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Retrofitting Multi-Period Heat Exchanger Networks using the Reduced Superstructure Synthesis Approach

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In this paper, the reduced superstructure synthesis method is applied to the retrofit of heat exchanger networks involving multi-period operations. The first step in the synthesis procedure entails solving the multi-period problem to obtain a grass-root solution using the existing multi-period stage-wise superstructure synthesis method. The second step entails the generation of the reduced multi-period superstructure using a combination of two sets of matches as the initialising binary variables. These matches include those selected in the grass-root solution of the first step and those that exist in the original network. The generated reduced superstructure of this second step is then solved as a mixed integer non-linear programming model to obtain a final retrofitted network. The solution obtained from the case study considered in this paper compares favourably with what was reported in the literature.

1. Introduction

Most of the papers that have been published in the area of synthesis of heat exchanger networks (HENs) have been based on single period operations. In reality, process plant parameters such as stream flowrates, stream supply and target temperatures, may change from time to time due to issues such as process upsets, changes in environmental conditions, changes in feed raw materials and/or product specifications, plant start-ups and shut-downs, etc. These changes, in some cases, may be multi-period in nature, which then establishes the need to design HENs that are capable of handling multi-period scenarios. A host of workers have addressed this multi-period issue using mostly mathematical programming approach. Such works include the paper by Verheyen and Zhang (2006) where the stage-wise superstructure of Yee and Grossmann (1990) was extended by introducing the maximum heat exchanger area approach in the objective function for multi-period scenarios. This approach was still further extended by Isafiade and Fraser (2010) to handle unequal period durations. In the work of Isafiade and Odejobi (2016) a sequential initialisation technique, which was based on the reduced superstructure synthesis approach, was adopted for the optimisation of multi-period HENs. Isafiade (2017) adopted the periodic heat storage approach for the synthesis of multi-period HENs.

It is worth stating at this point that the papers reviewed so far, together with a host of other ones in the literature, have mostly involved grass-root designs, with very few papers having addressed retrofit problems in multi-period heat exchanger network synthesis (HENS). The work of Kang and Liu (2014a) addressed retrofit cases in multi-period scenarios using the reverse matching order approach. This method was later extended by Kang and Liu (2014b) to handle cases involving restrictions on heat exchanger operating pressure. Kang and Liu (2015) further extended the reverse order matching method using three strategies which include: the addition of extra heat transfer areas, substitution and/or addition of new exchangers. Another paper by Kang and Liu (2017) addressed scenarios where both the multi-period network's total annual cost and CO_2 are minimized.

It should be known that of the very few papers that have addressed retrofit scenarios in multi-period HENS, most have been based on the reverse order matching approach which was first presented by Kang and Liu (2014a). The method entails two major steps which are: determining a retrofit network target and re-matching of existing heat transfer areas with the required areas using the reverse order matching approach. It is worth stating that the reverse order matching approach, which is the second step in the method of Kang and Liu (2014a), is somewhat sequential in nature because the matches selected in the retrofit target of the first step are not given the opportunity to be simultaneously traded-off with the existing matches (i.e. units) in the original

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network. In this paper, a simple and effective method which simultaneously trades-off utilities, existing matches in the original network, and potential new matches for the retrofit network, is presented. The method is based on the reduced superstructure synthesis approach, which was first presented by Isafiade et al. (2015) for grass-root scenarios.

2. Problem statement

Given the supply and target temperatures as well as the heat capacity flowrates at various periods of operations for the existing set of hot and cold process streams in the original network to be retrofitted. Given a set of hot and cold utilities together with their supply and target temperatures, heat transfer coefficients and unit costs. Given the set of existing heat exchangers in the original network alongside their stream pairs, sizes and locations. Other parameters given are installation costs, area costs and area cost exponents for new heat exchangers that may have to be installed; existing exchangers that may need to be enlarged; and existing exchangers that may need to be reassigned. The objective is the minimization of the total annual cost of the retrofitted network considering factors such as reduction in energy consumption, usage of existing heat exchanger areas as much as possible and minimal addition of new exchangers or new heat exchanger areas.

