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A New Approach to Generate Flexible Multiperiod Heat Exchanger Network Designs with Timesharing Mechanisms

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S Supporting Information

ABSTRACT: Seasonal changes in demands, supplies, and also in the operating conditions of a chemical process may call for different system structures to optimize the performance of its heat exchanger network (HEN). To produce a multiperiod HEN design, the traditional approach is to solve a single mathematical program that minimizes the total annual cost (TAC). This objective function, that is, TAC, is usually the sum of the annualized capital costs and annual utility costs determined according to given durations of all periods in a year. As a result, the conventional designs are often suboptimal, since the period lengths may have to be adjusted in response to the unexpected disturbances during actual operations. A new design approach is taken in the present study to circumvent the aforementioned drawback. In particular, a single-period model is first constructed and solved to produce the optimal design for each period individually. A timesharing strategy is then applied to integrate all such single-period designs so as to reduce the overall capital investment as much as possible while still keeping the utility consumption rates in every period at the minimum levels. In addition to their economic benefits, the new designs should be considered to be more flexible, since they are optimal despite unforeseen changes in the operation schedule. Finally, the numerical results of extensive case studies are also reported in this paper to demonstrate the effectiveness of the proposed approach.

INTRODUCTION

Heat exchanger network (HEN) synthesis has been a well-studied subject over the last three decades. The mathematical programming approaches for this task can be classified into two different types, that is, the sequential and simultaneous optimization strategies.[1−3] The former usually calls for decomposition of the design procedure into several consecutive steps so as to reduce the computation effort. Such a practice inevitably leads to suboptimal solutions because the trade-off issues between energy consumption and capital expenditure cannot be properly addressed. Although this shortcoming can be overcome with the simultaneous strategy in principle, the required optimization runs may not always be convergent.

In a realistic production environment, the demands, supplies, and also the operating conditions of a chemical process may undergo seasonal variations. Such changes could cause the operation of its HEN inefficient if the network structure is configured under a single-period assumption. Various design methods have already been developed to generate the optimal multiperiod HEN designs. On the basis of given process data, Floudas and Grossmann[4,5] first suggested to produce a feasible HEN design by separately achieving the minimum utility cost, the minimum number of units, and the minimum investment cost for each time period. Since the global optimum cannot be reached with such a sequential strategy, extensive subsequent studies have thus been performed in recent years to develop effective simultaneous approaches.

Aaltola[6] first developed a mixed integer nonlinear programming (MINLP) model for the purpose of generating the multiperiod HEN design in a single step. This model, based on the stage-wise superstructure of Yee et al.,[2] has been successfully applied to several industrial problems. In a later study, Chen and Hung[7] proposed a four-step procedure to create flexible multiperiod HEN designs. Verheren and Zhang[8] then modified Aaltola's model and presented a systematic network synthesis methodology. Although encouraging results were reported in these works, there are still drawbacks in practical applications:

- The durations of all periods in a year were assumed to be identical and fixed in the above studies. Although Isafiade and Fraser[9] adopted unevenly distributed durations in the objective function, these periods were still required to be determined in advance and then incorporated into the model formulation. As a result, the conventional designs are often suboptimal in industrial environments due to the obvious need to adjust production schedule for coping with the unexpected changes in supplies, demand, and/or process conditions.
- Another undesirable feature in the conventional designs stems from the convention in assigning the heat-transfer areas. Specifically, a single unit is utilized to facilitate the same match in different periods, and thus, its actual heat-transfer area must be large enough to perform all required heat duties. If the operating conditions of this unit change significantly from one period to another, extra heat-exchange capacities are wasted in periods with much smaller duties.
- The conventional multiperiod model is clearly more complex than its single-period counterpart. As a result, the corresponding optimization runs may not always be convergent, since the computation time increases exponentially with the numbers of streams and periods.

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A novel design procedure has been developed in this work to address the above issues. Instead of solving one MINLP model that minimizes total annual cost (TAC) under the fixed-duration assumption, a distinct HEN design is separately created for each period. The resulting designs are then merged into one by incorporating all required matches with their maximum heat-transfer areas. The total utility cost can be cut down considerably by this strategy with or without schedule change, while the total investment cost of the combined network may be driven to a higher level. This capital penalty is mitigated in this study by introducing timesharing mechanisms into the network designs.[10] In particular, the embedded exchangers are allowed to be shared by more than one match in several different periods. With this strategy, it is possible not only to reduce the capital investment of the merged network but also to improve its operational flexibility.

The remaining materials in this paper are organized as follows. The conventional MINLP model is first described in the next section and its undesirable features are illustrated with an example. The proposed methods to generate the optimal single-period HEN designs for all periods and to merge them into a multiperiod preliminary design are then described in the Optimal Single-Period HEN Designs section. The same example is used again for illustrating the implementation steps. To further reduce the capital cost of this preliminary design, an algorithmic strategy has been applied to introduce timesharing mechanisms into the HEN. This strategy is outlined in the Timesharing Schemes section. To demonstrate the superiority of the proposed design procedure, thorough analyses of the trade-off issues between capital and operating costs and also the impacts of schedule adjustment are given in the subsequent two sections. Finally, additional results in extensive case studies are reported in the Additional Case Studies section to support our claims, and conclusions are drawn at the end of this paper.

■ CONVENTIONAL MULTIPERIOD HEN DESIGNS

As mentioned previously, the conventional multiperiod HEN designs can be generated by solving the MINLP model reported in the literature, for example, Verheyen and Zhang.[8] The equality and inequality constraints of this model are listed in Appendix A, while the objective function is the TAC given below:

$$\mathrm{TAC} = \sum_{p\in \mathrm{PR}} \frac{\mathrm{DP}_p}{\mathrm{NP}}\left(\sum_{i\in \mathrm{HP}} C_{\mathrm{CU}} q_{i,p}^{\mathrm{CU}} + \sum_{j\in \mathrm{CP}} C_{\mathrm{HU}} q_{j,p}^{\mathrm{HU}}\right) + r\cdot C_{E,1}\left(\sum_{i\in \mathrm{HP}}\sum_{j\in \mathrm{CP}}\sum_{k\in \mathrm{ST}} z_{i,j,k} + \sum_{j\in \mathrm{CP}} z_j^{\mathrm{HU}} + \sum_{i\in \mathrm{HP}} z_i^{\mathrm{CU}}\right) + r\cdot C_{E,2}\left[\sum_{i\in \mathrm{HP}}\sum_{j\in \mathrm{CP}}\sum_{k\in \mathrm{ST}} (A_{i,j,k}^{\max})^{\beta} + \sum_{j\in \mathrm{CP}} (A_j^{\mathrm{HU,max}})^{\beta} + \sum_{i\in \mathrm{HP}} (A_i^{\mathrm{CU,max}})^{\beta}\right] \quad (1)$$

where DP_p (mon) denotes the duration of period p; NP(mon/yr) is the total length of operation time in a year; $q_{i,p}^{\mathrm{CU}}$ (kW) and C_{CU} (USD/(kW yr)), respectively, represent the heat duty of a cooler for hot stream i in period p and the unit cost of the corresponding cold utility; $q_{j,p}^{\mathrm{HU}}$ (kW) and C_{HU} (USD/(kW yr)), respectively, represent the heat duty of a heater for cold stream j in period p and the unit cost of the corresponding hot utility; $C_{E,1}$ and $C_{E,2}$ are the cost coefficients used to evaluate the fixed and variable capital costs of a heat exchanger; and r is the annualization factor. Notice that $z_{i,j,k}$, z_j^{HU}, and z_i^{CU} are dimensionless binary variables used to respectively denote if the exchangers for matches (i, j, k), (HU, j, 0), and (i, CU, NOK+1) are present in the network. These variables can be related to the corresponding logic variables in every period, that is,

$$z_{i,j,k} = 1 - \prod_{p\in \mathrm{PR}} (1 - z_{i,j,k,p}) \quad (2)$$

$$z_j^{\mathrm{HU}} = 1 - \prod_{p\in \mathrm{PR}} (1 - z_{j,p}^{\mathrm{HU}}) \quad (3)$$

$$z_i^{\mathrm{CU}} = 1 - \prod_{p\in \mathrm{PR}} (1 - z_{i,p}^{\mathrm{CU}}) \quad (4)$$

Finally, $A_{i,j,k}^{\max}$, $A_j^{\mathrm{HU,max}}$, and $A_i^{\mathrm{CU,max}}$ can be regarded as the heat-transfer areas (m^2) for matches (i, j, k), (HU, j, 0), and (i, CU, NOK+1), respectively, and they can be determined by imposing the following constraints in the MINLP model:

$$A_{i,j,k}^{\max} \geq A_{i,j,k,p}; \quad i \in \mathrm{HP},\ j \in \mathrm{CP},\ k \in \mathrm{ST},\ p \in \mathrm{PR} \quad (5)$$

$$A_j^{\mathrm{HU,max}} \geq A_{j,p}^{\mathrm{HU}}; \quad j \in \mathrm{CP},\ p \in \mathrm{PR} \quad (6)$$

$$A_i^{\mathrm{CU,max}} \geq A_{i,p}^{\mathrm{CU}}; \quad i \in \mathrm{HP},\ p \in \mathrm{PR} \quad (7)$$

where $A_{i,j,k,p}$, $A_{j,p}^{\mathrm{HU}}$, and $A_{i,p}^{\mathrm{CU}}$ denote respectively the heat-transfer areas required to facilitate matches (i, j, k), (HU, j, 0), and (i, CU, NOK+1) in period p.

