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An algorithmic approach to generate timesharing schemes for multi-period HEN designs

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ABSTRACT

Without changing the conceptual configuration of a given multi-period HEN design, it has been shown in this work that the total capital cost can be significantly reduced by allowing a chosen set of exchangers to be shared by more than one match in different periods. Systematic synthesis strategies have been developed to generate the timesharing schemes needed for realizing this novel idea. The proposed strategies can be implemented either with generic area allocation algorithms or by solving a MINLP model. The former approach is not only easy to use but also effective for creating practical solutions which are near optimal. Somewhat better results may be obtained by using the latter method with considerably larger computation effort. Based on the extensive case studies performed so far, it was found that both approaches are applicable for generating the timesharing schemes that achieve significant saving in capital investment.

Keywords: Heat exchanger network; Multi-period design; Timesharing scheme; Mathematical programming model; Area allocation; MINLP model

1. Introduction

HEN synthesis is a well-studied design issue for the chemical processes (Akbarnia et al., 2009; Azeez et al., 2012; Bogataj and Kravanja, 2012; Isafiade and Fraser, 2010; Laukkanen et al., 2012). Many effective methods have already been developed on the basis of *fixed* process parameters. To account for seasonal variations in these parameters, Aaltola (2002) modified the MINLP model proposed by Yee et al. (1990) so as to solve the corresponding multi-period optimization problem. In a subsequent study, Chen and Hung (2005) proposed a three-step optimization procedure to generate flexible HEN designs that are operable in all periods. Verheyen and Zhang (2006) also improved the available models for the same purpose. Ma et al. (2008) suggested synthesizing the multi-period designs with the genetic/simulated annealing algorithms. Ahmad et al. (2012) also used simulated annealing to optimize HEN designs for multi-period operations. A common feature in these studies is that a single unit was utilized to satisfy different heat-exchange needs of the same match in all periods. This practice is beneficial only when the heat-transfer area of every exchanger in HEN is sufficiently large for all required duties and also its operating conditions do not change significantly from one period to another. If any unit lacks the latter attribute, extra processing capacities are essentially wasted in periods with much smaller duties and, in worse cases, the HEN becomes inoperable.

The aforementioned drawbacks of the traditional multi-period HEN designs have been circumvented in this study with timesharing schemes. In particular, a chosen set of exchangers are allowed to be shared by more than one match in multiple periods. With this approach, it is possible not only to reduce the capital investment of a conventional network but also to improve it operability. It is also assumed in this work that, before synthesizing the proposed timesharing scheme, a preliminary multi-period design with minimum total annual cost

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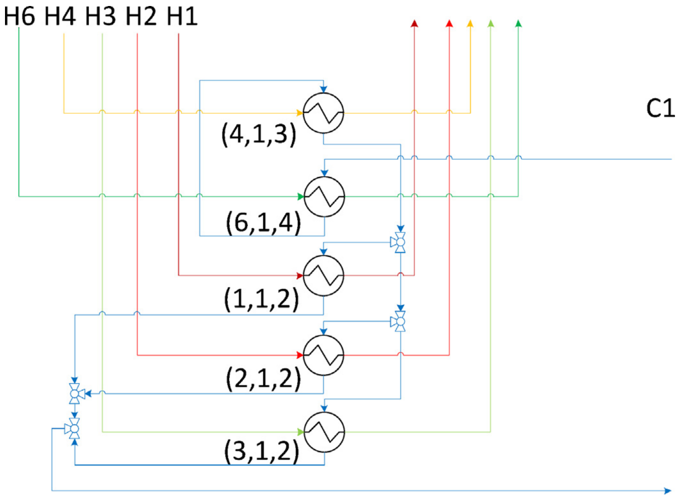

Fig. 1 – Pipeline structure of conventional HEN design obtained in Aaltola (2002).

(TAC) can be made available with the traditional simultaneous approaches (Chen and Hung, 2005; Verheyen and Zhang, 2006; Ma et al., 2008; Ahmad et al., 2012). Two algorithmic procedures have been developed in the present work to create near optimal timesharing solutions on the basis of this preliminary structure. Alternatively, a simple mathematical programming model has also been formulated to automatically generate the best scheme.

