



A systematic strategy for multi-period heat exchanger network retrofit under multiple practical restrictions☆



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ABSTRACT

A systematic strategy for retrofit of the multi-period heat exchanger network (HEN) on the basis of the multi-objective optimization is developed. In this three-stage procedure, a simplified multi-objective optimization model of the multi-period HEN is first established and then solved to target the retrofit, aiming to minimizing the total annual cost and total annual CO₂ emissions. The obtained Pareto front represents series of retrofit targets under different emission limitations, from which the most desirable one can be selected. The matching of the existing and the required heat exchangers is further implemented to finalize the retrofit, which will meet the practical retrofit requirements and matching restrictions. The application of the proposed procedure is illustrated through a case study of a HEN in a vacuum gas oil hydro-treating unit.

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1. Introduction

Heat exchanger network (HEN) is one of the most important energy utilization sub-systems in process industries, such as oil refining, petrochemical processes, steel, pharmacy and food [1]. A well-designed HEN benefits both the economic and environmental sustainability [2,3]. However, the variation of production plan and ambient conditions may cause the existing HEN, designed at fixed operation condition, becomes insufficient to the variable or multi-period operations [4]. Moreover, the existing HEN, designed years ago, may fail to meet the economic and emission requirements due to increasing energy cost and tighter environmental regulations [5]. Thus, a favorable retrofit of the HEN should not only satisfy the multi-period operations, but also meet the economic and emission requirements through proper retrofit actions. This problem can thus be formulated as a multi-objective optimization problem of multi-period HENs. However, the present research on this topic is mainly focused on the single objective optimization of HEN retrofit at fixed operating conditions, aiming to maximizing energy consumption reduction (emission reduction) or minimizing the cost for retrofit [6].

For energy consumption reduction purpose, pinch technology based methods and their variants are commonly adopted, where the retrofit target is determined *via* the graphic tools before the retrofit is performed according to simple heuristic rules [7]. Examples of these

methods include the modified pinch approaches [8,9], path analysis method [10] and various improved graphic tools, such as retrofit thermodynamic diagram [11] and the extended grid diagram [12]. These methods, to some extent are helpful to reduce the CO₂ emissions in HENs because energy consumption is the main source of the CO₂ emissions in HENs. In spite of the successful applications of these methods in CO₂ emission reduction in HENs, other strategies, such as fuel switching [13] and heat pump installation [14] are also developed for retrofit of HENs where the existing structure and energy utilization have been optimal.

To consider the economic efficiency of HEN retrofit, a mixed-integer nonlinear programming (MINLP) model is involved [15]. Extensive research activity has been focused on the development of the solving strategies for this MINLP model which can be solved by either one-step method where the topology modification, HE assignment and cost optimization are carried out simultaneously [16–18], or multi-step method where the HEN retrofit model is solved in a step-wised manner [19,20]. Besides, there are also some multi-objective optimization models for HEN retrofit, considering both economic efficiency and CO₂ emissions of HENs [14]. However, these methods are based on the assumption that the operation parameters of the HENs keep unchanged, which is not the case in practice.

To address this problem, Zhang and Zhu [21] studied the interactions between process changes and HEN retrofit. For the HEN with variable heat capacity flow rates, Sreepathi and Rangaiah [5] formulated the heat capacity flow rates of streams as a function of temperatures *via* polynomial fitting. The HE assignment strategies [22] were then adopted to complete the retrofit. Unlike this continuous approach, Smith *et al.* [23] solved this HEN retrofit problem by using an interval approach, where the temperature range of the stream was divided

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into several intervals of constant specific heat capacity for calculations. This problem was then considered a multi-period HEN retrofit problem [24]. A reverse order matching method [25] and a graph-theoretic approach [26] were proposed to solve this kind of problem. In these two methods, the retrofit target of multi-period HEN was determined by solving a HEN model involving multi-period operation [27], the existing HEs and the required HEs were then matched to finalize the retrofit through a series of retrofit actions. It is worth noting that the graph-theoretic method defined the HEs matching problem as a bipartite graph matching problem, where the existing HEs and required HEs are matched to meet different objectives under various restrictions. The main advantage of this method is that the computational effort in solving the HEN retrofit problem can be significantly reduced through the application of well-established graph algorithms.

However, the research on HEN retrofit in multi-period operation is still premature. Although the practical restrictions should be reinforced during HEN retrofit, as mentioned by some researchers [22,26,28], the restrictions on physical size and operating pressures of the existing HEs during the reassignment of HEs and heat transfer areas are often neglected in most of the cases. This, to some extent, may underestimate the capital cost for HEN retrofit. In addition, some strategies for CO₂ emission reduction in single period HENs take the assumption that the existing structure and energy utilization have been optimal. However, it is not the case in retrofit of multi-period HENs where the existing HEN has failed to meet the current operation conditions and energy and/or emission limitations. Thus, a trade-off between cost and emission of the multi-period HEN during the retrofit *via* process integration turns out to be necessary.

In this direction, the major objective of this work is to develop a systematic strategy for retrofit of the multi-period HEN on the basis of the multi-objective optimization, aiming at minimizing the cost for retrofit and CO₂ emissions. In the proposed procedure, a simplified multi-objective optimization (MOO) model of the multi-period HEN is constructed and solved to target the retrofit, and the required HEs and the existing ones are then matched to select the proper retrofit schemes under the constraints of physical sizes and operating pressures of HEs. A multi-period HEN retrofit in a vacuum gas oil hydro-treating unit is employed to illustrate the application of the proposed procedure.

2. Retrofit Strategy of the Multiperiod HENs

This section introduces the procedure for retrofit of the multi-period HEN considering emission limitation and practical retrofit restrictions, which includes the following three phases:

- (1) Establishing a simplified multi-period HEN model through single period optimization;
- (2) Targeting the multi-period HEN retrofit based on the multi-objective optimization;
- (3) Selecting the retrofit schemes *via* matching the required and existing HEs.

