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Synthesis of Multiperiod Heat Exchanger Networks Involving 1 Shell Pass – 2 Tube Pass Design Configurations

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This paper presents a systematic synthesis method that considers multiple shells and logarithmic mean temperature difference (LMTD) F_T correction factor for heat exchanger networks (HENs) involving multiple periods of operation. The approach adopted entails firstly generating a reduced multiperiod HEN superstructure using network solutions obtained when the STEP (Stream Temperature Versus Enthalpy Plot) and HEAT (Heat Allocation and Targeting) synthesis methods are applied to each subperiod. The second stage entails generating an initial multiperiod HEN solution from the reduced superstructure synthesis approach. The number of shells, as well as the F_T correction factor, required by each exchanger in each period of the initial multiperiod HEN are then manually calculated and used to initialise the multiperiod HEN to obtain updated representative heat exchanger areas for all stream pairs in all periods of operations. The solution obtained, when the method of this paper is applied to a literature example, shows that the assumption of 1 – 1 (1 shell pass – 1 tube pass) design configuration for multiperiod HEN problems, underestimates the representative heat exchanger areas by 12.3%.

1. Introduction

Due to the rising concerns on carbon emissions, process plants are faced with the challenge of minimising the use of fossil-based energy sources. Heat exchanger network synthesis (HENS) has been successfully used to achieve significant reduction in not only utility utilisation in process plants, but capital costs as well. Most of the methods that have been presented for HENS in the literature have assumed that stream parameters such as supply and target temperatures, flowrates, etc., are constant. However, due to variations in feed quality, product demand, environmental conditions, and process upsets, stream parameters do fluctuate in both predictable and unpredictable ways. The predictable fluctuation scenario requires multiperiod networks, while the unpredictable scenario requires flexible networks. This paper focuses on the synthesis of multiperiod networks.

Aaltola (2002) was the first to adapt the stage-wise superstructure (SWS) model of Yee and Grossmann (1990) to the synthesis of HENs involving multiperiod operations. In the model of Aaltola (2002), the representative heat exchanger for the same stream pairs existing in multiple periods of operations was determined using the average area approach. According to Verheyen and Zhang (2006), who also used the multiperiod version of the SWS model of Yee and Grossmann (1990), the average area approach fails to give the optimal network, so they developed the maximum area approach. The maximum area approach was also used by Isafiade and Short (2016) who adopted the reduced superstructure synthesis approach for multiperiod HENs involving multiple utilities. Isafiade and Short (2020) extended the reduced superstructure synthesis method of Isafiade and Short (2016) by including additional initialising units, obtained from the STEP method of Wan Alwi and Manan (2010), in the superstructure. Yoro et al. (2019) is among the few papers that have adopted pinch technology to solve multiperiod HENs.

What is common to the multiperiod synthesis methods reviewed so far, including most of the other methods in the literature, is that the design of the individual exchangers constituting the network have been simplified by assuming 1 – 1 design configuration. Such simplifications may be due to the presence of non-convex and bilinear terms in the design of heat exchangers. Although, for a given heat duty, and overall heat transfer coefficient, the 1 – 1 configuration requires smaller heat exchanger area compared to the 1 – 2 (1 shell pass –

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2 tube passes) design (Smith, 2005). This is because the flow in the 1 – 2 configuration involves both co-current and counter-current profiles which leads to reduced effective temperature difference for heat exchange (Smith, 2005). The F_T correction factor is used in design to account for the reduced effective temperature difference. However, the 1 – 2 design is used in the industry due to its advantages over the 1 – 1 design in terms of practical applications (Smith, 2005). For the 1 – 2 designs in single period HENs, ignoring the F_T correction factor implies that the resulting heat exchangers may be underestimated. The implication of such underestimation will be significant in multiperiod HENs since exchangers in the network will experience periodic changes in stream parameters. Even when the F_T correction factor is not ignored in multiperiod HENS, consideration still needs to be given to the design to ensure that the exchanger requiring the maximum area also requires the maximum number of shells.

