METHODOLOGICAL FRAMEWORK FOR SYNTHESIS OF MULTIPERIOD HEAT EXCHANGER NETWORKS WITH MINIMUM TOTAL ANNUAL COST USING AN OPTIMIZATION MODEL AND AREA REASSIGNMENT TECHNIQUE

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ABSTRACT

Heat exchanger network synthesis is one of the most important fields in the chemical processes. They are used to exchange heat among hot and cold streams. In this way, a great amount of heat can be recovered leading to a reduced utilities consumption, hence, improving the plant economics. Using heat exchangers increases the capital costs, therefore, a trade-off between the utility costs and capital costs should be considered. The optimal design of a multiperiod heat exchanger network is to configure a heat recovery system that achieves the temperature targets of the different periods at the minimum total annual costs. This paper presents a framework for designing multiperiod HENs, so that the trade-off between energy costs and capital costs can be simultaneously optimized. The proposed technique depends on a two-stage strategy, in the first stage, a model is built then solved using mathematical programming for the specified design periods to obtain a feasible configuration that achieves the heating targets with minimum total annual cost possible. In the second stage, further reduction in the total annual cost is obtained by using a technique that reassigns the heat exchangers areas over the different periods so that no excessive heat transfer areas are oversized.

KEYWORDS: Heat Exchanger Network Synthesis, Total Annual Cost, Multiperiod, Area Reassignment, MINLP

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INTRODUCTION

High energy costs involved in chemical processes have motivated extensive research into energy recovery methods and heat integration techniques to seek the optimum energy utilization and total cost minimization. Thus, heat exchanger network synthesis had a considerable amount of research over the past forty (40) years. In 1944, The HEN design problem was discussed into the literature for the first time by Ten Broeck¹. However, the first work in grassroots HENS was presented by Hwa² in 1965. Then, in 1969, the HENS problem was first rigorously defined by Masso and Rudd³. The first systematic technique used to consider energy recovery was the thermodynamic approach of pinch analysis concept, introduced during the 1970s. This was followed by mathematical programming, stochastic optimization approaches and hybrid methods developed from these. Furman and Sahinidis (2002)⁴ reported that more than 400 papers have been published on this subject over the last four decades.

Targeting and Decomposition-Based Technique

For the synthesis problem of the HEN, the thermodynamic approach of pinch analysis was introduced by the work of Hohmann (1971)⁵ and Linnhoff and Flower (1978a, b)^{6,7}. As a result of the pinch concept, the single task approaches were shifted to procedures introducing techniques for decomposing the problem into three subtasks; minimum utility cost, minimum unit's number and minimum investment cost network configurations. The main advantage of decomposing the HEN synthesis problem is that subproblems can be handled more easily than the original one-task problem. The HEN synthesis strategy presented by Floudas et al. (1986)⁸, is a decomposition-based method (sequential approach). This synthesis strategy involves getting the problem partitioned into temperature intervals and, if possible, into subnetworks according to the pinch method. Then, the problem is decomposed into three subproblems which are then solved depending on the heuristic of finding the minimum cost network resulting from the minimum number of units, which is resulted from the minimum utilities costs. The decomposition-based approaches have proved in many case studies to be powerful HEN synthesis tools. The main shortcoming of the sequential approaches is the fact that, the trade-off between energy, units and area are not considered rigorously. Furthermore, the decision to decompose the original problem into subproblems relying on pinch analysis may result in sub-optimal networks. Therefore, the HEN synthesis problem should be treated as a single task problem.