2.1. Establishing a simplified multi-period HEN model

To reduce the subsequent computations, a simplified multi-period HEN model is constructed according to the procedure in our previous work [29]. In this way, the number of binary variables reduces and introducing of commonly shared matches helps to improve the solution generation [30]. Note that if the operation pressures are considered, a cost correction factor f_p will be introduced to distinguish the cost difference between a high-pressure HE and a low-pressure HE. In this work, a high-pressure HE is the one through which at least one of these high-pressure streams flows; otherwise, the HE is considered as a low-pressure one.

2.2. Targeting the multi-period HEN retrofit

To obtain a retrofitted HEN that meets both the multi-period operations and the emission requirement, a CO₂ emission objective is appended to the model of multi-period HEN. ε -Constraint method is then adopted to solve this multi-objective optimization model so that a Pareto front of the economic and emission objectives is generated for selection of the retrofit target.

2.2.1. Economic objective

The TAC of the multi-period HEN is the sum of the capital cost and the operating cost. The capital cost is mainly the cost of HEs and the operating cost includes the costs of heating utility, cooling utility and electricity that consumed by compressors and pumps.

$$\text{Min TAC} = Af \left[\sum_{k \in NS} \sum_{j \in CS} \sum_{i \in HS} f_p \left(C^f z_{ijk} + C^a A_{ijk}^\beta \right) + \sum_{i \in HS} f_p \left(C^f z_i^{cu} + C^a (A_i^{cu})^{\beta, \beta} \right) + \sum_{j \in CS} f_p \left(C^f z_j^{hu} + C^a (A_j^{hu})^{\beta, \beta} \right) \right] + \sum_{p \in PS} \frac{\text{DOP}_p}{\text{NOP}} \left(\sum_{i \in HS} C^{cu} q_i^{cu} + \sum_{j \in CS} C^{hu} q_j^{hu} + C^{ele} \sum (N_{\text{comp}} + N_{\text{pump}}) Y \right) \quad (1)$$

where Af is the annual factor; C^f is the fixed cost of the HE; C^a and β are the coefficient and exponent of area cost. f_p is a cost correction factor caused by the pressure. z is a binary variable denoting the existence of a heat transfer unit. A is the heat transfer area and q is the heat load of the utility. DOP and NOP are the duration of a subperiod and the duration of operation. Y is the annual operating time of the plant. N_{comp} and N_{pump} are the power of compressor and pumps which can be calculated as [31]

$$N_{\text{comp}} = \frac{n}{n-1} \frac{P_{\text{in}} V_{\text{in}}}{10^3 \eta_{\text{comp}}} \left[1 - \left(\frac{P_{\text{out}}}{P_{\text{in}}} \right)^{\frac{n}{n-1}} \right] \quad (2)$$

where P_{in} and P_{out} are the pressures at the inlet and outlet of the compressor. V_{in} is the volume flow rate of gas at the inlet of the compressor. n is the ratio of the heat capacity at constant pressure and that at constant volume, $n = C_p/C_v$. η_{comp} is the isentropic efficiency of the compressor [31].

$$N_{\text{pump}} = \frac{\Delta P \cdot V}{10^3 \eta_{\text{pump}}} \quad (3)$$

where ΔP and η_{pump} are the pressure difference and efficiency of the pump; and V is the volume flow rate of pumping fluid with the unit of $\text{m}^3 \cdot \text{h}^{-1}$. For process pumps, the volume flow rate of the streams can be calculated as

$$V = \frac{F}{\rho} \quad (4)$$

and the volume flow rate of cooling water is [32]

$$V = \frac{\sum_{j \in CS} q_j^{hu}}{\rho c_p (T_{\text{out}}^{cu} - T_{\text{in}}^{cu})} \quad (5)$$

where F is the mass flow rate of the process stream. ρ and c_p are the density and specific heat capacity of the cooling utility; and T_{in}^{cu} and T_{out}^{cu} are the inlet and outlet temperatures of the cooling utility.

2.2.2. CO₂ emission objective

According to the previous investigations, the recessive CO₂ emissions in the construction stage of the HEN can be eliminated when CO₂ emitted by utility and electricity are involved. Thus, in this work,

only the CO₂ emissions in operating stage of the HEN are considered as the total CO₂ emission (TCE) of the HEN.

$$\text{Min TCE} = \omega^{\text{hu}} \sum_{j \in \text{CS}} q_j^{\text{hu}} + \omega^{\text{ele}} \sum (N_{\text{comp}} + N_{\text{pump}}) Y \quad (6)$$

where ω^{hu} and ω^{ele} are the emission coefficients of heating utility and electricity and can be calculated according to our previous work [33].

2.3. Selecting the retrofit scheme by matching of heat exchangers

In this section, a heuristic method and a graph-theoretic method that are proposed in our previous work [26] are introduced and extended to match the HEs. Four retrofit objectives are considered as follows:

- O1: Minimal modification of the existing HEN structure;
- O2: Maximum number of substituted HEs after retrofit;
- O3: Minimum additional heat transfer areas after retrofit;
- O4: Minimal capital cost for retrofit for a given retrofit target.

To reach the first objective (O1), the retrofit target is determined by solving the multi-period HEN model with fixed structure, such that the existing HEN structure is maintained and only the heat transfer areas are modified to meet the multi-period operations. The rest of these objectives (O2–O4) are achieved based on the retrofit target obtained by solving the simplified multi-objective optimization model of the multi-period HEN. In this case, both the existing structure and the heat transfer areas are adjusted during the retrofit.

Following two practical restrictions will be considered during the matching of HEs:

- *The restriction of physical size of the existing HE*; If additional heat transfer area of an existing HE exceeds 15% of its original heat transfer area, a new HE should be considered.
- *The restriction of operating pressures of HE*; The required HEs at high operation pressures can only match with the existing HEs at high operation pressures, and the required HEs at low operation pressures can match with the existing HEs at low or high operation pressures.

