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Design of optimum flexible heat exchanger networks for multiperiod process

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Mixed Integer Linear Programming (MILP)

Abstract Due to the rising of energy prices, energy saving became very important. Optimum design of Heat Exchanger Networks (HEN) is a successful way to minimize energy consumption. The present work discusses the design of optimal flexible heat exchanger networks that adapt with changes in streams' start and target temperatures and heat capacity flowrates. For a process consisting of n periods, multiperiod LP and MILP models were used to determine the target utility requirements and the heat exchanger network configuration that achieves the minimum number of units and remain flexible to ensure minimum utility requirements at each period of operation. Applying these models on a multiperiod literature problem resulted in different solutions corresponding to different iteration runs. The optimum solution that realizes the least exchangers' cost was compared with literature results for the same problem.

1. Introduction

In the past three decades, extensive efforts have been made in the fields of energy integration and energy recovery technologies because of the steadily increasing energy cost and CO2 discharge. A heat recovery system consisting of a set of heat exchangers can be treated as a heat exchanger network (HEN), which is widely used in processing industries such as gas processing and petrochemical industries, to exchange heat energy among several process streams with different supply temperatures. By the use of HENs, a large amount of utility costs such as the costs of steam and cooling water, as well as the costs of heaters and coolers, can be saved. However, it would increase the investment for the additional heat exchangers, and therefore a balance between the capital costs and running costs should be established [1].

HENs are mostly synthesized under the assumption of a specified operating condition and many methods have been developed for HEN synthesis in the last few decades [2–6]. A detailed review on HEN synthesis methods proposed in the 20th century can be found in [7] and in the excellent book, Energy Optimization in Process Systems [8].

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Nomenclature

HEN	Heat exchanger network
HENS	Heat exchanger network synthesis
LP	Linear programming
MILP	Mixed integer linear programming
MINLP	Mixed integer non linear programming
NLP	Non linear programming
$A_{i,j,p}$	Heat transfer area of match (*i*, *j*) in period (*p*).
B_{ij}^{st}	The upper bound for possible heat exchange between streams (*i*,*j*) in subnetwork st.
C_{Akt}	The augmented set of cold stream present in interval *k* in period t.
$C_{i,j,p}$	Annual cost for match (*i*, *j*) in period (*p*).
CP	Heat capacity flow rate.
Cs_i	Unit cost of such hot utility.
Cw_j	Unit cost of such cold utility.
HAkt	The augmented set of hot streams present at or above the interval *k* in period t.
$LMTD_{i,j,p}$	Log mean temperature difference of match (*i*, *j*) in period (*p*).
P_a	The set of pairs (*i*, *j*) that satisfy condition a.
P_b	The set of pairs (*i*, *j*) that satisfy condition b.
$Q_{i,j,p}$	Heat load of every heat exchanger of match (*i*, *j*) in period (*p*).
Qs_i	Duty of the hot utilities.
Qw_j	Duty of the cold utilities.
Q_{ik}^{h}	Heat content of hot stream *i* in interval *k*.
Q_{jk}^{c}	Heat contents of cold *j* stream in interval *k*.
Q_{jkst}^{c}	The heat load of cold stream *j* entering the temperature interval *k* in subnetwork *st*.
Q_{ikst}^{h}	The heat load of hot stream *i* entering the temperature interval *k* in subnetwork *st*.
R_k	Heat residual leaving interval *k*.
R_{k-1}	Heat residual entering interval *k*.
$R_{i,kst}$,$R_{i,k-1st}$	The heat residuals that correspond to hot stream *i* in subnetwork *st* of period t and

Temperature intervals k,k-1 respectively

s	Set of hot utilities.
st	Subnetwork
T_{is} & T_{it}	Start and target temperatures of hot stream *i*.
t_{js} & t_{jt}	Start and target temperatures of cold stream *j*.
$U_{i,j}$	Heat transfer coefficient for match (*i*, *j*).
u_{ij}	Number of units
W_{ij}	Weighing factor
w	Set of cold utilities
Y_{ij}	Match between hot stream *i* and cold stream *j*

Most of the methodologies proposed to solve the heat exchanger network problem have not rigorously considered as streams undergoing phase change (streams that transfer their latent heat) whether being isothermal (a pure component) or non-isothermal (multi-component). A common practice is to consider these streams as transferring their latent heat with 1 K temperature difference [8,9]. Ortega et al. [9] proposed an MINLP model for optimal HENS that handles isothermal streams. The proposed model that includes isothermal (transferring their latent heat) and non-isothermal streams (transferring their sensible heat) is based on the superstructure formulation of Yee and Grossmann [5]. Farouque Hasan et al. [10] proposed a MINLP formulation and a solution algorithm to incorporate non-isothermal phase changes in HENS. They approximated the non-linear T-H curves via empirical cubic correlations and proposed a procedure to ensure minimum temperature approach at all points in exchangers.