Simultaneous Optimization Technique

The primary limitation of decomposition-based methods is that costs due to energy, units and area cannot be optimized simultaneously, and as a result the trade-offs are not taken into account appropriately. The selection of HRAT and partition into subnetworks affects the number of units and the heat exchange area in the final configuration. Therefore, the decomposition of the HEN synthesis problem may lead to sub-optimal networks. Simultaneous heat exchanger network synthesis methods aim to get the optimal network without or with some decomposition of the problem. Simultaneous optimization normally results in MINLP formulations. Floudas and Ciric (1989)⁹ proposed a match-network hyperstructure model to simultaneously optimize all of the capital costs related to the heat exchanger network. This MINLP formulation depends on the combination of the transshipment module of Papoulias and Grossmann (1983)¹⁰ for match selection, and the minimum investment cost network configuration model of Floudas and Grossmann (1986)¹¹ for determining the heat exchanger areas, temperatures, and the flowrates in the network. This MINLP formulation does not include any problem decomposition into design targets but, it simultaneously optimizes trade-offs between energy, units and area. Ciric and Floudas (1991)¹² also demonstrated the benefit of a simultaneous approach versus sequential methods. Another simultaneous synthesis formulation was proposed by Yee and Grossmann (1990b)¹³ where the model depends on the stage-wise super structure representation of Yee et al. (1990a)¹⁴. The simplified superstructure is composed of a number of stages, and in each stage, there are many different stream matching possibilities that are allowed to take place. Simultaneous approaches have proven that it is superior to sequential approaches.

Multiperiod Heat Exchanger Network

Previous sections dealt with heat exchanger network synthesis under the assumptions of fixed operating conditions of a process design. When the environment introduces significant changes or the process requires different sets of conditions, a synthesized HEN must also be thermodynamically feasible for the different operating modes. Floudas and Grossmann (1986)¹¹ introduced a multiperiod MILP model for the minimum utilities cost and minimum number of matches target problems, based on Papoulias and Grossmann's (1983)¹⁰ transshipment model. In this model the changes in the pinch point

and utility required at each time period are taken into account. Extensions were presented first by Floudas and Grossmann (1987a)¹⁵, an NLP formulation based on a superstructure presentation of possible network topologies to derive automatically network configurations schemes that have minimum investment cost, fewest number of units, and minimum utility cost for each time period. The sequential targeting, fixing and optimization approach presented has the advantage of decomposing the synthesis problem. However, it does have the disadvantage that trade-offs between energy, number of units, area are not rigorously taken into account. Aaltola (2002)¹⁶ introduced a model which optimizes the multi-period MINLP problem simultaneously for minimum costs, without depending on sequential decomposition. This model is based on the stage-wise superstructure representation of Yee et al. (1990)¹⁷, it has been successfully applied to high scale industrial HEN problems. As the design of the multiperiod HEN involves using the same exchangers for different heat loads periods, this will require bypassing portion of a stream or even the entire stream from the heat exchanger. Chen and Hung (2004)¹⁸ presented a three-stage technique for designing multi-period HEN, which depends on the stage-wise HEN super structure representation of Yee et al. (1990b)¹⁷ and the mathematical algorithm of Aaltola (2002)¹⁶. The authors had to use the maximum area consideration in their objective function to overcome the problem of different areas required for matches in each period which leads to a very high network costs.

Cost Reduction by Units Area Re-assignment Technique

The proposed MINLP model provides the optimal HEN structure, which minimizes costs when the conductance of every match is allowed to change separately under each specified period. The heat exchanger areas depend on the conductance; thus, the optimal solution may represent more than one value of area for each match. However, there is only one investment decision to make, so that the maximum area (A_{max}) is usually chosen by researchers to meet the requirements for the periods which need the largest exchanger area. Using maximum areas could lead to increasing the network total annual cost, which is considered a drawback to the optimization problem. To overcome this issue, a new approach is utilized in this work by making a reassignment for the heat exchangers areas over the different periods. So that the considered exchangers are permitted to be shared by more than one matching in many different periods. With this technique, it is possible to reduce the multi period network capital investment.

