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Simultaneous Synthesis of Controllable Heat Exchanger Networks

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The heat exchanger network (HEN) is an efficient energy recovery system to improve the energy integration between industrial process streams and thus able to reduce the use of utility. However, as a HEN becomes more integrated, potential control difficulties may arise significantly. In addition, these difficulties will further increase due to the uncertainty which is very likely to occur in a real operation of HEN. It is therefore crucial to ensure the controllability as well as the economy of HEN. Nevertheless, the previous researches aiming for controllable HENs sequentially addressed the network synthesis and improved the controllability. Its step-wise nature imposes restrictions on optimisation ability, consequently often leads to suboptimal solutions under global objective. Therefore, in this paper, an optimised-based framework is proposed for the simultaneous synthesis of controllable HEN where bidirectional communication between the network structure and the controllability is involved. The framework is based on a two-stage strategy, coupling the structure synthesis stage with the decision variables optimisation stage. In the first stage, the structure is synthesised incorporated with the proposed heuristic rules and renewed by the bypasses, resulting in the economical and controllable qualified HEN. In the second stage, the location and fraction of bypasses are used as the decision variables and their optimisation can still react on the network structure and control loop interaction to gain desirable economy and controllability. A case study is used to illustrate the effectiveness of the proposed framework.

1. Introduction

The heat exchanger networks (HEN) synthesis aiming for minimal total annual cost (TAC) is of vital importance in chemical industry process. Its complexity increases with the number of possible combinations in process streams, which strengthens the interaction between heat exchangers. These interactions greatly complicate the inherent characteristics of the network and result in poor controllability (Yuan et al., 2012). More important issue is that it may not be possible to guarantee the operational performance of HEN in its optimal design state and make the control extremely difficult due to the uncertainty in the complex operation environment. Therefore, the HEN synthesis demands controllable characteristics that allow the optimisation performance achieved in a practical operating environment.
The control loop refers to the pairing of a controlled variable and one manipulated variable. The whole set of these pairings constitute the control structure (Escobar et al., 2013). Highly integrated networks often result in strong interactions between control loops and thus impose limitations on process operation and control performance. Hence, several works have tackled the controllable HEN problem by selecting optimal control structures with the objective of control loop interaction. For instance, Kookos and Perkins (2016) proposed a new nonlinear process model for control structure selection based on back-off methodology. Kang et al. (2016) introduced a graph-theoretic approach to select the desirable control structure with optimal structural coupling characteristics between manipulated variables and controlled variables which are outlet temperatures of the streams. Braccia et al. (2017) introduced an approach to address multivariable control structure selection by using the sum of squared deviations (SSD) as well as the net load evaluation (NLE) concepts. More recent works also have developed the optimal control structures based on the maximum matching of the network (Leitold et al., 2018).

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Although the studies mentioned above have already received attention, they still need great improvement due to the inappropriate assumption that the controllability was independent on the network structure. However, it is difficult to study this problem because of the unclear relation between the network structure and controllability. Still, some attempts for studying the influence of network structure on the controllability have been made. Masoud et al. (2016) proposed a stepwise strategy for designing HEN with minimal TAC and optimal controllability. Baker et al. (2016) utilised the value of the minimum temperature difference (ΔT_{min}) to select the optimal design target of HEN, while considering controllability. However, ignoring the bidirectional communication between network structure and controllability will only lead to the economically oriented results, so that the economy and controllability aspects in the HEN synthesis were isolated to some extent. Such stepwise nature imposes restrictions on optimisation ability, and consequently leads to suboptimal solutions. Thus, there is an urgent need in this paper for simultaneous synthesis of controllable HEN in which to investigate the bidirectional communication between network structure and controllability.