3. Methodology

The adopted method entails two steps. In the first step, the original network's problem data are extracted and solved to obtain a grass-root network solution using the existing multi-period stage-wise superstructure of Verheyen and Zhang (2006). The cost of all exchangers in the superstructure at this stage are the costs that would have been used if new exchangers were to be installed in the network. The set of matches selected in the optimal solution of this step are identified to be used in the reduced superstructure of the second step.
The second step entails the construction of the reduced multi-period superstructure using two sets of matches as the initialising binary variables. The first set of matches are those selected in an optimal grass-root solution of the network in the first step of the methodology, while the second set of matches are the existing units in the original network. Using just these two sets of matches as the initialising binary variables at this stage makes the superstructure a reduced one in terms of number of binary variables when compared to the grass-root superstructure. Matches which are common to both the grass-root multi-period solution network and the original network are represented once in the reduced multi-period superstructure. Although the reduced superstructure has fewer binary variables compared with the grass-root superstructure, they still have the same number of stages.
The resulting reduced superstructure is then solved as a mixed integer non-linear programming (MINLP) model. This is beneficial in that the final retrofitted network may require fewer matches when compared to the number of binary variables in the reduced superstructure. Another benefit of solving the reduced superstructure as an MINLP model is that other promising matches, that were either not part of the grass-root solution network or the existing matches of the original network, can still be added to the reduced superstructure. Alternatively, some less promising matches may even be removed from the initializing variables to further reduce both the solution search space and computational burden involved in the solution generation process.
The multi-period retrofit objective function is adjusted accordingly to accommodate various options of retrofit scenarios such as installation of new exchangers, addition of extra heat exchanger areas and substitution of heat exchangers. Since the method of this paper adopts the existing multi-period stage-wise superstructure of Isafiade, et al (2015) for the base models, the detailed set of model equations will not be repeated here. However the objective function and a few other equations which are unique to this paper are shown in Eq 1 to 3.

$$A_{i,j,k}^{Select} = \frac{q_{i,j,p,k}}{\left(U_{i,j,p} \cdot LMTD_{i,j,p,k}\right)} \tag{1}$$

In Eq 1, $q_{i,j,p,k}$ represents the quantity of heat exchanged between hot stream i and cold stream j in period p and stage k of the reduced superstructure, $U_{i,j,p}$ is the overall heat transfer coefficient for stream pairs i,j, in period p, $LMTD_{i,j,p,k}$ is the logarithmic mean temperature difference between hot stream i and cold stream j in period p and stage k of the reduced superstructure. $A_{i,j,k}^{select}$ in Eq 1 represents the area of the selected heat exchanger based on the solution of the reduced superstructure. It should be known that this heat exchanger size is the maximum area required by the same set of stream pair i,j,k in all periods where they exchange heat. Eq 2 shows how the sizes of new heat exchanger area $A_{i,j,k}^{New}$ is determined based on the sizes of the selected exchangers $A_{i,j,k}^{select}$ of Eq 1 and size of existing exchangers $A_{i,j,k}^{Exist,orig}$ in the original network.

