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Flexible Synthesis of Inter-Plant Heat Exchanger Networks Considering the operation of Intermediate Circles

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Synthesis of Heat Exchanger Networks (HENs) is widely recognized as one of the most energy-saving techniques in the process industry. However, most existing HEN synthesis methods and intentions concentrate only on solving the problems of fixed process stream data, which means for a certain network, things would get worse or even infeasible when operating conditions such as stream input temperature and flowrate vary in practice. It is of great significance to ensure the designed HENs having adequate competence to tolerate the fluctuations in operating conditions, which is called flexibility. This paper presents a stepwise methodology to perform flexible inter-plant HENs synthesis, especially for the indirect heat integration involving intermediate fluid circles. The flexible synthesis step is based on the flexible analysis of an initial network. To improve the flexibility of the entire system, a new strategy is proposed, that is additional utility heat exchangers are introduced not only into each intra-plant HEN but also on intermediate fluid circles for the sake of utilizing the broad relevance of the circles. So in the work, the temperature, network structure, heat exchanger area and the location to place additional equipment are all optimized. An improved design that can tolerate fluctuations with lower total annual cost (TAC) can be found by using this methodology. Finally, a case study is presented to demonstrate the proposed method, and the results have confirmed the effectiveness and feasibility.

1. Introduction

Heat exchanger networks (HENs) have been widely used for energy recovery in the process industry. However, the flexibility problem was usually ignored in HENs design, making it lack of sufficient ability against process fluctuations. On the other hand, the synthesis of inter-plant HENs has received increasing attention in recent years because of its potential in total site energy saving. Inter-plant HENs will face more operability problem due to the strong interactions among plants, so there is of great significance to launch flexible synthesis towards inter-plant HENs, a challenge which has not been touched before.

Flexibility analysis is the foundation and essential process of flexible synthesis. Swaney and Grossmann (1985) first proposed a direct search method, directly searched all the vertices of the hyper-rectangle. Then two improved methods called the heuristic vertex search and the branch-and-bound procedure were introduced. Li et al. (2015) exploited a novel method for the flexibility analysis of non-convex HENs, the direction matrix was proposed to describe the deviation direction of the uncertain parameters. The directions were no longer limited to the vertices, so that this method can be well adapted to solve non-convex problems. As for the flexible synthesis problem, Pintaric and Kravanja (2008) presented a synthesis method based on the identification of critical points. Three algorithms were used in their work: Karush-Kuhn-Tucher formulation, the two-level method and the approximate one-level method. Li et al. (2014) proposed a stage-wise method which performed flexible HENs synthesis by two main steps, initial structure synthesis at nominal operating point and critical points, followed by heat transfer area optimization using an iterative approach. In addition to the uncertain operating conditions, Bai et al. (2017) have also taken into account the growth of fouling resistance in their study, aiming at reducing the redundancy of the resulted network.

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nter-plant heat integration is extended from single-plant heat integration but focusing more on heat exchange between plants, for which, the indirect heat integration mode involving intermediate fluid circles is considered more applicable. Three kinds of connection patterns for intermediate fluid, in series, shunt and parallel, are studied and discussed by Wang et al. (2014). Chang et al. (2017) proposed a superstructure to contain all possible interconnects between plants. The use of intermediate fluid can be simultaneously optimized with the determination of intra-plant HEN. Recently, Liu et al. (2020) have studied the potential of using multiple intermediates to perform the inter-plant heat exchange, the results indicate that cascade heat recovery could be reached be using the intermediates at different temperature intervals.

It is noted that the mentioned flexible synthesis methods are only available for single plant HEN problem, cannot be directly used to solve the inter-plant HENs problem. Intermediate fluid circles connect the plants into a whole, so the fluctuations may spread from one to others and makes the flexible synthesis more complicated. This paper presents a stepwise methodology to address the problem, the effect of intermediate fluid circles on flexibility is investigated by performing different networks improving strategies. A desired flexible HEN will be finally achieved with meeting the qualified flexibility and cost expectation.

