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Synthesis of Heat Exchanger Networks Taking into Account Cost and Dynamic Considerations

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Abstract

In this work an approach is presented for the synthesis of near cost optimal heat exchanger networks with a high controllability. The presented methodology is based on a sequential approach utilizing different algorithms and mathematical models. The procedure is carried out in three steps. A genetic algorithm is used to produce a high diversity of promising structures that suffice the needs for cost reduction and controllability characteristics. For selected structures controllability evaluations are carried out, which are mainly based on relative gain array and condition number assessments. Therefore, a linear model is utilized which was further used to calculate the area adjustments and nominal bypasses for complete disturbance rejection for perfect control. As a last step simplified mathematical solution models are used to further extend insight gained for decision-making. These models are used to carry out dynamic simulations for testing the impact of different possible decentralized feedback control structure designs developed by previous methods. The application of the developed approach will be shown using an example from literature.

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Keywords: Heat exchanger network synthesis; dynamics; controllability; decentralized control; heat integration

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1. Introduction

The implementation of heat integration strategies has a huge potential of reducing the use of primary energy carriers significantly and thus increasing the energy efficiency and cost effectiveness of a process.

The synthesis of heat exchanger networks (HENs) thus was a vital topic in the last decades and it is still a vital topic in literature today. There are numerous methods and approaches available and there are still new developments made, for example in a recent publication from Peng and Cui [1] where a simulated annealing algorithm is utilized for simultaneous synthesis of HENs. Another example is the work of Pouransari and Maréchal [2] who laid stress on large-scale industry and constraints which are inspired by layout considerations. The major synthesis problem is often reduced to the minimization of the total annual costs. These include the costs for the investment in heat exchangers and the costs for utilities like steam, thermal oil or cooling water. However, the thermal coupling of hot and cold

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streams via heat exchangers may promote the disturbance propagation throughout the HEN and could possibly cause controllability issues. The topic of controllability has been addressed in several publications. Yan et. al [3] developed an iterative procedure for the bypass design of HENs. Escobar et. al [4] introduced a computational framework for simultaneous synthesis of HENs based on the SYNHEAT model.

Following, a sequential methodology is proposed which utilizes a genetic algorithm to generate near cost optimal heat exchanger networks to create a basis of structurally different networks for the comparison with the help of characteristic numbers. These numbers are calculated with a linearized steady-state model. Furthermore, a dynamic comparison was carried out to overcome the shortcomings of the steady-state approaches.

Nomenclature

N_s	number of stages
N_h	number of hot streams
N_c	number of cold streams
u	bypass fraction
indices	
c	cold
h	hot
s	supply
t	target
hx	heat exchanger

2. Analysis and Modelling

In the following part the main algorithms and mathematical models of the applied procedure are described briefly. The first part covers the genetic algorithm followed by the linear model with the characteristic numbers and in the last part the dynamic model is explained.

2.1. Genetic algorithm

The synthesis of heat exchanger networks was carried out using a modified version of the genetic algorithm developed by Fieg et. al [5]. This algorithm derives HEN structures based on the superstructure by Yee et. al [6].The objective of the solution of a heat exchanger network synthesis problem is the minimization of the total annual costs in \$/a. These include the costs for the investment in heat exchangers and the costs for utilities like steam, thermal oil or cooling water. An abbreviated form is given in equation 1:

$$\min C(x) = \sum_{n=1}^{N_h+N_c} C_{U,n} + \sum_{i=1}^{N_s}\sum_{j=1}^{N_h}\sum_{k=1}^{N_c} C_{E,ijk} \tag{1}$$

The costs for the utility heat exchangers and the costs for the supply of utilities are combined in C_U. The costs for the process to process heat exchangers are considered with the factor C_E. The algorithm is modified to carry out multiple optimizations. When carrying out these optimizations equal solutions are forbidden to generate numerous results which differ in structure.

2.2. Linear model

Apart from the consideration of costs the HENs are examined under the attention of controllability. In our case, the HENs are to be controlled by bypasses around the process to process heat exchangers and the flowrates of the utilities used. The resulting control system is realized by decentralized feedback control. In the controllability investigation the relative gain array (RGA) and the condition number are commonly used [7]. The RGA was introduced by Bristol [8]. It is used as a measure of interaction within the considered system and helps to find a suitable the input output pairing of the associated control system. Additionally the performance RGA (PRGA) was used to investigate significant one-way coupling in the HEN [9]. The quantification of the interaction within the HEN is carried out by the calculation of the RGA number [10]. The basis for the calculation of the characteristic numbers for the HEN is predicated on a developed linear model which utilizes the logarithmic mean temperature difference as the driving force for heat transfer. The designation of the variables used for one ideal countercurrent heat exchanger can be found in Fig. 1.

