective crowding (EC) and orthogonal crossover (OCX) operators are added in GA/SA.

6.3 Outline of sequential procedure for HEN synthesis with flexibility and system reliability

On the basis of the contents presented above, procedures for HEN synthesis with flexibility and

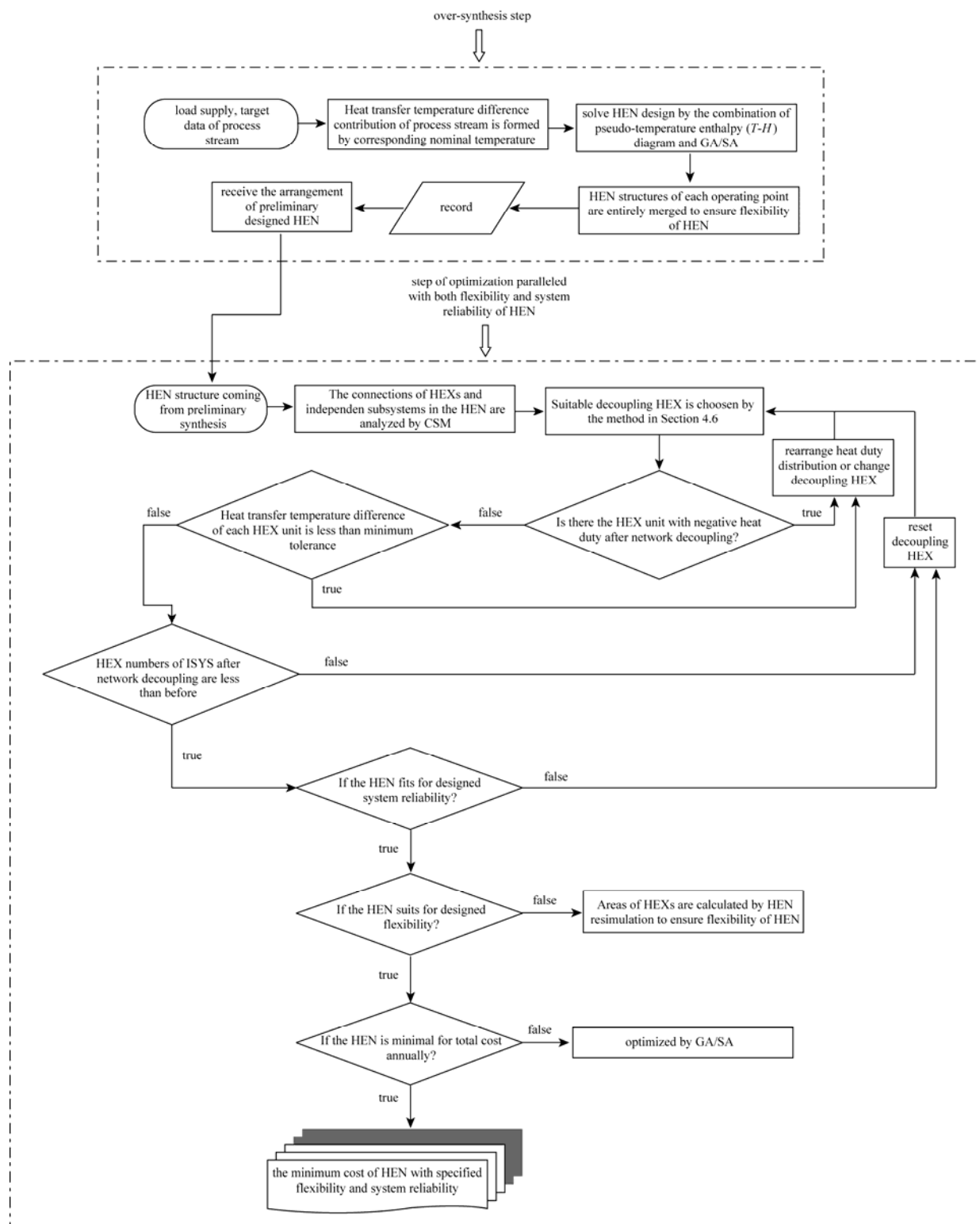


Figure 4 Outline of sequential procedure for HEN synthesis with flexibility and system reliability

system reliability are concentrated in Fig. 4.