HENs have to adapt to inevitable parameter variations because of the changes in the operating and economic environments of a process, such as supply temperatures, flow rates, seasonal variation, etc. Even for the optimally synthesized HEN based on a certain operation condition, these changes are to deprive the design of its thermodynamic and economic efficiency. In general, flexibility/resilience used to be defined as the ability to operate feasibly in the region spanned by the deviations in process parameters from their nominal values [8,11,12]. Therefore, in order to carry forward these methods into the plants that are actually implanted in practice, flexibility issues should be considered during the synthesis and design of HEN.

For networks that are subject to continuous variations in process parameters such as stream flow rates or temperatures, Marselle et al.[11] developed a design procedure to yield resilient designs which handle fluctuations within the condition of maximum energy efficiency. The underlying assumption is that by designing the network for a number of well selected extreme operating conditions enough resiliency is generated to cover all intermediate cases.

For multi-period operations, the different operating modes resemble the corner points of the feasible regions. Floudas and Grossmann [12] introduced a multi-period MILP model based on the transshipment model of Papoulias and Grossmann [13]. This model defines minimum utilities at each period and minimum number of matches for the final flexible HEN. Floudas and Grossmann [14] extended their work to a NLP model that automatically develops the flexible network configuration.

The model proposed by Papalexandri and Pistikopoulos [15,16] simultaneously explored alternatives in an MINLP problem. This limits the size of the problem to relatively small-scale problems. Aaltola [17] proposed a model which simultaneously optimizes the multi-period MINLP problem for minimum costs and flexibility, this model is based on the stage-wise HEN superstructure representation of Yee et al. [6]. This formulation allows the elimination of bypass modeling, which introduced non-linear constraints into the formulation.

Chen and Hung [18] proposed a three-step approach for designing flexible multi-period HENs, which is based on the stage-wise HEN superstructure representation of Yee and Grossmann [5] and Yee et al.[6] and the mathematical formulation of Aaltola [17]. The authors introduced the maximum area consideration in the objective function and decomposed the problem into three main iterative steps: simultaneous HEN synthesis, flexibility analysis and removal of infeasible networks.

The present work uses the MILP model equations of Floudas and Grossmann [12] for the design of flexible HENs of a literature problem and discusses the alternative networks produced as a result of performing random different iteration runs. The discussion includes the number of units, total area and total fixed cost. It also compares the new networks with those reported by Floudas and Grossmann [12,14] and that produced according to minimum annualized total cost analysis concept [19].

2. Transshipment models

Linear programming LP and mixed integer linear programming MILP have been formulated by Papoulias and Grossmann [13] to calculate the minimum utility requirements and the heat exchanger network configuration that achieves these utility targets at the minimum number of units. The synthesized heat exchanger networks are optimal for a single operation period i.e. for fixed value of stream heat capacity flowrates, start and target temperatures. Floudas and Grossmann [12] extended the above mentioned model to handle the case when stream temperatures and/or heat capacity flowrates vary for certain periods of operation. Thus, multiperiod LP and MILP models were formulated to determine the target utility requirements and the heat exchanger network configuration that achieves the minimum number of units and remain flexible to ensure minimum utility requirements at each period of operation. Because multiperiod LP and MILP are extensions to those for single period operation models, a brief review for the latter models will be introduced followed by detailed description for the multiperiod models.

2.1. LP transshipment model

The linear programming LP version is used to find the minimum utility cost and the pinch location for a given set of hot and cold streams. The entire problem temperature range is divided into K intervals. By performing a simple heat balance on each interval k, the following LP formulation is obtained by Papoulias and Grossmann [13].

Model P1

$$\min Z = \sum_{i\in s} Qs_{\rm i} Cs_{\rm i} + \sum_{j\in w_k} Qw_{\rm j} Cw_{\rm j} \tag{1}$$

Subject To:

$$R_k - R_{k-1} - \sum_{i\in sk} Qs_{\rm i} + \sum_{j\in wk} Qw_{\rm j} = \sum_{i\in H_k} Q_{\rm ik} - \sum_{j\in c_k} Q_{\rm jk} \tag{2}$$

$$R_0 = R_k = 0.0 \tag{3}$$

$$R_k \geq 0.0,\ k = 1,2,\ldots,k-1 \tag{4}$$

$$Qs_{\rm i} \geq 0.0,\ i \in s \tag{5}$$

$$Qw_{\rm j} \geq 0.0,\ i \in w \tag{6}$$

where: $Qs_{\rm i}$, duty of the hot utilities with unit cost $Cs_{\rm i}$; $Qw_{\rm j}$, duty of the cold utilities with unit cost $Cw_{\rm j}$; s, set of hot utilities; w, set of cold utilities; $Cs_{\rm i}$, unit cost of such hot utility; $Cw_{\rm j}$, unit cost of such cold utility; $R_{k\text{-}1}$, heat residual entering interval k; R_k, heat residual leaving interval k; $Q^h_{\rm ik}$, heat contents of hot streams; $Q^c_{\rm jk}$, heat contents of cold streams.

2.2. MILP transshipment model

Since the utility flowrates and their corresponding heat contents are known, the utility streams can be added to sets of process streams. Then the problem temperature span can be divided into two or more subnetworks at the pinch points. To determine the minimum number of matches and the heat to be exchanged at each of these matches, 0–1 binary variables are introduced to check the existence of a match between a hot stream (i) and a cold stream (j) in a given subnetwork. MILP model is performed for each subnetwork separately and the optimum solution is found which achieves the minimum number of heat exchangers as shown in the next formulation.