2.3.1. Heuristic matching strategy

The main advantage of the heuristic method is that it is easy to implement and no mathematical formulations or complex algorithms are required. For each objective, the heuristic procedures for matching of the HEs are as follows.

2.3.1.1. O1: minimal modification of the existing HEN structure. In this case, the retrofit target is first obtained by solving the multi-period HEN model with fixed structure. The following rules are then adopted to minimize the structural modification.

For an existing HE and a required HE with the same stream match,

- If the area of the existing HE is greater than that of the required HE, a dotted arrow is drawn from an existing HE to a required HE, implying that this required HE can be directly substituted by the existing HE.
- If the required area is greater than the existing area and the additional area is less than 15% of the existing area, a dotted arrow is drawn from a required HE to an existing HE; otherwise, there is no line linked between a required HE and an existing HE, implying that the existing HE is deleted and the required HE needs to be newly added.

Note that the operating pressures of HEs are automatically satisfied because the operating pressures of a required HE and an existing HE

with the same stream match will be the same. In addition, by following these matching rules, the existing HEs will not be rearranged and the existing HEN structure will be less modified.

2.3.1.2. O2: maximum number of substituted HEs after retrofit. For a given retrofit target, when the number of substituted HEs is maximized, the number of newly added HEs and HEs that need to increase the areas is minimized, implying that the existing HEs are fully utilized. In this direction, the reverse order matching method can be adopted, which is developed on the basis of the convex–noconvex property of the area cost function with respect to the additional areas. However, this method is only applicable to matching HEs without considering practical restrictions. The procedure of the reverse order matching method is as follows:

Initially, we check the number of the required HEs and that of the existing HEs, and add the HEs of zero area to make them consistent. Then, all the required and existing HEs are ranked in descending order by their heat transfer areas.

- If an existing HE is adjacent to and located above a required HE, a dotted arrow is drawn from an existing HE to a required HE. Once matched, they are removed from the ranks. This step will be continued until all the required HEs are located below the existing HEs.
- When the remaining required HEs are matched with the existing HEs in reverse order and their heat transfer areas are not zero, a solid arrow is drawn from a required HE to an existing HE.
- If one of them has a zero area after reverse order matching, there is no line linked between a required HE and an existing HE. In such case, the required HE needs to be newly added, and the corresponding existing HE is deleted.

2.3.1.3. O3: minimum additional heat transfer areas after retrofit. The minimum additional heat transfer areas after retrofit can be achieved by matching the HEs in serial order. The matching procedure is inferred from the convex–noconvex property of total additional area function. Similar to the reverse order matching method, this procedure is only suitable to matching HEs without any restrictions.

In this procedure, the numbers of the required HEs and the existing HEs are first matched by adding auxiliary HEs of zero areas. The required HEs and the existing HEs are individually ranked in descending order by their heat transfer areas. Two HEs with same orders are correspondingly matched.

- If the area of the existing HE is greater than that of the required HE, a dotted arrow is drawn from an existing HE to a required HE. In this case, the required HE is directly replaced by the existing HE.
- If the area of the existing HE is smaller than that of the required HE, a solid arrow is drawn from a required HE to an existing HE, which indicates that the area of the existing HE needs to be increased.
- If one of them has a zero area, there is no line linked between a required HE and an existing HE. It implies that the existing HE is deleted and the required HE should be newly added.

2.3.2. Graph-theoretic matching strategy

Unlike matching HEs via heuristic rules, the graph-theoretic approach enables the consideration of practical matching restrictions, extra retrofit objectives and various investment costs simultaneously. In this method, the matching of HEs is defined as a bipartite graph matching problem, which is accessible to take the advantage of the well-established graph algorithms to solve the problems. The corresponding relationships between the matching of HEs with different objectives and the matching of bipartite graph are given in Table 1.

Table 1
Relationships between the matching of HEs and the matching of bipartite graph

Objective	Bipartite graph matching	Weight matrix	Graph algorithm
O2	Maximum matching	Matrix of the substituted HEs	Augmenting path algorithm
O3	Minimum weight matching	Matrix of additional heat transfer area	Hungarian algorithm
O4		Matrix of retrofit investment cost	

Table 1 shows that the objective of the maximum number of substituted heat transfer units after retrofit can be achieved by solving a maximum matching of the bipartite graph, taking the matrix of the substituted HEs as the weight matrix. The classic algorithm for this problem is the *augmenting path algorithm*. The objectives of the minimum additional heat transfer areas and the minimum cost for retrofit equals to solve the corresponding minimum weighted matching of the bipartite graph, taking the additional heat transfer area and retrofit investment cost as an edge weight, respectively. The *Hungarian algorithm* can be used to find the desired matching.

The key to this method is to construct weight matrices whose elements are calculated by considering the practical restrictions and retrofit objectives. The definition and construction of weight matrices can be found in our previous work [26].

3. Case Study

3.1. Fundamentals of the HEN in a VGO hydrotreating unit

In this section, a HEN of vacuum gas oil (VGO) hydro-treating unit in a refinery in China is employed. The annual processing capacity of the unit is 2.6 million tons [33]. For the VGO process, the reaction is carried out under high temperature and high pressure. A well-designed HEN of such system leads to both economic and environmental benefits. The existing HEN structure is shown in Fig. 1, in which six hot streams and four cold streams are involved, and the minimum temperature difference is 20 °C. In this unit, the existing operating parameters under nominal operating conditions are presented in Table 1. We can see that the reactor effluent (H1), gas from high pressure separator (H5 and H6), mixture feed (C1) and mixture hydrogen (C4), with pressures of about 10 MPa are the high-pressure streams in this unit. The rest of the streams are low-pressure streams with pressures less than 2 MPa.

