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New Approach for Designing an Optimum and Flexible Heat Exchanger Network

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Abstract

It is significant to study and improve the flexibility of chemical plants. The flexibility defined as the capability to operate this plant over a range of conditions under external disturbances or inherent uncertainty while satisfying performance specifications by convenient control variables adjustment. The target of this work is to introduce a new approach for designing optimal flexible Heat Exchanger Network (HEN) in a similar fashion of multi-period design depending on similar period durations of worst operating conditions. These worst conditions lie within the uncertainty range in terms of extreme heat load requirements to decrease number of exhaustive iteration and enhance flexibility index from the first design step. This contribution work presents a combined systematic procedure for optimum flexible HEN design based on several mathematical models using linear Interactive and Discrete Optimizer (LINDO) software and Heat Integration Network Targeting (HINT) software. Also provide with comparison and evaluation of existing methods with case study. This presented work resulted in optimum flexible HEN with controllable structure without losing stream targets while keep working at minimum energy consumption levels and achieved minimum Total Annual Costs (TACs) rather than two works in comparison.

Introduction

The HEN design links the utility system with the process flow sheet; therefore, it includes a large fraction of both operating and capital costs, consequently the optimum HEN design considered the key factor to gainful industry. During the last few decades, design strategies focused on single nominal operating conditions, which still a substantial gab between designs obtained and those needed practically. Therefore, design a flexible HEN that can adapted to inevitable parameter variations turned into a must to grantee operable and controllable operation with quality and stability transition to the new set of operating conditions without losing stream temperature targets as a main objective and minimizing utility targets as a secondary goal. The operating parameters fluctuation may be scheduled stets of periods (multi-period) or random around a set of nominal values due to unfrozen events, consequently they usually defined within ranges instead of single nominal value. Robustness is the first flexibility level at which HEN can absorb disturbances without changing the flow rate of utilities [1]. Linnhoff [2] presented sensitivity tables for retrofitting nominal design to compensate for the process variations. Marselle [3] developed a resilient design procedure for many well-selected ultimate operating conditions and combined those configurations manually without any systematic procedure assuming it will cover all intermediate cases, which is impossible in large size problems. A scalar flexibility index launched by Swaney and Grossman [4, 5] aimed to quantify the maximum parameter deviation from the nominal conditions relative to target that HEN can tolerate and still operate feasibly. Floudas and Grossman [6] formulated Rigorous flexibility analysis by mathematical programming based on active constraint strategy using either Mixed Integer Linear Programming (MILP) or Mixed Integer Nonlinear Programming (MINLP) depending on constraints nature. They also introduced the multi-period sequential model [7, 8]. A great progress proposed by Yee and Grossmann [9] is a simultaneous HEN design

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of least total annual cost. Altota [10] extended the simultaneous design for multi-period HEN. Nevertheless, the objective function relies on the average area requirement as the representative. Such assumption underestimates the required area consequently underestimates costs. Verheyen [11] introduced the maximum area approach as the representative in the objective function.

Chang and Sadeli [12] applied the time sharing mechanism for flexible multi-period HENs; they suggest swapping units with other stream pairs. That switching between periods would drawback not only expending operating costs and time for cleaning units, but also it would need extra fixed costs of construction for supplementary piping and accompanying instrumentation for bypasses and streams rerouting. Li et al. [13] improved two-stage design approach for flexible HENs using simulated annealing and decoupling strategy. Escobar et al. [14] extended the Lagrangean decomposition for solving flexible multi-period HENs, with up to 15 process streams. Leandro [15] used post optimization to adapt single period design to handle a multi-period HEN. Bakr et al. [16] discussed the effect of optimality factor (Δtmin) on controllability and flexibility prediction at the preliminary design stages. Li et al [17] studied individual heat exchangers passive performance aspects such as fouling, pressure drop, intensified heat transfer and thermal performance with their effects on whole network thermal performance. Lately many research works study Work and Heat Exchange Network (WHEN) simultaneously that based on variable stream temperature and pressure as well [18, 19].