Model P2

$$\min \sum_{i\in HA} \sum_{j\in CA} W_{\rm ij} Y_{\rm ij} \tag{7}$$

Subject To:

$$R_{\rm ik} - R_{{\rm i},k-1} + \sum_{i\in sk} Qs_{\rm i} + \sum_{j\in wk} Qw_{\rm j} = \sum_{i\in H_k} Q_{\rm ik} - \sum_{j\in c_k} Q_{\rm jk} \tag{8}$$

$$\sum_{i\in HAk} Q_{\rm ijk} \equiv Q^c_{\rm jk}, j \in CAk, k \in IT \tag{9}$$

$$\sum_{k\in IT} Q_{\rm ijk} - B_{\rm ij} Y_{\rm ij} \leq 0.0, i \in HA, j \in CA \tag{10}$$

$$B_{\rm ij} = \min\left[\sum_{k\in IT} Q^h_{\rm ik}, \sum_{k\in IT} Q^c_{\rm jk}\right] \tag{11}$$

$$R_{\rm ik} \geq 0.0,\ i \in HAk,\ k \in IT \tag{12}$$

$$Q_{\rm ijk} \geq 0.0,\ i \in HAk,\ j \in CAk \tag{13}$$

$$Y_{\rm ij} = 0 - 1, i \in HA,\ j \in CA \tag{14}$$

The objective function is to minimize the number of matches $[Y_{\rm ij}]$ where, $W_{\rm ij}$ is the weighing factor for preference matching. The first constraint is energy balance for each hot stream (i) in the interval (k). The second constraint says that the sum of heat exchanged in each interval (k) is equal to the heat that can be taken up by the cold stream (j) in such interval. $R_{\rm ik}$ represents residual heat of hot stream (i) that has not been utilized and transferred to the next interval. The third constraint says that the upper bound of heat exchanged is equal to the minimum of the heat that can be utilized from the hot stream (i) and that can be absorbed by the cold stream (j). Eqs. (12) and (13) are non-negativity constraints for both heat residuals and heat exchanged between hot and cold streams.

2.3. Multi-period transshipment model

The Multiperiod transshipment model includes:

i- Multiperiod LP transshipment model.
ii- Multiperiod MILP transshipment model.

The first step is not different from LP transshipment model for a single period. It is formulated separately for each period. Therefore, the pinch point and the minimum hot and cold utilities will be determined for each period independently. It is clear that the pinch location may vary from one period to the other and so do the cooling and heating utilities. This variation of the pinch point means variations in the boundaries of the subnetworks.

In the second step, the objective function is to develop a flexible heat exchanger network that achieves minimum utility cost at each period of operation while keeping the minimum number of units. Each heat exchanger can be designed to handle variable heat loads; this implies the availability of bypasses in each heat exchanger to be adjusted to the desired loads. Also, the same heat exchanger should be specified for each pair of streams exchanging heat in a given subnetwork of each period of operation.

Similar to the single period operation mode, model P2, a binary variable Y_{ijst} is introduced to denote the possible existence of heat exchange between hot stream i and cold stream j in the subnetwork st in period t as was shown by Floudas and Grossmann[12].

To reduce the number of assigned binary variables the exchange between pairs of streams in the different periods was classified into three categories [12]:

a- The match between pairs (i, j) is only possible in a single subnetwork in each time period.

b- The match is possible in more than one subnetwork in only one period of operation which is called the dominant period. In all other periods the match is possible only in a single subnetwork.

c- The match is possible in several subnetworks in all periods of operation which is the general case.

For case a: No more than one possibility of exchange is required for each match then:

$$u_{ij} = Y^a_{i,j}, (i,j) \in P_a \quad (15)$$

For case b: Having the maximum possible number of heat exchange possibilities between pairs (i, j) in one period (dominant), guarantees the existence of potential exchange in each subnetwork for all other periods, consequently

$$u_{ij} = \sum_{sd \in ISd} Y^b_{ijsd}, (i,j) \in P_b \quad (16)$$

where: Y^b_{ijsd}, binary variables associated with the sub networks Sd of the dominant period d; P_b, the set of pairs (i, j) that satisfy condition b.

For case c: this is a general case where pairs of streams exchange heat in several subnetworks in more than one period. The formulation will be as follows:

$$u_{ij} \geq [\sum_{st \in IST} Y_{ijst}]$$
$$i \in HA, j \in CA, \quad t = 1,2,\ldots,N, (i,j) \notin P_a, P_b \quad (17)$$

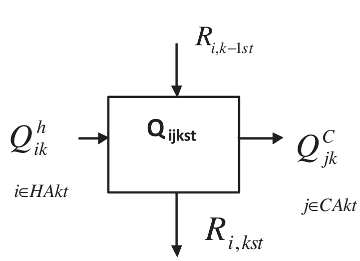

Figure 1 Heat balance at interval K for (MILP) transshipment model.

The number of units is restricted to those not satisfying conditions a or b.