METHODOLOGY

Problem Definition

The multi-period HEN synthesis problem to be presented in this work can be stated as follows: A set of cold streams to be heated and hot streams to be cooled are given which involves multi period stream data with inlet and outlet temperatures, heat capacity flow rates and heat transfer coefficients. In addition, a set of hot and cold utilities are specified. The objective then is, within the specified operating conditions, to synthesize a heat exchanger network for the maximum energy recovery possible between the given set of hot and cold streams, so that the annual cost of the equipment (heat exchange units) plus the annual cost of utilities will be minimized.

Scope of the Research

The main objective of this research is to develop a method for solving multiperiod HEN synthesis problems, so that the trade-offs between energy costs, fixed charges for units and costs for the exchanger area can be simultaneously optimized. The proposed framework depends on two-stage strategy, the first step is to build an optimization MINLP model that is solved using GAMS software for the required design periods to obtain a feasible heat exchanger network configuration that

is able to achieve the heating targets with minimum total annual cost. The second step makes further reduction in the multiperiod network total cost using a new strategy that reassigns the exchangers areas (or swap the streams matches) over the different periods so that no excessive heat transfer areas are overdesigned leading to a high costive network. Unlike many simultaneous methods in the literature, the developed framework should be capable of solving high scale industrial problems efficiently and optimally within a short-time.

Stage-Wise Superstructure Presentation

This section shows the stage-wise HEN superstructure presentation of Yee et al.(1990a)¹⁴, which is used in the optimization model presented in this work. The simplified superstructure composes of a number of stages, in each stage, different potentialities for stream matching are allowed. In each stage, the existing stream is split and conducted to a heat exchanger for each probable match between each cold and hot stream. The outlets from the exchangers are then mixed and the mixed stream is directed to the next stage. Each stage outlet temperatures are treated as variables. Heaters and coolers are located at the outlets of the streams. This superstructure presentation does not need the determination of the pinch point or partitioning into subnetworks. Superstructure scheme for two hot and cold streams is shown in figure 1.

Figure 1: HEN Stage-Wise Superstructure.

Two stages are used, so the superstructure consists of:

- Four utilities placed at the ends of the superstructure
- Eight exchangers, with four possible matches in each stage
- Four temperature variables between each stage

Overview of the Presented Framework

To make the synthesis easier to follow the basic information about the different optimization steps included are listed below. The most important information about the presented optimization scheme is summarized by the following steps:

- The basic multiperiod stream data is defined. This data is related to the most common conditions including inlet and outlet stream temperatures, heat capacity flow rates and heat transfer coefficients for each hot and cold stream, also the cost data is included as the heat exchanger area and utilities cost.
- MINLP model is built for each individual period data including the process conditions and period duration.

- The simultaneous MINLP model is solved with the specified entry data and a solution is obtained including stream matches, assigned heat exchangers areas, utilities duty required, utility cost, heat exchangers fixed cost and finally the minimum total annual cost.
- Further TAC reduction is achieved using a new technique that reassigns the heat exchangers areas (or swap the matches) between the different periods. A scheme for the proposed framework steps is shown below in figure 2.

Figure 2: Scheme for the Proposed Framework Procedures.

Heat Transfer Area Calculation

The heat transfer area $A_{i,j,k}$ for match i,j in stage k for

- Heat exchanger load $Q_{i,j,k}$
- Hot stream inlet $t_{i,k}$ and outlet temperatures $t_{i,k+1}$
- Cold stream inlet t_{j+1} and outlet temperatures $t_{j,k}$ and
- The heat transfer coefficient $U_{i,j}$ for match i,j

Can be calculated by the use of LMTD method as follows:

$$A_{i,j,k} = \frac{Q_{i,j,k}}{U_{i,j} \cdot LMTD_{i,j,k}} \quad (1)$$

$$LMTD_{i,j,k} = \frac{(t_{i,k} - t_{j,k}) - (t_{i,k+1} - t_{j,k+1})}{\ln \frac{t_{i,k} - t_{j,k}}{t_{i,k+1} - t_{j,k+1}}} \quad (2)$$