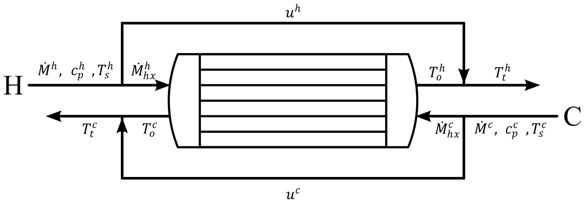

Fig. 1. Heat exchanger balance.

The model is based on a linearization around the steady-state operating point. The describing equations for the heat transfer and the mixer balances can be found in the following equations 2-6.

Heat transfer equations:

$$\dot{Q} = \dot{M}_{hx}^h cp^h \left(T_s^h - T_o^h\right) \tag{2}$$

$$\dot{Q} = \dot{M}_{hx}^c cp^c \left(T_o^c - T_s^c\right) \tag{3}$$

$$\dot{Q} = hA \frac{\left(T_s^h - T_o^c\right) - \left(T_o^h - T_s^c\right)}{\ln\left(\dfrac{T_s^h - T_o^c}{T_o^h - T_s^c}\right)} \tag{4}$$

Equations for the mixer balances:

$$T_t^h = \left(1 - u^h\right) T_o^h + u^h T_s^h \tag{5}$$

$$T_t^c = \left(1 - u^c\right) T_o^c + u^c T_s^c \tag{6}$$

The preceding equations for each heat exchanger are arranged using the method described by Yan et. al [3]. The final model gives the dependence of the change in the target temperatures δT_t of the HEN on the change in bypasses δu, changes in the supplied temperatures δT_s and the heat capacity flowrates $\delta(Mc_p)$ depicted in equation 7.

$$\delta T_t = G \cdot \delta u + G_{d,T} \cdot \delta T_s + G_{d,w} \cdot \delta\left(\dot{M} c_p\right) \tag{7}$$

In order to achieve a feasible bypass control system the extended RGA method and the iterative bypass adaption by Yan et. al [3] is used. The resulting HEN from the application of the genetic algorithm are evaluated with the before mentioned characteristic numbers. For particular HENs all possible control configurations are examined and dynamic simulations are carried out.

2.3. Dynamic model

The dynamic model for the HEN is based on a cell-model for the heat exchangers and uses ordinary PI feedback control for the control loops in the bypass control. The equations for the mathematical characterization of one cell of a heat exchanger are given in the following:

$$\frac{dT_i^h}{dt} = \frac{\dot{V}^h}{V_i^h}\left(T_{i-1}^h - T_i^h\right) - \frac{hA_i}{\rho^h V_i^h c_p^h}\Delta T_{m,i} \tag{8}$$

$$\frac{dT_i^c}{dt} = \frac{\dot{V}^c}{V_i^c}\left(T_{i+1}^c - T_i^c\right) - \frac{hA_i}{\rho^c V_i^c c_p^c}\Delta T_{m,i} \tag{9}$$

$$\Delta T_{m,i} = \frac{\left(T_{i-1}^h - T_i^c\right) - \left(T_i^h - T_{i+1}^c\right)}{\ln\left(\dfrac{T_{i-1}^h - T_i^c}{T_i^h - T_{i+1}^c}\right)} \tag{10}$$

Like in the linear model the logarithmic mean temperature difference is utilized. As a consequence there is no deviation from the steady-state description of an ideal countercurrent heat exchanger. These equations are integrated in a modular tool to enable arbitrary connections of heat exchangers.

3. Results and discussion

In this part the application of the proposed methodology is conducted. The first step is the generation of promising structures by using the modified genetic algorithm. Therefore, an example from literature is analyzed. The example was taken from Luo et. al [11] and consists of four hot streams and five cold streams. A detailed overview for the problem data is given in table 1.

Table 1. Problem data for the example case.

Stream	T_s (°C)	T_t (°C)	$\dot{W}$ (kW/K)	h (kW/(m²K)
H1	327	40	100	0.50
H2	220	160	160	0.40
H3	220	60	60	0.14
H4	160	45	400	0.30
C1	100	300	100	0.35
C2	35	164	70	0.70
C3	85	138	350	0.50
C4	60	170	60	0.14
C5	140	300	200	0.60
HU (hot oil)	330	250	-	0.50
CU (cooling water)	15	30	-	0.50

Annual cost of heat exchangers (\$/a) = 2000 + 70A (A in m²)
Annual cost of hot utility per unit duty (\$/kWa) = 60
Annual cost of cold utility per unit duty (\$/kWa) = 6

The modified genetic algorithm provides numerous solutions within a close range of the total annual costs. From these results merely configurations with five streams heated or cooled by utilities and four streams where the heat transfer is only affected by process to process heat exchangers are taken. This reduction is carried out because of improving the clearness for the following steps. Therefore, five output temperatures are controlled by the utility flowrates and four output temperatures are controlled with bypasses around the heat exchangers. The selected solutions are given in table 2. The solutions are sorted in a descending order considering their total annual costs. These are in a range from 2938084 \$/a to 2994158 \$/a, which is equivalent to 1.9 % in cost deviation for the considered results. Based on the superstructure which was mentioned before, the results are assigned a specifying sequence of numbers.

