

Controllability and Resiliency Analysis in Heat Exchanger Networks

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Synthesis of heat exchanger network (HEN) is a subject of great industrial interest. In an industrial process, it is possible to take advantage of the existing energy in its own process streams and, consequently, to reduce the utilities consumption. Operability considerations are important for the HEN design due to the uncertainties in streams temperatures and flow rates, which are very common in real operations. Therefore, the HEN design, in addition to economic interests, must consider flexibility, controllability and resiliency aspects. This paper performs the analysis of controllability and resiliency (C&R). For the configuration of the HEN control system, it is used the Relative Gain Array and Disturbance Cost index. This analysis of operability is applied in a literature example. A modification in the literature HEN is then suggested to improve network resiliency.

1. Introduction

An industrial process system consists of three main interactive components: the industrial process itself, the utilities system and the energy recovery system. Hot and cold utilities are used for process streams heating and cooling. The synthesis of heat exchanger network (HEN) is a subject of great industrial interest because it is possible to avoid excessive use of utilities, which contributes to reduce operating and environmental costs. However, if the network is designed for a single operation period, this can increase operating costs or make the process unviable in a real production environment under variations in certain periods of the year. Thus, a flexible HEN is a network able to support changes in operating conditions such as variations in inlet and outlet temperatures and stream flowrates. While flexibility is related to the steady state behavior of the process, the controllability is concerned with short-term answers (dynamic aspects). Thus, the main goal of a control system in a HEN is to keep, in the easiest possible way, the outlet temperature of the streams on the pre-established values or even control those that do not have a specific goal.

Process control can be achieved through entries that can be manipulated, such as: control of utilities flowrates; use of bypass fractions; implementation of streams splitters fractions; control of the flowrates of input process streams; use of additional areas in heat exchangers and control of recycle flowrate. In a decentralized control system, to eliminate the disturbance caused to the system by external environment, each manipulated variable can be paired with a controlled variable, resulting in a control loop. The set of loops constitutes the control structure (Escobar et al., 2013).

Controllability is a property of the plant itself, which is strongly affected by the network configuration and it is not dependent on the controller design. According to Bristol (1966), a way of measuring controllability is using Relative Gain Array (RGA), which is a controllability index of the system in steady state. Uzturk and Akman (1997) used this index for selecting the appropriate match between the bypass and the outlet controlled temperature. Westphalen et al. (2003) used the RGA analysis for the selection of the control structure.

Bristol (1966) introduced RGA with the objective of measuring the interaction between process variables. The RGA is a normalized gain matrix that describes the impact of each control variable on each output. The normalization of these gains is based on the potential impact of each input and output pair. This controllability index can be calculated experimentally or by means of stationary process gains matrix. In De Leon *et al.* (2016) the disturbance cost (DC) and the relative gain array (RGA) were used to analyse a HEN and to determine if the addition of bypasses could improve the controllability and the stability of the system. A

thermodynamic analysis was also provided.

The resiliency describes the ability of a process to avoid external disturbances and measures the degree of maintenance of the outputs of multivariable processes in their setpoints (Morari, 1983). According to Lewin (1996), a way of evaluating the resiliency is using Disturbance Cost (DC). This index indicates the settling time for disturbance rejection and the limitations due to actuator constraints.

Seider et al. (2009) presented the impact of process design decisions on operability in four case studies, using RGA and DC index. It is essential that decisions about process design consider controllability and resiliency (C&R) due to uncertainties and disturbances. All of these papers treat the cases of synthesizing HEN for a single period. In the present paper, the literature procedure for the C&R analysis, using RGA and DC index is used to synthesize a multiperiod HEN. The HEN here presented has improved resiliency.

2. Controllability and Resiliency Analysis

In industrial processes it is a very important feature to consider the C&R of a HEN during the design task, due to uncertainties and disturbances in the process model. Steady state C&R analysis provides useful information for HEN assessment, describing the effects of the control variables and disturbances on the process outputs, and it requires less work than dynamic analysis. Thus, a procedure proposed by Seider et al. (2009) for assessing steady state C&R of a process is described.