When the temperature approaches are equal in both ends of the exchanger, the logarithmic mean temperature difference calculation causes numerical difficulties as a result of division by zero. However, good approximations have been developed for the LMTD calculation to avoid such difficulties. In this work the following approximation published by Chen (1987)¹⁹ is used:

$$\left((t_{i,k,p} - t_{j,k,p}) \cdot (t_{i,k+1,p} - t_{j,k+1,p}) \cdot \left[\frac{(t_{i,k,p} - t_{j,k,p}) + (t_{i,k+1,p} - t_{j,k+1,p})}{2} \right] \right)^{\frac{1}{3}} \quad (3)$$

Model Development

The existence of each potential heat exchanger in the superstructure is represented by binary variables. This means that if a heat exchanger exists in any period, it must exist in every period, and the fixed cost is charged accordingly. The formulation includes continuous variables assigned to temperatures and to the heat loads of each case. The model is solved to minimize the annualized cost of the equipment plus the annual cost of utilities. This model provides matches that take place ($Z_{i,j,k}$, Z_i^{cu} and Z_i^{hu}), areas of each exchanger ($A_{i,j,k}$, A_i^{cu} and A_j^{hu}), corresponding exchanger loads ($q_{i,j,k}$, q_i^{cu} and q_j^{hu}). In order to formulate the MINLP model for total annual cost comprising of utility cost, fixed cost for exchanger units and areas, see list of symbols in Appendix-1.

The set of constraints consists of:

- **Overall Heat Balance for Each Stream**

Overall heat balances are to ensure sufficient heating and cooling of each process stream. These equality constraints assign that each stream heat content equals the sum of heat exchanged with other streams at each stage plus the exchange with the utility.

$$(T_i^{IN} - T_i^{OUT})F_i = \sum_{k \in ST} \sum_{j \in CP} q_{i,j,k} + q_i^{cu}, \quad i \in HP \quad (4)$$

$$(T_j^{OUT} - T_j^{IN})F_j = \sum_{k \in ST} \sum_{i \in HP} q_{i,j,k} + q_j^{hu}, \quad j \in CP \quad (5)$$

- **Heat Balance at each Stage**

Heat balance is required for each stream at each stage of the superstructure to determine temperatures. To properly define the temperature variables and stages, the index k is used. The set $k = 1, \dots, NOK$ is used to represent the NOK stages while the set $k = 1, \dots, (NOK+1)$ is for temperature locations in the superstructure. The heat balances are as follows:

$$(t_{i,k} - t_{i,k+1})F_i = \sum_{j \in CP} q_{i,j,k}, \quad k \in ST, \quad i \in HP \quad (6)$$

$$(t_{j,k} - t_{j,k+1})F_j = \sum_{i \in HP} q_{i,j,k}, \quad k \in ST, \quad j \in CP \quad (7)$$

- **Assignment of Inlet Temperatures**

The superstructure inlet corresponds to temperature location $k = 1$ for hot streams, while for cold streams to location $k = NOK+1$:

$$T_i^{IN} = t_{i,1}, \quad i \in HP \quad (8)$$

$$T_j^{IN} = t_{j,NOK+1}, \quad j \in CP \quad (9)$$

- **Monotonic Decrease in Temperatures**

Constraints for feasibility of temperatures are needed to specify a monotonic decrease of temperature at each stage. Also, an upper bound for the outlet temperature of each stage is set at the respective stream's outlet temperature.