In this work, flexible HEN design introduced with good initiation to cover vertex through entire range. That saves time and effort; this has approved with the introduced case study.

Problem statement

Data given: two sets of process streams to be heat exchanged; hot "source" and clod "destination". Giving for each stream, the nominal inlet, outlet temperatures and heat capacity flow rate with their fluctuation range. Also, available both auxiliary cooling and heating with their temperature levels. Specifying each unit heat transfer coefficients and cost parameter.

Objective agenda: the main goal is to design an optimal HEN, while remaining flexible under entire parameter bounds deviation without violation physical constraints (negative flow, negative heat load, temperature cross).

Methodology

The typical method is to design firstly without considering flexibility for the nominal operating point, using either sequential or simultaneous method. Then, apply the 'flexibility test' to this initial design. If the results not satisfied, the critical operating points will have identified.

Thus, the design should be repeated within a loop until satisfy target as illustrated in Figure 1. The subsections below clarify the proposed different steps getting a flexible HEN.

Step 1: HEN synthesis in multi-period fashion

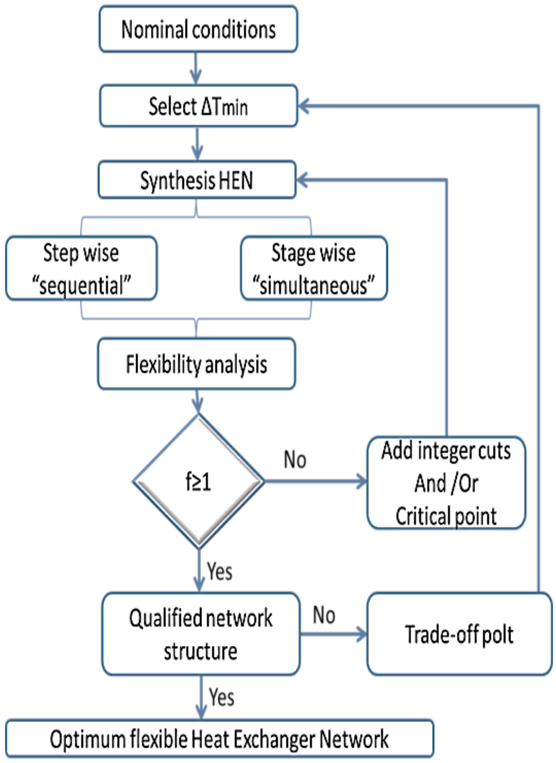

Figure 1 Methodology for optimum flexible HEN design

<u>**Apply the Sequential Step Wise Superstructure:**</u> regarding this scenario, the network assumed as a multi-period HEN. Thus, each heat exchanger designed to process variable heat loads using splitting fractions and bypasses (control variables) in addition to variable load utilities. Marselle [3] recommended selection periods of the extreme heating and cooling requirements for HEN. That guarantee for any operating set in the fluctuation range, the pinch point will be located between the pinch temperatures of both situations [20]. Adding conditions of maximum total heat exchange capacity and maximum total area.

First, Solving Papoulias and Grossmann LP (P 1) model [21] using LINDO software, the objective function is to define pinch point locations and the minimum utility requirements for each selected period independently based on energy balances for each steam around each temperature interval.

$$\left\{\begin{array}{ll}
\text{Min } C_{OP} = \sum_{m\in S} C_m Q_m^S + \sum_{n\in W} C_n Q_n^W & \\
\text{s.t.}\quad R_{ik} - R_{i,k-1} + \sum_{j\in C} Q_{ijk} + \sum_{n\in W} Q_{injk} = Q_{ik}^H & \forall i \in H \quad \forall k \in K \\
R_{mk} - R_{m,k-1} + \sum Q_{ijk} - Q_m^s = 0 & \forall m \in S \quad \forall k \in K \\
\sum_{i\in H} Q_{ijk} + \sum_{m\in S} Q_{mjk} = Q_{jk}^C & \forall j \in C \quad \forall k \in K \\
\sum_{i\in H} Q_{ink} - Q_n^W = 0 & \forall n \in W \quad \forall k \in K \\
R_{ik}, R_{mk}, Q_{ijk}, Q_{ink}, Q_m^S, Q_n^W \geq 0 & \\
R_{i0}, R_{ik} = 0 &
\end{array}\right\} \quad \text{(P 1)}$$