The first synthesis method to include detailed heat exchanger designs in multiperiod HENs is that of Short et al. (2016). Their technique used the multiperiod SWS model of Verheyen and Zhang (2006) to generate feasible networks involving simplified heat exchanger designs. The exchangers are then further designed to establish the required number of shells and tubes. The detailed designs are then used to improve the network solution of the simplified SWS model using correction parameters in the objective function. Since the method of Short et al. (2016) relies on directly solving the multiperiod SWS mixed integer non-linear program (MINLP) model of Verheyen and Zhang (2006), applying it to large HEN problems will be non-trivial. Therefore, this paper presents a new systematic synthesis approach for multiperiod HENs involving 1 – 2 configurations. The procedure involves a hybrid of the sequential synthesis method and mathematical programming approach. In the sequential synthesis step, the STEP and the HEAT plots of Wan Alwi and Manan (2010) are both used to obtain utilities and area targets and network designs for all subperiod networks in the problem. Heat exchanger design features such as the F_T correction factor and other key heat exchanger design parameters for the 1 – 2 configurations are then calculated for each unit in the resulting HEAT diagrams. At this stage, consideration is given to multiple shells in series for cases where the single shell 1 – 2 configuration gives infeasible design. The heat exchangers, as well as the parameters, obtained from the HEAT diagram of each subperiod network in the sequential step are then used to initialise a reduced multiperiod MINLP superstructure in the simultaneous optimisation step. The solution of the simultaneous optimisation step is then investigated to see whether there is the need to re-initialise the reduced superstructure based on the number of shells required by the maximum heat exchanger area. The newly developed method is applied to a literature example.

2. Problem statement

Given is a set of hot and cold process streams (HP and CP), having supply and target temperatures (T^s and T^t) and heat capacity flowrates (F). The streams are to be heated and cooled with available hot (HU) and cold (CU) utilities, and their supply and target temperatures, as well as flowrates, can vary periodically. Also given are periodic duration (DOP), stream heat transfer coefficients, (h), heat exchanger area, installation costs (CF) for counter-current heat exchangers, and exchangers with 1 – 2 configurations. The objective is to design an optimal multiperiod HEN involving 1 – 2 exchanger configurations.

3. Methodology

The technique adopted entails four main steps (see Figure 1). The first involves generating feasible networks for each of the subperiods in the multiperiod problem using the STEP and HEAT synthesis methods for single period HENs developed by Wan Alwi and Manan (2010). The STEP and HEAT plots are both used to obtain utilities and area targets and network designs. The second synthesis step entails calculating the required number of shells (N_{SHELLS}), F_T correction factor, and the revised heat exchanger area required by each of the matches obtained in the first synthesis step. To determine the N_{SHELLS}, F_T, and exchanger area (A), parameters such as ratio of heat capacities of the two streams flowing through each exchanger (R), exchanger thermal effectiveness (P), and other variables (W, Z and X_P) that are required in determining the true heat exchanger areas, must also be calculated in Step 2. The equation for calculating the N_{SHELLS} is shown in Eq(1) for cases where R is not equal to 1. The definition of the parameter W is shown in Eq(2). If R = 1, then the N_{SHELLS} is determined using Eq(3). Note that to avoid the steep slopes on the F_T, curves and obtain practical designs, P must be restricted to some fraction of the maximum P using a user defined variable X_P (Smith 2005). The variable Z is defined to calculate the value of P for each shell in situations where 1 – 2 shell configurations are in series. In the third step, a reduced superstructure is generated for the multiperiod problem using the matches obtained for each of the subperiods in Step 1. It should be noted that the STEP and HEAT synthesis methods of Wan Alwi and Manan (2010) have the tendency to produce network solutions whose number of units is greater than the minimum possible number of units. Also, the STEP and HEAT plots may not always generate the same number of stages and matches for all subperiods in a multiperiod problem. This should be considered when generating a reduced superstructure for the multiperiod model. The reduced superstructure, which is both initialised with the set of matches obtained in Step 1 and the parameters calculated for each match in Step 2, is solved in the third step of the synthesis procedure as an MINLP model. Step 4 entails calculating exchanger parameters for each exchanger obtained in Step 3 and then checking the calculated parameters to see whether the selected representative matches for the multiperiod network also requires the largest number of shells when compared to the shell requirements of the other periods. This highlights the deficiency of the existing multiperiod synthesis methods where the maximum area is just selected as the representative heat exchanger without checking feasibility of such exchangers based on the temperature cross principle. If the maximum area exchanger is also the exchanger that requires the largest number of shells, then the final multiperiod network is obtained. If on the other hand, there exists two exchangers where one has the maximum area while the other requires the largest number of shells, then Steps 2, 3 and 4 must be repeated using the network solution generated in Step 4 as a starting network. Since the simultaneous synthesis aspect of the method of this paper is based on the SWS multiperiod model, which can be found in many papers in the literature such as Verheyen and Zhang (2006), only the equations for maximum area and objective function are shown here in Eq(4) and Eq(5). The objective function comprises annual operating and annual capital costs.