In this case a “0” stands for the connection of stream “H1” with stream “C1” and a “1” for the connection of stream “H1” with stream “C2” respectively.

Table 2. Structures and controllability measures for selected solutions of the genetic algorithm.

No.	Structure	RGA number	PRGA number	Condition number
1	0,9,13,16,17,21,37	0.00	0.04	12.76
2	0,9,13,16,21,37	0.00	0.08	3.97
3	0,9,13,26,36,41,57	0.00	0.48	7.41
4	0,9,13,16,24,37,41	0.00	3e-5	18.23
5	0,9,13,17,26,41	0.00	0.29	10.42
6	0,9,11,17,21,33	0.00	0.48	8.21
7	0,6,9,13,17,21	0.00	0.16	4.38
8	0,6,13,21,29,39,57	0.00	0.05	5.63
9	0,6,13,17,21,29	0.00	0.05	5.47
10	4,13,17,25,29,40,41	0.22	0.76	3.62
11	0,9,13,17,21,36	0.00	0.00	4.33
12	0,9,13,17,21,25	0.00	0.01	4.21
13	0,9,13,17,21,35	0.00	0.03	4.24
14	0,4,13,17,21,29,45	0.00	0.22	4.84
15	0,9,13,17,21,36	0.00	0.00	4.33
16	0,9,13,17,21	0.00	0.00	4.33
17	0,9,11,17,18	0.00	0.00	4.33
18	4,5,13,21,29,39,57	0.00	0.00	261.08

It should be noted here, that the calculation of the characteristic numbers is carried out assuming no disturbances in the input streams. Depending on different process disturbances the characteristic numbers will change and have to be analyzed separately. Considering the RGA numbers all HENs should be well controllable, except for HEN No. 10, which has considerable interaction in the possible control loops. This is also pointed out by the PRGA which confirms significant one-way coupling compared to the other structures. Because the control structures are chosen according to the extended RGA, the RGA number is zero in most cases. It becomes obvious that a good controllability pointed out by a low condition number does not necessarily involve low total annual costs of the network. For further analysis HEN No. 2 is chosen to show the principle of the described methodology. A representation of the structure of HEN No. 2 is given in Fig. 2.

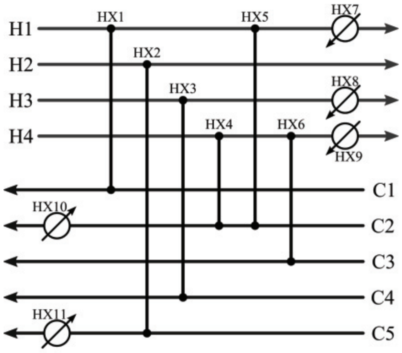

Fig. 2. Structure of HEN No. 2.

In addition to the structure of HEN No. 2 detailed information of the heat load distribution and the heat exchanger areas is given in table 3.

Table 3. Examined structure from selected solutions.

HX	Hot stream	Cold stream	Area (m^2)	Q (kW)
HX1	H1	C1	3598	20000
HX2	H2	C5	1567	9600
HX3	H3	C4	1886	6600
HX4	H4	C2	388	2066
HX5	H1	C2	898	5626
HX6	H4	C3	4955	18550
HX7	H1	CU	381	3074
HX8	H3	CU	451	3000
HX9	H4	CU	2686	25384
HX10	HU	C2	34	1338
HX11	HU	C5	1863	22400

There are six process to process heat exchangers in the considered HEN structure resulting in 12 possible bypasses to choose from to control the four output streams. If one considers all possible combinations of input output pairings of this particular structure, there are 48 solutions with an RGA number of 0. Bypasses on both sides of the heat exchangers were neglected to avoid singular control behavior. Four of these 48 solutions have a minimal condition number equal to 3.97. Based on a solely steady-state point of view using the condition number and the RGA these four alternatives would be equally good. The alternatives are shown in table 4. Considering table 4 a “1” means a bypass is placed and a “0” means that no bypass is placed on the specific side of the heat exchanger.

Table 4. Control structure alternative configurations.