Then, apply model (P 2) using LINDO software with considering both utilities as a known duty streams from the previous step to determine and select the least number of matches for the selected periods simultaneously and determine their amount of heat exchanged. The logical constraint $U_{ij} \in \{0, 1\}$ encodes HEX presence (1) / absence (0) where Y_{ij} categorized into three sorts:

a) The match (i, j) has a single potential in only one sub-network per period.

$$U_{ij} = Y^{a}_{ij} \qquad (i, j) \in P_a$$

b) The match (i, j) is probable in more than one sub-network in just one period (dominant period), but for the others it is probable only in single sub-network.

$$U_{ij} = \sum_{sd \in ISd} Y^{b}_{ijsd} \qquad (i, j) \in P_b$$

c) The match (i, j) has several potentials in different sub-networks in each period (general case). The number of matches is limited to those not corresponding to conditions for cases mentioned in a) or b) categories.

$$U_{ij} \geq [\sum_{st \in IST} Y_{ijst}]$$

$$i \in HA,\ j \in CA,\ t = 1,2 \ldots N\ (i, j) \notin P_a, P_b$$

(P 2)

$$\min \sum_{i \in HA} \sum_{j \in CA} u_{ij}$$

s.t. (a) Constraint for number of units

$$U_{ij} = Y^{a}_{ij},\ (i, j) \in P_a$$

$$U_{ij} = \sum_{sd \in ISd} Y^{b}_{ijsd}\ (i, j) \in P_b$$

$$U_{ij} \geq [\sum_{st \in IST} Y_{ijst}] \qquad i \in HA,\ j \in CA,\ t = 1,2 \ldots N$$

(b) Heat balance constraints:

$$R_{i,kst} - R_{i,k1st} + \sum_{j \in CAkt} Q_{ijkst} = Q^{h}_{ikst}$$

$$i \in HAkt,\ k \in ITst,\ st \in ISt,\ t = 1, 2 \ldots N$$

$$\sum_{I \in CAkt} Q_{ijkst} = Q^{C}_{jkst}$$

$$j \in CAkt,\ K \in IT_{st},\ st \in IS_t,\ t = 1,2 \ldots N$$

(c) Logical constraints:

$$\sum_{K \in ITst} Q_{ijkst} - B^{st}_{ij} Y^{a}_{ij} \leq 0$$

$$St \in IS_T,\ t = 1,2 \ldots N,\ (i, j) \in P_a$$

$$\sum_{k \in IT} Q_{ijkst} - B^{sd}_{ij} Y^{b}_{ijsd} \leq 0$$

$$sd \in ISd,\ t \neq d,\ (i, j) \in P_b$$

$$\sum_{k \in ITst} Q_{ijkst} - B^{st}_{ij} \sum_{sd \in ISd} Y_{ijsd} \leq 0 \qquad st \in ISt,\ t = d$$

$$\sum_{k \in ITst} Q_{ijkst} - B^{st}_{ij} Y_{ijst} \leq 0$$

$$st \in IST,\ t = 1, 2 \ldots N,\ i \in HA,\ j \in CA,\ (i, j) \neq P_a, P_b$$

(d) Non-negativity constraints:

$$R_{ikst} \geq 0, \qquad Q_{ikst} \geq 0, \qquad u_{ij} \geq 0$$

(e) Binary variables {0, 1} constraints:

$$Y_{ijst} = 0, 1 \qquad Y^{a}_{ij} = 0, 1 \qquad Y^{b}_{ijsd} = 0, 1$$

Finally determining the optimum interconnection between streams and heat exchangers with the minimum investment cost and sizing of the selected unit applying NLP model [8].