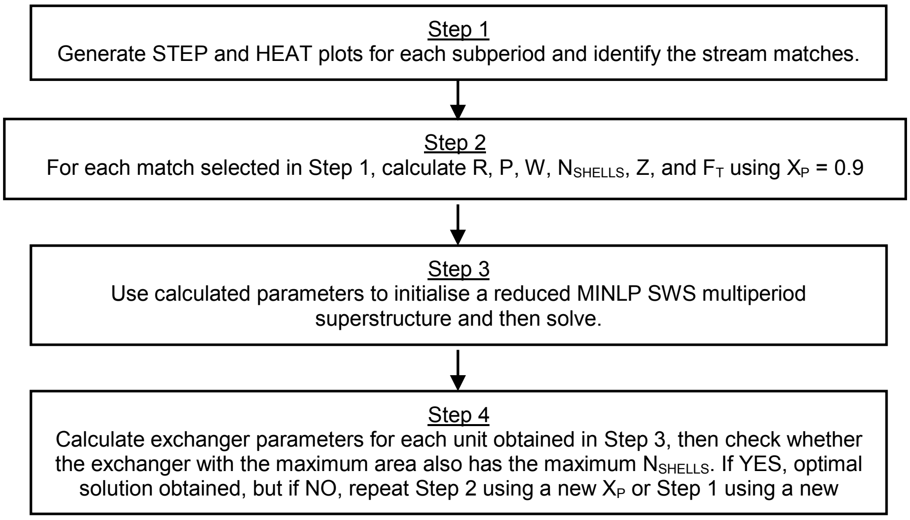
$$R \neq 1: \qquad N_{SHELLS} = \frac{LN((1-RP)/(1-P))}{LN(W)} \tag{1}$$

$$W = \frac{R + 1 + \sqrt{R^2+1} - 2RX_P}{R + 1 + \sqrt{R^2+1} - 2X_P} \tag{2}$$

$$R = 1: \qquad N_{SHELLS} = \frac{(P/1-P)\left(1 + \left(\sqrt{2}/2\right) - X_P\right)}{X_P} \tag{3}$$

$$A_{i,j,k} \geq \frac{q_{i,j,k,p}}{\left(LMTD_{i,j,k,p}\right)\left(F_{Ti,j,k,p}\right)\left(U_{i,j}\right)} \tag{4}$$

$$\begin{aligned} min\Bigg\{ \sum_{p\in P}\Bigg(& \frac{DOP_P}{\sum_{p=1}^{NOP} DOP_p} \sum_{i\in HP}\sum_{j\in CU}\sum_{k\in K} CUC_j \cdot q_{i,j,k,p} + \frac{DOP_P}{\sum_{p=1}^{NOP} DOP_p} \sum_{i\in HU}\sum_{j\in CP}\sum_{k\in K} HUC_i \cdot q_{i,j,k,p}\Bigg) \\ & + AF\Bigg(\sum_{i\in HP}\sum_{j\in CP}\sum_{k\in K} CF_{i,j} \cdot z_{i,j,k} + \sum_{i\in HP}\sum_{j\in CP}\sum_{k\in K} AC_{i,j} \cdot A_{i,j,k}^{ACI}\Bigg)\Bigg\} \\ & \forall\, i \in HP; j \in CP; k \in K; p \in P \end{aligned} \tag{5}$$



Step 1
Generate STEP and HEAT plots for each subperiod and identify the stream matches.