2. Outline of the solution strategy

In this work, for achieving the objectives of minimal TAC and optimal control structure simultaneously, an optimisation framework based on a two-stage strategy is proposed, which investigates the incorporation of economy and controllability. The outline of the framework is sketched in Figure 1. The two stages are the structure synthesis stage and decision variables optimisation stage. The first one incorporating the proposed heuristic rules which can reflect the bidirectional communication between the network structure and controllability would cause the changes of the network such as an increase of the bypass. Then there will be some shared bypasses which are defined as the one that exists in both the results of the synthesis containing the above rules and the control structure selection. And then this stage is performed through iterations among these bypasses, subsequently, resulting in the economical and controllable qualified HEN with the topology union of bypasses. Since the redundancy caused by the topology union of the first stage, the decision variables optimisation stage is applied to optimise the fraction and location of bypasses for further optimising the obtained HEN in the first stage.

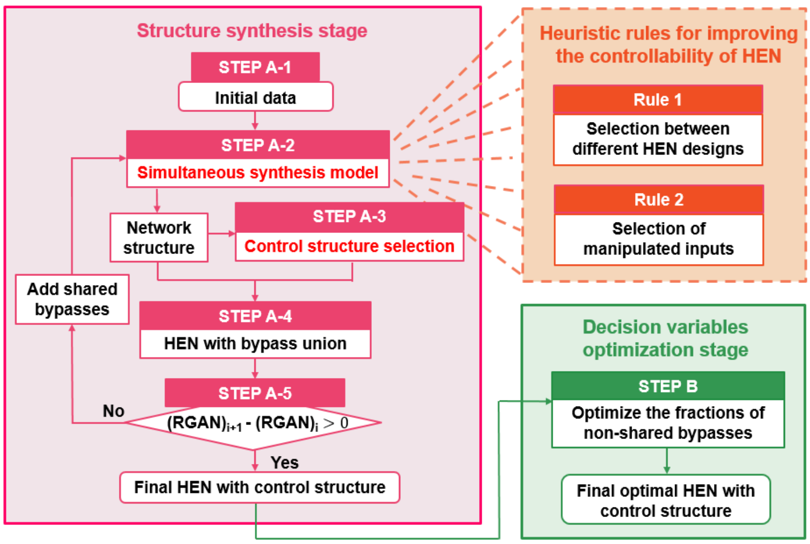


Figure 1: Outline of the proposed optimisation framework

3. Mathematical formulation

3.1 Simultaneous synthesis model

In this work, the HEN synthesis model is based on the non-split stage-wise superstructure proposed by Yee and Grossmann (1990). The difference is that each heat exchanger may be bypassed on both its cold and hot sides. The model features the same assumptions as the Yee and Grossmann's work.

Objective function: The objective function of the synthesis model is to minimise the TAC, as shown in Eq(1). Binary variable z_{ijk} equals one so that the heat exchanger exists. CF is the fixed installation cost of the heat exchanger, C is the area cost coefficient, and CU is the unit utility cost.

$$\min TAC = \min \left(\begin{array}{l} \sum_i \sum_j \sum_k \mathrm{CF} \cdot z_{ijk} + \sum_i \mathrm{CF} \cdot z_{cu_i} + \sum_j \mathrm{CF} \cdot z_{hu_j} \\ + \sum_i \sum_j \sum_k \mathrm{C_{ij}} \cdot A_{ijk}^{\beta} + \sum_i \mathrm{C_{cu_i}} \cdot A_{cu_i}^{\beta} + \sum_j \mathrm{C_{hu_j}} \cdot A_{hu_j}^{\beta} + \sum_i \mathrm{CU_{cu}} \cdot q_{cu_i} + \sum_j \mathrm{CU_{hu}} \cdot q_{hu_j} \end{array} \right) \quad (1)$$

Constraints:
(i) Process model:
The process model is an indispensable constraint condition of the HEN synthesis model which is mainly used to describe the characteristics of the network. It includes a series of equality constraints such as heat balance equations, and a number of inequality constraints for assessing feasibility and defining logical operations (Escobar et al., 2013). In addition, several important constraints are proposed as follows.
(ii) Heuristic rules for improving HEN controllability:
Rule 1: Avoiding both of the outlet temperatures of one heat exchanger as the controlled variables at the same time.
Obviously, this will disturb the adjustments by the two manipulated variables and complicate the variations of the temperature in the heat exchanger, which decreases the HEN controllability. This rule can be presented as Eq(2).