In this unit, only the power consumed by the water pumps changes during the HEN retrofit. Thus, the CO₂ emissions of heating utility and electricity consumed by water pumps are considered in this example. The total annual CO₂ emission of the existing HEN is 50 kt.

Consider a variation of the production demands, three additional operating periods are introduced, corresponding to the 80%, 90% and 110% of the existing processing capacity. The operating conditions of these additional periods are listed in Table 2, which are obtained via simulation performed on the software package ASPEN Plus.

Table 2
Fundamental data under the nominal operating condition of the HEN

Streams	$T_{in}/^{\circ}\text{C}$	$T_{out}/^{\circ}\text{C}$	$F/\text{kW}\cdot^{\circ}\text{C}^{-1}$	Pressure/MPa
H1 Reactor effluent	399	250	351.1	10.8
H2 Hydrowax	351	90	179.8	2.0
H3 Diesel product	282	80	29.4	1.5
H4 Backflow diesel	254	200	172.6	0.66
H5 Gas from high pressure separator	250	165	100.0	10.2
H6 Gas from high pressure separator	122	50	156.4	10.0
C1 Mixture feed	177	368	325.8	11.8
C2 Feed of fractionation tower	243	385	236.4	1.0
C3 Feed oil	135	168	204.5	1.1
C4 Mixture hydrogen	102	214	75.9	11.8

The capital cost of the HE is calculated by $10000 + 324 A$ (A is heat transfer area, m²). The annual costs of the heating utility, cooling utility and electricity are 70 USD·kW⁻¹, 7 USD·kW⁻¹ and 0.1604 USD·(kW·h)⁻¹. When considering the HEN retrofit, we adopt the Smith's method [31] to calculate the potential costs for retrofit, including construction cost of the newly added HEs, repiping cost of HEs requiring additional heat transfer areas and rearrangement cost of the HE when the stream matches change.

3.2. Retrofit of the multi-period HEN without any restrictions

In this section, neither the emission limitation nor the restrictions on HE matching are imposed. Initially, we obtain the optimal HEN matches in each sub-period by solving the single period HEN models. The commonly shared matches in four subperiods are selected and used to construct the simplified multi-period HEN model. This simplified model is then solved to determine the retrofit target of the multi-period HEN, aiming at minimizing the TAC. For comparison purpose, the retrofit targets under the fixed structure, referred as Scenario 1 (S1), and without

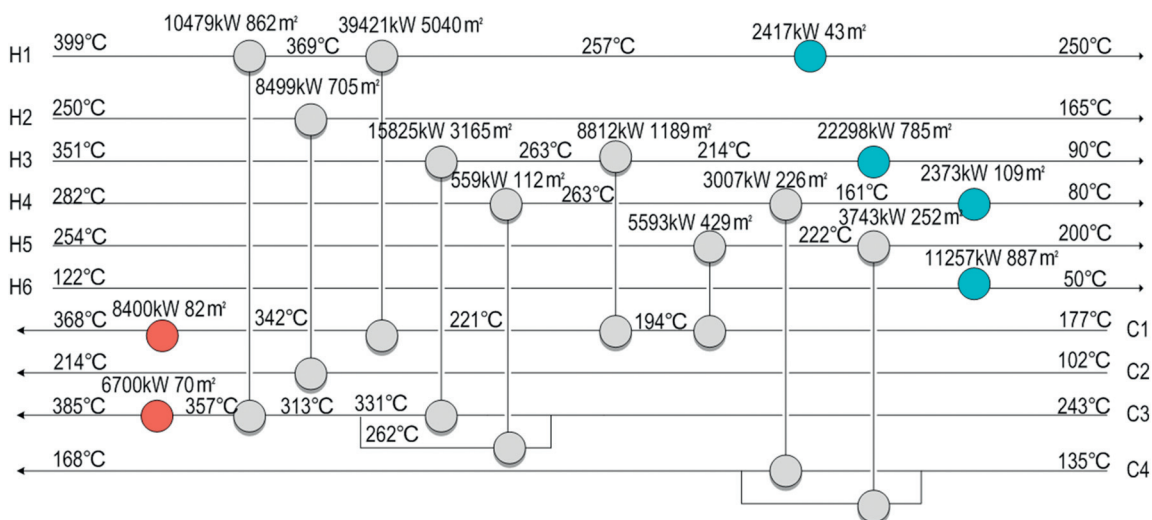


Fig. 1. The existing HEN structure of the VGO system.

fixing the structure, referred as Scenario 2 (S2) are separately obtained. Both the heuristic method and graph-theoretic method are further adopted to finalize the retrofit scheme.

3.2.1. Establishing the simplified multi-period HEN model

By solving the single period optimization model of the HEN, the optimal matches and corresponding heat transfer areas in each subperiod are obtained, which can be found in Supplementary materials. The optimal MTDs of the HENs in the four sub-periods are 20 °C, 17 °C, 21 °C and 19 °C. According to the optimal structures, seven HEs are

commonly shared in the four sub-periods. By fixing the optimal MTD in each subperiod and introducing these commonly shared HEs, a simplified multi-period HEN optimization model is constructed.

3.2.2. Targeting the retrofit of the multi-period HENs through single objective optimization

The retrofit targets in two scenarios (*i.e.* S1 and S2) are listed in Supplementary materials. According to the results, the required matches in Scenario 1 are the same as the existing matches in Scenario 2, and few matches required are the same as those in the existing HEN.

3.2.3. Matching of heat exchangers

Based on the retrofit targets obtained above, the required HEs and the existing HEs are matched to meet the following objectives:

- Minimal modification of the existing structure (S1-O1);
- Maximum number of the substituted HEs after retrofit (S2-O2);
- Minimal additional heat transfer areas after retrofit (S2-O3).