Step 2
For each match selected in Step 1, calculate R, P, W, N_{SHELLS}, Z, and F_T using X_P = 0.9

Step 3
Use calculated parameters to initialise a reduced MINLP SWS multiperiod superstructure and then solve.

Step 4
Calculate exchanger parameters for each unit obtained in Step 3, then check whether the exchanger with the maximum area also has the maximum N_{SHELLS}. If YES, optimal solution obtained, but if NO, repeat Step 2 using a new X_P or Step 1 using a new

Figure 1: Structure of solution procedure of proposed methodology

In Eq(4), $A_{i,j,k}$ (m^2) represents the maximum heat exchanger area required to transfer heat between hot stream i and cold stream j in interval k of the multiperiod SWS model. This area is the biggest area required by the same stream pairs exchanging heat $q_{i,j,k,p}$ (kW) in one or more periods of operations. $U_{i,j}$ in Eq(4) represents overall heat transfer coefficient between hot stream i and cold stream j (kW/m^2·K), $LMTD_{i,j,k,p}$ (K) is the logarithmic mean temperature difference between hot stream i and cold stream j in interval k and period p. Note that since this paper focuses on 1 – 2 exchanger configuration, the F_T correction factor is included in Eq(4). In Eq(5), which is the objective function comprising annual operating and annual capital costs, DOP_p represents duration of operational period p while NOP stands for the number of periods in the problem. CUC_j and HUC_i in Eq(5) represent cost per unit of cold utility j (53.064 \$/(kW·y)) and cost per unit of hot utility i (150.163 \$/(kW·y). AF in Eq(5) represents the annualisation factor and a value of 0.1 was used in the example of this paper. $CF_{i,j}$ represent heat exchanger installation cost and a value of 0 was used. $z_{i,j,k}$ is the binary variable that indicates the existence, or otherwise, of a heat exchanger. $AC_{i,j}$ (4,333 \$/m^2) represents unit cost per unit of heat exchanger area while ACI (0.6) represents area cost exponent.

4. Example

The example of this paper, which was taken from Jiang and Chang (2013), involves two hot streams, two cold streams, one hot utility, one cold utility, and three periods of equal durations. The stream data for the problem is shown in Table 1. Applying the first step of the synthesis procedure to periods 1, 2 and 3, at a $\Delta T_{\min}$ of 10 K, resulted in STEP and HEAT plots having 9 intervals for each of the subperiods. When condensed, by tracing each stream in terms of the actual interval where they are present, the 9 intervals resulted in 7 SWS intervals for the reduced superstructure. The second step of the procedure shown in Figure 1 requires that heat exchanger design parameters such as R, P, W, N_{SHELLS}, Z, and F_T be calculated for each of the 11 matches starting with an X_P value of 0.9. The matches, and the calculated parameters, should then be used to initialise a reduced multiperiod MINLP superstructure in Step 3. The reduced superstructure, which is shown in Figure 2, requires cold utilities in intervals 3 and 6 due to the networks obtained for the HEAT plots of subperiods 1 and 3.

Due to the highly non-convex nature of the reduced superstructure, the application of Step 2 did not give a feasible solution in Step 3. It is hoped that this will be resolved in future work. For this paper, the 11 matches, without the calculated parameters of Step 2, were used to initialise the reduced superstructure which was then solved in Step 3. The multiperiod solution obtained, which selected 7 out of the 11 potential matches, has a total annual cost (TAC) of 207,282 \$/y. This solution compares favorably with other solutions in the literature such as that of Jiang and Chang (2013), which has a TAC of 205,283 \$/y with 6 units, and the solution of Isafiade and Short (2016) which has a TAC of 205,934 \$/y with 7 units. Note that the solution with a TAC of 207,282 \$/y, as well as those presented by Jiang and Chang (2013) and Isafiade and Short (2016), all assumed that all the exchangers in the solution network will require 1 – 1 design configurations. However, the assumption of 1 – 1 configuration is not practical since most industrial shell and tube heat exchangers use multiple pass configuration. Having solved the reduced superstructure, the heat exchanger design parameters for each of the exchangers selected in the solution are calculated as shown in Table 2, for heat exchangers 1, 2, 3 and 4, and in Table 3 for heat exchangers 5, 6, and 7. As required by Step 4 of the synthesis procedure, inspecting Tables 2 and 3, it can be observed that apart from exchanger 4, the subperiod with the maximum exchanger area also requires the largest number of shells. For exchanger 4, the representative exchanger for its subperiods is that of Period 2, since it has the largest area. However, Period 1 requires 6 shells which is more than the 5 shells required by Periods 2 and 3. This implies that the exchanger in Period 2 cannot be the representative exchanger for the subperiods in exchanger 4.