7 CASE STUDY

HEN with 10 hot streams and 10 cold streams from literature [12] is designed to test effectiveness of the presented approach. Related basic data for calculation are provided by Table 6, the cost (in USD) for each exchanger is given annually as $8000 + 800 \times [\text{area (m}^2\text{)}]^{0.8}$. Respective annual expenditure of hot and cold utility is taken as 70 and 10 ($\text{USD} \cdot \text{kW}^{-1}$). Reliability of individual exchanger is set as 0.98. Measurement of system-based reliability tolerance is not less than 0.9.

Initial synthesis is presented in Fig. 5.

Then the CSM of HEN in Fig. 5 is obtained in Table 7:

Table 7 reflects the ISYS in Fig. 5 which includes 23 HEXs. The system reliability of the HEN in Fig. 5 is calculated as:

$$0.98^{23} = 0.6283$$

Comparisons with different type parameters for suitable decoupling HEX are presented in Table 8.

According to the selection method of suitable decoupling HEX, firstly E_{17} is used and then E_{11} is sent as decoupling HEX. After that E_{16} is arranged for decoupling HEX and finally E_4 is taken to be decoupling HEX. Enumeration shows that no desirable network decoupling effect can be produced except such decoupling arrangement. The selection method of suitable decoupling HEX directly locates few HEXs, excluding unnecessary decoupling try with other HEXs that has inferior decoupling effect, and thus computational burden can be reduced. After these 4 steps of network decoupling, the sequential approach in Section 5 is applied. The system reliability and TAC after each HEN decoupling are presented in Table 9. TAC before and after optimization with GA/SA are also included

Table 6 Stream data for HEN synthesis

Stream	T_{in}/K	T_{out}/K	$FC_p/\text{kW} \cdot \text{K}^{-1}$	$h/\text{kW} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$
H_1	453.15	348.15	30	2.0
H_2	553.15	393.15	15	0.6
H_3	453.15	348.15	30	0.3
H_4	413.15	318.15	30	2.0
H_5	493.15	393.15	25	0.08
H_6	453.15	328.15	10	0.02
H_7	443.15	318.15	30 ± 5	2.0
H_8	453.15	323.15	30	1.5
H_9	553.15	363.15	15	1.0
H_{10}	453.15	333.15	30	2.0
C_1	313.15	503.15	20	1.5
C_2	393.15	533.15	35	2.0
C_3	313.15	463.15	35	1.5
C_4	323.15 ± 10	463.15	30	2.0
C_5	323.15	523.15	20	2.0
C_6	313.15	423.15	10	0.06
C_7	313.15	423.15	20	0.4
C_8	393.15	483.15	35	1.5
C_9	313.15	403.15	35	1.0
C_{10}	333.15	393.15	15	0.7
hot utility	598.15	598.15	—	1.0
cold utility	298.15	313.15	—	2.0

in Table 9. The optimum network structure that accommodates flexibility and reliability is presented in Fig. 6.