$$A_{i,j,k}^{New} = A_{i,j,k}^{Select} - A_{i,j,k}^{Exist,orig} \quad (2)$$

The purpose of Eq 2 is to ensure that the extra heat exchanger area $A_{i,j,k}^{New}$ that may have to be added to an existing heat exchanger area $A_{i,j,k}^{Exist,orig}$ is determined as the difference between $A_{i,j,k}^{Select}$ and $A_{i,j,k}^{Exist,orig}$. It is worth noting that $A_{i,j,k}^{New}$ will be large enough to exchange heat between the same set of stream pair in all periods of operations where they are present. An illustrative scenario is a case where $A_{2,3,2}^{select}$ is selected in the solution process of the reduced superstructure of step 2 and if $A_{2,3,2}^{Exist,orig}$ existed in the original network, then $A_{i,j,k}^{New}$ would be the difference between $A_{2,3,2}^{Select}$ and $A_{2,3,2}^{Exist,orig}$, which implies that the amount by which $A_{2,3,2}^{Exist,orig}$ increases, i.e. $A_{i,j,k}^{New}$, is what is costed as capital equipment to be paid for in the retrofitted network.
It is worth stating that the binary variable that represented $A_{2,3,2}^{Exist,orig}$ in the reduced superstructure came from the initializing set of matches in the original network. However, for a case where $A_{2,3,2}^{select}$ is selected and $A_{2,3,2}^{Exist,orig}$ did not exist in the original network, then $A_{2,3,2}^{Select}$ which by default becomes $A_{2,3,2}^{New}$ is not costed as an extra area being paid for but as a new heat exchanger having both area and installation costs. If $A_{i,j,k}^{Select}$ is less than $A_{i,j,k}^{Exist,orig}$, then the difference, which is an unused exchanger area can systematically be reassigned for use elsewhere in the retrofit network. Although, the set-up of the reduced superstructure approach for retrofitting heat exchanger networks ensures that most of the time, $A_{i,j,k}^{Exist,orig}$ is fully selected so that overall fewer entirely new exchangers would need to be included in the retrofit network.
The objective function used is shown in Eq 3. In this equation, HUC_i and CUC_j are costs per unit of hot and cold utilities, AF_{HE} represents the annualisation factor of heat exchangers, $CF_{i,j}$ represents the cost of installing new heat exchangers, $AC_{i,j}$ represents heat exchanger area cost, and $z_{i,j,k}$ represents binary variables. The binary variable is used to establish whether a match exists. It should be known that this binary variable is the one used in step 2 of this paper where the reduced superstructure is generated. Each of the capital cost parameters, i.e. AF_{HE}, $CF_{i,j}$, $AC_{i,j}$, are included in the superstructure model to represent any of the scenarios such as costing of new heat exchanger, existing exchanger or reassigned exchanger, etc.

$$TAC = min\left\{\left\{\left(\sum_{i\epsilon HP}\sum_{j\epsilon CU}\sum_{k\epsilon K} CUC_j \cdot q_{i,j,p,k}\right) + \left(\sum_{i\epsilon HU}\sum_{j\epsilon CP}\sum_{k\epsilon K} HUC_i \cdot q_{i,j,pk}\right)\right\} + \left[AF_{HE}\left(\sum_{i\epsilon HP}\sum_{j\epsilon CP}\sum_{k\epsilon K} CF_{i,j} \cdot z_{i,j,k} + \sum_{i\epsilon HP}\sum_{j\epsilon CP}\sum_{k\epsilon K} AC_{i,j} \cdot A_{i,j,k}^{New}\right)\right]\right\} \quad (3)$$
$$\forall \; i\epsilon HP;\; j\epsilon CP;\; k\epsilon K$$

The models of this paper are solved using General Algebraic Modelling System (GAMS), version 24.2.3 (Rosenthal, 2012), as the solver environment. The machine used operates on Microsoft® Windows 7 Enterprise™ 64 bit, Intel® Core™ i5-3210M processor running at 2.50 GHz with 4 GB of installed memory. CPLEX and CONOPT, in conjunction with DICOPT, were used as the solvers for the MILP and NLP sub-problems.

4. Case study

The proposed method is applied to a problem adapted from Verheyen and Zhang (2006). The problem has also been solved by Kang and Liu (2015). The heat exchanger capital cost function is given as € $8,333.3+641.7A^{0.7}$, hot utility cost is given as 115.2 €/(kW·y), while cold utility cost is given as 1.3 €/(kW·y). Stream heat transfer coefficient was back calculated from Kang and Liu (2015) as 2,000 W/(m^{2}°·C). Figure 1 shows the original network while Figure 2 shows the minimum investment cost network obtained by Kang and Liu (2015). Applying the method of this paper gives the reduced superstructure shown in Figure 3. In this figure, the matches represented in grey colour are the matches that are common to both the original network and the solution of the grass-root network obtained in this paper. The matches represented in black colour are those that are present only in the original network while those represented in white colour are those that are present only in the grass-root solution network. All of these matches were used to generate the reduced superstructure shown in Figure 3. The model was solved as an MINLP and it gave the solution network shown in Figure 4.