In order to show various undesirable features of the conventional design approach, let us try to solve a simple problem according to the process data presented in Table 1.[11] Both the inlet and outlet temperatures of heating utility are assumed to be 680 K in this case, while those of the cooling water are fixed at 300 and 330 K, respectively. Let us also assume that there are three periods and all durations are identical, that is, $\mathrm{DP}_1/\mathrm{NP} = \mathrm{DP}_2/\mathrm{NP} = \mathrm{DP}_3/\mathrm{NP} = 1/3$. In addition, the following cost parameters are adopted: $C_{\mathrm{CU}} = 53.064$, $C_{\mathrm{HU}} = 150.163$, $C_{E,1} = 0$, $C_{E,2} = 4333$, $r = 0.1$, $\Delta T_{\min} = 10$, and $\beta = 0.6$.

Table 1. Process Data Used in Example 1

stream	period	T_{in} (K)	T_{out} (K)	F (kW/K)	h (kW/(m^2 K))
H1	1	650	370	10	1
H1	2	630	380	10.2	1.03
H1	3	645	350	10	1.01
H2	1	590	370	20	1
H2	2	570	340	20.5	1.04
H2	3	600	350	20.3	1.04
C1	1	410	640	15	1
C1	2	390	630	15	1.02
C1	3	420	660	14.3	1.05
C2	1	350	500	13	1
C2	2	340	520	13.5	1.05
C2	3	320	540	13	1.03

There are 361 constraints and 313 variables (including 48 binary variables) in the corresponding MINLP model, and this model was solved with solver BARON in the GAMS environment on an Intel Core 2 Quad CPU, 2.66 GHz computer.

Table 2a. Conventional HEN Design for Period 1 in Example 1 (p = 1)

match	(i, j, k)	(1, 1, 1)	(1, 2, 2)	(2, 1, 2)	(1, CU, 3)	(2, CU, 3)	(HU, 1, 0)
$A_{i,j,k,p}$	(m^2)	66.8	73.1	243.8	6.9	36.3	16.7
$q_{i,j,k,p}$	(kW)	600.0	1950.0	2550.0	250.0	1850.0	300.0
$rh_{i,j,k,p}$		1.0	1.0	1.0	1.0	1.0	
$rc_{i,j,k,p}$		1.0	1.0	1.0			1.0
$F^H_{i,p}$	(kW/K)	10.0	10.0	20.0	10.0	20.0	
$F^C_{j,p}$	(kW/K)	15.0	13.0	15.0			15.0
$t^H_{i,k,p}$	(K)	650.0	590.0	590.0	395.0	462.5	680.0
$t^H_{i,k+1,p}$	(K)	590.0	395.0	462.5	370.0	370.0	680.0
$ths_{i,j,k,p}$	(K)	590.0	395.0	462.5	370.0	370.0	680.0
$t^C_{j,k,p}$	(K)	580.0	350.0	410.0	300.0	300.0	620.0
$t^C_{j,k+1,p}$	(K)	620.0	500.0	580.0	320.0	320.0	640.0
$tcs_{i,j,k,p}$	(K)	620.0	500.0	580.0	320.0	320.0	640.0

Table 2b. Conventional HEN Design for Period 2 in Example 1 (p = 2)

match	(i, j, k)	(1, 1, 1)	(1, 2, 2)	(2, 1, 2)	(2, 2, 2)	(2, CU, 3)	(HU, 1, 0)
$A_{i,j,k,p}$	(m^2)	66.8	83.2	243.8	18.5	49.7	8.1
$q_{i,j,k,p}$	(kW)	612.0	1938.0	2550.0	492.0	1673.0	438.0
$rh_{i,j,k,p}$		1.0	1.0	0.865	0.135	1.0	
$rc_{i,j,k,p}$		1.0	0.798	1.0	0.202		1.0
$F^H_{i,p}$	(kW/K)	10.2	10.2	20.5	20.5	20.5	
$F^C_{j,p}$	(kW/K)	15.0	13.5	15.0	13.5		15.0
$t^H_{i,k,p}$	(K)	630.0	570.0	570.0	570.0	421.6	680.0
$t^H_{i,k+1,p}$	(K)	570.0	380.0	421.6	421.6	340.0	680.0
$ths_{i,j,k,p}$	(K)	570.0	380.0	426.2	391.9	340.0	680.0
$t^C_{j,k,p}$	(K)	560.0	340.0	390.0	340.0	300.0	600.8
$t^C_{j,k+1,p}$	(K)	600.8	520.0	560.0	520.0	320.0	630.0
$tcs_{i,j,k,p}$	(K)	600.8	520.0	560.0	520.0	320.0	630.0

Table 2c. Conventional HEN Design for Period 3 in Example 1 (p = 3)

match	(i, j, k)	(1, 1, 1)	(1, 2, 2)	(2, 1, 2)	(2, 2, 2)	(1, CU, 3)	(2, CU, 3)	(HU, 1, 0)
$A_{i,j,k,p}$	(m^2)	66.8	83.2	243.8	18.5	7.7	48.4	17.7
$q_{i,j,k,p}$	(kW)	450.0	2308.1	2431.0	551.9	191.9	2092.1	551.0
$rh_{i,j,k,p}$		1.0	1.0	0.813	0.187	1.0	1.0	
$rc_{i,j,k,p}$		0.823	0.807	1.0	0.193			1.0
$F^H_{i,p}$	(kW/K)	10.0	10.0	20.3	20.3	10.0	20.3	
$F^C_{j,p}$	(kW/K)	14.3	13.0	14.3	13.0			14.3
$t^H_{i,k,p}$	(K)	645.0	600.0	600.0	600.0	369.2	453.1	680.0
$t^H_{i,k+1,p}$	(K)	600.0	369.2	453.1	453.1	350.0	350.0	680.0
$ths_{i,j,k,p}$	(K)	600.0	369.2	452.6	455.0	350.0	350.0	680.0
$t^C_{j,k,p}$	(K)	590.0	320.0	420.0	320.0	300.0	300.0	621.5
$t^C_{j,k+1,p}$	(K)	621.5	540.0	590.0	540.0	320.0	320.0	660.0
$tcs_{i,j,k,p}$	(K)	628.2	540.0	590.0	540.0	320.0	320.0	660.0

The optimization run took more than 27 h. The cost-optimal multiperiod HEN design is summarized in Tables 2a–2c, and the final structure can be found in Figure 1. Notice that the heat-transfer areas required for some of the matches vary from period to period. Since the largest heat-transfer area is selected for the exchanger associated with each match in the aforementioned model, an unnecessarily large overdesign level may be introduced by this practice. The TAC of this design is \$205 832.6, in which \$34 176.3 is the annualized capital cost and the rest (\$171 656.3) is the yearly utility expenditure.

As mentioned before, the conventional designs are generated according to the predetermined period durations. If the actual durations are required to be adjusted online in a realistic operation, the resulting utility consumption rates should reach higher-than-minimum levels, since the hardware structure of HEN is fixed for minimizing the *original* objective function.