By using the heuristic matching method, we obtain the diagrams of HE matching with three objectives, as shown in Fig. 2. A comparison of results is presented in Table 3. Results show that by using the heuristic method, all objectives (O1–O3) can be well achieved.

Table 3
Multi-period operation conditions of the HEN

Streams	$T_{in}/^{\circ}\text{C}$	$T_{out}/^{\circ}\text{C}$	Average $F/\text{kW} \cdot ^{\circ}\text{C}^{-1}$
<i>Period 1 (80% capacity)</i>			
H1	392	250	282.7
H2	250	165	83.8
H3	347	90	143.6
H4	281	80	23.5
H5	252	200	137.5
H6	121	50	132.4
C1	179	362	263.8
C2	102	215	63.0
C3	233	380	186.2
C4	135	168	162.1
<i>Period 2 (90% capacity)</i>			
H1	394	250	317.0
H2	250	165	91.6
H3	348	90	162.3
H4	281	80	26.1
H5	252	200	159.0
H6	122	50	143.2
C1	180	365	294.1
C2	103	215	69.6
C3	240	380	212.4
C4	135	172	182.4
<i>Period 3 (110% capacity)</i>			
H1	402	250	384.1
H2	250	165	108.9
H3	353	90	198.5
H4	282	80	32.7
H5	253	200	187.0
H6	123	50	168.2
C1	175	370	358.1
C2	102	214	82.6
C3	244	385	259.9
C4	135	165	225.0

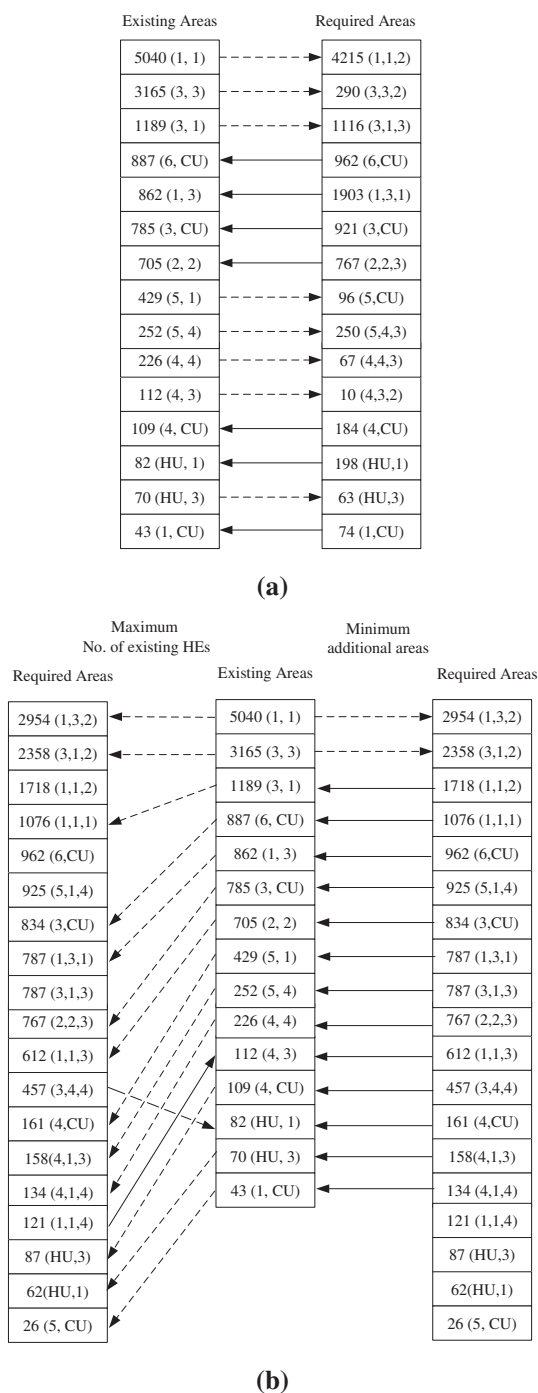


Fig. 2. The diagram of HE matching via heuristic-based method in the single objective optimization case with the (a) minimal modification of the existing structure (S1-O1) and the (b) maximum utilization of the existing heat transfer units (S2-O2) and areas (S2-O3).

In Fig. 2(a), although there is only one existing HE requiring re-arrangement, the minimum modification among all retrofit cases, seven HEs require additional heat transfer areas. A main disadvantage of the method is that it assumes that the existing HEN structure is optimal or still suitable to the multi-period operations. However, the retrofit target in Scenario 2 shows that the optimal structure has different stream matches and number of HEs with the existing

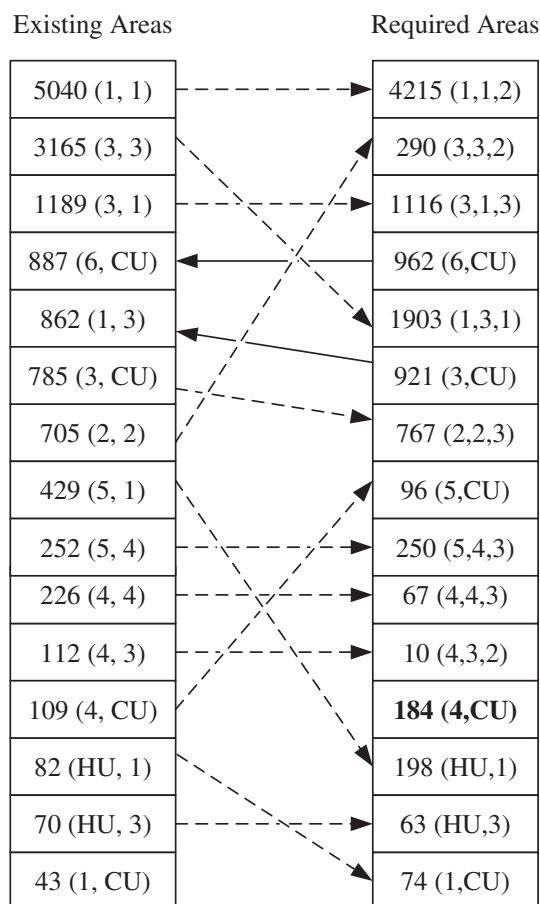


Fig. 3. The diagram of HE matching solved by graph-theoretic method in Scenario 1 (S1-O4).