Finally, it should be noted that having the ability to configure a practical timesharing scheme may alter the traditional philosophy for designing the multi-period heat-exchanger networks. Since the capital cost of essentially any given design may be reduced with the proposed techniques, the preliminary structures should not be limited to only those generated with a single MINLP model that minimizes TAC. Conceivably, the utility consumption rate in each period may be minimized individually so as to drive the overall annual operating cost to a very low level. Due to space limitation, these further applications of timesharing schemes are considered in a separate study. The focus of present paper is placed upon the development of various algorithms for generating the timesharing schemes.

2. Strategy I – switching exchanger services

Let us first assume that, for the purpose of generating the timesharing scheme of a multi-period HEN design, the optimal solution of the conventional MINLP model (Aaltola, 2002; Chen and Hung, 2005; Verheyen and Zhang, 2006) can be obtained in advance, e.g., see Table 1 and Fig. 1 and the more detailed design specifications given in Table S1 in *Supplementary Material*. Notice that the largest area required to facilitate each match is underlined in Table 1 and this value is also the actual exchanger area adopted in the conventional design. While the conceptual structure of a conventional HEN and also the operating conditions of its embedded matches are kept intact, the total capital cost may be further reduced by allowing the exchanger services for matches in different periods to be switched.

This idea can be realized in the above example. If in this case only the exchanger services for match (1,1,2) and match (6,1,4) are switchable, then two units equipped respectively with heat-transfer areas 137 m^2 (unit A) and 130.1 m^2 (unit B) can be adopted to satisfy their required heat duties in all four

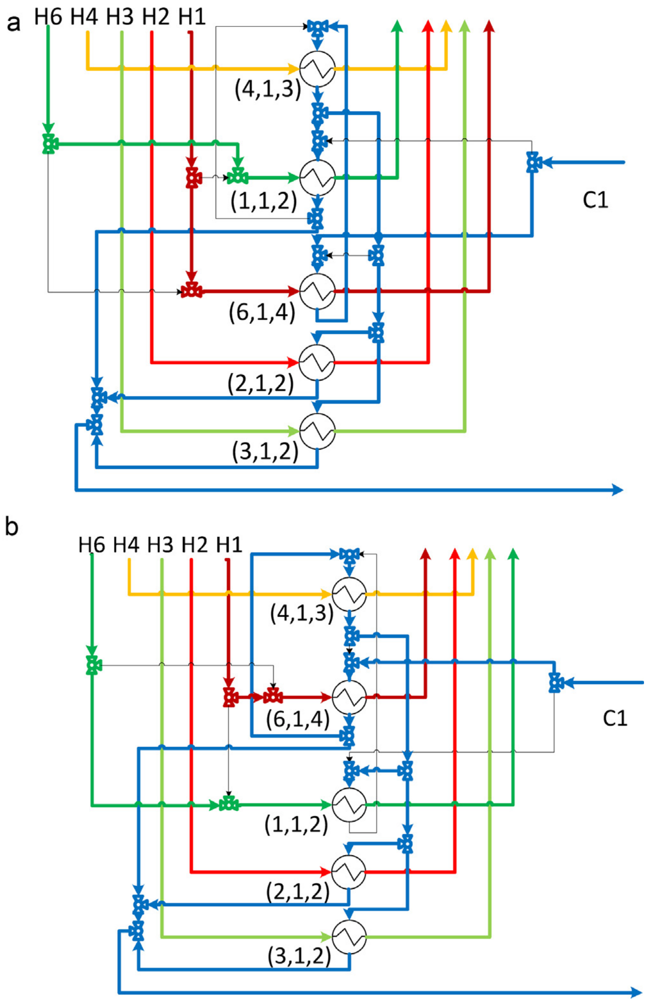

Fig. 2 – (a) Pipeline structure of timesharing scheme derived from Aaltola's conventional HEN design for periods 1 and 4. (b) Pipeline structure of timesharing scheme derived from Aaltola's conventional HEN design for periods 2 and 3.

periods. Notice that the match assignments in every period are also specified in Table 1. Since the conventional approach is to select the largest area for each match, a reduction of 2.3 (= 132.4 – 130.1) m^2 can be achieved by switching services in this example. Fig. 2a shows the pipeline structure in periods 1 and 4, while Fig. 2b shows an alternative configuration for periods 2 and 3.

A generic algorithm has been developed in this study for identifying the most appropriate areas of n ($n \geq 2$) switchable exchangers. Its implementation steps are summarized 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.

For further clarification, let us consider another conventional HEN design, which can be fully characterized by the design specifications given in Table 2, Fig. 3 and Table S2 in

Table 1 – A conventional multi-period HEN design (Aaltola, 2002).