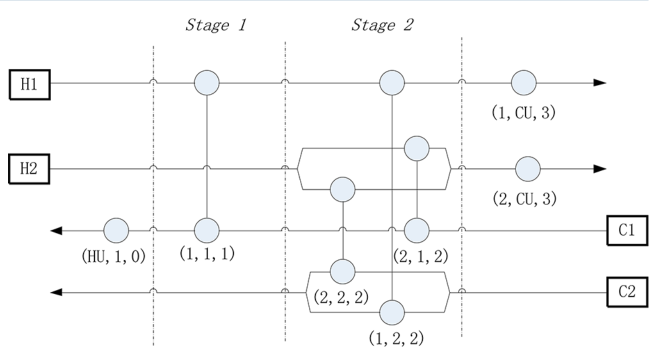

Figure 1. Conventional multiperiod HEN design in example 1.

For example, if the three periods in above example are changed to yield DP_1/NP = 1/12, DP_2/NP = 4/12, and

$DP_3/NP = 7/12$, then the annual utility cost should be increased to \$183 519.9.

■ OPTIMAL SINGLE-PERIOD HEN DESIGNS

To achieve a higher level of operational flexibility with the proposed procedure, it is necessary to first produce an optimal HEN design for every single period. Specifically, the objective function of MINLP model now becomes

$$\begin{aligned}\mathrm{TAC}_p = &\sum_{i\in \mathrm{HP}} C_{\mathrm{CU}} q_{i,p}^{\mathrm{CU}} + \sum_{j\in \mathrm{CP}} C_{\mathrm{HU}} q_{j,p}^{\mathrm{HU}} \\ &+ r\cdot C_{E,1}\left(\sum_{i\in \mathrm{HP}}\sum_{j\in \mathrm{CP}}\sum_{k\in \mathrm{ST}} z_{i,j,k,p} + \sum_{j\in \mathrm{CP}} z_{j,p}^{\mathrm{HU}} \right.\\ &\left. + \sum_{i\in \mathrm{HP}} z_{i,p}^{\mathrm{CU}}\right) + r\cdot C_{E,2}\left[\sum_{i\in \mathrm{HP}}\sum_{j\in \mathrm{CP}}\sum_{k\in \mathrm{ST}} (A_{i,j,k,p})^{\beta}\right.\\ &\left. + \sum_{j\in \mathrm{CP}} (A_{j,p}^{\mathrm{HU}})^{\beta} + \sum_{i\in \mathrm{HP}} (A_{i,p}^{\mathrm{CU}})^{\beta}\right] \end{aligned} \quad (8)$$

where $p \in \mathrm{PR}$. The model constraints can be also found in Appendix A, while those given in eqs 2−7 should be excluded.

There are 97 constraints and 85 variables (including 12 binary variables) in the MINLP model for generating each single-period design. This model was repeatedly solved for three different periods according to the process data presented in Table 1, and the corresponding optimization runs last 25, 27, and 49 s, respectively. The resulting three HEN structures are summarized in Figure 2a−c and also in Tables 3a−3c. If the HEN is operated according to the predetermined schedule, the corresponding utility cost can be found to be \$171 656.3 per year, which is essentially the same as that needed in the aforementioned conventional design. However, by assuming that the largest area of each match is selected in the HEN, it can be found that the annualized investment cost of the combined structure (\$35 646.9) is higher. Thus, the independently generated single-period HEN designs should be integrated into a less expensive structure.

■ TIMESHARING SCHEMES

It can be observed from Tables 3a−3c that, for certain matches, the required areas in different periods are not same. Notice also that the HEN structure in period 1 is significantly different from those in the other two periods (see Figure 2 a−c), that is, only in period 1, match (1, CU, 3) is required while match (2, 2, 2) is not. These structural mismatches inevitably result in a high capital investment if the largest area of each match is selected to facilitate its heat duties in all periods.

For the purpose of circumventing this drawback, three alternative strategies have been developed in a separate study[10] to introduce timesharing mechanisms into the preliminary HEN designs generated independently for different periods. The first two algorithmic procedures were adopted to identify different near-optimal solutions respectively by switching exchanger services and by partitioning and reassembling heat-transfer areas in a preliminary structure. These algorithms can be easily implemented either by hand or with a computer program. Alternatively, a MINLP model was also formulated to automatically generate the minimum-cost designs in which both the aforementioned timesharing configurations can be incorporated. Although this third approach is obviously more rigorous than the other two, it may not always be feasible in practice because the required computer load grows exponentially with the problem size. Since the focus of the present paper is a novel two-step design strategy and the timesharing mechanism is only one of its components, the above-mentioned first algorithm is selected in the present study on the ground that it is the simplest approach to generate reasonable timesharing schemes. Note that, since the resulting network structures are suboptimal, they may serve as the basis for further refinements.

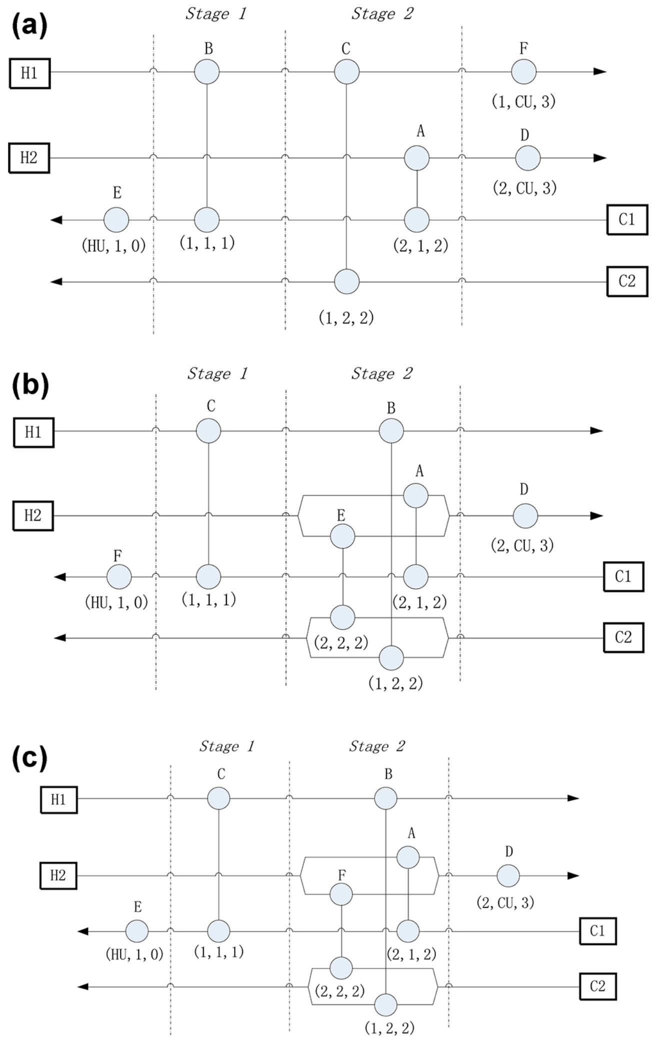

Figure 2. Optimal single-period HEN design for (a) period 1, (b) period 2, and (c) period 3 in example 1.

The service switching procedure is outlined below:

1. Sort the areas of all switchable exchangers and arrange them in descending order.
2. Select the first entry in the ordered list as one of the shared exchanger areas.
3. Identify the largest area in every period and assign the corresponding match to the exchanger chosen in the previous step.
4. Eliminate all assigned matches and their areas from the list.
5. If the ordered list is not empty, go to step 2. Otherwise, stop.