Table 1: Process stream data for the case study

Streams	Periods								
	Period 1			Period 2			Period 3		
	T^s (°C)	T^t (°C)	F (kW/°C)	T^s (°C)	T^t (°C)	F (kW/°C)	T^s (°C)	T^t (°C)	F (kW/°C)
HP1	393	60	201.6	406	60	205	420	60	208.5
HP2	160	40	185.1	160	40	198.8	160	40	175.2
HP3	354	60	137.4	362	60	136.4	360	60	134.1
CP1	72	356	209.4	72	365	210.3	72	373	211.1
CP2	62	210	141.6	62	210	141.0	62	210	140.5
CP3	220	370	176.4	220	370	175.4	220	370	174.5
CP4	253	284	294.4	250	290	318.7	249	286	271.2
HU1	500	500	-	500	500	-	500	500	-
CU1	15	25							

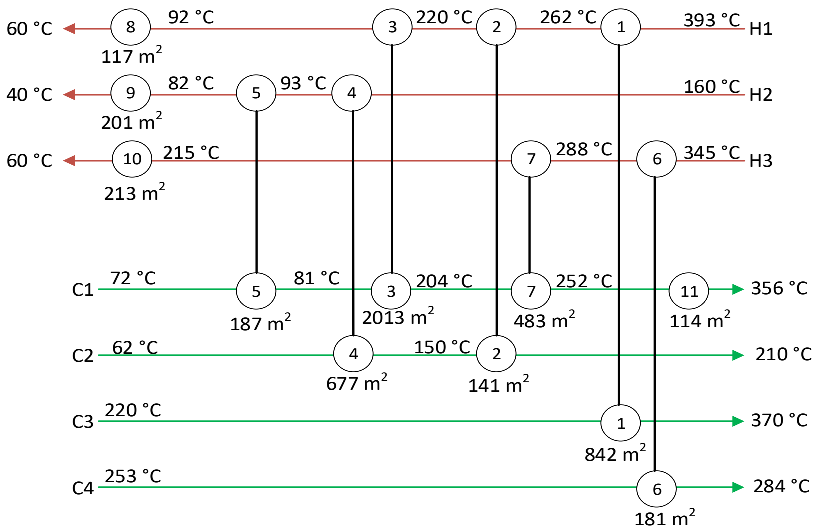

Figure 1: Original network for period 1 of the case study

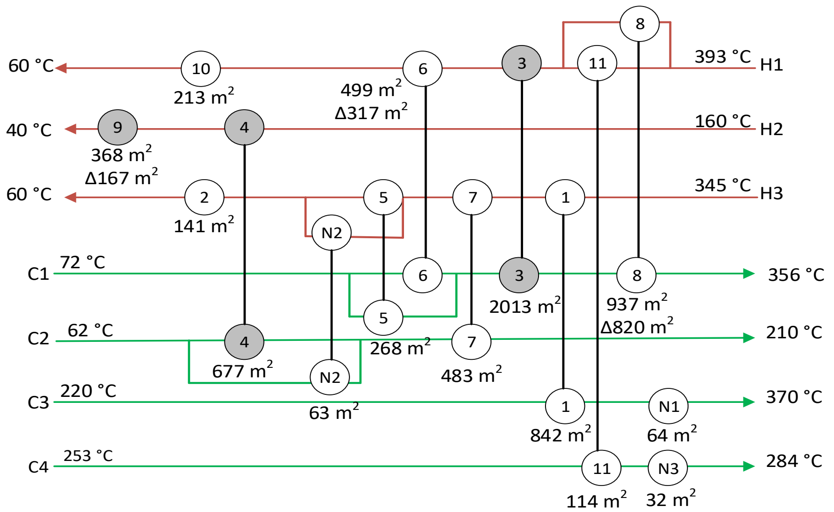

Figure 2: Minimum investment cost network for multi-period scenario (Kang and Liu, 2015)