2. Problem statement

The problem addressed can be stated as follows: the hot and cold streams in each plant are given with their initial temperatures, target temperatures, heat capacity flowrates and heat transfer coefficients. The cost of utilities and the properties of intermediate fluid is also known, so as to assist the determination of network structure. In addition to these basic data, the upper and lower bounds of the fluctuations, rather than the real-time data along time, should be also provided to consider the flexibility problem. The work aims to design an economical inter-plant HEN which has sufficient capability against process fluctuations.

3. Methodology

In this study, a framework including initial HEN synthesis, flexibility analysis, network retrofit is presented to handle the mentioned problem.

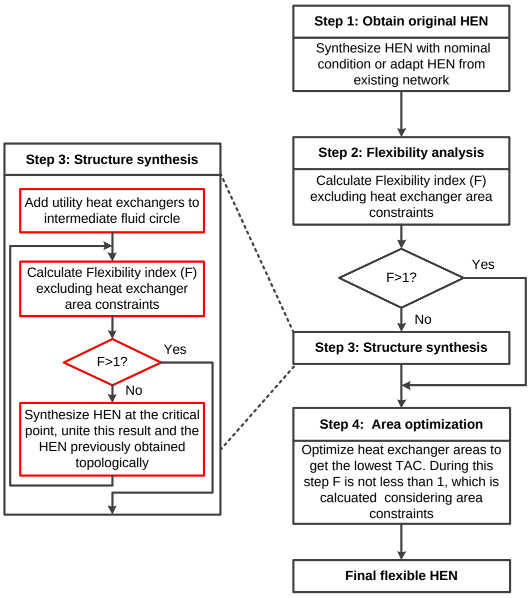

Figure 1a: The framework of the methodology

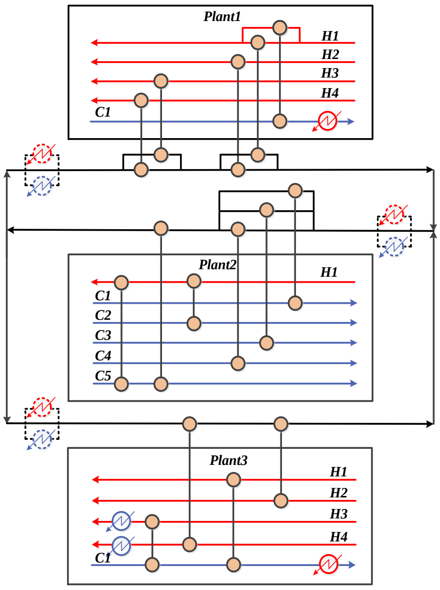

Figure 1b: The superstructure for adding utility heat exchangers on intermediate circles (The initial HEN of case study (solid line section))

A list of steps and iterations constitute the whole procedure (Figure 1a). Therein, considering the characteristics of indirect inter-plant heat integration, measures regarding to intra-plant HEN and intermediate circles are implemented to improve the flexibility of the entire system. This problem is solved by first finding a feasible structure for the uncertain constraints and then making the area optimization based on the obtained structure. The procedure presented in the framework can be expounded as follow:

(1) Step 1: Obtain the initial HEN network at the nominal operating condition. It can be newly synthesized or an existing network.
(2) Step 2: Calculate the flexibility index F of the network. Notice that the flexibility specifically indicates the structure flexibility excluding the heat exchanger area constraints, because the main target of this step is to judge whether HEN structure is feasible for the uncertain parameters. If F<1, it means the existing network has to be improved by structure retrofit, then record the flexibility index and critical points and turn to step 3. If F>1, it means the network structure can satisfy the design requirements but the heat exchange areas are redundancy, so then turn to step 4 to optimize the areas of all exchangers for a lower cost.
(3) Step 3: There are two measures to improve HEN structure. The first measure is to directly add utility heat exchangers to intermediate fluid, for the sake of adjusting intermediate fluid temperature as well as resisting fluctuations spread. The other measure is to re-synthesize HEN at each critical point, then obtain the topological union of the result networks and the base network. By this measure, new heat exchangers would be placed on intra-plant process streams. Due to the wide influence the intermediate circles imposes on inter-plant interaction, the first measure is performed in priority as indicated.
To perform the automatic optimization of HEN, a superstructure containing all possible locations for utility heat exchangers is established based on the initial network, as the example presented in Figure 1b. The dashed lines represent that hot or cold utility could be used according to the conditions. Since the spread of fluctuations from one plant to others has significant impact on flexibility, two strategies referring to the fluctuation spread across plants are proposed and studied to determine the adding of utility exchangers. In strategy 1 , the fluctuation spread is blocked completely, which means to keep the temperature of intermedium cycle entering each plant consistent with nominal operating condition. While in strategy 2, the temperature variation caused by different operating conditions are allowed. The comparison of the two scenarios will be presented with case study. After the optimization, the flexibility of the obtained HEN should be re-analyzed, and the procedure is similar with Step 2. That is, if F>1, indicates that it is able to achieve the qualified flexibility by involving the exchangers, but the areas should be further determined in Step 4; if F=1, the result can be output directly; if F<1, it means adding utility heat exchangers on the intermediate circle is sufficient, the second measure should be applied in the subsequent iterations till the flexibility is satisfied.
(4) Step 4: Optimize heat exchanger areas to get the lowest TAC subjecting to the flexibility constraint (F>=1). Area constraints are included into the flexibility analysis of this step, rather than be relaxed in previous steps.

4. Model Formulation

4.1 Formulation for inter-plant HEN synthesis

The model formulation for inter-plant heat exchanger networks synthesis includes: total energy balances for process streams and intermediate circles, energy balance for each superstructure stage, energy balance for each match, energy balances for utilities at the stream end of the superstructure, energy balances for isothermal mixing, constraints for the existence of heat exchanger units and the temperature differences in heat transfer units, heat exchanger areas calculation and so on. All these equations and constraints can refer to the model established in the work by Chang et al. (2017).

4.2 Formulation for flexibility analysis

The method in this work introduces direction matrix to represent the deviation direction, which is proposed by Li et al. (2015). Both the flexibility index and the critical operating points could be identified in this way. The mathematical formula of the flexibility index F is obtained as follows.

$$D_j = \begin{bmatrix} d_1 & & & \\ & d_2 & & \\ & & \cdots & \\ & & & d_n \end{bmatrix} \tag{1}$$

$$F = \min_j \delta^{D_j} \tag{2}$$

$$\delta^{D_j} = \max_{\delta,z} \delta \tag{3}$$

$$\theta = \theta^N + \delta D_j \times \Delta\theta \qquad \delta \geq 0 \tag{4}$$

$$f(z,\theta) \leq 0 \tag{5}$$

$$a(z,\theta) - a^N \leq 0 \tag{6}$$

The direction matrix D_j is a diagonal matrix, where d_i ($1 \leq i \leq n$) represents the direction on the uncertain operating parameter, and n equals to the number of uncertain operating parameters. The expected deviation $\Delta\theta$ is defined as $\Delta\theta = (\Delta\theta_1, \Delta\theta_2, \ldots \Delta\theta_n)^T$, δ^{Dj} represents the maximum deviation allowed in direction D_j. The superscript N represents the nominal operating condition. The vector z and θ denote the control variables and the uncertain operating variables such as feed temperatures and heat capacity flow rates. Eq(5) represents the HEN structure constraints and Eq(6) demonstrates the area limit. The model contains Eqs(1)-(5) are used in step 2 to calculate the flexibility index for the current HEN.