Having analyzed the cases for heat exchange in the different periods of operation and referring to the heat balance diagram for interval k Fig. 1, the full mathematical formulation of the multiperiod mixed integer linear programming transshipment model was given as follows as developed by Floudas and Grossmann [12].

Model P3

$$\min \sum_{i \in HA} \sum_{j \in CA} u_{ij} \quad (18)$$

Subject To:

(a) Constraints for number of units:

$$u_{ij} = Y^a_{i,j}, (i,j) \in P_a \quad (15)$$

$$u_{ij} = \sum_{sd \in ISd} Y^b_{ijsd}, (i,j) \in P_b \quad (16)$$

$$u_{ij} \geq [\sum_{st \in IST} Y_{ijst}]$$
$$i \in HA, j \in CA, t = 1,2,\ldots,N, (i,j) \notin P_a, P_b$$

(b) Heat balance constraints.

$$R_{i,kst} - R_{i,k-1st} + \sum_{j \in CAkt} Q_{ijkst} = Q^h_{ikst}$$
$$i \in HAkt, k \in IT_{st}, st \in IS_t, t = 1,2,\ldots N \quad (19)$$

$$\sum_{i \in CAkt} Q_{ijkst} = Q^C_{jkst}$$
$$j \in CAkt, k \in IT_{st}, st \in IS_t, t = 1,2,\ldots,N \quad (20)$$

(c) Logical Constraints.

$$\sum_{k \in IT_{st}} Q_{ijkst} - B^{st}_{ij} Y^a_{ij} \leq 0.0 \quad (21)$$
$$st \in IST, t = 1,2,\ldots N, (i,j) \in P_a$$

$$\sum_{k \in IT_{st}} Q_{ijkst} - B^{sd}_{ij} Y^b_{ijsd} \leq 0.0 \quad (22)$$
$$sd \in ISd, t \neq d, (i,j) \in P_b$$

$$\sum_{k \in IT_{st}} Q_{ijkst} - B^{st}_{ij} \sum_{sd \in Isd} Y_{ijsd} \leq 0.0 \quad (23)$$
$$st \in ISt, \; t = d$$

$$\sum_{k \in IT_{st}} Q_{ijkst} - B^{st}_{ij} Y_{ijst} \leq 0.0 \quad (24)$$
$$st \in IST, \; t = 1,2,\ldots N, \; i \in HA, \; j \in CA, (i,j) \notin P_a, \; P_b$$

(d) Non negativity constraints.

$$R_{ikst} \geq 0.0 \quad (25)$$

$$Q_{ikst} \geq 0.0 \quad (26)$$

$$u_{ij} \geq 0.0 \quad (27)$$

(e) 0–1 Constraint.

$$Y_{ijst} = 0 - 1, Y^a_{ij} = 0 - 1, Y^b_{ijsd} = 0 - 1 \quad (28)$$

where: HAkt, the augmented set of hot streams present at or above the interval k in period t; CAkt, the augmented set of cold stream present in interval k in period t; $R_{i,kst}$,$R_{i,k-1st}$,

Table 1 Stream data for the example problem [12].

Case no.	Stream no.	T_s °C	T_t °C	CP kW/°C
Base case				
Period 1	1	249	100	10.55
	2	259	128	12.66
	3	96	170	9.144
	4	106	270	15.00
Period 2	1	229	120	7.032
	2	239	148	8.44
	3	96	170	9.144
	4	106	270	15.00
Period 3	1	249	100	10.55
	2	259	128	12.66
	3	116	150	6.096
	4	126	250	10.00

Table 2 Pinch points & minimum utilities for each of the three periods of the example problem.

Period no.	Pinch point	Minimum hot utility kW	Minimum cold utility kW
1	249–239	338.4	432.15
2	–	1602.13	0.0
3	259–249	10.00	1793.15

the heat residuals that correspond to hot stream i at subnetwork st of period t and temperature intervals k, $k-1$ respectively; Q^h_{ikst}, the heat load of hot stream i entering the temperature interval k in subnetwork st; Q^c_{jkst}, the heat load of cold stream j entering the same temperature interval k in period t; B^{st}_{ij}, the upper bound for possible heat exchange between streams (i, j) in subnetwork st.

The upper bound B^{st}_{ij} can be computed a prior, and is given by the smallest of the heat content of hot stream i and cold stream j in subnetwork st. The inequality (21) applies to pairs satisfying condition "a"; the next two inequalities (22), (23) satisfying condition "b"; inequality (24) applies for pairs not satisfying either of the two conditions. Each inequality (21)–(24) has the effect of preventing the transfer of heat between a hot stream i and a cold stream j in a given subnetwork st when no unit is selected for the given pair ($Y_{\text{ij}} = 0$).

3. Application of the multiperiod transshipment model on a literature example

The example is a literature problem (example (1)) in Floudas and Grossmann [12] which has three modes of operation. Each period differs from other periods in supply, target temperatures and heat capacity flow rates. The problem data are given in Table 1.