Note that the outlet temperature does not necessarily correspond to the stream's target temperature, since heating and cooling using utilities may take place at the superstructure outlet.

$$t_{i,k} \geq t_{i,k+1}, \quad k \in ST, \quad i \in HP \quad (10)$$

$$t_{j,k} \geq t_{j,k+1}, \quad k \in ST, \quad j \in CP \quad (11)$$

$$T_i^{OUT} \leq t_{i,NOK+1}, \quad i \in HP \quad (12)$$

$$T_j^{OUT} \geq t_{j,1}, \quad j \in CP \quad (13)$$

- **Hot and Cold Utilities Load**

Energy balances for utility matches are determined for each process stream in terms of the corresponding outlet temperature in the last stage and the corresponding target temperature.

$$(t_{i,NOK+1} - T_i^{OUT})F_i = q_i^{cu}, \quad i \in HP \quad (14)$$

$$(T_j^{OUT} - t_{j,1})F_j = q_j^{hu}, \quad j \in CP \quad (15)$$

Logical Constraints

Logical constraints are used for the existence of matches (i, j) in stage k and for utilities.

$$q_{i,j,k} - Q^{UP} z_{i,j,k} \leq 0, \quad i \in HP, \quad j \in CP, \quad k \in ST \quad (16)$$

$$q_i^{cu} - Q^{UP} z_i^{cu} \leq 0, \quad i \in HP \quad (17)$$

$$q_j^{hu} - Q^{UP} z_j^{hu} \leq 0, \quad j \in CP \quad (18)$$

$$z_{i,j,k}, z_i^{cu}, z_j^{hu} \in \{0, 1\} \quad (19)$$

Calculations of temperature differences for each temperature location are used to ensure the feasible driving forces for exchangers. The binary variables are applied to activate these constraints. When a match (i, j) in stage k occurs, $z_{i,j,k}$ equals one and the constraint becomes active, so that the temperature difference is properly calculated. However, when the match does not take place ($z_{i,j,k}$ equals zero), DT^{UP} sets the upper bound for temperature approach. Here DT^{UP} is defined as a maximum positive temperature difference between hot and cold streams. Similar constraints are also used for utilities:

$$dt_{i,j,k} \leq t_{i,k} - t_{j,k} + DT^{UP}(1 - z_{i,j,k}), \quad i \in HP, \quad j \in CP, \quad k \in ST \quad (20)$$

$$dt_{i,j,k+1} \leq t_{i,k+1} - t_{j,k+1} + DT^{UP}(1 - z_{i,j,k}), \quad i \in HP, \quad j \in CP, \quad k \in ST \quad (21)$$

$$dt_i^{cu} \leq t_{i,NOK+1} - T_{CU}^{OUT} + DT^{UP}(1 - z_i^{cu}), \quad i \in HP \quad (22)$$

$$dt_j^{hu} \leq T_{HU}^{OUT} - t_{j,1} + DT^{UP}(1 - z_j^{hu}), \quad j \in CP \quad (23)$$

These constraints can be expressed as inequalities, since the minimization of the objective function, where the exchanger areas are calculated using the temperature approaches, drives the temperature approaches upwards. The objective function is non-linear and non-convex and hence, despite the linear set of constraints, the solution of the resulting

optimization model represents a local optimum. However, it is possible to generate a pool of the local optima by performing several runs with different upper bounds on the hot utility availability. Also, a value for the exchanger minimum approach temperature can be defined, setting the upper bound for a crisscross heat transfer i.e. nonvertical heat transfer on the composite curves. The lowest allowable minimum approach temperature is defined as:

$$dt_{i,j,k} \geq \epsilon \quad (24)$$

Total hot utility availability is limited by following constraints:

$$\sum_{j \in CP} q_j^{hu} \leq HU^{UP}, \quad j \in CP \quad (25)$$

The total annual costs are calculated within the optimization model as follows.

TAC (total annual costs) can be defined as the summation of:

- Unit costs for all matches
- Area costs for matches (i, j, k)
- Area costs for cold utility matches
- Area costs for hot utility matches
- Cold utility costs
- Hot utility costs.