No.	Required area (m^2)				
	Match	Period 1	Period 2	Period 3	Period 4
1	(1,1,2)	108.9 (A)	67.5 (B)	68.6 (B)	132.4 (A)
2	(2,1,2)	45.7	37.4	40.5	45.7
3	(3,1,2)	30.8	29.7	28.5	30.8
4	(4,1,3)	237.6	305.9	309.2	309.1
5	(6,1,4)	57.0(B)	137.0(A)	129.4 (A)	130.1 (B)

Table 2 – The conventional multi-period HEN design used in Case 1.

No.	Required area (m^2)			
	Match	Period 1	Period 2	Period 3
1	(1,1,2)	134.11	134.11	134.11
2	(2,1,2)	16.59	0	0
3	(2,2,2)	41.14	0	0
4	(3,2,1)	0	53.88	0
5	(1,CU,3)	14.08	14.08	14.08
6	(2,CU,3)	37.05	0	0
7	(3,CU,3)	0	61.02	0
8	(HU,1,0)	19.73	29.3	29.03
9	(HU,2,0)	0	0	8.71

Table 3 – The ordered area list generated in Case 1.

Match	Period	Area (m^2)	Unit
(1,1,2)	1	134.11	A
(1,1,2)	2	134.11	A
(1,1,2)	3	134.11	A
(3,CU,3)	2	61.02	B
(3,2,1)	2	53.88	C
(2,2,2)	1	41.14	B
(2,CU,3)	1	37.05	C
(HU,1,0)	2	29.3	D
(HU,1,0)	3	29.03	B
(HU,1,0)	1	19.73	D
(2,1,2)	1	16.59	E
(1,CU,3)	1	14.08	F
(1,CU,3)	2	14.08	E
(1,CU,3)	3	14.08	C
(HU,2,0)	3	8.71	D

the *Supplementary Materials*. Notice that the total heat-transfer area required in this conventional scheme is 395.88 m^2. Let us assume that all services are switchable in this example. After applying step 1, one can produce the ordered list in Table 3.

Note that a total of six exchangers can be identified and, for the sake of illustration clarity, they are labeled as units A–F respectively. The exchanger areas chosen in step 2 and the assigned matches and periods obtained in step 3 can be found in Table 4. In this table, these assignments are indicated with the symbol 'X'. The pipeline structure of corresponding time-sharing scheme is depicted in Fig. 4a–c. It can be determined from Table 4 that the total heat-transfer area is 308.98 m^2, which is considerably less than that used in the original design.

It can also be observed from the above two examples that, not only the total heat-transfer area in a HEN design can be significantly reduced by switching the exchanger services, but also a smaller number of units may be utilized to facilitate all required matches in the network. This is due to the fact that some matches in the conventional design may not be present in all periods (see Table 2). Consequently, it can be guaranteed that the number of exchangers selected with the aforementioned algorithm should be lower than or equal to that in the original network. This special feature also implies that the total capital cost can always be lowered with Strategy I. To be more specific, let us calculate the capital investment

Table 4 – The timesharing scheme obtained with Strategy I in Case 1.

Match	Period	Unit A 134.11 m^2	Unit B 61.02 m^2	Unit C 53.88 m^2	Unit D 29.30 m^2	Unit E 16.59 m^2	Unit F 14.08 m^2
(1,1,2)	1	×					
(2,1,2)	1					×	
(2,2,2)	1		×				
(1,CU,3)	1						×
(2,CU,3)	1			×			
(HU,1,0)	1				×		
(1,1,2)	2	×					
(3,2,1)	2			×			
(1,CU,3)	2					×	
(3,CU,3)	2		×				
(HU,1,0)	2				×		
(1,1,2)	3	×					
(1,CU,3)	3			×			
(HU,1,0)	3		×				
(HU,2,0)	3				×		