4.3 Formulation for for area optimization

Area optimization is implemented under a certain structure obtained after structure synthesis. Objective of the optimization is to minimize the total annualized cost under the area constraints. A MINLP model is introduced and areas are extracted and optimized separately in this model.

$$\min_{z,x} \underset{\theta}{E}\, TAC = \underset{\theta}{E}\, UC(Z^{(n)},\theta^{(n)}) + \underset{\theta}{E}\, EC(Z^{(n)},\theta^{(n)}) \qquad n \in VT \tag{7}$$

$$\underset{\theta}{E}\, UC(Z^{(n)},\theta^{(n)}) = \frac{1}{Nv+1}\left(\sum_{\forall n \in VT} \left(C_{CU} \sum_{i \in HP} Q_{CU,i}(Z^{(n)},\theta^{(n)}) + C_{HU} \sum_{j \in CP} Q_{HU,j}(Z^{(n)},\theta^{(n)}) \right)\right) \tag{8}$$

$$\underset{\theta}{E}\, EC(Z^{(n)},\theta^{(n)}) = A_f \cdot \sum_{k \in EP} \left[C_f \cdot Ym_k + C \cdot (Am_k)^B \right] \tag{9}$$

$$Am_k \geq \underset{\forall n \in VT}{A_k} (Z^{(n)},\theta^{(n)}) \qquad k \in EP \tag{10}$$

$$\theta^{(n)} = \theta^N + \delta D_j^{(n)} \times \Delta\theta \qquad \delta = 1 \tag{11}$$

In this step, the areas in the final network is extracted as variables independent of operating points and be optimized directly. The TAC can be calculated by Eqs(7)-(9). Where EUC, EEC represent the expectation of annual utility cost and heat exchanger Investment cost. n means each operating points. C_{CU}, C_{HU} are the costs of cold and hot utilities. The capital costs of heat exchangers can be expressed as: $C_f + C \times A^B$. The first item represents fixed installation costs, and the second item represents area costs. C, A and B represent the heat transfer area coefficients, the heat transfer area and index. A_f denotes annual factor of the capital cost. Binary variable Ym_k represents whether the heat exchanger exist or not. As is showen in Eq(10), the heat transfer areas Am_k in the final network is not less than the areas A_k required at each operation point, which means the maximum area of all conditions is employed. Eq(4) is changed into Eq(11), which indicates that all the expected deviation should be taken into account, meaning that the flexibility index F equals to 1 in the model.

5. Case study

To illustrate the effectiveness of the proposed method, an example adapted from Chang et.al (2017) is studied. All process data at nominal condition are given in Table1. The uncertain parameters that would fluctuate in operation are the input temperatures of the 5 streams listed in Table 2.

Table 1: Parameters for Case Study

Stream	F_{Cp}(kW/°C)	T_{in}(°C)	T_{out}(°C)	h(kW/m^2°C)	Stream	F_{Cp}(kW/°C)	T_{in}(°C)	T_{out}(°C)	h(kW/m^2°C)
H1(plant1)	85	240.0	200	1.2	C4 (plant2)	104	85	132	1.7
H2(plant1)	93	232.0	185	1.3	C5 (plant2)	102	60	115	1.3
H3(plant1)	81	205.0	125	1.6	H1 (plant3)	120	243	215	1.1
H4(plant1)	82	200.0	105	1.4	H2 (plant3)	90	228	207	1.3
C1(plant1)	60	190.0	272	1.2	H3 (plant3)	80	205	120	1.2
H1(plant2)	64	245.0	105	1.4	H4 (plant3)	102	200	80	1.3
C1(plant2)	81	125.0	200	1.6	C1 (plant3)	60	125	281	1.5
C2(plant2)	90	115.0	195	1.3	HPS	-	300	299	2.5
C3(plant2)	110	103.0	165	1.7	Cooling water	-	15.6	15.7	1.2

The ranges of the variations are specified, and can be found that the streams belong to different plants. For this case, the capital cost parameters of heat exchangers are Cf = 1,100, C = 150, B = 1, annualized factor of capital cost is Af = 0.264, the heat transfer coefficient of the intermediate fluid is assumed as a constant ho =

1.5 kW/m^2°C. The flexibility analysis model consisting of Eqs(1)-(5) is a NLP problem, while the area optimization model consisting of Eqs(7)-(11) is a MINLP problem. Both of them are coded in the GAMS23.6 (General Algebraic Modeling System) and BARON solver (Tawarmalani and Sahinidis., 2005) is used.