Thus, the objective function is as follows

min TAC =

$$\begin{aligned} & AF \left[\sum_{i \in HP} \sum_{j \in CP} \sum_{k \in ST} C_{i,j}^F Z_{i,j,k} + \sum_{i \in HP} \sum_{CU} C_{i,CU}^F Z_i^{cl} + \sum_{j \in CP} \sum_{HU} C_{j,HU}^F Z_j^{hu} \right] \\ & + AF \sum_{i \in HP} \sum_{j \in CP} \sum_{k \in ST} C_{i,j} \left[\frac{q_{i,j,k}}{LMTD_{i,j,k} U_{i,j}} \right]^{B_{i,j}} \\ & + AF \sum_{i \in HP} C_{i,CU} \left[\frac{q_i^{CU}}{LMTD_{i,CU} U_{i,CU}} \right]^{B_{i,CU}} \\ & + AF \sum_{j \in CP} C_{j,HU} \left[\frac{q_j^{HU}}{LMTD_{j,HU} U_{j,HU}} \right]^{B_{j,HU}} + \sum_{i \in HP} C^{CU} q_i^{CU} + \sum_{j \in CP} C^{HU} q_j^{HU} \end{aligned} \quad (26)$$

Cost Reduction by Units Area Re-Assignment

The proposed MINLP model provides the optimal HEN structure, which minimizes costs when the conductance of every match is allowed to change separately under each specified period. The heat exchanger areas are dependent on the conductance; thus, the optimal solution may represent more than one value of area for each match. However, there is only one investment decision to make, so that the maximum area (Amax) is usually chosen by researchers to meet the requirements for the periods which need the largest exchanger area. Using maximum areas could lead to increasing the

network total annual cost, which is considered a drawback to the optimization problem. To overcome this issue, a new approach is utilized in this work by making a reassignment for the heat exchangers areas over the different periods. So that the considered exchangers are permitted to be shared by more than one matching in many different periods. With this technique, it is possible to reduce the multiperiod network capital investment.

Area Reassignment Technique Steps

The heat exchangers units' areas reassignment (service switching) procedure is listed below:

- Arrange the areas of all heat exchangers and sort them in a decreasing order.
- Select the first value in the ordered list as one of the switchable exchanger areas.
- Designate the largest area in every period and assign the related match to the exchanger that had been chosen in step 2.
- Remove all assigned matches and their area values from the list.
- If the ordered list still has remaining entries, go to step 2. Otherwise, stop.

CASE STUDY

This section introduces results obtained using the proposed framework for an example found in the literature to illustrate the model strength in synthesizing a multi-period HEN with a min TAC. These results then are compared with those obtained by other authors from the literature. A set of tables are presented in each subsection that contains the application data and the results obtained by applying this model, then a figure is attached showing the network grid diagram. The model was coded and solved in GAMS software. The optimization process corresponds to runs performed in a PC with Intel Core 2.67 GHz processor with 4 GB memory.

Example

This numerical example was derived from (Juha Aaltola, 2002)¹⁶ work. The two period problem consists of two hot and two cold streams. One hot and one cold utilities are available. The heat capacity flowrate (MC_p) is an uncertain parameter. The problem data for the multiperiod application and costs are selected as is shown in Table 1. The objective is to design a heat exchanger network that is feasible in the specified periods of operation and has the minimum total annualized cost.

Table 1: Process Data for Example 1 from (Aaltola)

Stream	Period 1			Period 2		
	T ⁱⁿ (°K)	T ^{out} (°K)	MC _p (KW/°K)	T ⁱⁿ (°K)	T ^{out} (°K)	MC _p (KW/°K)
(H ₁)	723	553	2	723	553	2
(H ₂)	583	323	1	583	323	1.8
(C ₁)	388	563	2	388	563	2
(C ₂)	313	393	3	313	393	3
Steam	650	650	-	650	650	-
Water	300	320	-	300	320	-

Hot utility cost is 115.2 \$/(kW·yr) and for cold utility 1.3 \$/(kW·yr), the exchangers cost equation is $8333.3 \cdot \text{unit} + 641.7 \cdot \text{Area} (\$)$, lifetime is 3 years and rate of interest 18%, overall heat transfer coefficients for matches are $4 \text{ kW} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$. Period 1 lasts for 3 months/yr., Period 2 lasts for 9 months/yr.