Unlike some comparatively small HEN in which

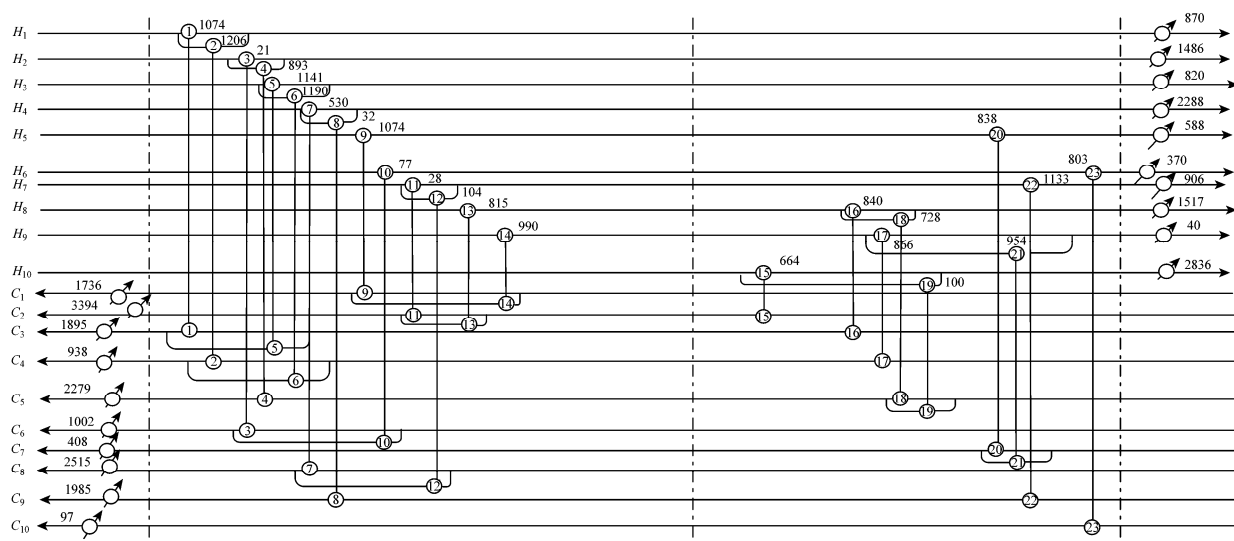


Figure 5 Network arrangement resulted from initial synthesis [system reliability of HEN is 0.6283, TAC (total annual cost) = 1832604 $\text{USD} \cdot \text{a}^{-1}$]

Table 7 CSM of HEN in Fig. 5

ICV		H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8	H_9	H_{10}	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
5	E_1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
5	E_2	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
4	E_3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
5	E_4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
5	E_5	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
5	E_6	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
4	E_7	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
4	E_8	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
4	E_9	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
4	E_{10}	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
◇	E_{11}	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
5	E_{12}	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0
◇	E_{13}	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
5	E_{14}	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
5	E_{15}	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
◇	E_{16}	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
◇	E_{17}	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
◇	E_{18}	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
5	E_{19}	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0
4	E_{20}	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
5	E_{21}	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
5	E_{22}	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
3	E_{23}	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		2	2	2	2	2	2	3	3	3	2	2	3	3	3	3	2	2	2	2	1

Note: elements wrapped with ◇ indicate maximum of ICV.

Table 8 Decoupling HEXs and their decoupling parameters

Decoupling HEX	E_{11}	E_{13}	E_{16}	E_{17}	E_{18}
$\sum_{k=0}^{M-1} (E_m)_{H,C_j}$	20	23	22	21	22
$E_m^{1CV_{max}}$	3	1	2	4	2
$E_m^{1CV_{min}}$	9	7	8	10	8

Table 9 System reliability and TAC after each HEN decoupling

Decoupling order	Decoupling HEX	System reliability	TAC/USD·a ⁻¹ (before optimization with GA/SA)	TAC/USD·a ⁻¹ (after optimization with GA/SA)
1	E_{17}	0.6951	2018955	1853953
2	E_{11}	0.7691	2040426	1873669
3	E_{16}	0.8507	2061898	1893387
4	E_4	0.9223	2081601	1911479

the number of independent subsystems can be remained unchanged, the HEN scale for case study is comparatively large and only by means of reduction for the HEX numbers in the ISYS the system reliability can

not be improved. In the studied case, new independent subsystems are formed. The comparisons of independent subsystems distributions before and after network decoupling are presented in Fig. 7.