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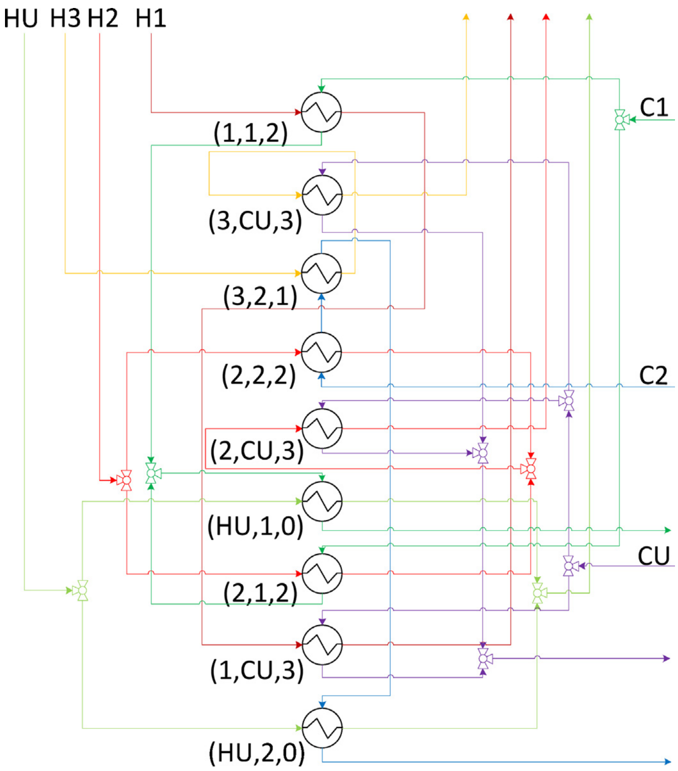

Fig. 3 – Pipeline structure of conventional HEN design in Case 1.

of each exchanger in HEN with the following cost model[5]

$$\varphi(x_e) = 4333x_e^{0.6} \quad (1)$$

where x_e represents the heat-transfer area (in m^2) of exchanger e. The annualized capital cost of the original HEN can be determined to be 351,804.15 USD/yr, while that of the improved design with switchable exchanger services is 257,772.46 USD/yr. This result represents a significant 26.73% saving.

3. Strategy II – partitioning and reassembling heat-transfer areas

The capital cost of a multi-period HEN may be further reduced with a second time-sharing strategy, i.e., partitioning and then reassembling the heat-transfer areas of switchable exchangers. For example, unit B in Table 4 can be replaced by three smaller exchangers with areas 19.88 m^2, 12.11 m^2 and 29.03 m^2 respectively. These units can obviously be assembled in three different combinations to facilitate match (3,CU,3) in period 2 (whose required area is 61.02 m^2), match (2,2,2) in period 1 (whose required area is 41.14 m^2) and match (HU,1,0) in period 3 (whose required area is 29.03 m^2). In addition to these three matches which have already been identified in Table 4, the free area in period 1 (19.88 m^2) can be utilized to facilitate match (HU,1,0) and the idle units in period 3 (with areas 19.88 m^2 and 12.11 m^2) could be adopted to serve (1,CU,3) and (HU,2,0) respectively. Another generic algorithm has also been developed to perform the aforementioned tasks systematically (see Appendix B). By implementing these proposed steps, one can then generate the timesharing scheme presented in Table 5. Notice that the total heat-transfer area can now be reduced to 292.39 m^2.

It should be noted that, although Strategy II is effective in reducing the total heat-transfer area for the present example, the capital cost is actually higher (i.e., 275,477.70 USD/yr) according to the cost model given in Eq. (1). Thus, it can be concluded that the optimal timesharing structure cannot always be synthesized with the algorithmic procedure presented in Appendix B. A more rigorous mathematical programming approach is required if partitioning and reassembling heat-transfer areas of switchable exchangers are to be allowed in generating the timesharing schemes.

4. Mathematical programming model

As mentioned above, a mathematical programming approach should be used to automatically generate the best structure that incorporates both aforementioned timesharing strategies. The model formulation is given below:

$$\min_{x_e, y_e, z_{m,p,e}} \sum_{e \in E} y_e \varphi(x_e) \quad (2)$$

subject to the following constraints:

$$\lambda A_{m,p} \geq \sum_{e \in E} x_e z_{m,p,e} \geq A_{m,p} \quad (3)$$

$$\sum_{m \in M} \sum_{p \in P} z_{m,p,e} \geq y_e \quad (4)$$

$$y_e \geq z_{m,p,e} \quad (5)$$

$$\sum_{m \in M} z_{m,p,e} \leq 1 \quad (6)$$

$$x_e \geq 0 \quad (7)$$

$$y_e, z_{m,p,e} \in \{0, 1\} \quad (8)$$

$$m \in M, \quad p \in P, \quad e \in E \quad (9)$$

where $A_{m,p}$ is a model parameter that represents the required heat-transfer area of match m in period p; x_e is a positive real variable representing the actual heat-transfer area of exchanger e; y_e is a binary variable reflecting whether or not exchanger e is present in the timesharing scheme; $z_{m,p,e}$ is another binary variable reflecting whether or not exchanger e is selected to facilitate match m in period p; φ is defined in Eq. (1), which is a function of exchanger area for computing the capital cost of exchanger e; $\lambda > 1.0$ is a model parameter used to impose a realistic upper bound on the heat-transfer area for match m in period p; M is the set of all matches; P is the set of all periods; E is the set of all heat exchangers. Eq. (3) essentially characterizes the realistic range of total area to facilitate match m in period p, while Eqs. (4)–(6) are used to impose the following logic constraints respectively:

- If exchanger e is adopted in the time-sharing scheme, then it is used to facilitate at least one match in a single period;
- If exchanger e is adopted to facilitate match m in period p, then it should be adopted in the time-sharing scheme;
- One exchanger (say unit e) is allowed to facilitate at most one match in a single period (say period p).

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Table 5 – The timesharing scheme obtained with Strategy II in Case 1.

Match	Period	Unit A′ 134.11 m^2	Unit B′ 37.05 m^2	Unit C′ 29.3 m^2	Unit D′ 29.03 m^2	Unit E′ 19.88 m^2	Unit F′ 16.83 m^2	Unit G′ 14.08 m^2	Unit H′ 12.11 m^2
(1,1,2)	1	×							
(2,1,2)	1						×		
(2,2,2)	1				×				×
(1,CU,3)	1			×					
(2,CU,3)	1		×						
(HU,1,0)	1					×			
(1,1,2)	2	×							
(3,2,1)	2		×				×		
(1,CU,3)	2							×	
(3,CU,3)	2				×	×			×
(HU,1,0)	2			×					
(1,1,2)	3	×							
(1,CU,3)	3					×			
(HU,1,0)	3				×				
(HU,2,0)	3								×

Table 6 – The optimal timesharing scheme obtained by solving mathematical programming model in Case 1.

Match	Period	Unit A″ 134.11 m^2	Unit B″ 61.02 m^2	Unit C″ 37.29 m^2	Unit D″ 29.3 m^2	Unit E″ 16.59 m^2	Unit F″ 14.08 m^2
(1,1,2)	1	×					
(2,1,2)	1					×	
(2,2,2)	1		×				
(1,CU,3)	1						×
(2,CU,3)	1			×			
(HU,1,0)	1				×		
(1,1,2)	2	×					
(3,2,1)	2			×		×	
(1,CU,3)	2						×
(3,CU,3)	2		×				
(HU,1,0)	2				×		
(1,1,2)	3	×					
(1,CU,3)	3						×
(HU,1,0)	3				×		
(HU,2,0)	3			×			

The aforementioned MINLP model was solved for Case 1 using solver BARON in the GAMS environment. To avoid trapping at one of the local minima, multiple runs were performed with randomly generated initial points. The machine platform used is an Intel(R) Core(TM) 2 Quad CPU, 2.66 GHz machine. The total number of runs is 20 and each computation time is restricted within 4 h. The best local solution obtained for Case 1 is summarized in Table 6 and Fig. 5a–c. Notice that this structure also contains six units with a total area of 292.39 m^2. Although these results are exactly the same as those generated by switching the exchanger services only (see Table 5), the exchanger areas are chosen differently and match (3,2,1) is facilitated jointly in this scheme with units C'' (37.29 m^2) and unit E'' (16.59 m^2). As a result, the annualized total capital cost can be further reduced to 248,383.53 USD/yr.

5. Case studies

Three additional case studies have been carried out in this work to validate the proposed timesharing strategies. Table 7 is a summary of the optimal HEN design reported in Isafiade and Fraser (2010), where the original process data were taken from Floudas and Grossmann (1987a). Based on a different set of process data given in Floudas and Grossmann (1987a), another design was also generated by the same authors (1987b), and its specifications are presented in Table 8. Notice that the maximum heat-transfer area of every match is underlined in both tables and, therefore, the total area required in each HEN can be calculated accordingly. Finally, the conventional multi-period HEN design of a hypothetical example is considered in the fourth case study (see Table 9).

Table 7 – The conventional multi-period HEN design used in Case 2 (Isafiade and Fraser, 2010).