Table 2: Ranges of variations for uncertain parameters

uncertain parameter	Nominal value (°C)	Lower value(°C)	Upper value(°C)
inlet temperature of H1(plant1)	240	230	250
inlet temperature of H2(plant1)	232	222	242
inlet temperature of C5(plant2)	60	50	70
inlet temperature of H1(plant3)	243	238	248
inlet temperature of H2(plant3)	228	223	233

Table 3: Results Comparison

Item	HEN 1 by Strategy 1	HEN 2 by Strategy 2
TAC($\$\cdot y^{-1}$)	1,172,286	1,041,091
Utility cost($\$\cdot y^{-1}$)	1,031,719	895,581
Number of additional utility heat exchangers	6	1
Additional utility heat exchangers area(m^2)	74.92	18.95
Flexibility index of final network	1.000	1.000

The aim of using the case is to show how to improve the inter-plant HENs' flexibility by proposed framework. So for convenience, the initial HEN is taken from literature (Chang et.al, 2017), as shown in Figure 1b. Employ flexibility analysis step to evaluate flexibility index of this initial network, the F is obtained at 0.735, implying the current network deployment cannot tolerate the full range fluctuations, so network improvement is required. Within this step, the critical point is also positioned, at (230, 222, 50, 238, 223) in uncertain parameter sequence ($Tin(H1)_{plant1}$, $Tin(H2)_{plant1}$, $Tin(C5)_{plant2}$, $Tin(H1)_{plant3}$, $Tin(H2)_{plant3}$). Then Step 3 should be implemented to find a better network to tolerate the expected fluctuations.

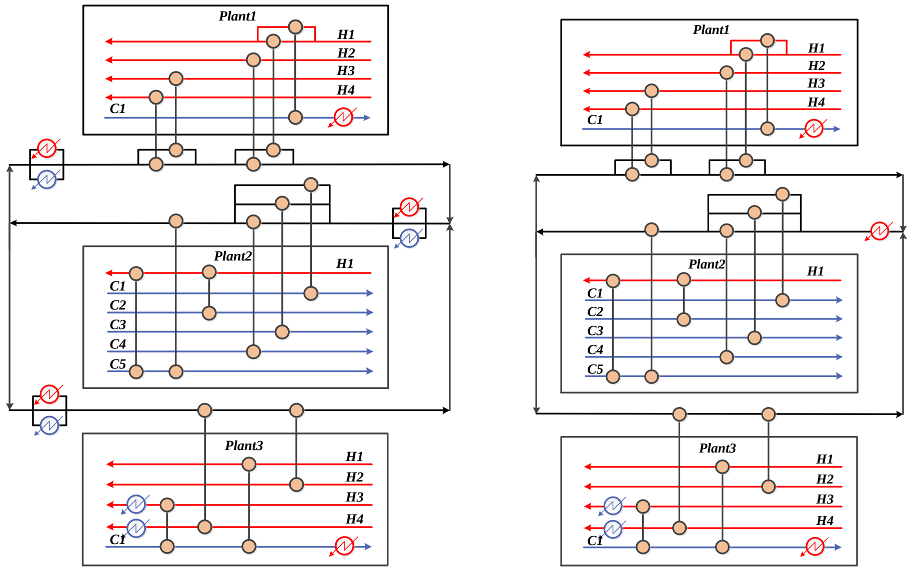

Figure 2a: HEN1 obtained by Strategy 1 *Figure 2b: HEN2 obtained by Strategy 2*

Within Step 3, the heat exchangers consuming utilities will be added on the intermediate circles to improve the network structure. Considering the role of the intermediate circles, the mentioned two retrofit strategies are both studied to investigate the network results for this case. That is, by strategy 1, the spread of temperature fluctuations across plants is forbidden, while by strategy 2 the spread is allowed. Under the specification of the two strategies, two new network structures are obtained with the flexibility of 2.087 and 3.500, indicating that the both networks are feasible under uncertain parameters, but the heat exchange areas are redundancy. Then the areas of the these newly added heaters/coolers are optimized to reduce TACs with maintain sufficient flexibility.