Table 4 shows the area assignments obtained by implementing the above algorithm in example 1. Notice that, in addition

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Table 3a. Optimal Single-Period HEN Design for Period 1 in Example 1 (p = 1)

match	(i, j, k)	(1, 1, 1)	(1, 2, 2)	(2, 1, 2)	(1, CU, 3)	(2, CU, 3)	(HU, 1, 0)
$A_{i,j,k,p}$	(m^2)	66.0	60.1	200.7	6.9	36.3	7.3
$q_{i,j,k,p}$	(kW)	600.0	1950.0	2550.0	250.0	1850.0	300.0
$\mathrm{rh}_{i,j,k,p}$		0.214	1.0	1.0	1.0	1.0	
$\mathrm{rc}_{i,j,k,p}$		1.0	1.0	1.0			1.0
$F_{i,p}^{H}$	(kW/K)	10.0	10.0	20.0	10.0	20.0	
$F_{j,p}^{C}$	(kW/K)	15.0	13.0	15.0			15.0
$t_{i,k,p}^{H}$	(K)	650.0	590.0	590.0	395.0	462.5	680.0
$t_{i,k+1,p}^{H}$	(K)	590.0	395.0	462.5	370.0	370.0	680.0
$\mathrm{ths}_{i,j,k,p}$	(K)	370.0	395.0	462.5	370.0	370.0	680.0
$t_{j,k,p}^{C}$	(K)	580.0	350.0	410.0	300.0	300.0	620.0
$t_{j,k+1,p}^{C}$	(K)	620.0	500.0	580.0	320.0	320.0	640.0
$\mathrm{tcs}_{i,j,k,p}$	(K)	620.0	500.0	640.0	320.0	320.0	640.0

Table 3b. Optimal Single-Period HEN Ddesign for Period 2 in Example 1 (p = 2)

match	(i, j, k)	(1, 1, 1)	(1, 2, 2)	(2, 1, 2)	(2, 2, 2)	(2, CU, 3)	(HU, 1, 0)
$A_{i,j,k,p}$	(m^2)	66.8	83.2	264.3	14.6	49.7	8.1
$q_{i,j,k,p}$	(kW)	612.0	1938.0	2550.0	492.0	1673.0	438.0
$\mathrm{rh}_{i,j,k,p}$		0.381	1.0	0.895	0.105	1.0	
$\mathrm{rc}_{i,j,k,p}$		0.597	0.798	0.916	0.202		1.0
$F_{i,p}^{H}$	(kW/K)	10.2	10.2	20.5	20.5	20.5	
$F_{j,p}^{C}$	(kW/K)	15.0	13.5	15.0	13.5		15.0
$t_{i,k,p}^{H}$	(K)	630.0	570.0	570.0	570.0	421.6	680.0
$t_{i,k+1,p}^{H}$	(K)	570.0	380.0	421.6	421.6	340.0	680.0
$\mathrm{ths}_{i,j,k,p}$	(K)	472.6	380.0	431.1	340.4	340.0	680.0
$t_{j,k,p}^{C}$	(K)	560.0	340.0	390.0	340.0	300.0	600.8
$t_{j,k+1,p}^{C}$	(K)	600.8	520.0	560.0	520.0	320.0	630.0
$\mathrm{tcs}_{i,j,k,p}$	(K)	628.4	520.0	575.6	520.0	320.0	630.0

Table 3c. Optimal Single-Period HEN Design for Period 3 in Example 1 (p = 3)

match	(i, j, k)	(1, 1, 1)	(1, 2, 2)	(2, 1, 2)	(2, 2, 2)	(2, CU, 3)	(HU, 1, 0)
$A_{i,j,k,p}$	(m^2)	55.3	113.3	208.2	7.3	50.8	17.7
$q_{i,j,k,p}$	(kW)	450.0	2500.0	2431.0	360.0	2284.0	551.0
$\mathrm{rh}_{i,j,k,p}$		0.153	1.0	0.929	0.071	1.0	
$\mathrm{rc}_{i,j,k,p}$		1.0	0.874	1.0	0.126		1.0
$F_{i,p}^{H}$	(kW/K)	10.0	10.0	20.3	20.3	30.3	
$F_{j,p}^{C}$	(kW/K)	14.3	13.0	14.3	13.0		14.3
$t_{i,k,p}^{H}$	(K)	645.0	600.0	600.0	600.0	462.5	680.0
$t_{i,k+1,p}^{H}$	(K)	600.0	350.0	462.5	462.5	350.0	680.0
$\mathrm{ths}_{i,j,k,p}$	(K)	350.0	350.0	471.1	350.0	350.0	680.0
$t_{j,k,p}^{C}$	(K)	590.0	320.0	420.0	320.0	300.0	621.5
$t_{j,k+1,p}^{C}$	(K)	621.5	540.0	590.0	540.0	320.0	660.0
$\mathrm{tcs}_{i,j,k,p}$	(K)	621.5	540.0	590.0	540.0	320.0	660.0

to the single-period designs generated previously, every match in Figure 2a−c is also marked with the assigned exchanger label in Table 4. The implied timesharing mechanisms can be realized with the pipeline network provided in Appendix B. It should be noted that the total number of heat exchangers is reduced from seven in the conventional design to six in this proposed design and the total area is decreased from 534.4 to 521.1 m^2. As a result, the annualized capital cost can be lowered from \$35 646.9 to \$33 627.0. Various costs of the designs generated for example 1 are summarized in Table 5. It can be seen that, although the annual utility costs of both the conventional and proposed designs are approximately the same, the annualized capital cost can be significantly reduced with the proposed approach to \$33 627.0, and the corresponding TAC is \$205 283.2.

It can be observed that the proposed pipeline structure is more complex than its conventional counterpart and additional operation steps are needed to switch from the required HEN configuration in one period to another in the next period. However, it should also be noted that these extra steps are performed very infrequently, since only a few periods (usually three or four) are considered in most applications. It is thus practically feasible and justifiable to introduce the added complexity in pipeline structure and operation procedure so as to achieve a lower utility cost and also a higher degree of process flexibility. On the other hand, the undesired mixing of different process fluids or contamination in the timesharing design is obviously another issue that must be addressed. It is assumed in this study that mixing/contamination can be avoided by thoroughly cleaning the exchangers between periods. This assumption is

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Table 4. Area Assignments Adopted in Timesharing Scheme of Example 1

period	match	required area (m^2)	assigned area (m^2)	exchanger label
2	(2, 1, 2)	264.3	264.3	A
3	(2, 1, 2)	208.2	264.3	A
1	(2, 1, 2)	200.7	264.3	A
3	(1, 2, 2)	113.3	113.3	B
2	(1, 2, 2)	83.2	113.3	B
2	(1, 1, 1)	66.8	66.8	C
1	(1, 1, 1)	66	113.3	B
1	(1, 2, 2)	60.1	66.8	C
3	(1, 1, 1)	55.3	66.8	C
3	(2, CU, 3)	50.8	50.8	D
2	(2, CU, 3)	49.7	50.8	D
1	(2, CU, 3)	36.3	50.8	D
3	(HU, 1, 0)	17.7	17.7	E
2	(2, 2, 2)	14.6	17.7	E
2	(HU, 1, 0)	8.1	8.1	F
1	(HU, 1, 0)	7.3	17.7	E
3	(2, 2, 2)	7.3	8.1	F
1	(1, CU, 3)	6.9	8.1	F

reasonable, since the washing time (hours or days) is usually much shorter than a typical period (months). Finally, from the pipeline network given in Appendix B, it is clear that implementation of the timesharing scheme would involve the use of additional pipes and valves that may increase the capital cost. It is therefore advisable to properly overestimate the total capital cost of heat exchangers if the a priori knowledge of plant layout is not given.

TRADE-OFF BETWEEN CAPITAL AND OPERATING COSTS

Since the objective function defined in eq 8 basically consists of two terms (representing the annual utility cost and the annualized capital cost respectively), the HEN structure may be altered by adjusting their weights in minimizing the TAC. The annualization factor r can be utilized to facilitate such an analysis. In the above example, this multiplier is 0.1, and the average ratio between utility and capital costs is 5.7 for the three single-period designs. The TAC, the annualized capital cost, and the annual utility cost are plotted as functions of annualization factor in Figures 3–5, respectively. It can be observed that

(1) All costs increase with the annualization factor.
(2) Although the capital investments required by both the conventional and the proposed designs are roughly the same, the latter tends to be more energy-efficient at a higher multiplier value.

The second observation is obviously due to the fact that the conventional optimization problem is more constrained. Finally,

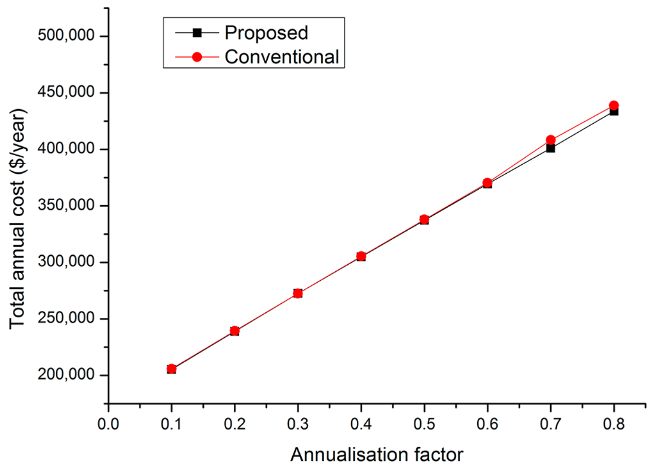

Figure 3. TACs at different values of annualization factor.