No.	Required area (m^2)			
	Match	Period 1	Period 2	Period 3
1	(HU,2,1)	31.2	32.1	11.71
2	(2,2,3)	5.12	5.12	5.12
3	(1,1,4)	8.07	14.39	1.96
4	(2,CU,4)	29.58	8.3	31.8
5	(1,CU,5)	21.67	2.39	28.54

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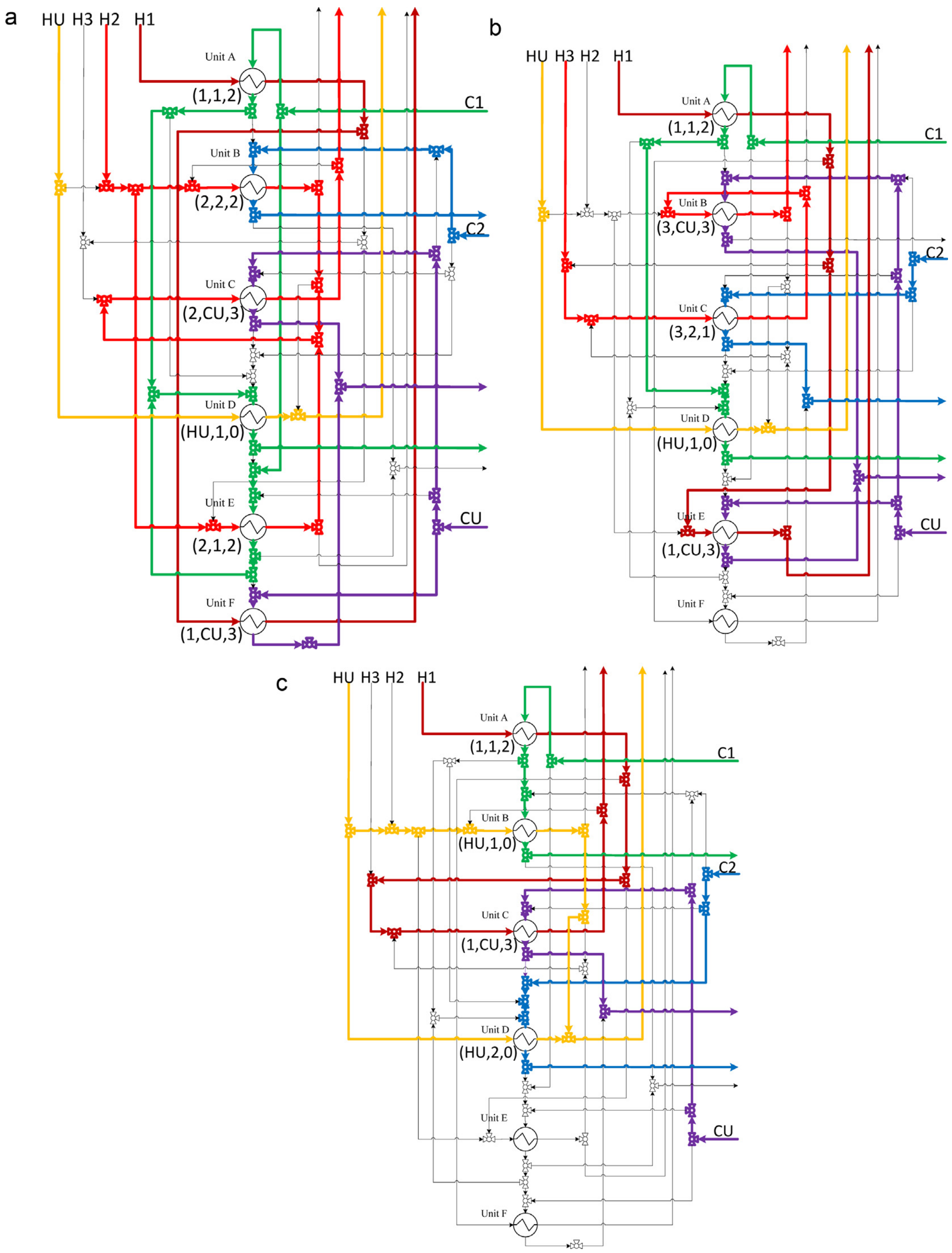

Fig. 4 – (a) Pipeline structure of timesharing scheme obtained with Strategy I for period 1 in Case 1. (b) Pipeline structure of timesharing scheme obtained with Strategy I for period 2 in Case 1. (c) Pipeline structure of timesharing scheme obtained with Strategy I for period 3 in Case 1.