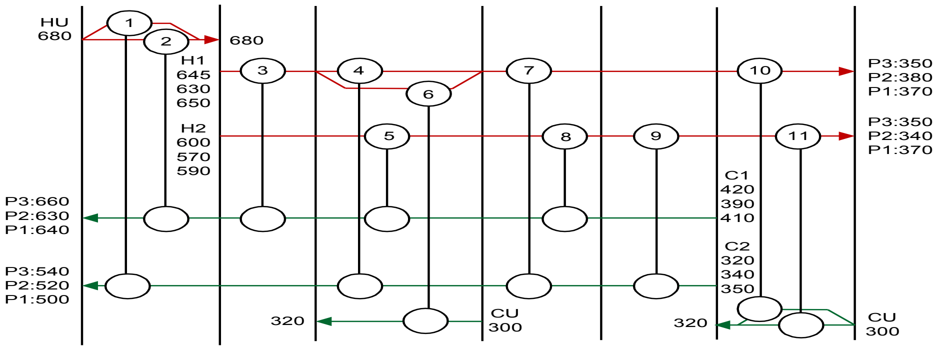


Figure 2: Reduced superstructure showing all potential heat exchangers considered in the MINLP

Table 1: Stream data of case study for start of operation, middle of operation and end of operation.

Streams	Period 1				Period 2				Period 3			
	T^s (K)	T^t (K)	F (kW·K)	h (Kw/m^2·K)	T^s (K)	T^t (K)	F (kW·K)	h (Kw/m^2·K)	T^s (K)	T^t (K)	F (kW·K)	h (Kw/m^2·K)
H1	650	370	10	1	630	380	10.2	1.03	645	350	10	1.01
H2	590	370	20	1	570	340	20.5	1.04	600	350	20.3	1.04
C1	410	640	15	1	390	630	15	1.02	420	660	14.3	1.05
C2	350	500	13	1	340	520	13.5	1.05	320	540	13	1.03
HU	680	680		5	680	680		5	680	680		5
CU	300	320		1	300	320		1	300	320		1

Table 2: Heat exchanger parameters obtained for Periods 1, 2 and 3 in Step 4 for exchangers 1 to 4

Heat exchangers	1			2			3			4		
Periods	1	2	3	1	2	3	1	2	3	1	2	3
X_P	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
N_{SHELLS}	1	1	1	3	3	3	3	5	5	6	5	5
F_T	0,99	0.99	0.99	0.85	0.84	0.88	0.89	0.82	0.82	0.82	0.75	0.79
A (m^2)	7,37	8.20	18.0	77.9	79.7	62.5	59.2	130	131	242	249	210

Table 3: Heat exchanger parameters obtained for Periods 1, 2 and 3 in Step 3 for exchangers 5 to 7

Heat exchangers	5			6			7		
Periods	1	2	3	1	2	3	1	2	3
X_P	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
N_{SHELLS}	1	1	1	1	1	1	1	1	1
F_T	0.99	0.76	0.93	0.98	0.98	0.95	0.97	0.93	0.95
A (m^2)	3.38	45.2	21.5	10.7	9.00	19.1	35.1	45.6	45.1

Table 4: Revised heat exchanger parameters obtained for Periods 1, 2 and 3 in Step 4 for exchangers 1 to 4