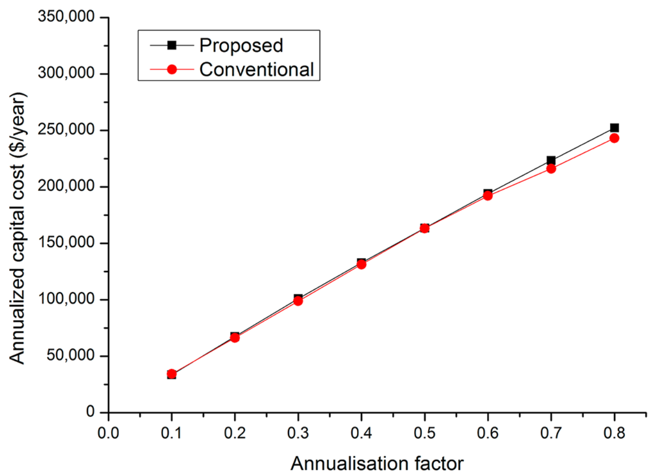

Figure 4. Annualized capital costs at different values of annualization factor.

Figure 6 shows the corresponding cost savings (in percentage of the costs of conventional designs) realized at different multiplier values. Notice that the largest TAC saving is around 2%.

IMPACTS OF SCHEDULE ADJUSTMENT

Other than the aforementioned cost savings, the proposed HEN designs should be considered as more flexible if online schedule adjustments are needed. As mentioned before, the conventional designs are generated according to fixed period durations. If the actual durations deviate from the predetermined values, the HEN cannot be operated optimally under such conditions. Let us consider example 1 again to illustrate this point. By adjusting the period durations, the annual utility costs of the conventional and proposed designs were both computed with an

Table 5. Cost Summary of Example 1

	no. of exchangers	total area (m^2)	annualized capital cost ($)	yearly utility cost ($)	TAC ($)
conventional	7	487.4	34 176.3	171 656.3	205 832.6
1-P (period 1)	6	377.3	27 391.5	156 483.3	183 874.8
1-P (period 2)	6	486.7	32 046.6	154 547.5	186 594.1
1-P (period 3)	6	452.7	31 313.4	203 938.0	235 251.4
1-P (combined)	7	534.4	35 646.9	171 656.3	207 303.2
proposed	6	521.1	33 627.0	171 656.3	205 283.2

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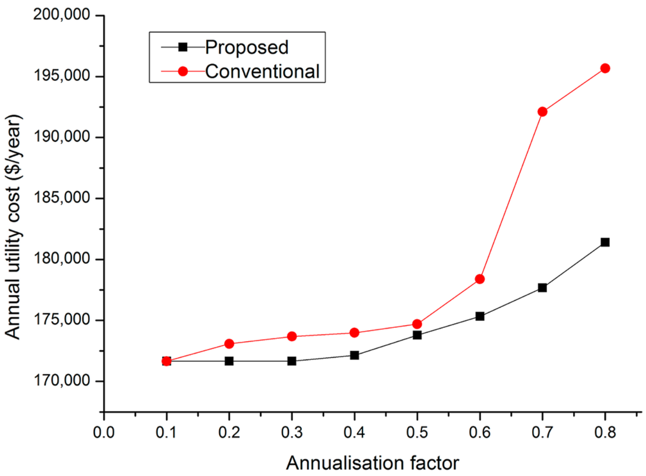

Figure 5. Annual utility costs at different values of annualization factor.

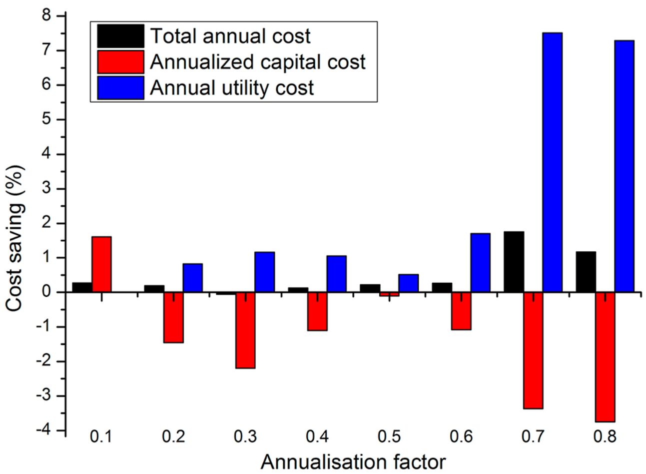

Figure 6. Cost savings at different values of annualization factor.

annualization factor of 0.7. The corresponding results are compared in Figures 7–9. To produce each figure, the duration

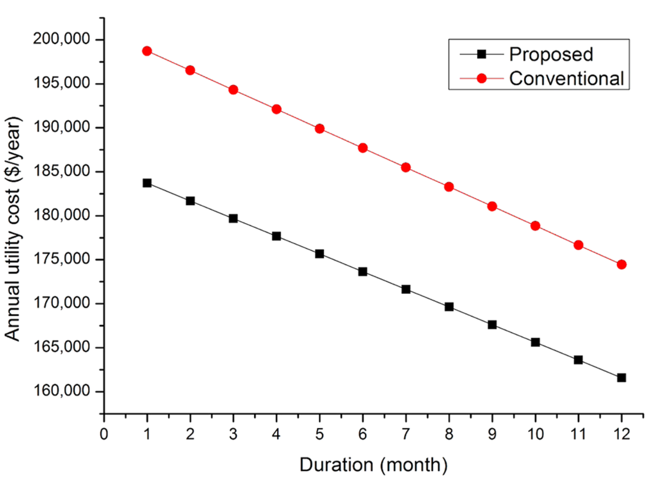

Figure 7. Annual utility costs required under different durations of period 1.

of one period was varied from 1 to 12 months while the remaining time in a year was assumed to be evenly divided between the other two periods. It can be seen that the proposed

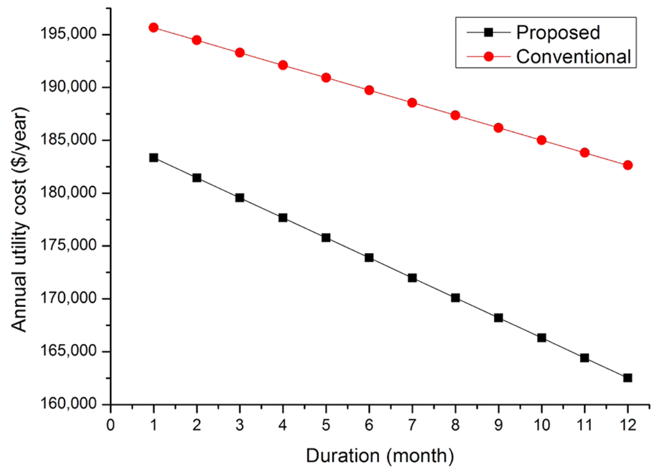

Figure 8. Annual utility costs required under different durations of period 2.

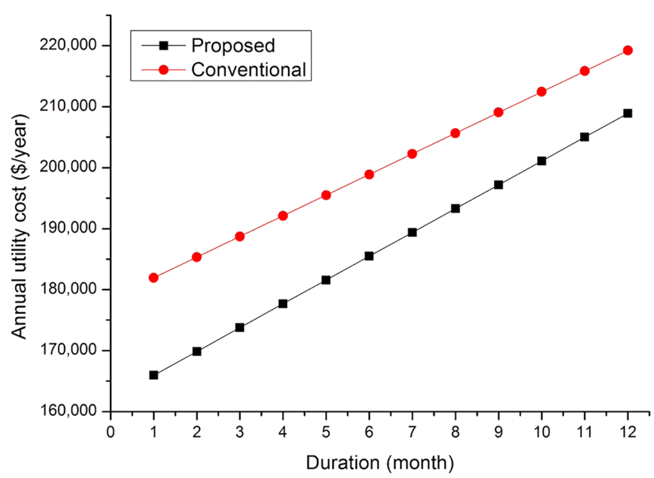

Figure 9. Annual utility costs required under different durations of period 3.

design is always a better alternative in every scenario considered in this study.

■ ADDITIONAL CASE STUDIES

Three additional case studies have been performed to further validate the proposed design method. The process data of these examples were taken from Isafiade and Fraser[8] and presented in the Supporting Information for the sake of completeness. In these cases, all durations are identical. Since the MINLP model adopted by Isafiade and Fraser[8] is slightly different from that given in the present work, for example, (1) the stages in superstructure are partitioned according to the supply and target temperatures of process streams and (2) the hot and cold utilities are allowed to be used at intermediate temperatures, the conventional designs have been recreated for comparison purpose. Additional details and both the conventional multiperiod designs and the optimal single-period designs for the three examples can also be found in the same Supporting Information.