Table 8 – The conventional multi-period HEN design used in Case 3 (Isafiade and Fraser, 2010).

No.	Required area (m^2)				
	Match	Period 1	Period 2	Period 3	Period 4
1	(2,3,1)	0.377	0	4.947	0
2	(2,2,2)	24.849	27.173	22.111	24.975
3	(1,2,3)	0	4.604	4.527	5.746
4	(3,1,3)	0	0	0	3.801
5	(1,1,5)	49.07	54.596	53.833	47.82
6	(1,3,5)	16.488	25.953	25.891	0.338

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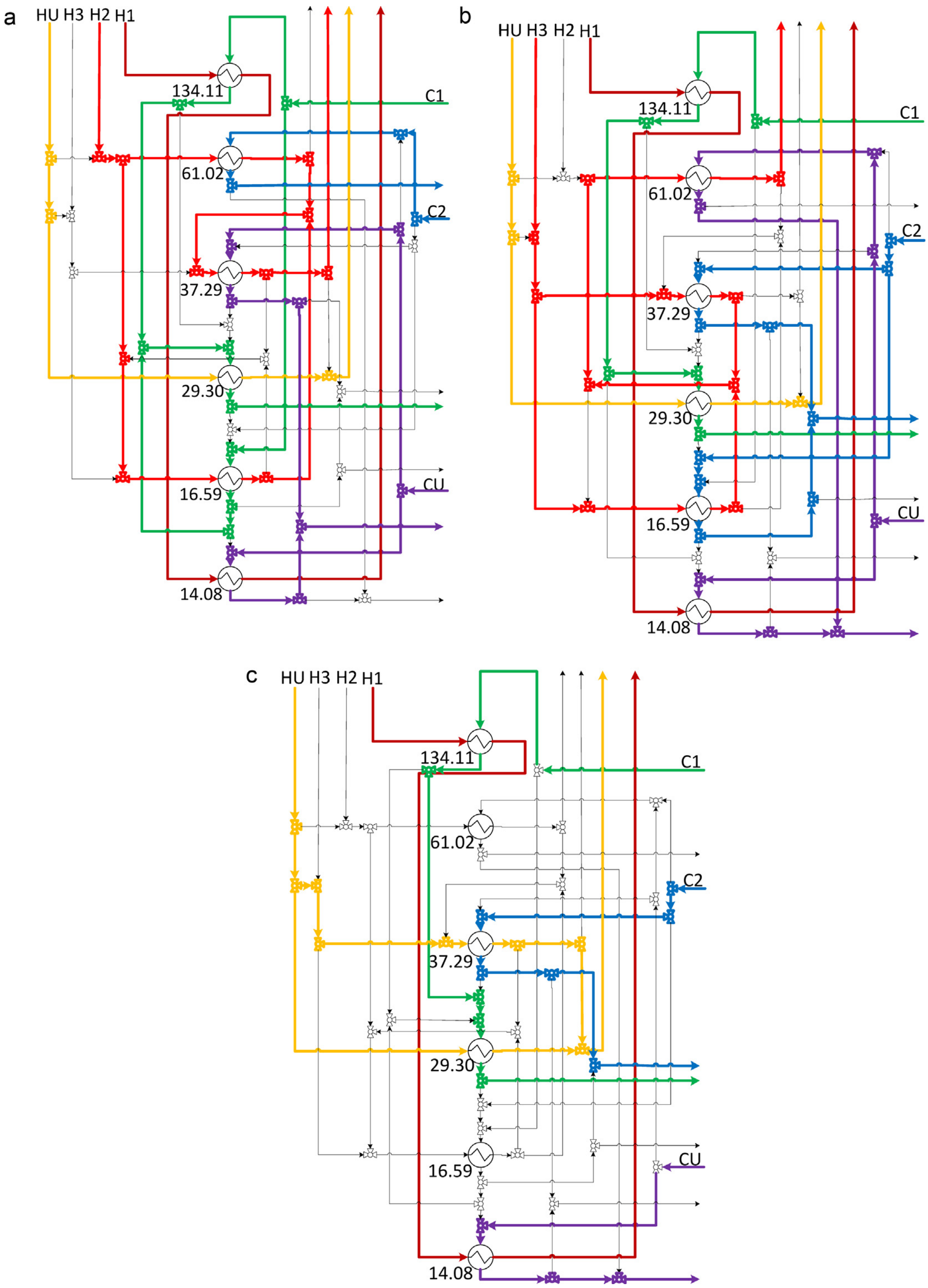

Fig. 5 – (a) Pipeline structure of timesharing scheme obtained with MINLP model for period 1 in Case 1. (b) Pipeline structure of timesharing scheme obtained with MINLP model for period 2 in Case 1. (c) Pipeline structure of timesharing scheme obtained with MINLP model for period 3 in Case 1.