In Figure 4, supply temperatures, target temperatures, and stream heat capacity flowrates for all three periods of operations are depicted. The exchangers that would have to be newly installed, which are four in number, are represented in grey colour. Their areas are shown in italics next to the bottom dumbbell shape of each of the matches. For all other exchangers, which are exchangers that exist in the original network and are being reused, two areas are shown next to their bottom dumbbell shapes.

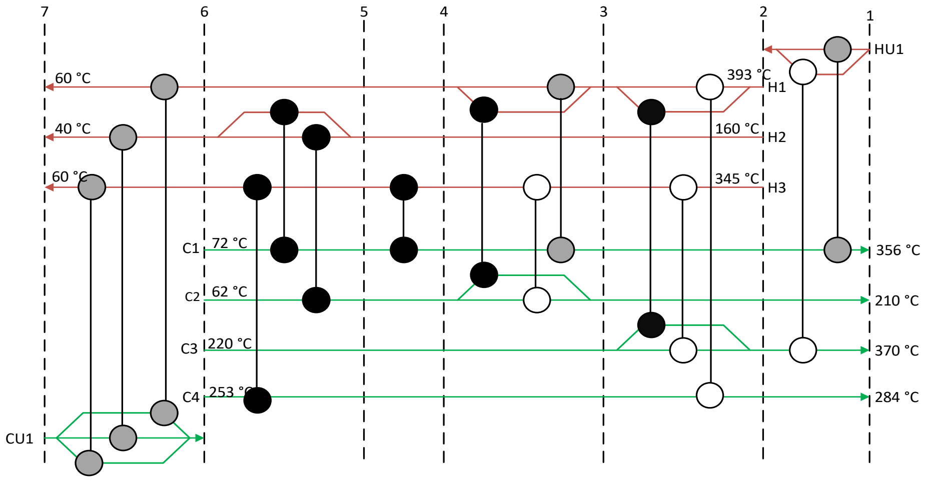

Figure 3: Reduced superstructure for the case study

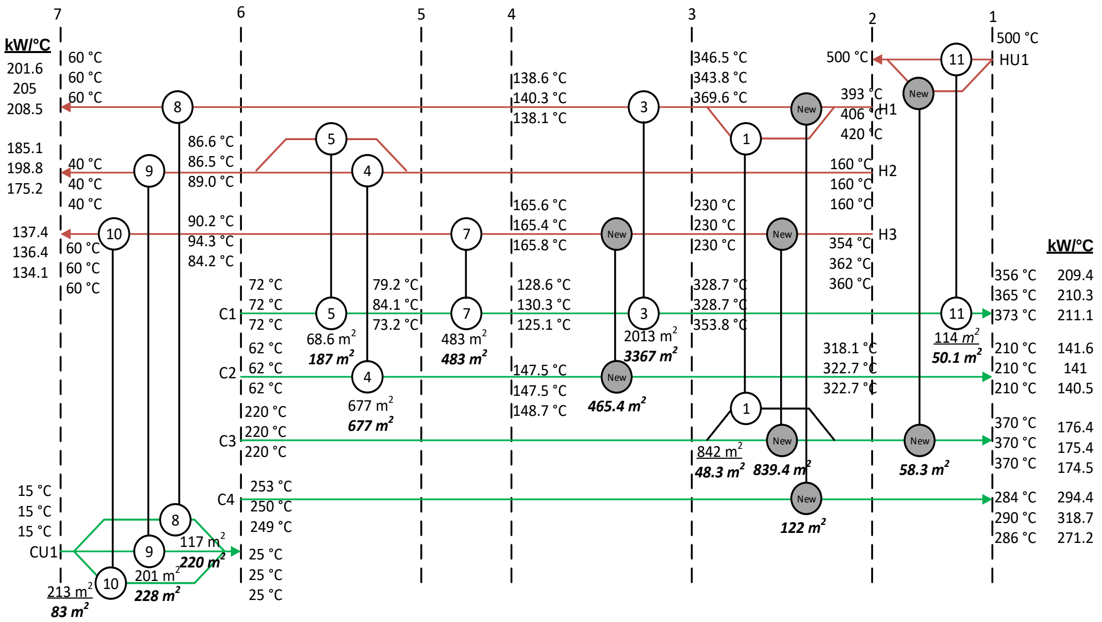

Figure 4: Minimum investment cost retrofit network for the multi-period case study

Table 2: Comparison of results with other solutions presented by Kang and Liu (2015)

Methods	Additional heat transfer area (m²)	Total area required in the network (m²)	Total energy required by the network (kW)	Cost of additional area (€)	Cost of energy Saved (€/y)
Scenario 1	1,766	-	-	170,904	863,587
Scenario 1	1,766	-	-	170,904	863,587
Scenario 2	1,219	-	-	182,009	863,587
Scenario 2	1,544	8,099	1,691,372	174,162	863,587
This work	2,969	7,816	1,694,451	304,618	860,507

Of these two areas, the first represents the existing area while the second represents the required area after retrofit. For exchangers 1, 10 and 11, the area required after retrofit are less than the existing area in each of the exchangers in the original network. Reassigning these excess areas alongside exchangers 2 and 6, which both exist in the original network but are not selected in the retrofit network, will further reduce the investment cost of the retrofit network, but this was not considered in this study. For exchangers 3, 8 and 9, additional heat exchange areas have to be added to the existing areas so as to meet heat load demand of the streams, while exchangers 4, 5 and 7 are fully used. It is worth stating that one of the key features of the solution obtained for this case study is that none of the exchangers changed location but re-piping will need to be done for some of the exchangers. This implies that investments costs will only be paid for the four new exchangers (including