The HEN1 and HEN2 in Figure 2a and Figure 2b are the final networks obtained by using the two strategies. In HEN1, 6 utility heat exchangers are added into the initial network, consequently, extra hot and cold utilities are required to keep the temperatures of intermediate circles entering each plant constant. While in HEN2, as indicated, only one heater is placed before the intermediate fluid flowing into Plant 2. Other major characteristics of the results are summarized in Table 3. As indicated, the flexibility index of the two networks both reach '1', demonstrating they have met the design request. HEN2 has lower TAC, utility cost, number and areas of additional utility heat exchangers, indicating that a more economically advantageous design can be obtained if fluctuation spread is not totally prevented.

6. Conclusions

This paper presents a systematic framework to address the flexibility issue within inter-plant HENs synthesis. The aim is to ensure sufficient flexibility by embellishing intermediate circles because they have a broad association with the plants, could spread and also eliminate the fluctuations. So in the proposed framework, new utility heaters and/or coolers are allowed to be added on the circles, prior to that must be placed inside the plants. This brings a new view to solve the problems which have common streams involved. Two strategies are proposed to deal with the fluctuation in intermediate circles for network retrofit. The results of the studied case demonstrate that adding utility heat exchangers on th intermediate circles can improve the flexibility of inter-plant HENs significantly. The complexity of the HEN structure has not raised much, so the feasibility of the method is also proved. A large cost gap can be found by using the two strategies, that is, the TAC by strategy 2 is 11.19% lower, the utility cost reduces by 13.19 % and only 1 utility exchanger is added. Conclusions can be reached that allowing fluctuations to spread would generate an economically competitive solution with adding fewer heat exchangers and consuming less utilities. Even though the advantage of the strategy 'eliminating fluctuation spread' cannot be overlooked, that is, it could offer the plants more freedom to adjust their production plan. The two network results are both flexibilities reliable, and which to use depends on process characters and the attitude of plant holders. Notice that, although the flexible synthesis is realized by the method proposed in this work, some possible solutions may be neglected due to its step-wise nature. A simultaneous method which enables the bilayer optimization for network synthesis and flexibility analysis is expected. Flexibility is just one aspect of the operability of a system, so to further improve the practicability of the design, other practical issues such as the HEN control and the dynamic scheduling problem of inter-plant HEN will be involved in the future study.

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References

Li J.L., Du J., Zhao Z.C., Yao P.J., 2014, Structure and area optimization of flexible heat exchanger networks, Industrial & Engineering Chemistry Research, 53(29), 11779-11793

Li J.L., Du J., Zhao Z.C., Yao P.J., 2015, An efficient method for flexibility analysis of large-scale nonconvex heat exchanger networks, Industrial & Engineering Chemistry Research, 54(43), 10757–10767

Pintarič Z.N., Kravanja Z., 2008, Identification of critical points for the design and synthesis of flexible processes, Computers & Chemical Engineering, 32(7), 1603-1624

Swaney R.E., Grossmann I.E., 1985, An index for operational flexibility in chemical process design Part II: Computational algorithms, AIChE Journal, 31(4), 631-641

Bai Y.Y., Liu L.L., Gu S.W., Du J., 2017, Synthesis of flexible heat exchanger networks considering fouling resistance, Chemical Engineering Transactions, 61, 511-516

Chang C.L., Chen X.L., Wang Y.F., Feng X., 2017, Simultaneous optimization of multi-plant heat integration using intermediate fluid circles, Energy, 121, 306-317

Wang Y.F., Feng X., Chu K.H., 2014, Trade-off between energy and distance related costs for different connection patterns in heat integration across plants, Applied Thermal Engineering, 70, 857-866

Liu L.L., Wu C.H., Zhuang Y., Zhang L., Du J., 2020, Interplant heat integration method involving multiple intermediate fluid circles and agents: single-period and multiperiod designs, Industrial & Engineering Chemistry Research, 59(10), 4698-4711.

Tawarmalani M., Sahinidis N. V., 2005, A polyhedral branch-and-cut approach to global optimization, Math. Program., 103 (2), 225− 249.