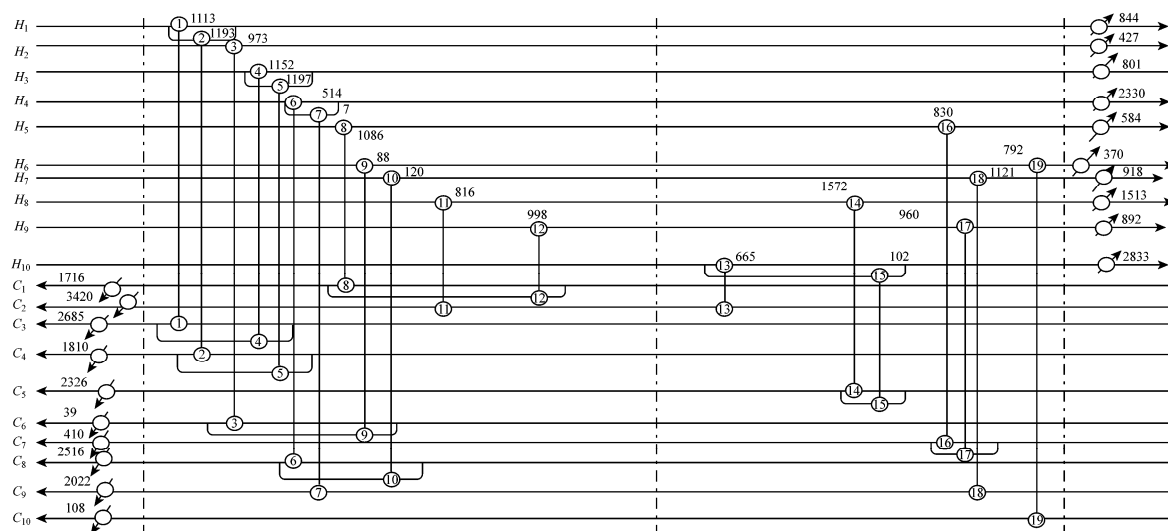


Figure 6 Optimal HEN structure with reliability and flexibility (system reliability of HEN is 0.9223, TAC = 1911479 USD·a⁻¹)

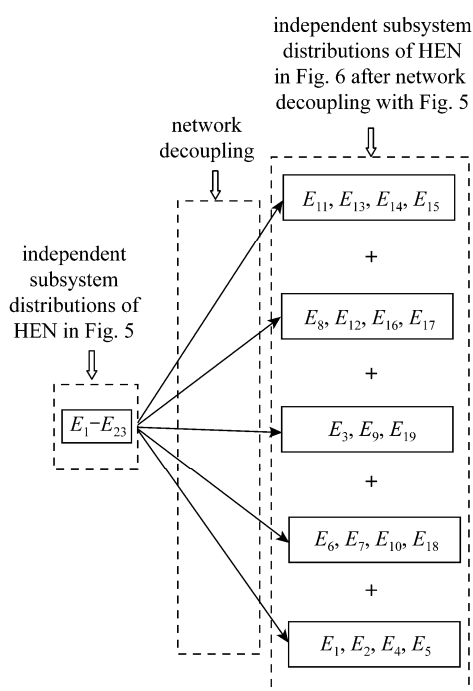


Figure 7 Comparison of independent subsystems distributions before and after network decoupling

8 CONCLUSIONS

A new method with consideration of both system reliability and flexibility is applied for HEN synthesis on GA/SA platform. Typical effective aspects in this process are reflected as: (1) On the basis of system analysis by CSM, distributions of independent subsystems are obtained and supplied as useful data for measurement of system reliability; (2) Network decoupling reduces dependent degrees among the HEXs, and therefore it is effective to promote the system reliability

of HEN; (3) Due to more HEX links, the HEXs embedded with ICV_{max} include suitable decoupling HEX. Further introduction of the helpful parameters, such as

$$\sum_{k=0}^{M-1} (E_m)_{H_i, C_j}, E_m^{ICV_{max}}, \text{ and } E_m^{ICV_{min}}, \text{ is beneficial}$$

to locate suitable decoupling HEX. The studied case checks the feasibility of the proposed method, and reminds that the method can serve as a competent tool for synthesis of heat exchanger networks with system reliability and flexibility. Furthermore, the method of determination for suitable decoupling HEX may provide reference for HEN control.

NOMENCLATURE

A	heat exchange area, m ²
b_{Mj}	the bottom row element for the CSM of HEN in Eq. (1), M is the index of bottom row, j is the index of certain column
$E_m^{ICV_{max}}$	parameter implying distribution of the independent subsystems in HEN (The value of $E_m^{ICV_{max}}$ is the number of HEXs whose ICV is ICV_{max})
$E_m^{ICV_{min}}$	parameter implying distribution of the independent subsystems in HEN (The value of $E_m^{ICV_{min}}$ is the number of HEXs whose ICV is ICV_{min})
F	cost for per unit of utility, USD·kW ⁻¹
F_c	annual fixed cost for exchanger, USD
F_{cp}	heat capacity flow rate of stream, kW·K ⁻¹
h	heat transfer coefficient of stream, kW·m ⁻² ·K ⁻¹
ICV_{max}	maximum of ICV
ICV_{min}	minimum of ICV
NOP	ratio of operating duration for each operation period
q	utility consumption, kW

Subscripts

i	index for hot stream
in	inlet of heat exchange unit
j	index of cold stream

k	index of enthalpy interval
out	outlet of heat exchange unit
p	index for operating condition
UC	cold utility
UH	hot utility
α	exponential item for area cost

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