First step: generate the process model and select the controlled variables ($y\{t\} = [y_1, y_2, y_3 \dots]$), the manipulated variables ($u\{t\} = [u_1, u_2, u_3 \dots]$) and the disturbances ($d\{t\} = [d_1, d_2, d_3 \dots]$).

Second step: linearize the model according to Eq(1).

$$\Delta y^T\{0\} = \mathbf{P}\{0\} \cdot \Delta u^T\{0\} + \mathbf{P}_d\{0\} \cdot \Delta \mathbf{d}^T \quad (1)$$

The procedure to linearize the model is:

- Solve the model equations using a numerical method, like Newton-Raphson, for the nominal values of the disturbance and manipulated variables to determine the state variables (x).
- Apply positive (p) and negative (n) small disturbances (Δu) to each manipulated variable (u), one at a time, and recalculate the values of the controlled variables. These values should be stored in the variables $y_{p,i,j}$ and $y_{n,i,j}$. Index j indicates the controlled variable. Column i of the steady state gain matrix ($\mathbf{P}\{0\}$) can be calculated using the central finite difference as shown in Eq(2). Parameter Δu_i^{\max} is the nominal value of the manipulated variable.

$$p_{ji}\{0\} = \Delta u_i^{\max} \cdot (y_{p,i,j} - y_{n,i,j}) / (2\Delta u_i) \quad (2)$$

- Apply positive and negative small perturbations (Δd) to each disturbance variable (d), one at a time and recalculate the values of the controlled variables. These values also must be stored in the variables $y_{p,i,j}$ and $y_{n,i,j}$. Column i of the steady state gain matrix ($\mathbf{P}_d\{0\}$) also should be calculated using the central finite difference as shown in Eq(3). Parameter Δd_i^{\max} is the maximum perturbation of the disturbance variable.

$$pd_{ji}\{0\} = \Delta d_i^{\max} \cdot (y_{p,i,j} - y_{n,i,j}) / (2\Delta d_i) \quad (3)$$

Third step: calculate the measures of controllability and resiliency using the matrix $\mathbf{P}\{0\}$ and $\mathbf{P}_d\{0\}$. The controllability is analysed by the RGA index (Bristol, 1966), which is calculated by multiplying the matrices $\mathbf{P}\{0\}$ and $(\mathbf{P}^{-1}\{0\})^T$ element-by-element, as in Eq(4). In this step, the controlled and manipulated variable are paired.

$$\mathbf{RGA} = \mathbf{P}\{0\} \otimes (\mathbf{P}^{-1}\{0\})^T \quad (4)$$

The resiliency of the HEN is examined with the DC calculation (Lewin, 1996) for pre-determined disturbances. These disturbances are normalized and arranged in a vector ($\Delta \mathbf{d}$). The action required to completely reject the disturbance, given the linearized model and assuming perfect control, is calculated by Eq(5).

$$\Delta u^T\{0\} = -\mathbf{P}^{-1}\{0\} \cdot \mathbf{P}_d\{0\} \cdot \Delta \mathbf{d}^T \quad (5)$$

A quantitative measure of the control effort to reject a given disturbance vector is the Euclidean norm. The 2-norm is the DC. Its value indicates the settling time for disturbance rejection and the limitations due to actuator constraints. Its result is independent of controller tuning, since the DC is based on the assumption of perfect control.

$$DC = \|\Delta \mathbf{u}^T\|_2 \quad (6)$$

Finally it is possible to determine the variables that should be paired and if the resiliency of the network is satisfactory or not. RGA values near one indicate the manipulated variables that must be paired with the controlled variables. The closer to one, the more insensitive to interaction will be the selected pair. Pairs with negative elements of RGA index are an indication of presence of destabilizing positive feedback due to unfavourable process interactions. These pairs should be avoided, because it is not possible to assure stability. In other words, the single input, single output (SISO) controllers should be paired in such a way that the RGA elements corresponding to the pairings are positive, so that closed-loop stability in the control loop can be assured. For the DC index, a value higher than one indicates that the actuator limitations can be exceeded and HEN should be modified to ensure adequate regulation.