The multiperiod transshipment model has been applied for this example in order to reach to the flexible HEN of the three periods of the example. The available utilities are steam at 300 °C as hot utility and cold water at 30 °C as a cold utility. The first step is partitioning the problem into temperature intervals according to the procedures of Grims et al. [20]. The second step is applying transshipment model P1 to each period separately. P1 equations were solved using the software [LINDO] "Linear Interactive and Discrete Optimizer" to locate the pinch point and determine the minimum hot and cold utilities, the results are shown in Table 2.

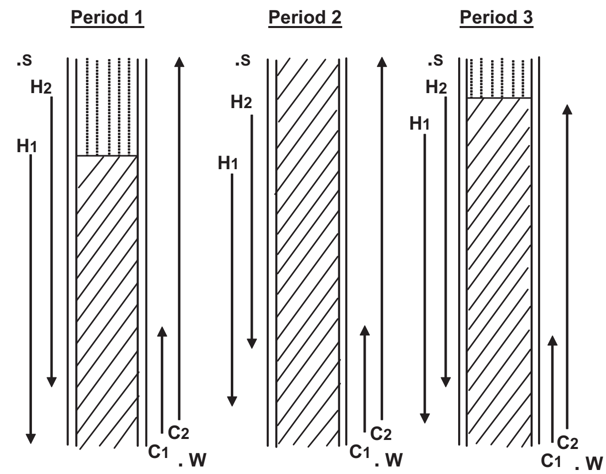

Figure 2 Stream existence in subnetwork for each period.

The next step is to apply the MILP multiperiod transshipment model P3 to the three periods simultaneously. Reducing the number of assigned binary variables [Y_{ijst}] as discussed in Section 2.3, a schematic diagram for stream existence in the three periods is shown in Fig. 2. Notice that heating and cooling utilities are now considered as streams. From this figure the following can be identified:

1. The number of matches for streams satisfying condition P_a is 6; (H1–C1, H1–C2, H2–C1, H1–W, H2–W, C2–S).
2. The number of matches for streams satisfying condition P_b is 2 due to existence of the match (H2–C2) in period 1 in the two sub networks (above and below the pinch point).

The total number of binary variables to be assigned for the multiperiod problem is, therefore, eight binary variables.

The MILP multiperiod transshipment model equations are formulated according to P3 algorithm. The optimum solution was found using [LINDO] software.

4. Results and discussions

Running the program several times at random, three different solutions resulted due to different iteration runs, where the solver stopped after 17, 22 and 77 iterations. Verheyen and Zhang [21] reported that an MILP' program can have multiple solutions. Table 3 summarizes the results obtained by the application of MILP transshipment model on the three periods of the example. By drawing the network for each period we can deduce the feasible network for the three periods for each run. Figs. 3–5 show the resulting feasible multiperiod networks for 17, 22, and 77 iterations runs respectively. For the three iteration runs the generated feasible networks have a split in the cold stream C2. Contrary to the feasible network after 77 iterations, a split in the hot stream H1 was also necessary to avoid temperature violations for the 17 and the 22 iteration runs as shown in Figs. 3 and 4. A similar result has been reached by Floudas and Grossmann [12] in their solution to the same problem. Again to avoid temperature violation the match H1–C1 has to be split into two exchangers in periods 1 and 3 for 17 iterations and in periods 2 and 3 for 22 iterations as shown in Figs 3 and 4. A similar action is not needed for the multiperiod network generated after 77 iterations as shown in Fig. 5, which contained neither splitting of the hot stream

Table 3 Loads* and number of units resulting from different iteration runs of model P3 and from Model P2 for the different periods of the example problem.

No of iterations		17			22			77			MILP model P2		
Unit number	Match	Period 1	Period 2	Period 3	Period 1	Period 2	Period 3	Period 1	Period 2	Period 3	Period 1	Period 2	Period 3
1	S–C2	338.4	1602.1	10.0	338.4	1602.1	10.0	338.4	1602.1	10.0	338.4	1602.1	10
2	H2–C2	126.6	0.0	0.0	126.6	0.0	0.0	126.6	0.0	0.0	126.6	0.0	0.0
3	H1–C1	676.65	676.6	207.3	676.65	676.6	207.3	676.65	676.6	207.3	0.0	676.66	207.3
4	H1–C2	817.93	89.8	1045.8	463.14	89.8	1045.8	463.14	89.8	0.0	1139.8	89.8	0.0
5	H2–C2	1177.1	768.04	184.15	1531.8	768.04	184.15	1591.8	768.04	1230.0	855.2	768.04	1230.0
6	H1–W	77.96	0.0	318.84	432.15	0.0	918.84	492.15	0.0	1364.8	432	0.0	1364.88
7	H2–W	354.79	0.0	1474.9	0.0	0.0	1474.9	0.0	0.0	428.46	0.0	0.0	428.46
8	H2–C1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	585.2	0.0	0.0
Min. no of units		7	4	6	6	4	6	6	4	5	6	4	5

Exchanger loads are in kW.