Step 2: Flexibility Analysis [6]

Two levels check analysis have described below:

1) *Qualitative feasibility test:* For determining if, the initially designed HEN is feasible to operate over full uncertainty range or not [22]. The decision based on sign of test.
2) *Quantitative flexibility index (F):* Evaluated by the minimum value of feasible scaled deviation δ relative to target among active set of the structure [5]. For a flexible HEN, flexibility index has to be at least greater than or equal to unity [4].

The operation represented by sets of equality constraints to describe equilibrium relations and inequality constraints representing design specifications. Active constraints (*F_j*) formulated as reduced inequalities by the significance of control variables [6]. Models **(P 3)** and **(P 4) Error! Reference source not found.**show active constraints testing by mixed integer optimization to automate the logical decision.

Feasibility test (P 3)

$$X(d) = \max_{\Theta, z, u, sj, \lambda j, yj}\ u$$

s.t. $f_j(d, Z, \boldsymbol{\theta}) + \boldsymbol{S}_j - \boldsymbol{u} = \mathbf{0}$

$$\sum_{j \in J} \lambda_j = 1$$

$$\sum_{j \in J} \lambda_j \frac{\partial f_j}{\partial z} = 0$$

$$\lambda_j - y_j \leq 0 \qquad j \in J\lambda$$

$$S_j - M(1 - y_j) \leq 0$$

$$\sum_{j \in J} y_j = n_z + 1$$

$$\Theta^{L} \leq \Theta^{N} \leq \Theta^{U}$$

$$y_j = \{0, 1\}; \qquad \lambda_j, S_j \geq 0$$

Flexibility test (P 4)

$$F = \min_{\Theta, z, \delta, sj, \lambda j, yj}\ \delta$$

s.t. $f_j(d, z, \Theta) + s_j = 0$

$$\sum_{j \in J} \lambda_j = 1$$

$$\sum_{j \in J} \lambda_j \frac{\partial f_j}{\partial z} = 0$$

$$\lambda_j - y_j \leq 0 \qquad \forall j \in J$$

$$S_j - M(1 - y_j) \leq 0$$

$$\sum_{j \in J} y_j = n_z + 1$$

$$\Theta^{N} - \delta\, \Delta\Theta^{-} < \Theta^{N} < \Theta^{N} + \delta\, \Delta\Theta^{+}$$

$$\delta \geq 0;\ y_j = \{0, 1\};\ \lambda, S_j \geq 0$$

Finally, post optimization for minimum approach temperature (Δt_{min}) takes place to make economics and controllability issues work compatibly as referred in Figure 1.

The case study

The investigated case study in the current research has four process steams (two hot and two cold). **Error! Reference source not found.** listed their source and destination temperatures, heat capacity flow rates with their expected fluctuations and the available utilities with their temperature levels.

Table 1 The investigated case study data

Stream	Inlet Temperature T_{in} (°K)	Outlet Temperature T_{out} (°K) "constant "	Heat Capacity Flow rate CP (KW/°K)
H1	583 ± 10	323	1.4 ± 0.4
H2	723	553	2
C1	313	393	3
C2	388 ± 5	553	2 ± 0.4
CU	303	323	
HU	573	573	

The costs of the heat exchanger, cooling and heating utilities are as follows:

Capital Cost of Heat exchanger ($) = $B + C{*}A_{ij}^{\beta}$

$= 26600 + 4333 * [A_{ij}(m^2)]^{0.6}$ [23]

Annual operating time (T_{total}) = 8600 (hr/Y) [24, 25]

Capital annual factor = 0.2 [24, 25]

Annual cooling / heating utility costs = 60.576 ($KW^{-1} Y^{-1}) / 171.428 ($KW^{-1} Y^{-1}) respectively [24, 25]

Results and Discussion

According to recent recommendations [26, 23], the capital costs equation should consider the fixed-term of construction and installation besides area-related term. Thus, both capital costs of the reference work [8] and [25] recalculated. **Error! Reference source not found.** shows a comparison of the current study results with two different reference networks under consideration **Error! Reference source not found.,Error! Reference source not found.,Error! Reference source not found.**. Firstly, applying the model **Error! Reference source not found.** the results confirmed that the variation in conditions between periods resulted in variations of both minimum utility requirements and sub-network boundaries between periods. Secondly, applying model **Error! Reference source not found. Error! Reference source not found.** shows that a minimum of five units required and it is the same number of units as obtained by reference work **Error! Reference source not found.**, but they selected different units with different duties. This consequently leads to different units' arrangement, areas as well as different capital costs. Referring to