No.	Control structure											
	HX1		HX2		HX3		HX4		HX5		HX6	
	u^h	u^c	u^h	u^c	u^h	u^c	u^h	u^c	u^h	u^c	u^h	u^c
1	0	1	1	0	0	1	0	0	0	0	0	1
2	0	1	1	0	1	0	0	0	0	0	0	1
3	1	0	1	0	0	1	0	0	0	0	0	1
4	1	0	1	0	1	0	0	0	0	0	0	1

The reason the four alternatives are equivalent is based on the linear model which was used. Due to the equal heat capacity flowrates of the streams H1 and C1 as well as the streams H3 and C4 the gain matrices of all for alternatives are equal. The gain matrix of configuration No. 1 is shown in equation 11. The configuration No. 1 is depicted as a grid diagram in Fig. 3.

$$\begin{pmatrix} \delta T_{t,C1} \\ \delta T_{t,H2} \\ \delta T_{t,C4} \\ \delta T_{t,C3} \end{pmatrix} = \begin{pmatrix} -88.1 & 0 & 0 & 0 \\ 0 & 26.0 & 0 & 0 \\ 0 & 0 & -37.8 & 0 \\ 6.7 & 0 & 0 & -22.3 \end{pmatrix} \begin{pmatrix} \delta u^{c}_{HX1} \\ \delta u^{h}_{HX2} \\ \delta u^{c}_{HX3} \\ \delta u^{c}_{HX6} \end{pmatrix} \tag{11}$$

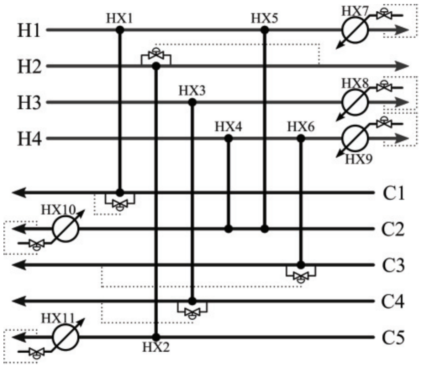

Fig. 3. Control structure for configuration No. 1.

To overcome the limitations of the applied steady-state approach the dynamic model will be used in the following part. For the dynamic considerations the effect of direct and indirect bypasses is investigated. Direct bypasses are referred to as bypasses on the same side of the heat exchanger as the controlled output stream. Hence a direct bypass would e.g. be a bypass on the cold side of the heat exchanger to control a cold output stream. For the following example a temperature disturbance of ±4°C is assumed for stream H1. Based on the linear model the increase in area of the heat exchangers HX1 and HX6 is calculated and nominal bypasses for these heat exchangers are calculated as well. The condition number changes slightly when utilizing disturbances differing from zero. The condition number increases to 4.54 for an indirect bypass configuration around heat exchanger HX1 and to 5.0 for the direct bypass configuration. Despite the fact that the indirect bypass configuration seems to be superior when utilizing the condition number for the assessment of the controllability, the direct bypass configuration is supposed to be superior from a dynamic point of view. Fig. 4 shows a dynamic simulation for the impact of the step response for a +3°C disturbance in stream H1 for the direct and the indirect bypass configuration on stream C1.

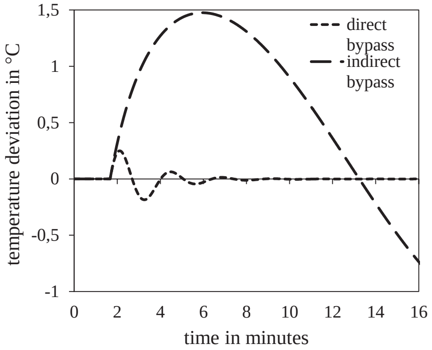

Fig. 4. Deviation of the output temperature in stream C1.

It can be seen that there are significant differences in the step response for both configurations. The direct bypass configuration shows a much faster adjustment of the target temperature for the given disturbance. In this case the indirect bypass configuration is far inferior to the direct bypass. The reason is the larger dead time of the indirect bypass configuration due to the large holdup in the heat exchanger. This behavior is supported by the problem selection, because the synthesis of the HENs leads to large heat exchanger areas and thus to large volumes of the heat exchangers. From the dynamic point of view it is not necessarily concluded that steady-state assumptions lead to the correct decision considering the bypass placement.

4. Conclusions

The synthesis of HENs which is based on the minimization of the total annual costs does not inevitably lead to solutions with the best controllability characteristics. By the application of the presented workflow it has been shown that utilizing an algorithm for the global total annual cost optimization coupled with a linear model and a dynamic model can achieve highly controllable HENs. On the basis of an example from literature it has been shown that the solution space contains many near cost optimal solutions with very divergent structures and thus different characteristic numbers for pure total annual cost optimization. The shortcomings of steady-state approaches were overcome by the application of dynamic simulations. It was shown that the bypass placement has a significant effect on the dynamics. The presented methodology greatly supports decision-making for the design of highly controllable HENs.

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