one. Moreover, Fig. 3 presents the diagram of HE matching corresponding to S1-O4 where the retrofit target is obtained by solving the multi-period HEN model with the fixed structure (S1) and the objective is to minimize the capital cost for retrofit. It can be seen that the capital cost of HEN retrofit without modification is higher than that with structure modifications, indicating the necessity of structure modification during retrofit. The payback period in Scenario 1 is infinite because the energy consumption increases after retrofit, which also shows the fact that the existing HEN structure may not be optimal, and the retrofit of the HEN with the fixed structure may lead to a worse performance on economy and energy utilization.

For the retrofit target without considering the fixed structure, the diagrams of HE matching in objectives O2 and O3 are given in Fig. 2(b). It can be seen that the required HEs and the existing HEs are matched in the reverse order in objective O2, whereas they are matched in the serial order to minimize the additional areas after retrofit. Results in Table 3 show that the maximum number of the substituted HEs and the minimal additional areas after retrofit are 13 and 3923 m². Note that the payback periods in these two objectives are reasonable, implying that compared with the existing HEN, the retrofitted HEN is energy-efficient.

Table 3 also gives the results of graph-theoretic matching method in the three objectives, i.e. O2, O3 and O4. The corresponding diagrams of HE matching can be found in Supplementary materials online. These results show that the graph-theoretic method enables to meet all different retrofit objectives. For a given retrofit target in Scenario 2, the maximum number of the substituted HEs is 13, and the heat transfer areas should be increased by at least 3923 m² after retrofit. The lowest capital cost for retrofit is 4.784×10^6 USD, corresponding to a shortest

payback period of 7.6 years. Although both two methods happen to reach the same results in objectives O2 and O3, the heuristic method cannot get a better solution in most cases. The major reason is that the matching problems in objectives O2 and O3 have multiple solutions and the graph-theoretic method can easily screen the optimal one with the lowest capital cost. In addition, the graph-theoretic method can guarantee the lowest capital cost for retrofit (O4), whereas the heuristic method cannot.

Therefore, by fixing the existing HEN structure, we can meet the requirements of the multi-period operations through area increase and obtain a HEN with minimal modification along with lower capital cost for retrofit. However, when the existing HEN structure is not optimal for the multi-period operations, the retrofit target obtained by fixing the existing structure may increase the energy consumption, leading to an infinite payback period for retrofit. On the contrary, for a given retrofit target obtained without fixing the existing structure, although the capital cost for retrofit is higher, the extra energy saving is reached, which results in a relatively reasonable payback period for retrofit. According to the abovementioned results, both the heuristic method and graph-theoretic method can be used for different objectives during HEN retrofit. However, the graph-theoretic method can solely guarantee a retrofitted HEN with lowest capital cost. Moreover, the problem of HEN retrofit considering multiple practical restrictions can also be realized by the graph-theoretic method.

3.3. Retrofit of the multi-period HEN based on the multi-objective optimization

In this section, the practical restrictions on CO₂ emission, physical sizes and operating pressures of HEs are imposed during the multi-period HEN retrofit. In this section, the multi-objective optimization (MOO) is employed to target the retrofit, and the graph-theoretic method is used to match the required and existing HEs. Four distinct objectives for the multi-period HEN retrofit are discussed under different combinations of the scenario and the objective, e.g. S1-O1, S2-O2, S2-O3 and S2-O4.

3.3.1. Establishing the simplified multi-period HEN model

The optimal stream matches and the corresponding heat transfer areas in four subperiods are obtained through the solutions to the HEN optimization model for the single period operation. The optimal MTDs of the HENs in four subperiods are 18 °C, 17 °C, 16 °C and 19 °C and ten commonly shared stream matches are selected and used to construct the simplified multi-period HEN model. More details of single period optimization can be found in Supplementary materials.

Note that, in this case, a cost correction factor f_p is introduced in the HEN optimization models such that $f_p = 1$ for a low-pressure HE and $f_p = 1.3$ for a high-pressure HE. In this example, as is shown in Table 1, the reactor effluent (H1), gas from high pressure separator (H5 and H6), mixture feed (C1) and mixture hydrogen (C4), with pressures of above 10 MPa are the high-pressure streams in this unit. The rest of the streams are low-pressure streams with pressures less than 2 MPa.

3.3.2. Targeting the retrofit of the multi-period HENs through multi-objective optimization

By solving the MOO model of the multi-period HEN, the retrofit targets under different total annual CO₂ emissions are obtained, as shown in Fig. 4.

Taking the minimum total annual cost and minimum CO₂ emissions in Fig. 4 as benchmarks, we can see that the range of the TAC is less than 0.3% when the TCE reduces from 38.4 kt to 18.2 kt (variation range > 110%). It suggests that a slight increase in TAC of the multi-period HEN will cause a significant decrease in total CO₂ emissions. Note that

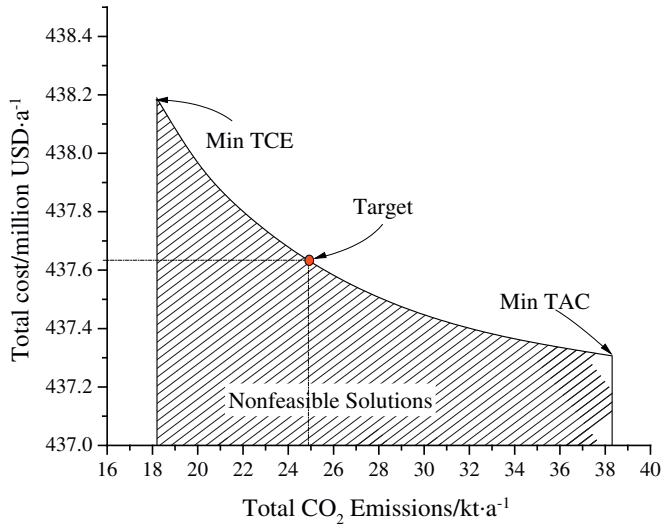


Fig. 4. The Pareto front of the multi-period HEN considering economic and emission objectives.

each point on Pareto front corresponds to a feasible retrofit target of the multi-period HEN, and decision-makers can choose a desirable one according to the practical economy and emission limitations.