RESULTS AND DISCUSSION

Applying First Stage of the Proposed Strategy

The first stage of the proposed two-stage strategy was applied to the example. In the first step, the multiperiod streams data were defined including conditions as inlet and outlet stream temperatures, heat capacity flow rates and heat transfer coefficients for all streams, also the cost data as the heat exchanger area and utilities cost. Then, MINLP mathematical optimization model was built for each individual period data. After that, the simultaneous MINLP model was processed with the specified entry data for each period using the GAMS software BARON solver, a solution was obtained for each period indicating the stream matches, assigned heat exchangers areas, utilities duty required, utility cost and heat exchangers fixed cost. Hereafter, the results obtained by own MINLP model are compared with those obtained by (Aaltola) work and listed below in tables 2, 3 respectively. ($DT_{\min}$) used is 10^0 K. According to the solution obtained in the first stage of the proposed optimization strategy, a HEN configuration was obtained, it consists of three process to process heat exchangers and one cold utility. For each exchanger there are two different areas and for the cold utility there are different heat loads for both periods. If it was possible to increase and decrease the areas of the exchangers through bypasses and regulate the cold utility load, this configuration would be able to operate under these two periods with the heat exchangers maximum area values as shown in Figure 3. Comparison of the multi-period network exchangers individual areas and total area between own work solution and Aaltola¹⁶ work is presented in table 4, that's to illustrate the strength of the proposed model in minimizing the HEN total annual costs.

Table 2: Results Obtained by GAMS through the Proposed Model

Match	Period 1				Period 2			
(I, j, k)	(1, 1, 1)	(2, 1, 2)	(2, 2, 3)	(CU, 2)	(1, 1, 1)	(2, 1, 2)	(2, 2, 3)	(CU, 2)
A, m ²	1.063	0.027	1.687	0.285	1.063	0.027	0.768	1.834
A _{max} , m ²	1.063	0.027	1.687	1.834	1.063	0.027	1.687	1.834
Q, KW	340	10	240	10	340	10	240	218
T _{hot} ⁱⁿ , °K	723	583	573		723	583	577.45	
T _{hot} ^{out} , °K	553	573	333		553	577.45	444.11	
T _{cold} ⁱⁿ , °K	393	388	313		393	388	313	
T _{cold} ^{out} , °K	563	393	393		563	393	393	

Table 3: Results Obtained by (Aaltola)

Match	Period 1				Period 2			
(I, j, k)	(1, 1, 3)	(2, 1, 1)	(2, 2, 2)	(CU, 1)	(1, 1, 3)	(2, 1, 1)	(2, 2, 2)	(CU, 1)
A, m ²	0.97	0.69	2.09	0.02	0.22	9.03	4.14	0.369
A _{max} , m ²	0.97	9.03	4.14	0.369	0.97	9.03	4.14	0.369
Q, KW	330	20	240	10	122	228	240	218
T _{hot} ⁱⁿ , °K	723	583	563		723	583	456	
T _{hot} ^{out} , °K	558	563	323		662	456	323	
T _{cold} ⁱⁿ , °K	388	553	313		388	449	313	
T _{cold} ^{out} , °K	553	563	393		449	563	393

Figure 3: HEN Diagram as per 1st Stage of the Optimization Strategy.

Table 4: Comparison of Areas between Own Work and Aaltola's

A, m ²	H1-C1	H2-C1	H2-C2	(H1-CU)	Total Area
Own Work	1.063	0.027	1.687	1.834	4.6
Aaltola	0.97	9.03	4.14	0.369	14.5

Note that the heat exchanger network TAC calculation took into account the utilities requirements durations over periods so that the actual utilities annual costs are estimated. As shown in Table 5, in the first stage of the proposed optimization strategy, the proposed MINLP model was able to achieve a multi-period HEN with a total annual cost reduction of 14% than of Aaltola work.