$$T_{ijk}^{\mathrm{h,out}} - T_{iN_K} = Th_{ijk} \quad (2.a)$$

$$T_{j1} - T_{ijk}^{\mathrm{c,out}} = Tc_{ijk} \quad (2.b)$$

$$\Gamma \cdot (1 - zhe_{ijk}) \le Th_{ijk} + Tc_{ijk} \le \Omega \cdot (1 - zhe_{ijk}) \quad (2.c)$$

Where $T_{ijk}^{\mathrm{h,out}}$ and $T_{ijk}^{\mathrm{c,out}}$ are the outlet temperature of the hot and cold stream side of the heat exchanger, respectively. The parameter Γ and Ω are the penalty factors. Binary variable zhe_{ijk} is to indicate the heat exchanger mentioned above. The sum of zhe_{ijk} is set as appropriate with the network size.
Rule 2: The bypass which has direct influence on the controlled variable is prior to others.
Escobar et al. (2013) suggested that the bypasses placed on the end of the streams had direct influence on their outlet temperatures. Hence, when these bypasses are selected, the relevant control loop can offer fast response for the temperature adjustment, i.e. giving the minimal interaction with other control loops. Otherwise, when the bypass occurs on a heat exchanger that is away from the outlet stream, the resulted control loop will be affected by other downstream exchangers. Moreover, in the work of Masoud et al. (2016), the above descriptions were employed to eliminate the undesirable bypasses from the complete enumeration of all possible ones. This rule can be presented as Eq(3).

$$\left(1 - Th_{ijk}\right) \cdot z_{ijk} \le zhby_{ijk} + zcby_{ijk} \quad (3.a)$$

$$\left(1 - Tc_{ijk}\right) \cdot z_{ijk} \le zhby_{ijk} + zcby_{ijk} \quad (3.b)$$

Binary variables $zhby_{ijk}$ and $zcby_{ijk}$ are set to be one if the heat exchanger z_{ijk} is bypassed.

3.2 Control structure selection

Relative gain is a scale used to quantify the relation between manipulated variables and controlled variables. Therefore, relative gain array (RGA) can be used to pair the manipulated variables with the controlled variables so as to obtain the control structure having minimal control loop interaction (Westphalen et al., 2003). It can be obtained by gain matrix **G**, which is shown in Eq(4).

$$\mathbf{RGA} = \mathbf{G} \otimes \left(\mathbf{G}^{+}\right)^{T} \quad (4)$$

The rows of matrix **G** represent the controlled variables in the HEN, and the columns are the manipulated variables which are bypasses. The element g_{lr} of matrix **G** represents the relation between the controlled variable and the manipulated variable. Thus, an equation which relates all the potential manipulated variables with the controlled variables is required in a fast and smooth manner.
As seen in Eq(5), Yan et al. (2001) developed a DP&C model based on a given HEN to calculate gain matrix **G**. Vectors $\mathbf{\delta T^s}$ and $\mathbf{\delta T^t}$ are the inlet and outlet temperatures of the streams, respectively. Vector $\mathbf{\delta MCP}$ presents heat-capacity flow rate. Vector $\mathbf{\delta f}$ is the bypass fraction. Matrices **B**, **D** and $\mathbf{D^m}$ are to characterise the HENs.

$$\boldsymbol{\delta T}^{t} = \mathbf{B}\boldsymbol{\delta f} + \mathbf{D}\boldsymbol{\delta T}^{s} + \mathbf{D}^{m}\boldsymbol{\delta}\mathbf{MCP} \tag{5}$$

In this work, a simplified DP&C model based on the superstructure is proposed so that it can be embedded into the synthesis model, considering all the possibilities. Moreover, the simplified model helps avoiding complex matrix calculations and reducing the computation loads. This model is presented by Eq(6), T_{ijk}^{in} and T_{ijk}^{out} are the inlet and the outlet temperature of the heat exchanger. Therefore, matrix **G** can be calculated from the Eq(6).

$$\boldsymbol{\delta T}^{t} / \boldsymbol{\delta f} = \mathbf{h}(T_{ijk}^{in}, T_{ijk}^{out}, f) \tag{6}$$

Besides, according to the characteristics of **RGA**, it's preferred to pair the controlled variables and manipulated variables to form the control loops when the diagonal elements of **RGA** are close to one. Therefore, the control structure selection can be based on the minimised RGA number (Skogestad and Postlethwaite, 1996), as shown in Eq(7).