In the second step, it is necessary to calculate the values of the controlled variables for positive and negative small perturbations of each manipulated and disturbance variable. With these values, the steady state gain matrix must be computed using the finite difference. Due to the use of positive and negative perturbations, it is recommended to use central finite difference.

3. Case study

This case study was adapted from Floudas and Grossmann (1987) and used by Miranda et al. (2016) for the synthesis of HEN for multiple periods of operation. Table 1 shows the input data for the example. Here, the purpose is C&R analysis of the HEN obtained for nominal conditions by Miranda et al. (2016). The problem has two hot and two cold streams and the global heat transfer coefficients (U) for all matches are 0.08 kW/m²K.

Table 1: Streams data

Stream	T_{in} (K)	T_{out} (K)	F (kW/K)
Nominal conditions			
H1	583	323	1.4
H2	723	553	2.0
C1	313	393	3.0
C2	388	553	2.0
Period 1			
H1	593	323	1.8
H2	723	553	2.0
C1	313	393	3.0
C2	383	553	2.4
Period 2			
H1	593	323	1.8
H2	723	553	2.0
C1	313	393	3.0
C2	393	553	1.6
Period 3			
H1	573	323	1.0
H2	723	553	2.0
C1	313	393	3.0
C2	383	553	2.4

The HEN was synthesized using a MINLP formulation based on the superstructure proposed by Yee and Grossmann (1990), as presented in Miranda et al. (2016). Because of space limitations in the present paper, Figure 1 (a) shows only the HEN for the nominal conditions. HEN for periods 1, 2 and 3 are synthesized in the same manner. For the HEN in nominal conditions, the four outlet temperatures of the streams (Th_5 , Th_8 , Tc_2 and Tc_5) are variables that must be controlled. The HEN has three heat exchangers (1, 2 and 3) and two coolers (4 and 5) with areas (A_i) of 24.1, 6.7, 22.0, 30.3 and 2.0 m². The thermal capacity of the cold utility used to cool streams H1 and H2 are 4.7 kW/K (FC_{p6}) and 2 kW/K (FC_{p5}). The energy balance for this system involves 27 variables: the thermal capacity and the temperatures of each stream, the heat exchanged in each equipment and the split fraction in hot stream H1: FC_{p1} , FC_{p2} , FC_{p3} , FC_{p4} , FC_{p5} , FC_{p6} , Th_1 , Th_2 , Th_3 , Th_4 , Th_5 , Th_6 , Th_7 , Th_8 , Tc_1 , Tc_2 , Tc_3 , Tc_4 , Tc_5 , Tc_6 , Tc_7 , Q_1 , Q_2 , Q_3 , Q_4 , Q_5 and ϕ . With the stream data in Table 1, it can be observed that there are four disturbance variables: the feed thermal capacity and the inlet temperature of

hot stream H1 (FC_{p1} and Th_1) and the feed thermal capacity and inlet temperature of cold stream C2 (FC_{p4} and Tc_3), with the maximum perturbation of 28 %, 10 K, 20 % and 5 K, respectively.

In this case, C&R is analysed for the HEN synthesized only for nominal conditions, not taking into account the multiperiod network, so the split fraction of hot stream H1 ($\phi = 0.884$) is considered constant. Also, bypasses to heat exchangers 1, 2 and 3 are not considered. Furthermore, the inlet and outlet temperatures of the cold utility ($Tc_6 = 303$ K and $Tc_7 = 323$ K) are fixed variables. The network is required to be resilient to disturbances in hot stream H1 and cold stream C2.

For constant heat capacities and no phase change, a steady state model for the network consists of three energy balances for each heat exchanger and an energy balance for a mixer located in hot stream H1, totalizing 16 equations.