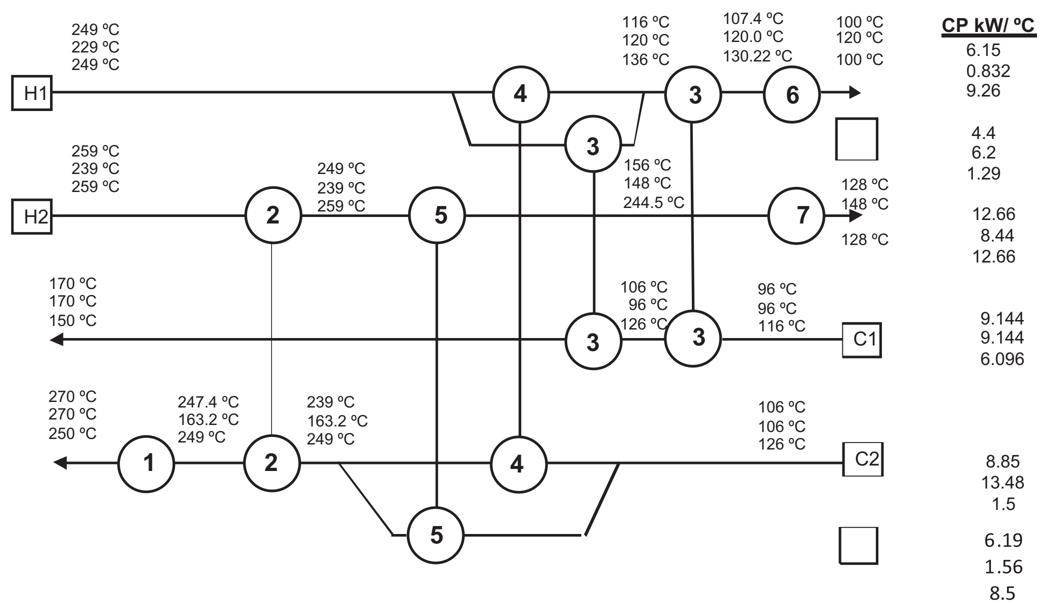

Figure 3 Network configuration for the feasible multiperiod operation generated by MILP transshipment model for the example problem after 17 iterations.

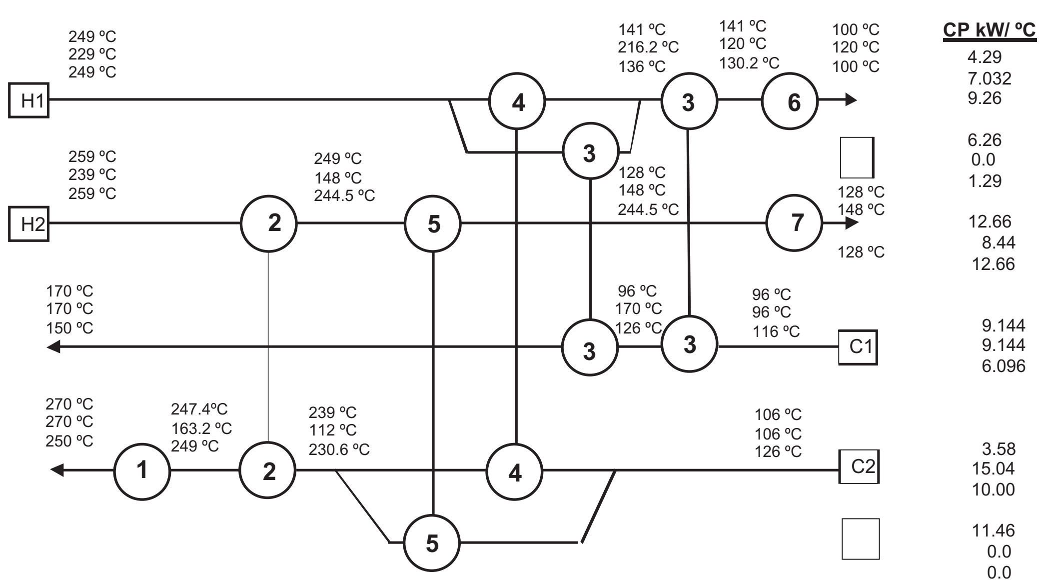

Figure 4 Network configuration for the feasible multiperiod operation generated by MILP transshipment model for the example problem after 22 iterations.