If the CO₂ emission of the existing HEN is reduced to its half, the TCE of the HEN after retrofit should be less than 24.9 kt·a⁻¹, as marked as red solid circle in Fig. 4. The corresponding operation parameters can be found in Supplementary materials. Table 4 gives a comparison of the retrofit targets obtained with and without emission restrictions.

It can be seen that for a given retrofit target, the number of HEs in HEN obtained with emission restriction is less than that in HEN without emission restriction; total areas and TAC of the HEN with emission restriction increase when compared with those of the HEN without emission restriction. When the CO₂ emission is restricted, the TCE of the HEN in Scenario 1 will be 65.7 kt·a⁻¹, which is greater than that of the existing HEN.

3.3.3. Matching heat exchangers

By using the graph-theoretic approach, the diagrams of HE matching corresponding to four objectives (O1–O4) are shown in Fig. 5(a)–(c). The diagram of HE matching for the case of S1–O4 is also given in Fig. 6.

In Fig. 5, when the restrictions of the physical sizes and operating pressures of the existing HEs are considered, the feasible matches between the required HEs and the existing HEs (*i.e.* the HE matches where the required HEs can be substituted or matched by increasing the area of the existing HE) reduce, and the number of newly added HEs increases after retrofit. The additional areas and the capital cost for the multi-period HEN retrofit thus increase. In addition, the matching relationships in objectives O2 and O3 will not be consistent with the reverse order matching or serial order matching rules because

Table 4

A comparison of results in SOO case

	Scenario & objective	No. of replaced HEs	No. of repiped HEs	No. of newly added HEs	No. of rearranged HEs	Additional areas/m ²	Cost for retrofit/USD	Payback period/a
Heuristic-based method	S1–O1	7	7	1	1	1632	1777244	∞
	S2–O2	13	2	4	14	4776	5876076	9.33
	S2–O3	2	13	4	15	3923	6085186	9.67
Graph-theoretic method	S1–O4	12	2	1	7	318	1496484	∞
	S2–O2	13	2	4	14	4776	5876076	9.33
	S2–O3	2	13	4	15	3923	6085186	9.67
	S2–O4	6	9	4	9	4925	4784003	7.60

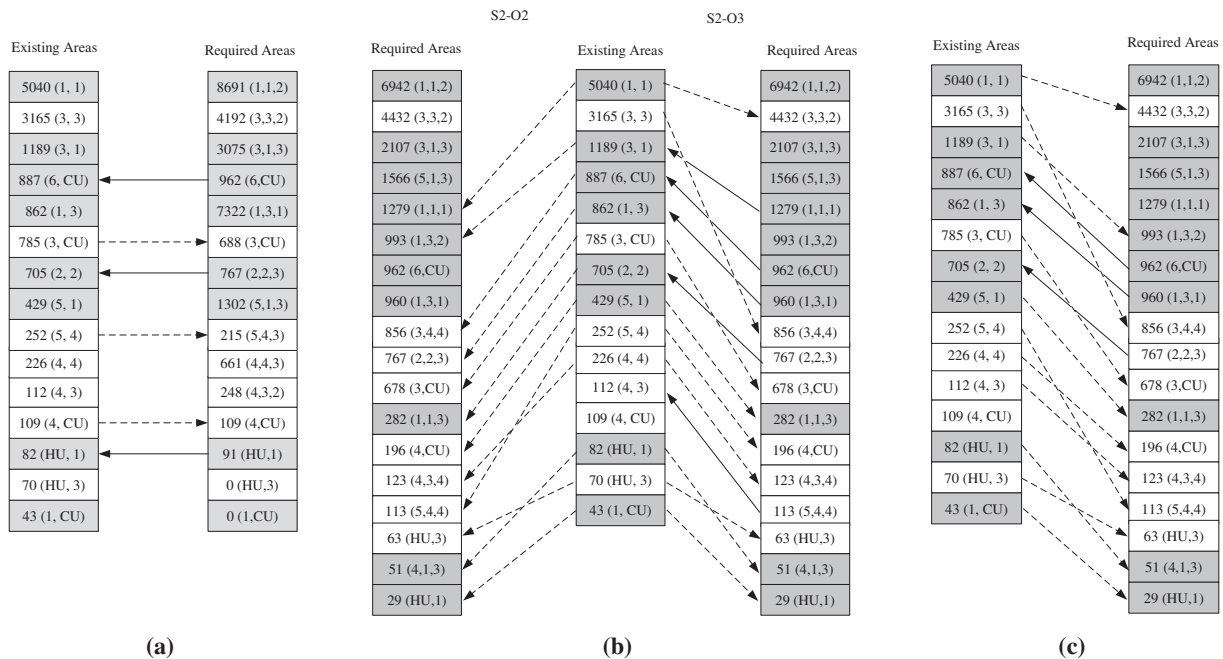


Fig. 5. Diagrams of HE matching solved by graph-theoretic method in MOO case with the (a) minimal modification of the existing HEN (S1–O1), (b) maximum utilization of the existing heat transfer units and areas (S2–O2 and S2–O3) and the (c) minimal cost for retrofit (S2–O4).