For heat exchanger 1:

$$f_1\{x\} = Q_1 - FC_{p1} \cdot (Th_1 - Th_2) = 0 \quad (7)$$

$$f_2\{x\} = Q_1 - FC_{p3} \cdot (Tc_2 - Tc_1) = 0 \quad (8)$$

$$f_3\{x\} = Q_1 - UA_1 \cdot \frac{(Th_1 - Tc_2) - (Th_2 - Tc_1)}{\ln[(Th_1 - Tc_2)/(Th_2 - Tc_1)]} = 0 \quad (9)$$

The degrees of freedom analysis for the HEN indicated that four variables could be manipulated for controlling variables Th_5 , Th_8 , Tc_2 and Tc_5 . Several possible control systems can be investigated, and in this case, variables FC_{p6} , FC_{p5} , FC_{p3} and FC_{p2} were selected as manipulated variables. Using $\Delta u = 0.01$ and $\Delta d = 0.01$ for all variables, $\Delta \mathbf{u}^{\max} = [4.7, 2, 3, 2]$ and $\Delta \mathbf{d}^{\max} = [28 \%, 10 \text{ K}, 20 \%, 5 \text{ K}]$, the resulting linearized model is represented by:

$$\begin{bmatrix} \Delta Th_5 \\ \Delta Th_8 \\ \Delta Tc_2 \\ \Delta Tc_5 \end{bmatrix} = \begin{bmatrix} 13.7 & 0.0 & 0.0 & 0.0 \\ 0.0 & 240.0 & 0.0 & 10.0 \\ 89.6 & 0.0 & -51.8 & 0.0 \\ 0.0 & 0.0 & 0.0 & -74.6 \end{bmatrix} \cdot \begin{bmatrix} \Delta FC_{p6} \\ \Delta FC_{p5} \\ \Delta FC_{p3} \\ \Delta FC_{p2} \end{bmatrix} + \begin{bmatrix} 4.1 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ -23.9 & 0.1 & 0.0 & -0.6 \\ 11.2 & 351.0 & -8.5 & -172.7 \end{bmatrix} \cdot \begin{bmatrix} \Delta FC_{p1} \\ \Delta Th_1 \\ \Delta FC_{p4} \\ \Delta Tc_3 \end{bmatrix} \quad (10)$$

The RGA computation is made using matrix $\mathbf{P}\{0\}$:

$$RGA = \begin{bmatrix} 1.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 1.0 \end{bmatrix} \quad (11)$$

The steady-state RGA indicates that the diagonal pairing is preferred ($Th_5 - FC_{p6}$, $Th_8 - FC_{p5}$, $Tc_2 - FC_{p3}$ and $Tc_5 - FC_{p2}$), providing answers perfectly dissociated. These pairs are recommended because the elements of the main diagonal are equal to one, as shown in Eq(11). Since the other elements of the matrix are zero, one can conclude that the process interaction is only in one direction and precludes the possibility of the occurrence of destabilizing feedback control. The resilience of the HEN is examined (Table 2) calculating the DC at the steady state for disturbances of $\pm 28 \%$ on FC_{p1} , ± 10 K on Th_1 , $\pm 20 \%$ on FC_{p4} and ± 5 K on Tc_3 . In Figure 1 (b) it is presented the proposed modified HEN for nominal conditions, considering this analysis.

The modified HEN has three heat exchangers (1, 2 and 3), two coolers (4 and 5) and one heater (6) with areas of 24.1, 6.7, 11.4, 30.3, 6.4 and 31.6 m², respectively. The thermal capacity of the cold utility used to cool stream H1 (FC_{p6}) is the same as in the original HEN (4.7 kW/K) but to cool stream H2 (FC_{p5}) it is modified to 7 kW/K. The thermal capacity of the hot utility used to heat stream C2 (FC_{p7}) is 100 kW/K.

With the heater, the energy balance involves 32 variables: FC_{p1} , FC_{p2} , FC_{p3} , FC_{p4} , FC_{p5} , FC_{p6} , FC_{p7} , Th_1 , Th_2 , Th_3 , Th_4 , Th_5 , Th_6 , Th_7 , Th_8 , Th_9 , Th_{10} , Tc_1 , Tc_2 , Tc_3 , Tc_4 , Tc_5 , Tc_6 , Tc_7 , Tc_8 , Q_1 , Q_2 , Q_3 , Q_4 , Q_5 , Q_6 and ϕ . The disturbances variables are the same (FC_{p1} , Th_1 , FC_{p4} and Tc_3) and in addition to the three previous fixed variables (inlet and outlet temperatures of the cold utility and the split fraction of hot stream H1), also the inlet and outlet temperatures of the hot utility ($Th_9 = 573$ K and $Th_{10} = 572$ K) are fixed variables. Again, the network is required to be resilient to disturbances in hot stream H1 and in cold stream C2.