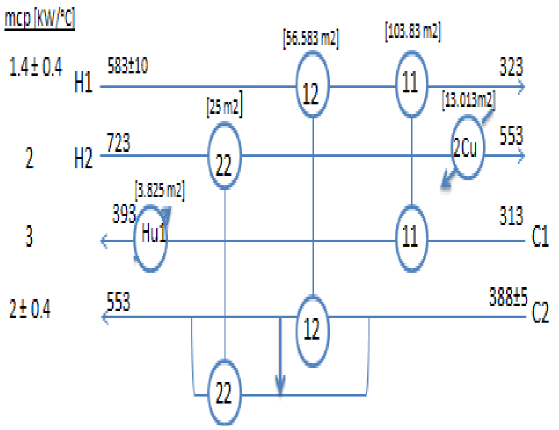

Figure 4: The resulting Network of the considered case study

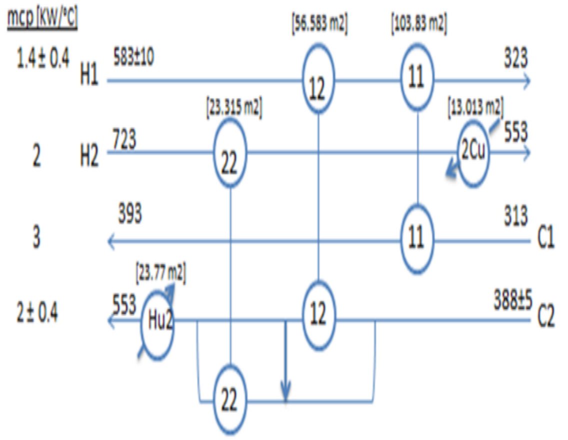

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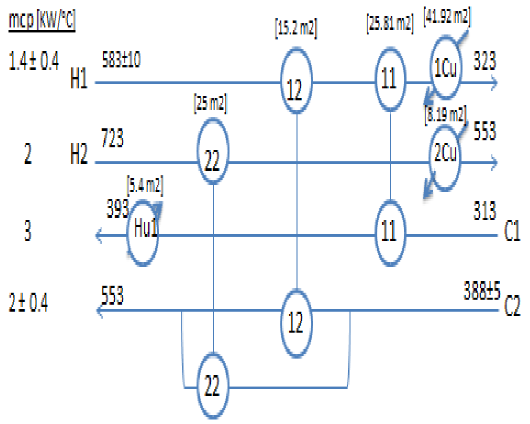
Figure 2 HEN obtained by Floudas and Grossmann [8]



splitting of the second cold stream C2 and a special

Figure 3 HEN obtained by Chen and Ping [25]

splitting in the branch of (H1-C2) that tolerates series, parallel, or other arrangements for exchangers and similarly the mixing ratio will have considered as a control variable in the next step.

Such resulted structure guarantee obtaining an optimum and feasible network with minimum energy consumption and area targets for the four selected parameter periods. Nevertheless, this HEN needs testing for determining its flexibility over the entire range of parameter variations.

The next step is testing for flexibility. The considered HEN resulted in a flexibility index of one, consequently it shows good performance toward any expected fluctuation within the given uncertain rang. Thus, good design initiation will accelerate the achievement of an optimum flexible HEN by decreasing the search space.