Cost summaries of the above examples can be found in Table 6. The proposed designs in general outperform the conventional ones in all three cases. Under the predefined period durations, the TAC savings can be found to be 3.34%, 11.62%, and 2.21%, respectively. In addition, notice that the required number of heat

Table 6. Cost Summary of Case Studies

case no.	design method	exchanger no.	total area	capital cost	utility cost	TAC
1	conventional	6	200.2	40 375.5	135 586.6	175 962.2
	proposed	6	177.2	35 587.9	134 496.8	170 084.7
2	conventional	6	127.8	30 063.6	12 691.9	42 755.4
	proposed	5	118.4	26 789.5	10 997.8	37 787.3
3	conventional	11	23961.0	3 105 149.2	3 397 330.3	6 502 479.5
	proposed	10	25038.6	3 230 125.0	3 128 808.1	6 358 933.1

exchangers can often be reduced with the proposed timesharing schemes, for example, cases 2 and 3 in Table 6. However, a smaller exchanger number does not always result in a reduction in the total capital cost (see case 3). This is because an increase in the total heat-transfer area is needed to facilitate better trade-off between the utility cost and the annualized capital cost.

■ CONCLUSIONS

As indicated previously, the conventional approach to produce the multiperiod HEN designs suffers a few serious drawbacks that are primarily derived from the original model formulation, that is, the fixed-duration assumption adopted in constructing the objective function, the area assignment convention utilized for sizing exchangers, and the comprehensive constraints used to satisfy the process requirements of all periods. These drawbacks can be circumvented with a novel design strategy developed in this work. Instead of solving a single MINLP model for all periods, one design is created independently for each period, and thus, several different HEN structures can be made available in the initial stage of the proposed procedure. The timesharing schemes are then introduced so as to reduce the overall capital investment as much as possible. The effectiveness of the above two-stage procedure is demonstrated in this paper with several examples.

Finally, it should be cautioned that any HEN structure generated with the proposed strategy can only be treated as a conceptual (or preliminary) design. Not only further refinements of the timesharing mechanism may be identified but also the other practical issues, such as rangeability, operability, and controllability, may have to be assessed more rigorously in an additional study.

■ APPENDIX A: EQUALITY AND INEQUALITY CONSTRAINTS USED IN THE CONVENTIONAL MINLP MODEL FOR MULTIPERIOD HEN DESIGNS

1. Overall heat balances:

$$[T_{i,p}^{\mathrm{H,in}} - T_{i,p}^{\mathrm{H,out}}]F_{i,p}^{\mathrm{H}} = \sum_{k\in \mathrm{ST}}\sum_{j\in \mathrm{CP}} q_{i,j,k,p} + q_{i,p}^{\mathrm{CU}};\quad i \in \mathrm{HP},\ p \in \mathrm{PR} \tag{A.1}$$

$$[T_{j,p}^{\mathrm{C,in}} - T_{j,p}^{\mathrm{C,out}}]F_{j,p}^{\mathrm{C}} = \sum_{k\in \mathrm{ST}}\sum_{i\in \mathrm{HP}} q_{i,j,k,p} + q_{j,p}^{\mathrm{HU}};\quad j \in \mathrm{CP},\ p \in \mathrm{PR} \tag{A.2}$$

2. Stage-wise heat balances:

$$[t_{i,k,p}^{\mathrm{H}} - t_{i,k+1,p}^{\mathrm{H}}]F_{i,p}^{\mathrm{H}} = \sum_{j\in \mathrm{CP}} q_{i,j,k,p};\quad i \in \mathrm{HP},\ k \in \mathrm{ST},\ p \in \mathrm{PR} \tag{A.3}$$

$$[t_{j,k,p}^{\mathrm{C}} - t_{j,k+1,p}^{\mathrm{C}}]F_{j,p}^{\mathrm{C}} = \sum_{i\in HP} q_{i,j,k,p};\quad j \in \mathrm{CP},\ k \in \mathrm{ST},\ p \in \mathrm{PR} \tag{A.4}$$

3. Heat balance for each exchanger:

$$[t_{i,k,p}^{\mathrm{H}} - \mathrm{ths}_{i,j,k,p}]\mathrm{rh}_{i,j,k,p}F_{i,p}^{\mathrm{H}} = q_{i,j,k,p};\quad i \in \mathrm{HP},\ j \in \mathrm{CP},\ k \in \mathrm{ST},\ p \in \mathrm{PR} \tag{A.5}$$

$$[\mathrm{tcs}_{i,j,k,p} - t_{j,k+1,p}^{\mathrm{C}}]\mathrm{rc}_{i,j,k,p}F_{j,p}^{\mathrm{C}} = q_{i,j,k,p};\quad i \in \mathrm{HP},\ j \in \mathrm{CP},\ k \in \mathrm{ST},\ p \in \mathrm{PR} \tag{A.6}$$

4. Sum of split ratio:

$$\sum_{j\in \mathrm{CP}} \mathrm{rh}_{i,j,k,p} = 1;\quad i \in \mathrm{HP},\ k \in \mathrm{ST},\ p \in \mathrm{PR} \tag{A.7}$$

$$\sum_{i\in \mathrm{HP}} \mathrm{rc}_{i,j,k,p} = 1;\quad j \in \mathrm{CP},\ k \in \mathrm{ST},\ p \in \mathrm{PR} \tag{A.8}$$

5. Outlet temperature of each exchanger:

$$\sum_{j\in \mathrm{CP}} \mathrm{rh}_{i,j,k,p}\mathrm{ths}_{i,j,k,p} = t_{i,k+1,p}^{\mathrm{H}};\quad i \in \mathrm{HP},\ k \in \mathrm{ST},\ p \in \mathrm{PR} \tag{A.9}$$

$$\sum_{i\in \mathrm{HP}} \mathrm{rc}_{i,j,k,p}\mathrm{tcs}_{i,j,k,p} = t_{j,k,p}^{\mathrm{C}};\quad j \in \mathrm{CP},\ k \in \mathrm{ST},\ p \in \mathrm{PR} \tag{A.10}$$

6. Temperature feasibility constraints:

$$T_{i,p}^{\mathrm{H,in}} = t_{i,1,p}^{\mathrm{H}};\quad i \in \mathrm{HP},\ p \in \mathrm{PR} \tag{A.11}$$

$$T_{j,p}^{\mathrm{C,in}} = t_{j,\mathrm{NOK}+1,p}^{\mathrm{C}};\quad j \in \mathrm{CP},\ p \in \mathrm{PR} \tag{A.12}$$

$$t_{i,k,p}^{\mathrm{H}} \geq t_{i,k+1,p}^{\mathrm{H}};\quad i \in \mathrm{HP},\ k \in \mathrm{ST},\ p \in \mathrm{PR} \tag{A.13}$$

$$t_{j,k,p}^{\mathrm{C}} \geq t_{j,k+1,p}^{\mathrm{C}};\quad j \in \mathrm{CP},\ k \in \mathrm{ST},\ p \in \mathrm{PR} \tag{A.14}$$

$$T_{i,p}^{\mathrm{H,out}} \leq t_{i,\mathrm{NOK}+1,p}^{\mathrm{H}};\quad i \in \mathrm{HP},\ p \in \mathrm{PR} \tag{A.15}$$

$$T_{j,p}^{\mathrm{C,out}} \geq t_{j,1,p}^{\mathrm{C}};\quad j \in \mathrm{CP},\ p \in \mathrm{PR} \tag{A.16}$$

7. Utility loads:

$$[t_{i,\mathrm{NOK}+1,p}^{\mathrm{H}} - T_{i,p}^{\mathrm{H,out}}]F_{i,p}^{\mathrm{H}} = q_{i,p}^{\mathrm{CU}};\quad i \in \mathrm{HP},\ p \in \mathrm{PR} \tag{A.17}$$

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$$[T_{j,p}^{\text{C,out}} - t_{j,1,p}^{\text{C}}]F_{j,p}^{\text{C}} = q_{j,p}^{\text{HU}}; \quad j \in \text{CP}, \ p \in \text{PR} \tag{A.18}$$