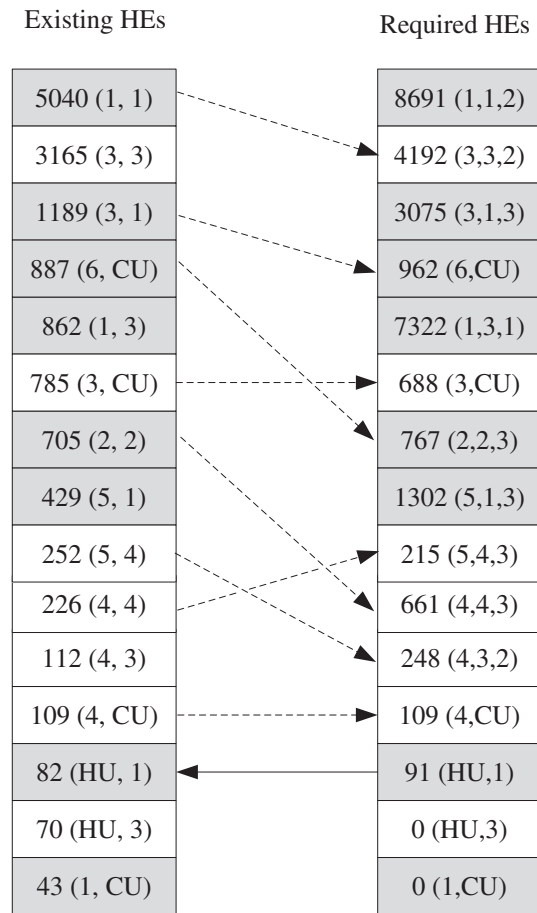


Fig. 6. The diagram of HE matching in the case of S1–O4.

the corresponding HEs cannot be matched due to oversize of the HE or compatible operating pressures.

Results in Table 5 show that different objectives can be well satisfied by using the graph-theoretic method under practical restrictions. Whenever the existing HEN structure is fixed or not, the number of utility exchangers in retrofit target with the emission limitation decreases. The payback periods for retrofit in different cases are finite, implying additional energy saving due to a limitation on CO₂ emission. Note that, for the retrofit target with fixed structure, the capital cost

for retrofit is higher and the payback period is longer when comparing with those corresponding to the retrofit targets without fixing the existing structure. It is likely that the total heat transfer areas of the multi-period HEN will increase when the emission limitation is considered. Although by fixing the existing structure, the required stream matches will be the same with those in the existing HEN, they cannot match due to additional area restrictions. The number of newly added HEs thus increases, leading to a higher capital cost for retrofit. Moreover, fixing the existing structure may also hinder the energy saving of the multi-period HEN. However, when the existing structure is not fixed, the retrofit target can be achieved through a trade-off between the economic and emission objectives, and the multi-period operational conditions can be satisfied by adjusting the stream matches, increasing heat transfer areas and heat transfer units. A more favorable energy saving and payback period are accordingly reached, as listed in Table 6.

4. Conclusions

In this paper, a systematic strategy for retrofit of the multi-period HENs is developed. A simplified multi-objective optimization model is constructed and solved to target the retrofit of the multi-period HEN, aiming to minimizing the retrofit cost and CO₂ emissions. After the selection of a retrofit target according to the practical cost and emission limitations, the required and existing HEs are matched to finalize the retrofit via the heuristic and graph-theoretic strategies considering distinct retrofit requirements and matching restrictions. A HEN of vacuum gas oil hydro-treating unit is used to illustrate the application of the procedure.

When the retrofit is targeted by minimizing the TAC and the matching restrictions are absent, both the heuristic and graph-theoretic methods can guarantee the specific objectives during retrofit. In particular, a retrofitted HEN with minimal modification and lower capital cost can be reached through determination of the retrofit target with fixed HEN structure. However, such practice may increase energy consumption and lead to an infinite payback period for retrofit. When the retrofit is targeted without fixing the existing HEN structure, additional energy saving and a desirable payback period for retrofit will be reached although the capital cost for retrofit of the multi-period HEN is higher.

When multi-objective optimization is employed to target the retrofit of the multi-period HENs considering practical restrictions, the heuristic method becomes not applicable, and the graph-theoretic method is used for multi-period HEN retrofit. Compared with the results obtained without any restrictions, the number of feasible HE matches reduces

Table 5

A comparison of retrofit targets obtained with and without emission restriction

	Scenario	No. of HEs	Total areas/m ²	TAC × 10 ⁻⁶ USD · a ⁻¹	TCE/kt · a ⁻¹
With emission restriction	Scenario 1	13	28,323	438.2	24.9
	Scenario 2	15	22,399	437.6	24.9
Without emission restriction	Scenario 1	14	11,931	437.9	65.7
	Scenario 2	19	14,851	437.3	38.3

Table 6

A comparison of results in MOO case

Matching strategy	Scenario-objective	No. of replaced HEs	No. of repiped HEs	No. of newly added HEs	No. of rearranged HEs	Additional areas	Cost for retrofit/USD	Payback period/a
Graph-theoretic method	S1-O1	3	3	7	0	25,637	27465183	26.5
	S1-O4	8	1	4	6	20,399	23912849	23.1
	S2-O2	12	0	6	8	16,969	18434836	17.8
	S2-O3	9	5	4	8	11,934	16010669	15.5
	S2-O4	10	4	4	7	12,140	15721398	15.1

and the number of newly added HEs increases, resulting in more additional areas and higher capital cost for retrofit. However, the energy consumption and CO₂ emission are suppressed, and a reasonable payback period is attained. In addition, the retrofit targets of the multi-period HEN determined through the multi-objective optimization method are useful for the decision-makers. According to these methods, one can readily select a desirable scheme according to the practical economic and emission restrictions.

Supplementary Material

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.cjche.2017.01.002>.

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