A steady state model for the network consists of 19 equations: three equations relative to each heat exchanger and an energy balance for the mixer located in hot stream H1. For the modified HEN for the nominal conditions, the number of degrees of freedom is four.

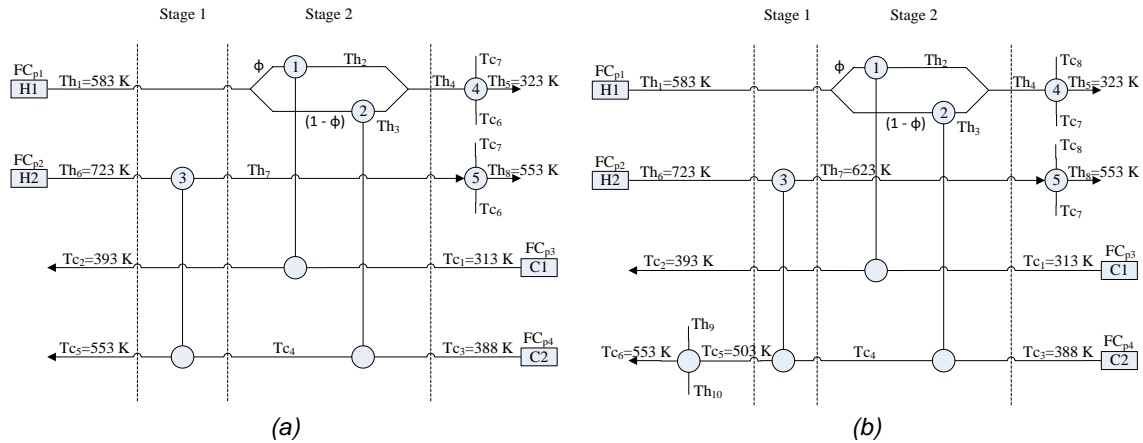


Figure 1: Heat Exchanger Network for (a) nominal conditions and (b) modified

Table 2: Changes on variables and Disturbance Cost

ΔFC_{p1}	ΔTh_1	ΔFC_{p4}	ΔTc_3	ΔFC_{p6}	ΔFC_{p5}	ΔFC_{p3}	ΔFC_{p2}	DC
+28 %	0	0	0	-0.3001	-0.0063	-0.9794	0.1509	1.0354
+28 %	+10 K	0	0	-0.3001	-0.2024	-0.9766	4.8576	4.9680
+28 %	+10 K	+20 %	0	-0.3001	-0.1976	-0.9762	4.7429	4.8557
+28 %	+10 K	+20 %	+5 K	-0.3001	-0.1011	-0.9881	2.4272	2.6396
0	+10 K	+20 %	+5 K	0	-0.0948	-0.0087	2.2763	2.2783
0	0	+20 %	+5 K	0	0.1013	-0.0114	-2.4304	2.4326
0	0	0	+5 K	0	0.0965	-0.0118	-2.3158	2.3178
-28 %	+10 K	-20 %	+5 K	0.3001	-0.0981	0.9699	2.3547	2.5661
-28 %	-10 K	-20 %	-5 K	0.3001	0.1011	0.9881	-2.4272	2.6396
+28 %	-10 K	+20 %	-5 K	-0.3001	0.0981	-0.9699	-2.3547	2.5661

Thus, four controlled variables (Th_5 , Th_8 , Tc_2 and Tc_6) can be paired with four manipulated variables (FC_{p6} , FC_{p5} , FC_{p3} and FC_{p7}). Using $\Delta u = 0.01$ and $\Delta d = 0.01$ for all variables, $\Delta \mathbf{u}^{\max} = [4.7, 7, 3, 100]$ and $\Delta \mathbf{d}^{\max} = [28 \%, 10 \text{ K}, 20 \%, 5 \text{ K}]$, the resulting linearized model is represented by Eq(12).