Finally, according to recommendations of post optimization to the assumed Δtmin [8], HINT software based on modified pinch technology could study the effect of (Δtmin) on area targeting, number of units and economics of capital, operating and total costs. Applying the HINT on the current case study at nominal conditions over Δtmin range of (0:50°C) shows that the optimum Δtmin is approximately 25 °C. Figure 5 shows a sharp decrease in the capital costs over Δtmin= 10°C and confirms the enhancement of logarithmic mean temperature difference Δtlm on both exchanger sides, which leads to area reduction. Alternatively, referring to the considered simultaneous optimization Figure 4, the units work approximately at Δtmin of 25 °C as the optimum value. Thus, flexibility test at the set point of 10°C Δtmin can tolerate up to 1.71, Table 2. That is the reason behind the simultaneous strategy does not need further optimization for Δtmin and usually gives flexibility index values exceed unity.

Therefore, a lower (Δt_{min}) gives lower controllability criteria "higher sensitivity and lower flexibility"; accordingly, it tightens the operation range. Otherwise, a lower (Δt_{min}) gives full energy integration, so decreases operating costs, while increases capital cost. Therefore, optimization for all factors of economics and operation must be compatible to work together.

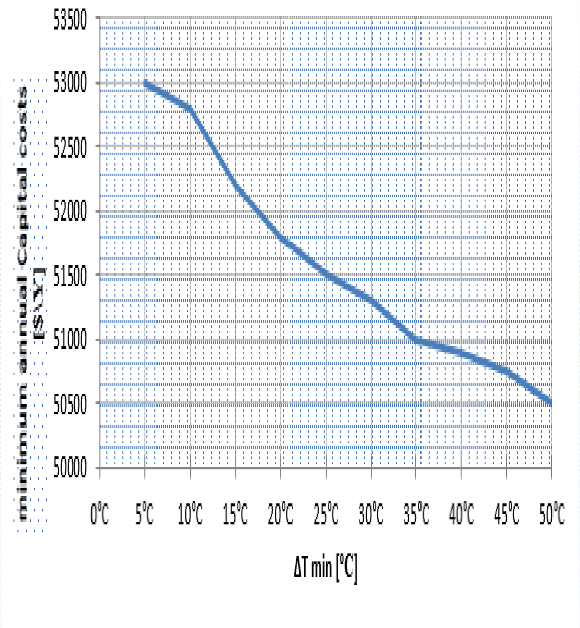


Figure 5: Minimum annual capital costs VS. ΔTmin at nominal conditions

Table 2 Results of the investigated case study compared with two other models

Study	Floudas and Grossmann (1987)	Chen and Ping (2004)	The current study
Used Model	Sequential	Simultaneous	Sequential
Number of selected units	5	6	5
Mean operating costs [$/Year]	10499	11772	10499
Annual capital costs [$/Year]	65980	62024	62365
Total annual costs TAC [$/Year]	76479	73796	72864
Flexibility Index *F*	1	1.71	1

Regarding **Error! Reference source not found.** although, all of the three HENs provide a sufficient flexibility index, the simultaneous HEN shows the highest *F*. On the other hand, the two sequential HENs satisfy the maximum energy recovery as a global optimum of minimum operating costs compared to the simultaneous HEN, which in turn regarded not energy efficient. Whereas the present world considered this single-step, optimization as short time optimization [26] and prefers sequential method of multi-step procedure. Although, the annual capital costs for the simultaneous method are the lowest, it shows higher TAC due to the increased number of selected units; six units compared to five units in the two other HENs. The reason behind is assuming isothermal mixing, which eliminates nonlinear energy balances at the expense of reduction of many effective structures in order to shorten the problem size.

It is clear that the procedure used in the present study shows flexibility with the minimum TAC and this in turn makes this approach preferable over other models. In the present study, the introduced design procedure achieves all optimality and energy saving besides flexibility.

Conclusion

Many research works studied different approaches to achieve an optimum and flexible HEN. This work introduces a new strategy for such design consists of the following two steps:

- The first step considers design with good initiation using sequential method.
- The second step directed to flexibility analysis over the full uncertainty range (vertices and non-vertex operating points).

For showing the benefits of the developed new approach, it is compared to other two strategies. The results showed that the introduced approach achieves the minimum total annual costs with a good flexibility index in one iteration. This consequently makes this approach preferable over the other models.

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Conflicts of interest

There are no conflicts to declare

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