Heat exchangers	1			2			3			4		
Periods	1	2	3	1	2	3	1	2	3	1	2	3
X_P	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8
N_{SHELLS}	1	1	1	3	3	3	3	5	5	7	7	6
F_T	0.99	0.99	0.99	0.84	0.84	0.88	0.90	0.82	0.81	0.88	0.89	0.86
A (m^2)	7.44	8.21	18.0	78.7	79.7	62.5	57.3	133	133	218	210	192

Table 5: Revised heat exchanger parameters obtained for Periods 1, 2 and 3 in Step 4 for exchangers 5 to 7

Heat exchangers	5			6			7		
Periods	1	2	3	1	2	3	1	2	3
X_P	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
N_{SHELLS}	1	1	1	1	1	1	1	1	1
F_T	1.0	0.78	0.93	0.98	0.98	0.95	0.97	0.93	0.95
A (m^2)	4.4	45.2	21.0	11.5	8.75	18.8	34.6	45.9	45.3

To get a feasible representative heat exchanger size for exchanger 4, X_P, which is an optimisation variable, can be decreased from 0.9 to 0.8. This was done by calculating the F_T for all periods when X_P is 0.8 for exchanger 4 while X_P for other exchangers remain fixed at 0.9. The resulting F_T from exchanger 4, as well as all other F_T, were then used to initialise the reduced superstructure (i.e., the network with TAC = 207,282 $/y). The resulting network solution has the set of exchanger parameters shown in Tables 4 and 5. In Table 4, all exchangers, including exchanger 4, now have the exchanger with the maximum area also requiring the largest number of shells. This solution, which is shown in Figure 3, is the final network that will feasibly exchange heat between all streams in all periods. The solution has a TAC of 210,379 $/y. This solution, whose TAC is 1.5 % higher than the solution that assumed 1 – 1 design configurations for all exchangers, is better because all exchangers can feasibly exchange heat in all periods since potential temperature crosses are eliminated through the inclusion of multiple shell arrangements in series.

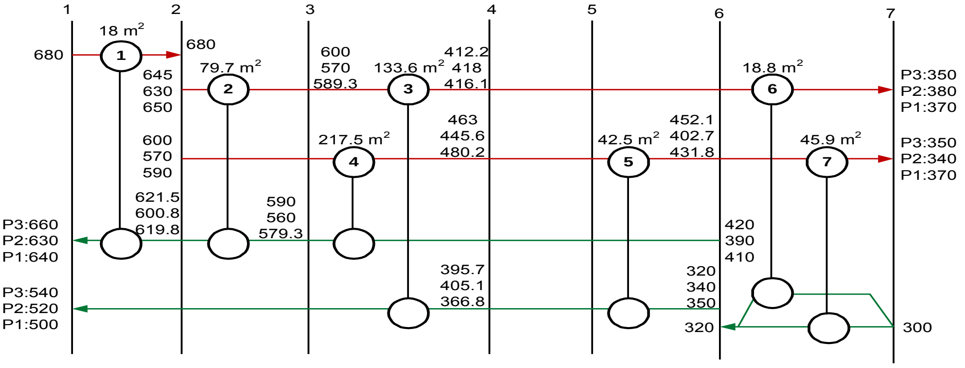


Figure 3: Optimal solution for the example featuring maximum sized exchangers for all subperiods

5. Conclusions

This paper has presented a systematic procedure for optimising HENs involving multiperiod operations. The procedure involves ensuring that feasible heat exchangers that do not have temperature crosses are obtained. The paper has shown that existing methods for multiperiod HENS, which have mostly adopted simplified heat exchanger design approaches, have presented exchangers for multiperiod operations where the maximum area exchanger was selected, however, such exchanger may not feasibly exchange heat in all periods. For the literature example considered in the paper, it was found that existing methods underestimates network heat exchanger area by 12.3 %. The approach used in this paper is sequential, which implies that it will be tedious to apply to large multiperiod problems. To circumvent this problem, future works will consider optimising the network simultaneously by ensuring that the reduced superstructure of Step 3 is initialised with not only the matches selected in the STEP and HEAT plots, but with all exchanger parameters obtained in Step 2 of the synthesis procedure.

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