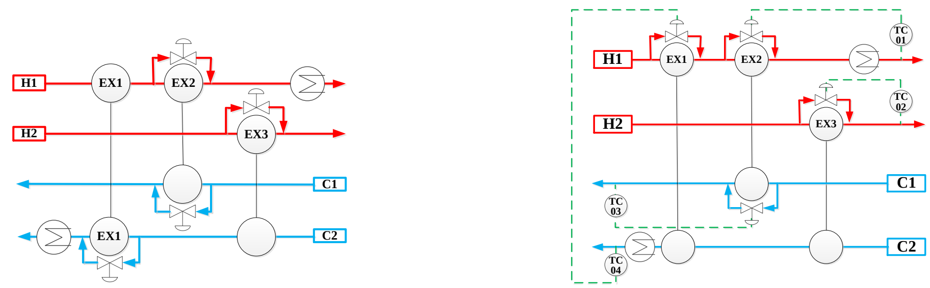
$$\Lambda = RGAN = \| \mathbf{RGA} - \mathbf{I} \|_{sum} \tag{7}$$

4. Case study

A case study is given in this section to illustrate the application of the proposed framework. This case involves two hot streams and two cold streams. The problem data is listed in Table 1. ΔT_{min} is set as 10 K. The bypass fractions are assumed greater than 0.1 in the structure synthesis stage according to the work of Masoud et al. (2016). The range for the values of *RGAN* are normalised from 0.1 to 1 in order to facilitate the analysis and comparison of the results.

Table 1: Problem data for example

Stream	T^{in} (K)	T^{out} (K)	*FCP* (kW·K^{-1})	*h* (kW·m^{-2}·K^{-1})
H1	512	393	7.032	1.53
H2	512	421	8.440	1.25
C1	379	423	6.096	1.47
C2	399	523	10.000	1.50
HU	850	850	-	2.80
CU	293	313	-	3.00



(a) (b)

Figure 2: Network structure: (a) the result of the step A-2; (b) the result of the step A-3

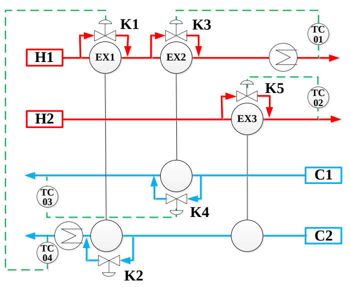


Figure 3: The result of the step A-4

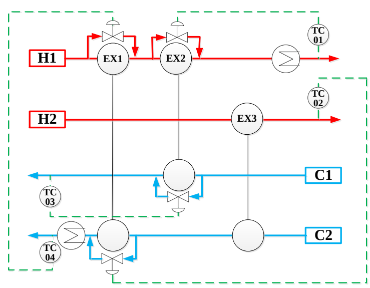


Figure 4: The result of the traditional method

Initially, the synthesis model is solved according to the step A-2 and the result is depicted in Figure 2a. The obtained network structure containing four bypasses is mainly dominated by economy and possesses controllable characteristic meanwhile. For which, the optimal control structure with minimum control loop interaction of the result for step A-3 is found, as shown in Figure 2b. It can be seen that there are three shared bypasses. Such a large proportion of the shared bypass also indicates that the proposed Rule 2 is applicable to improve the controllability in structure synthesis stage. Finally, the HEN with desirable controllability is shown in Figure 3 following the step A-4.

In this HEN, bypasses K3, K4 and K5 are the shared ones, while bypasses K1 and K2 are the non-shared ones. In terms of economy and controllability, the comparisons of the HEN in Figure 2a and Figure 3 are shown in the Table 2. The final HEN has smaller value of *RGAN* than that of the initial HEN, showing desirable controllability. At the same time, the EX1 (as shown in Figure 3.) area of the final HEN increased by 9.19% compared to the initial HEN.