8. Heat load constraints:

$$q_{i,j,k,p} - Q_{\text{UP}}z_{i,j,k,p} \le 0; \quad i \in \text{HP}, \ j \in \text{CP}, \ k \in \text{ST}, \ p \in \text{PR} \tag{A.19}$$

$$q_{i,p}^{\text{CU}} - Q_{\text{UP}}z_{i,p}^{\text{CU}} \le 0; \quad i \in \text{HP}, \ p \in \text{PR} \tag{A.20}$$

$$q_{j,p}^{\text{HU}} - Q_{\text{UP}}z_{j,p}^{\text{HU}} \le 0; \quad j \in \text{CP}, \ p \in \text{PR} \tag{A.21}$$

9. Approach temperatures:

$$\text{dt}_{i,j,k,p} \le t_{i,k,p}^{\text{H}} - \text{tcs}_{i,j,k,p} + \Gamma(1 - z_{i,j,k,p}); \quad i \in \text{HP}, \ j \in \text{CP}, \ k \in \text{ST}, \ p \in \text{PR} \tag{A.22}$$

$$\text{dt}_{i,j,k+1,p} \le \text{ths}_{i,j,k,p} - t_{j,k+1,p}^{\text{C}} + \Gamma(1 - z_{i,j,k,p}); \quad i \in \text{HP}, \ j \in \text{CP}, \ k \in \text{ST}, \ p \in \text{PR} \tag{A.23}$$

$$\text{dt}_{j,p}^{\text{HU}} \le T^{\text{HU,out}} - t_{j,1,p}^{\text{C}} + \Gamma(1 - z_{j,p}^{\text{HU}}); \quad j \in \text{CP}, \ p \in \text{PR} \tag{A.24}$$

$$\text{dt}_{i,p}^{\text{CU}} \le t_{i,\text{NOK}+1,p}^{\text{H}} - T^{\text{CU,out}} + \Gamma(1 - z_{i,p}^{\text{CU}}); \quad i \in \text{HP}, \ p \in \text{PR} \tag{A.25}$$

10. Approach temperature bounds:

$$\text{dt}_{i,j,k,p}, \ \text{dt}_{j,p}^{\text{HU}}, \ \text{dt}_{i,p}^{\text{CU}} \ge \Delta T_{\min}; \quad i \in \text{HP}, \ j \in \text{CP}, \ k \in \text{ST}, \ p \in \text{PR} \tag{A.26}$$

11. Heat transfer areas for stream and utility matches:[8]
    (a) For the stream matches:

$$A_{i,j,k,p} = \frac{q_{i,j,k,p}}{\Delta T_{i,j,k,p}^{\text{LMTD}}}\left(\frac{1}{h_{i,p}^{\text{H}}} + \frac{1}{h_{j,p}^{\text{C}}}\right) \tag{A.27}$$

$$\Delta T_{i,j,k,p}^{\text{LMTD}} \approx \left[\frac{1}{2}\text{dt}_{i,j,k,p}\text{dt}_{i,j,k+1,p}(\text{dt}_{i,j,k,p} + \text{dt}_{i,j,k+1,p})\right]^{1/3} \tag{A.28}$$

    (b) For the hot-utility matches:

$$A_{j,p}^{\text{HU}} = \frac{q_{j,p}^{\text{HU}}}{\Delta T_{j,p}^{\text{LMTD-HU}}}\left(\frac{1}{h^{\text{HU}}} + \frac{1}{h_{j,p}^{\text{C}}}\right) \tag{A.29}$$

$$\Delta T_{j,p}^{\text{LMTD-HU}} \approx \left\{\frac{1}{2}\text{dt}_{j,p}^{\text{HU}}(T^{\text{HU,in}} - T_{j,p}^{\text{C,out}}) \times [\text{dt}_{j,p}^{\text{HU}} + (T^{\text{HU,in}} - T_{j,p}^{\text{C,out}})]\right\}^{1/3} \tag{A.30}$$

    (c) For the cold-utility matches:

$$A_{i,p}^{\text{CU}} = \frac{q_{i,p}^{\text{CU}}}{\Delta T_{i,p}^{\text{LMTD-CU}}}\left(\frac{1}{h^{\text{CU}}} + \frac{1}{h_{i,p}^{\text{H}}}\right) \tag{A.31}$$

$$\Delta T_{i,p}^{\text{LMTD-CU}} \approx \left\{\frac{1}{2}\text{dt}_{i,p}^{\text{CU}}(T_{i,p}^{\text{H,out}} - T^{\text{CU,in}}) \times [\text{dt}_{i,p}^{\text{CU}} + (T_{i,p}^{\text{H,out}} - T^{\text{CU,in}})]\right\}^{1/3} \tag{A.32}$$

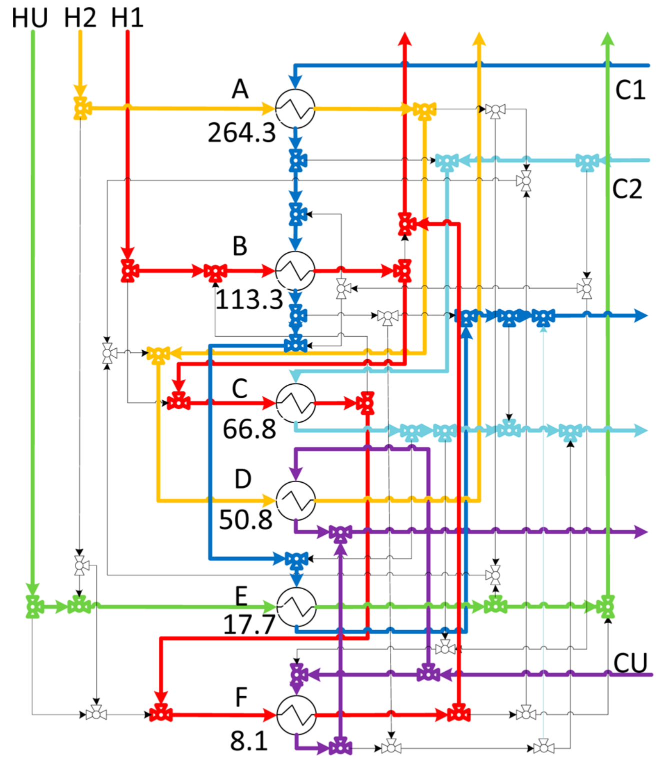

Figure B.1. Pipeline structure of timesharing scheme in period 1.

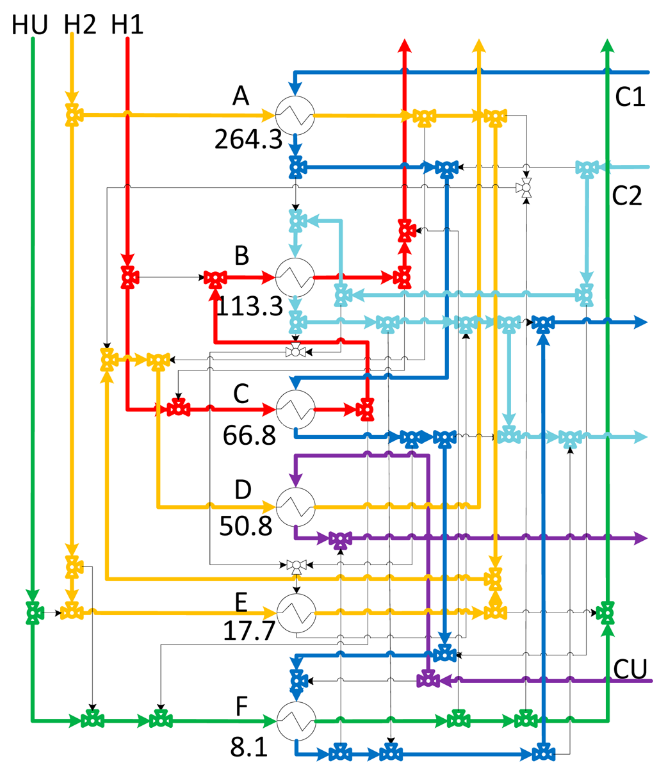

Figure B.2. Pipeline structure of timesharing scheme in period 2.

APPENDIX B: PIPELINE NETWORK USED TO REALIZE THE TIMESHARING SCHEMES IN EXAMPLE 1

The pipeline network of Example 1 can be synthesized according to the following procedure:

1. The pipeline structure of single-period HEN in every period is drawn individually first.
2. All single-period structures are then combined by merging the shared exchangers and common pipelines.
3. Multiway valves are finally added to facilitate connections that are not utilized in all periods.