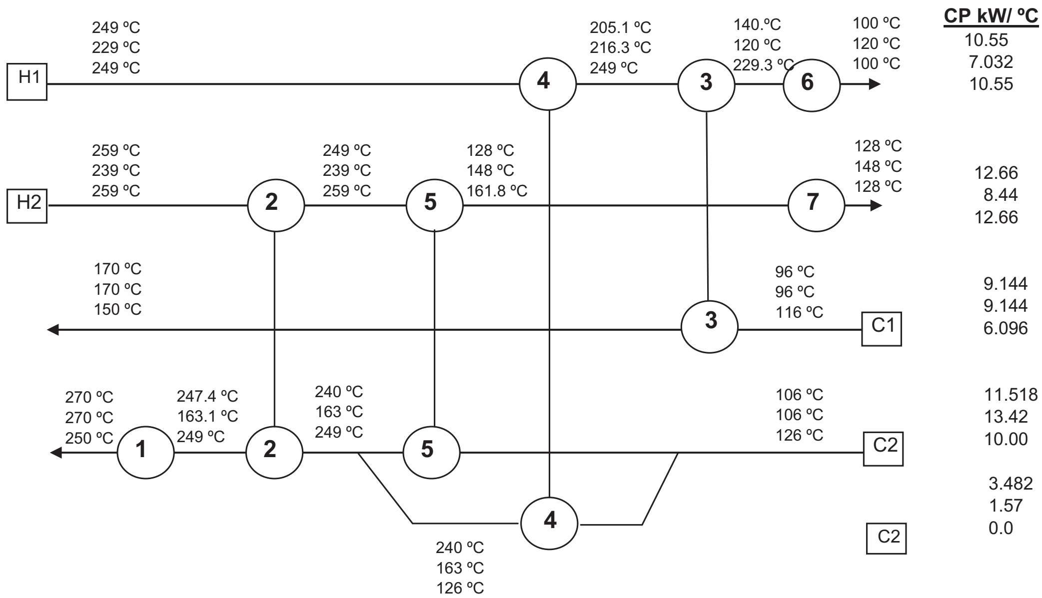

Figure 5 Network configuration for the feasible multiperiod operation generated by MILP transshipment model for the example problem after iterations—No of Units is 7.

H1 nor splitting of the match H1-C1. The generated networks in this communication are different from the networks generated by Floudas and Grossmann [12,14], and Isafiade and Fraser [19] for the same example.

It is interesting to find out the configuration of the feasible network composed by the combination of energy optimal networks generated by the application of the single period MILP model, P2. The results of the application of model P2 are shown in Table 3. It can be noticed that a new match H2–C1 has now appeared. A similar observation was reported by Floudas and Grossmann [12]. However, periods 2and 3 are exactly the same as those obtained by MILP multiperiod model P3 after 77 iterations (see Table 3) only period one is different where the match H2–C2 appeared. The combined multiperiod network is shown in Fig. 6. It can be noticed that despite the appearance of this new match in period 1, yet the design resemblance of the multiperiod 77 iteration network Fig. 6 and the combined network in Fig. 6 is striking. This finding is contrary to the statement of Floudas and Grossmann [12] that it is a non trivial task to combine the configurations for the different periods. It is thought that combination of minimum energy individual networks is worth considering for designing flexible multiperiod HENs.

Now we have generated four different multiperiod networks shown in figs. 3–6 which satisfy minimum energy requirements at each period. To find the optimal network we need to perform economic analysis which will be limited to compare the installed cost of the heat exchangers in each

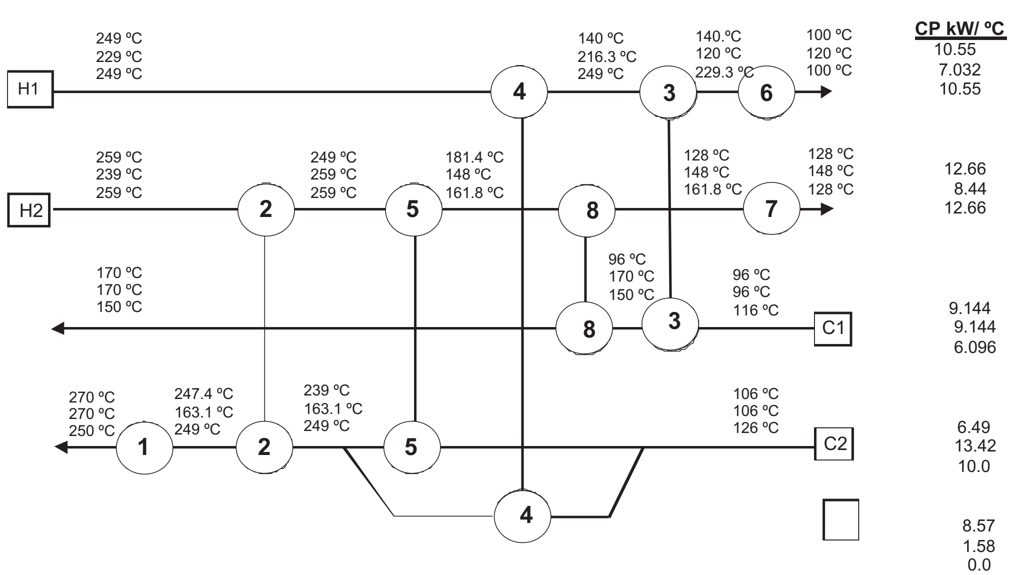

Figure 6 Flexible HEN combined from individual MILP solutions for each separate period.

Table 4 Economic analysis of the different network designs.