Table 2: The economy and controllability of HEN

	TAC($\$\cdot y^{-1}$)	RGA number
HEN in Figure 2a	112,105	0.856
HEN in Figure 3	112,731	0.667

The decision variables optimisation stage is applied in order to further optimise the obtained network structure in the first stage. The shared bypasses are the same ones that appeared in the results of the process synthesis and control structure selection. Therefore, there is no need to adjust the fraction of the shared bypasses. While the non-shared bypasses need to be optimised.

The bypasses fractions of the HEN obtained from the structure synthesis stage are 0.1. So, adjust upwards or downwards the bypasses fractions from 0.1. As depicted in Table 3 and Table 4, fixing any one of the non-shared bypasses fraction while increasing the other one would lead to the increase of TAC. Such result is mainly attributed to the fact that increasing the bypass fraction leads to a smaller ΔT_{min} and larger heat exchange area. Therefore, the smaller bypass fractions are preferred for economy. As for the RGA number, the result indicated that if the fraction of bypass K1 is fixed, decreasing bypass fraction of K2 would weaken the controllability. Minimizing values of the fraction in bypass K2 is preferred. However, the resultant relation between the fraction of bypass K1 and the value of *RGAN* is contrary with that of bypass K2. Maximum value of the fraction in bypass K2 is preferred for controllability. The reason is that bypass K2 is chosen by the optimal control structure, so the greater the fraction is, the better the controllability. According to the above analyses, the final result in the decision variables optimisation stage is that the fraction of bypass K1 is 0.3 and the fraction of bypass K2 is 0. The TAC of the final result is 113,990 $\$\cdot y^{-1}$, and the RGA number is 0.260. The result shows that the area redundancy of the EX1 is reduced by 19.93% after performing the decision variables optimisation stage.

Table 3: The effect for bypass fraction of K2 on TAC and RGA number

Fraction of K1	Fraction of K2	TAC($\$\cdot y^{-1}$)	RGA number
0.1	0	112,426	0.470
0.1	0.02	112,482	0.504
0.1	0.04	112,541	0.541
0.1	0.06	112,602	0.581
0.1	0.08	112,665	0.622
0.1	0.10	112,731	0.667

Table 4: The effect for bypass fraction of K1 on TAC and RGA number

Fraction of K1	Fraction of K2	TAC($\$\cdot y^{-1}$)	RGA number
0.1	0	112,426	0.469
0.2	0	113,180	0.345
0.3	0	113,990	0.260
0.4	0	114,852	0.220
0.5	0	115,760	0.100

The proposed framework gives the results of HEN synthesis and control structure selection simultaneously, showing economy and high controllability. With the same purpose, the results using the traditional method, i.e. the sequential one, are offered to illustrate the proposed framework, shown in Figure 4. In that HEN, the total expenditure is 108,188 $\$ \cdot y^{-1}$ and RGA number is 1.000. In this context, the TAC of the HEN obtained by the proposed framework has a 5 % increase to the sequential result, while its RGA number has a 74 % decrease. The above comparisons show the superiority of the simultaneous synthesis framework proposed in this paper.

5. Conclusions

In this work the simultaneous synthesis of controllable HEN has been addressed. A two-stage optimised-based framework was developed to incorporate both economy and controllability aspects. In the structure synthesis stage, a controllability-qualified network is found by the structure synthesis and control structure selection, where the proposed heuristic rules are involved in the structure synthesis for improving HEN controllability. And then the iterations of the shared bypasses are employed to generate new HEN structure. In the second stage, the HEN is further optimised with the fraction and location of bypasses. Different from the stepwise method in which only considers the influence of economy on the controllability of HENs, the proposed framework considers their bidirectional communication so as to explore their reasonable trade-off. Finally, the case study results indicate that the optimisation framework presents almost the same economic performance compared with traditional HEN synthesis approach, however, the controllability has been significantly improved.

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