Table 9 – The conventional multi-period HEN design used in Case 4.

No.	Required area (m^2)			
	Match	Period 1	Period 2	Period 3
1	(1,1,1)	14.8	15.7	14
2	(1,2,2)	87.6	54.6	52.3
3	(2,1,2)	28.2	27.9	30.8
4	(2,2,3)	214.1	231.4	304.6
5	(2,3,4)	0	143.2	0
6	(1,CU,5)	0	0	56.6
7	(2,CU,5)	100.9	108.3	105.2

Table 10 – Comparison of timesharing schemes generated with different synthesis strategies.

	Case 1	Case 2	Case 3	Case 4
Conventional				
Total number of units	9	5	6	7
Total exchanger area (m^2)	746.8	111.95	122.13	746.8
Total capital cost (USD/yr)	351,804.15	134,630.34	143,091.16	459,923.51
Strategy I				
Total number of units	6	5	5	6
Total exchanger areas (m^2)	308.98	96.54	113.05	678.7
Total capital cost (USD/yr)	257,772.46	121,941.66	123,478.82	408,120.51
Cost saving (%)	26.73	9.42	13.71	11.26
Mathematical programming				
Number of HE	6	5	6	6
Total exchanger areas (m^2)	292.39	96.77	112.98	709.8
Total capital cost (USD/yr)	248,383.53	122,199.57	130,637.46	418,570
Cost saving (%)	29.4	9.23	8.7	8.99

The timesharing schemes of all aforementioned examples have been synthesized both with Strategy I and automatically with the proposed mathematical program. Favorable results can be identified in all cases. A comparison of these schemes can be found in Table 10. It can be observed that the conventional designs in general call for a larger number of units and higher cost when the required heat-exchange areas in different periods vary greatly. It is also clear that near optimal solutions can be easily produced with the proposed algorithmic procedure (Strategy I) and in certain cases these solutions even outperform the ones generated with the programming approach. This is due to the fact that a global optimum of the MINLP model given in Eqs. (2)–(9) cannot always be located with multiple runs in the GAMS environment. In the future, better schemes may be identified by committing additional computation resources and/or devising more effective optimization strategies.

6. Conclusions

Effective synthesis strategies are proposed in this paper to produce the timesharing schemes of any given multi-period HEN design. Without changing the conceptual structure of the given design and also the operating conditions of its embedded matches, it has been shown that the total capital cost can be significantly reduced by allowing a chosen set of exchanger units to be utilized by more than one match in multiple periods. The proposed strategies can be implemented either by following a systematic procedure or automatically by solving a MINLP model. The former approach is easy to apply and also effective for the purpose of creating practically acceptable solutions. Although somewhat better results may be obtained with the latter method, the required computation effort can be quite demanding. Based on the extensive case studies performed so far, it can be concluded that both approaches are feasible for generating the timesharing schemes that achieve significant capital saving. However, if the sharing structures obtained by hand calculations are satisfactory, the more rigorous optimization runs may not be necessary.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.cherd.2014.04.011.

Appendix B. Partitioning and reassembling algorithm

1. Sort all switchable exchanger areas and arrange them in descending order.
2. Identify the largest area in every period.
3. Label all areas identified in step 2 respectively as $A_1, A_2, \ldots, A_P$ (where $A_1 \geq A_2 \geq \cdots \geq A_P$). Partition A_1 into $A_1 - A_2, A_2 - A_3, \ldots, A_{P-1} - A_P$ and A_P, and use them as the areas of P different exchangers.
4. Combine the last $P - i + 1$ exchangers to meet the required area A_i exactly. Eliminate the corresponding match and its area from the ordered list. Repeat this step for $i = 1, 2, \ldots, P$.
5. Identify additional matches from the ordered list with a total area less than $A_1 - A_i$. If there are multiple choices, select the ones with the largest total area. Eliminate these matches and their areas from the ordered list. Repeat this step for $i = 1, 2, \ldots, P$.
6. If the ordered list is not empty, go to step 2. Otherwise, stop.

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