Table 5: Compare between (O.C), (C.C) and (TAC) Obtained by (Aaltola) and Own Work

	Operating Cost (\$/yr)	Capital Cost (\$/yr)	TAC (\$/yr)	Cost Saving
Aaltola	216	19,613	19,616	14%
Own Work	144	16,692	16,835	

Applying Second Stage of the Proposed Strategy

The previous multiperiod problem network capital cost can be further reduced by using the area reassignment technique discussed previously. First, the matches required areas for each period were extracted from table 2 and listed in table 6.

Table 6: Results Obtained by GAMS for the Proposed Model

(I, j, k)	H1-C1	H2-C1	H2-C2	(H2,CU)
Period 1				
Area, m ²	1.063	0.027	1.687	0.285
Period 2				
Area, m ²	1.063	0.027	0.768	1.834

Then, by using the proposed re-assignment technique, the new adopted area assignments are listed as shown in table 7. Finally, as per the new HEN configuration obtained by applying the area reassignment technique discussed previously, the multiperiod network total annual cost was recalculated. It is noted that a further reduction in the network TAC was obtained. A comparison of the obtained results with Juha Aaltola's are listed below in table 8.

Table 7: Matches Area Re-Assigned

Period	Match	Required Area	Assigned Area	Exchanger Label
2	2, CU	1.834	1.834	A
1	2, 2, 3	1.687	1.834	A
1	1, 1, 1	1.063	1.063	B
2	1, 1, 1	1.063	1.063	B
2	2, 2, 3	0.768	0.768	C
1	2, CU	0.285	0.768	C
1	2, 1, 2	0.027	0.027	D
2	2, 1, 2	0.027	0.027	D

Table 8: Comparison between (O.C), Exchangers Total Area, (C.C) and (TAC) Obtained by (Aaltola) and Own Work After Area Reassignment

Work	O.C (\$/yr)	A _{total}	C.C (\$/yr)	TAC (\$/yr)	Cost Saving
Aaltola	216	14.5	19,613	19,616	14%
Own (1 st Stage)	144	4.6	16,692	16,835	
Own (2 nd Stage)	144	3.7	16,420	16,564	1.6%

As shown in Table 8, in the second stage of the proposed optimization framework, the area reassignment technique was able to achieve a further reduction in the HEN total annual cost of 1.6% from that obtained in the first stage. Then, the proposed two-stage strategy optimization framework was able to produce a feasible multi-period HEN with overall reduction in the TAC of 15.6% from that obtained by Aaltola's. The final HEN configuration for both periods after area reassignment are shown in figures 4, 5.

Figure 4: HEN Scheme in Period 1 after Area Reassignment.

Figure 5: HEN Scheme in Period 2 after Area Reassignment.

CONCLUSIONS

This work presents a framework to synthesize an optimal multiperiod HEN that has the minimum possible total annual cost. The proposed framework consists of two stages, in the first stage a simultaneous MINLP model is built for each period data so that the trade-offs between utilities costs, fixed costs for units and costs for the exchangers area can be simultaneously optimized. The model is then solved using a mathematical programming optimization software as GAMS to obtain a feasible heat exchanger network configuration that is able to achieve the heating targets with minimum total annual cost. In the second stage, a further reduction in the multi-period network total annualized cost is achieved by using a technique that reassign the heat exchangers areas (swap the matches) between the different periods so that all different HENs configurations are integrated in one multiperiod network, also, no excessive heat transfer areas are overdesigned which could lead to a high costive network. Unlike many methods in the literature, the presented framework should be capable of solving high scale industrial cases efficiently and optimally within a short-time.

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