The resulting network is represented below with three figures (Figures B.1−B.3. The black lines in these figures represent the pipelines that are not currently in use, while the colored lines represent the activated pipelines for transferring different process and utility fluids, that is, red denotes H1, orange denotes H2, light green denotes HU, blue denotes C1, accent denotes C2, and purple denotes CU.

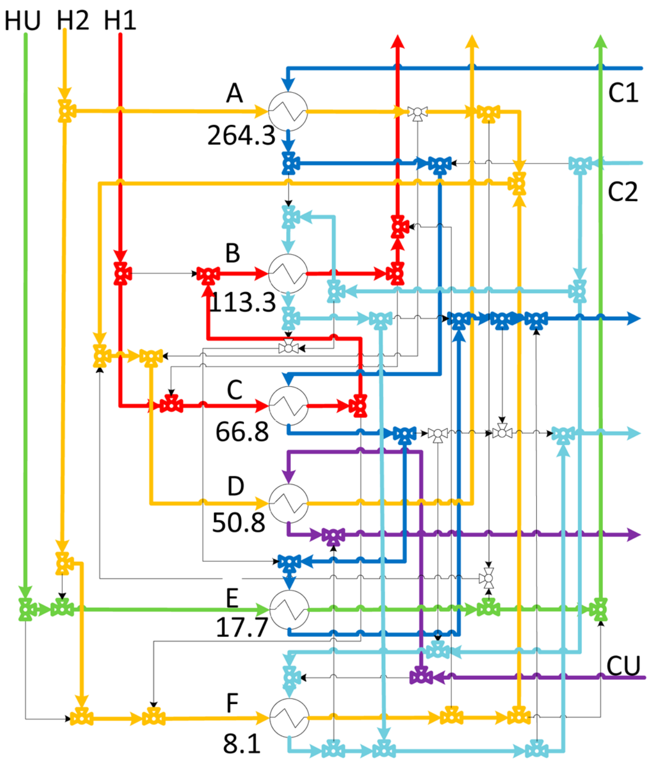

Figure B.3. Pipeline structure of timesharing scheme in period 3.

ASSOCIATED CONTENT

Supporting Information

Additional remarks and process data and HEN designs of cases 1, 2, and 3. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

NOMENCLATURE

$A_{i,j,k}^{\max}$	Maximum heat transfer area of a match between hot stream i and cold stream j at stage k (m^2)
$A_j^{HU,\max}$	Maximum heat transfer area of a match between cold stream j and hot utility (m^2)
$A_i^{CU,\max}$	Maximum heat transfer area of a match between hot stream i and cold utility (m^2)
$A_{i,j,k,p}$	Heat transfer area of match between hot stream i and cold stream j at stage k in period p (m^2)
$A_{j,p}^{HU}$	Heat transfer area of match between cold stream j and hot utility (m^2)
$A_{i,p}^{CU}$	Heat transfer area of a match between hot stream i and cold utility (m^2)
C_{CU}	Unit cost of cold utility (USD/(kW yr))
$C_{E,1}$	Cost coefficients for capital costs of a heat exchanger
$C_{E,2}$	Cost coefficients for capital costs of a heat exchanger
C_{HU}	Unit cost of hot utility (USD/(kW yr))
DP_p	Duration of period (dimensionless)
$dt_{i,j,k,p}$	Temperature difference for match of hot stream i and cold stream j at stage k in period p (K)
$dt_{j,p}^{HU}$	Temperature difference for match of cold stream j and hot utility in period p (K)
$dt_{i,p}^{CU}$	Temperature difference for match of hot stream i and cold utility in period p (K)
F	Heat capacity flow rate of hot or cold stream (kW/K)
$F_{i,p}^{H}$	Heat capacity flow rate of hot stream in period p before split (kW/K)
$F_{j,p}^{C}$	Heat capacity flow rate of cold stream in period p before split (kW/K)
h	Individual film heat-transfer coefficient of cold or hot stream (kW/(m^2 K))
$h_{i,p}^{H}$	Individual film heat-transfer coefficient of hot stream i in period p (kW/(m^2 K))
$F_{j,p}^{C}$	Individual film heat-transfer coefficient of cold stream j in period p (kW/(m^2 K))
h^{HU}	Individual film heat-transfer coefficient of hot utility (kW/(m^2 K))
h^{CU}	Individual film heat-transfer coefficient of cold utility (kW/(m^2 K))
HEN	Heat exchanger network
MINLP	Mixed integer nonlinear programming
NOK	Number of stages (dimensionless)
NP	Number of periods (dimensionless)
Q_{UP}	Upper bound on heat exchange capacity (kW)
$q_{i,j,k,p}$	Heat exchanged between hot stream i and cold stream j in stage k in period p (kW)
$q_{i,p}^{CU}$	Heat exchanged between hot stream i and cold utility in period p (kW)
$q_{j,p}^{HU}$	Heat exchanged between cold stream j and hot utility in period p (kW)
r	The annualization factor for capital cost (dimensionless)
$rh_{i,j,k,p}$	Split ratio of hot stream in a match between hot stream i with cold stream j at stage k in period p (dimensionless)
$rc_{i,j,k,p}$	Split ratio of cold stream in a match between hot stream i with cold stream j at stage k in period p (dimensionless)
$T_{i,p}^{H,in}$	Inlet temperature of hot stream i in period p (K)

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$T_{i,p}^{H,out}$ Outlet temperature of hot stream i in period p (K)

$t_{i,k,p}^{H}$ Inlet temperature of hot stream in a match between hot stream i and cold stream j at stage k in period p (K)

$t_{i,k+1,p}^{H}$ Outlet temperature of hot stream in a match between hot stream i and cold stream j at stage k in period p (K)

$t_{i,NOK+1,p}^{H}$ Temperature of hot stream at stage NOK+1 in period p (K)

$ths_{i,j,k,p}$ Outlet temperature of hot stream in a match between hot stream i and cold stream j at stage k in period p if stream splitter presents (K)

$T_{j,p}^{C,in}$ Inlet temperature of cold stream j in period p (K)

$T_{j,p}^{C,out}$ Outlet temperature of cold stream j in period p (K)

$T_{j,k,p}^{C}$ Inlet temperature of cold stream in a match between hot stream i and cold stream j at stage k in period p (K)

$t_{i,k+1,p}^{C}$ Outlet temperature of cold stream in a match between hot stream i and cold stream j at stage k in period p (K)

$t_{j,NOK+1,p}^{C}$ Temperature of cold stream in at stage NOK+1 in period p (K)

$tcs_{i,j,k,p}$ Outlet temperature of cold stream in a match between hot stream i and cold stream j at stage k in period p if stream splitter presents (K)

$T^{HU,in}$ Inlet temperature of hot utility (K)

$T^{HU,out}$ Outlet temperature of hot utility (K)

$T^{CU,in}$ Inlet temperature of cold utility (K)

$T^{CU,out}$ Outlet temperature of cold utility (K)

T_{in} Inlet temperature of stream (K)

T_{out} Outlet temperature of stream (K)

TAC Total annual cost (USD/yr)

$z_{i,j,k}$ Existence of match between hot stream i and cold stream j in stage k(dimensionless)

$z_{i,j,k,p}$ Existence of match between hot stream i and cold stream j in stage k in period p (dimensionless)

$z_{i,p}^{CU}$ Existence of match between hot stream i and cold utility in period p (dimensionless)

$z_{j,p}^{HU}$ Existence of match between cold stream j and hot utility (dimensionless) in period p

Γ Upper bound for temperature difference

$\Delta T_{i,j,k,p}^{LMTD}$ Log mean temperature difference for match of hot stream i and cold stream j at stage k in period p (K)

$\Delta T_{j,p}^{LMTD\text{-}HU}$ Log mean temperature difference for match between cold stream j and hot utility in period p (K)

$\Delta T_{i,p}^{LMTD\text{-}CU}$ Log mean temperature difference for match between hot stream i and cold utility in period p (K)

ΔT_{min} Minimum approach temperature (K)

β Heat exchanger area exponent factor (dimensionless)

Indices

i Hot process stream or hot utility

j Cold process stream or cold utility

k Stage number or temperature interval

p Period of operation

Sets

CP Set of a cold process stream j

HP Set of a hot process stream i

PR Set of a operation period, p = 1, ..., NP

ST Set of a stage in the superstructure, k = 1,......, NOK

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