$$\begin{bmatrix} \Delta Th_5 \\ \Delta Th_8 \\ \Delta Tc_2 \\ \Delta Tc_6 \end{bmatrix} = \begin{bmatrix} 13.7 & 0.0 & 0.0 & 0.0 \\ 0.0 & 356.8 & 0.0 & 57.7 \\ 89.6 & 0.0 & -51.8 & 0.0 \\ 0.0 & 0.0 & 0.0 & -19.7 \end{bmatrix} \cdot \begin{bmatrix} \Delta FC_{p6} \\ \Delta FC_{p5} \\ \Delta FC_{p3} \\ \Delta FC_{p7} \end{bmatrix} + \begin{bmatrix} 4.1 & 0.0 & 0.0 & 0.0 \\ 1.1 & 0.3 & -9.9 & 2.1 \\ -23.9 & 0.1 & 0.0 & -0.6 \\ 0.0 & 0.0 & -1.5 & 0.0 \end{bmatrix} \cdot \begin{bmatrix} \Delta FC_{p1} \\ \Delta Th_1 \\ \Delta FC_{p4} \\ \Delta Tc_3 \end{bmatrix} \quad (12)$$

The steady state RGA computation is made using matrix $\mathbf{P}\{0\}$.

$$RGA = \begin{bmatrix} 1.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 1.0 \end{bmatrix} \quad (13)$$

Again RGA indicates that the diagonal pairing is preferred ($Th_5 - FC_{p6}$, $Th_8 - FC_{p5}$, $Tc_2 - FC_{p3}$ and $Tc_6 - FC_{p7}$), providing answers perfectly dissociated. The resilience of the HEN is examined calculating the DC for disturbances of $\pm 28 \%$ on FC_{p1} , $\pm 10 \text{ K}$ on Th_1 , $\pm 20 \%$ on FC_{p4} and $\pm 5 \text{ K}$ on Tc_3 and it is presented in Table 3. It is also presented the variation values in the manipulated variables for the disturbances, assuming perfect control.

It is noted in Table 3 that the rejection of disturbances is achieved by the manipulated variables with little control effort. Therefore, the resilience of the network for nominal conditions is acceptable when a heater in stream C2 is added, because it provides DC values less than or close to one.

Table 3: Changes on variables and Disturbance Cost for modified Heat Exchanger Network

ΔFC_{p1}	ΔTh_1	ΔFC_{p4}	ΔTc_3	ΔFC_{p6}	ΔFC_{p5}	ΔFC_{p3}	ΔFC_{p7}	DC
+28 %	0	0	0	-0.3001	-0.0032	-0.9794	0.0000	1.0243
+28 %	+10 K	0	0	-0.3001	-0.0042	-0.9766	0.0000	1.0217
+28 %	+10 K	+20 %	0	-0.3001	0.0361	-0.9762	-0.0771	1.0248
+28 %	+10 K	+20 %	+5 K	-0.3001	0.0303	-0.9881	-0.0771	1.0359
0	+10 K	+20 %	+5 K	0	0.0335	-0.0087	-0.0771	0.0845
0	0	+20 %	+5 K	0	0.0345	-0.0114	-0.0771	0.0852
0	0	0	+5 K	0	-0.0058	-0.0118	0.0000	0.0132
-28 %	+10 K	-20 %	+5 K	0.3001	-0.0439	0.9699	0.0771	1.0192
-28 %	-10 K	-20 %	-5 K	0.3001	-0.0303	0.9881	0.0771	1.0359
+28 %	-10 K	+20 %	-5 K	-0.3001	0.0439	-0.9699	-0.0771	1.0192

4. Conclusions

It is necessary to consider the concepts of flexibility, controllability and resiliency for designing a heat exchanger network due to the uncertainties and disturbances in industrial processes. This was the motivation to describe the C&R analysis, using RGA and DC index. This paper presented the procedure used by Seider et al. (2009) to analyze the C&R in steady state. A literature example, which only aimed to synthesize a multiperiod HEN, was used to apply the C&R analysis. It was presented the diagonal pairing as preferred. Furthermore, the analysis performed in the present paper indicated that a HEN modified with the addition of a heater in stream C2 exhibits superior performance than the original HEN from the controllability point of view.

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