installation costs) and the extra areas added to exchangers 3, 8 and 9 (note that re-piping cost is not included in this paper as part of investment cost). Table 2 shows a comparison of the results obtained in this paper with those of Kang and Liu (2015). It is worth stating that very few papers have considered retrofit of multi-period HENs, which is the reason the solution of this paper is only compared with those of Kang and Liu (2015). From the paper of Kang and Liu (2015), it is not clear how the retrofit investment cost was calculated so only the cost of additional area is shown in column 5 of Table 2. In this paper, the extra areas added to exchangers 3, 8 and 9 and the full cost of acquiring the four new exchangers were included as the cost of additional area. This cost resulted in a payback period of 0.35 years. In order to ensure a fair comparison of the solutions of Kang and Liu (2015) with those of this paper, the total area required by the retrofit network of Kang and Liu (2015) shown in Figure 2 was calculated to be 8,099 m^2 which is 3.5 % bigger than the total area required by the solution of this paper. The total energy per annum required by the retrofit network of Kang and Liu (2015) was also calculated to be 1,691,372 kW. This energy is less than 1 % lower than the total energy required by the solution network of this paper which is 1,694,451 kW.

5. Conclusions

The reduced superstructure retrofit synthesis approach has been successfully applied to the retrofit of HENs involving multi-period operations. The method entails the use of promising matches as initialising matches in a reduced superstructure. This has the benefit of giving multi-period retrofit networks that have fewer reassigned matches or fewer matches changing location. The solution obtained in this paper was compared to some other methods in the literature and it was found that the method of this paper gave results that compare favourably in terms of fewer number of units, fewer stream splits, energy saved, and total annual cost which is 1,999,069 €/y as compared to the best value reported in the literature which is 1,865,534 €/y.

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