Match	U kW m^{-2} °C^{-1}	17 Iterations		22 Iterations		77 Iterations		Combined individual networks		Floudas and Grossmann [12]		Floudas and Grossmann [14]	
		Area m^2	Cost $	Area m^2	Cost $	Area m^2	Cost $	Area m^2	Cost $	Area m^2	Cost $	Area m^2	Cost $
S–C2	0.8	28.45	57519.73	28.45	57519.73	28.45	57519.73	28.45	57519.73	28.45	57519.73	28.45	57519.73
H2–C2	1	11.72	44761.13	11.72	44761.13	11.72	44761.13	17.72	44761.13	11.765	44802.94	11.765	44802.94
H1–C1	1	17.5 + 8.55	91330.15	19.96	51596.7	14.40	47149.6	7.855	40884.0	63.411	76613.26	20.15	51739.20
H1–C2	1	75.8	82265.7	75.8	82265.7	32.2	53957.7	58.12	74065.87	81.79	84869.11	123.44	101186.45
H2–C2	1	47.3	68547.21	100.8	92648.46	100.8	92648.46	60.76	75348.87	75.8	82265.70	54.84	72440.03
H1–W	0.4	10.63	43728.0	13.5	46369.1	29.40	58134.40	29.40	58134.40	26.7	56364.13	26.7	56364.13
H2–W	0.3	34.92	61564.8	34.92	61564.8	13.63	46483.1	13.63	46483.1	18.67	50614.47	18.67	50614.47
H2–C1	–	–	–	–	–	–	–	29.318	58082.75	–	–	–	–
Total		234.87	449716.72	285.15	436726	230.6	400654	245.3	455280	306.6	453049	284.1	434667

Area in m^2, Cost in $, U in kW/ m^2 °C.

network (since minimum energy is achieved in each case). The exchangers' areas are calculated for those corresponding to the highest loads in the three periods with the approach temperatures specific to these loads. For matches with equal loads in different periods, exchanger area is calculated for the match with the lowest LMTD. The exchanger area is calculated using Eq. (29) as given by Verheyen and Zhang [21].Where, U the overall heat transfer coefficient for each match is given in Table 3 [14].

$$A_{i,j,p} = \frac{q_{i,j,p}}{LMTD_{i,j,p} * Ui,j} \tag{29}$$

$$LMTD_{i,j} = \frac{(T_{is} - t_{jt}) - (T_{it} - t_{js})}{\ln[(T_{is} - t_{jt})/(T_{it} - t_{js})]} \tag{30}$$

The exchanger installed cost is calculated using Eq. (31) which was used by Khorasany and Fesanghary [22]. This form of equation is generally accepted for calculating heat exchangers' cost [23,24], where it takes into consideration a fixed term that accounts for installation cost and an area related term. It was chosen to reflect the effect of number of units on HENs' cost.

$$C_{i,j,p} = 26,600 + 4147.5A_{i,j,p}^{0.6} \tag{31}$$

where: $A_{i,j,p}$, Heat transfer area of match (i, j) in period (p); $q_{i,j,p:}$ Heat load of every heat exchanger of match (i, j) in period (p); LMTD$_{i,j,p}$: Log mean temperature difference of match (i, j) in period (p); T_{is} & $T_{it:}$ Start and target temperatures of hot stream i; t_{js} & t_{jt}: Start and target temperatures of cold stream j; $U_{i,j}$: Heat transfer coefficient for match (i, j); $C_{i,j,p}$: Cost for match (i, j) having the largest area in all periods.Included in the comparison are the networks generated by Floudas and Grossmann [12,14]. The exchanger cost of the reference work is calculated using the same Eq. (31). Table 4 shows the results of calculated area and cost for each match, and the total exchangers' area and total cost. Table 4 reveals that the least area and least cost corresponded to the 77 iteration case of the present work. The highest area corresponded to the work of Floudas and Grossmann [12]. Although the combined individual network case does not have the highest area, yet it does have the highest cost. This is logical since it has the largest number of units and the cost equation that we use contains a constant term that multiplies with the number of units. The Floudas and Grossmann [14] NLP model, though added more sophistication to their original model [12] it did not show much better results. Also it allowed for exchanger minimum approach temperature (EMAT) violation for exchanger H1–C2 of their network.Isafiade and Fraser [19] developed a model that minimizes the annualized total cost for the synthesis of multiperiod HENs. Their application of their model to the example problem produced an HEN that has a total area of 111.95 m^2 which is much lower than the areas reported above. On the other hand the utilities are several times higher than the minimum utilities. The hot utilities were 1889.76, 2000 and 773.49 kW for the periods 1, 2, and 3 respectively as compared to the minimum hot utility of 338.4,1602.13 and 10 kW for the same periods. Similarly the cold utilities were 1983.31, 397.83 and 2556.64 kW for the periods 1, 2, and 3 respectively as compared to the minimum cold utility of 432.15, 0.0 and 1793.46 for the same periods.

5. Conclusion

The problem of designing a flexible heat exchanger network for a multiperiod operation, can be solved by applying a systematic procedure based on a MILP transshipment model. This model provides different solutions corresponding to different iteration runs. The optimum solution has to be found out among those solutions that realize the least exchanger cost. The optimum flexible HEN derived from single optimum HEN design for the separate periods should not be overlooked in our search for a cost optimum HEN.

With the present world economic situation of escalating energy prices, the new methods that focused on a single step overall cost optimization [19] may result in flexible HENs that are only optimal for a short time because they are not energy efficient. Therefore, returning back to sequential, multi-step procedures of optimizing utility cost first and then equipment cost may be worth considering for HEN design.

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