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Comparison of Sequential and Simultaneous Approaches for Multiperiod Heat Exchanger Network Synthesis and Application for Crude Preheat Train

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Global energy demand has increased continuously since the last few decades and it has been a critical issue especially in industrial sector. Heat exchanger network (HEN) has received considerable attention for improving heat recovery in industrial processes. In this work, HEN synthesis for multiperiod operation has been studied. Sequential and simultaneous approaches for multiperiod HEN design are proposed and compared by a case study. The most efficient method will be applied to a case study of crude distillation unit (CDU) where different kinds of crudes are used. The objective for both methods is to minimize total annualized cost (TAC) including capital cost and utility cost. The sequential approach consists of three steps. First, an MINLP superstructure-based model is used to generate an initial HEN for a chosen period. Then it will be adapted by NLP model to generate HENs which are fitted to other period conditions. Lastly, HENs for each period are integrated to obtain the multiperiod HEN design. By varying the chosen period in the first step with all periods, it will result in different multiperiod HEN candidates. The best one will be selected as the final solution for sequential method. For simultaneous approach, an MINLP simultaneous model takes into account all periods concurrently and solve at once. Maximum-area-per-period concept is used in area calculation. The results demonstrate that the simultaneous approach showed better performance than sequential approach. Thus, the simultaneous approach is then applied further to the industrial case study of crude preheat train in CDU to assure that the model can deal with larger problem. In this case, an initialization strategy has been carried out to find an initial feasible solution. It showed that the initialization technique can reduce computational time substantially. Moreover, the final solution of HEN will be validated by commercial process simulator, PRO/II, to affirm its feasibility in real process.

1. Introduction

Energy demand has increased continuously and became more important worldwide issue in the last few decades. As well as other industries, the petroleum refinery industry encounters the similar crisis especially in crude distillation unit (CDU) which is one of the largest energy-consuming units in the refinery plant. Heat exchanger network synthesis (HENS) is a widely used technique to recover excess energy from heat source (hot process streams) and transfer to heat sink (cold process streams). This can help in reducing operating expenditure spent on utilities. In reality, the process streams may have variation in condition due to many causes such as changes in feed/product specifications, control failure, unstable environment, etc. Therefore, multiperiod heat exchanger network design is essential to apply in such processes to maintain feasible operation and plant flexibility over uncertain operating conditions. Many researchers have attempted to propose their algorithms to solve multiperiod problems. Aaltola (2002) proposed a simultaneous mixed-integer nonlinear programming (MINLP) model using mean area of different periods in objective function. A sequential decomposition technique relying on Lagrangean decomposition concept was proposed by Escobar et al. (2014). Pejpichestakul and Siemanond (2013)

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adopted pinch design method to n-stage model sequentially and applied for retrofitting in crude preheat train. In this study, both sequential and simultaneous approaches for multiperiod problem are proposed based on stage model by Yee and Grossmann (1990). The two methods are compared by a simple case study and the best method will be applied with refinery case study of crude preheat train including initialization technique and validation procedures.

2. Methodology

2.1 Sequential approach

For sequential approach, there are three steps in sequence as shown in Figure 1(a). First, one of all periods is chosen for synthesizing initial HEN by MINLP stage-wise superstructure model (Yee and Grossmann, 1990) for single period. Next, the initial HEN is adapted by nonlinear programming (NLP) model in order that it can be operable for each of other period conditions besides the chosen period in the first step. The strategy of the NLP model is to fix heat exchangers topology, and no allowance of addition and/or removal of any exchangers. However, areas of heat exchangers can be changed to satisfy heat balance. The objective function of this NLP model is sum of additional area required as illustrated in Eq(1). Finally, the initial HEN and the adapted HENs are integrated to be a multiperiod HEN. There will be different multiperiod HEN candidates which correspond to a chosen period in the first step. Total annualized cost (TAC) is considered as the decision variable for selecting the best multiperiod HEN design.

$$
\begin{aligned}
objective\ \ function &= \sum_{i\in HP}\sum_{j\in CP}\sum_{k\in ST}\max(0, Area\_new(i,j,k) - Area\_old(i,j,k)) \\
&+ \sum_{j\in CP}\max(0, AreaHU\_new(j) - AreaHU\_old(j)) \\
&+ \sum_{i\in CP}\max(0, AreaCU\_new(i) - AreaCU\_old(i))
\end{aligned} \qquad (1)
$$

Where HP and CP is a set of hot process stream i and cold process stream j, respectively. ST is a set of stage in the superstructure.

2.2 Simultaneous approach

In this approach, multiperiod HEN is generated by multiperiod MINLP superstructure-based model. All process streams data are input into the model and solve simultaneously as shown in Figure 1(b). The isothermal mixing assumption is made. The maximum-area-per-period concept proposed by Verheyen and Zhang (2006) is used in area calculation.

2.3 Application for refinery case study

One of two approaches which performs better is applied with refinery case study of crude preheat train to assure the performance of the model when dealing with larger problem.

2.4 Initialization technique

In this step, an initialization technique is presented since the refinery case study is a large problem that requires more computational time. This technique can provide an initial feasible solution before solving for the real optimal solution. This can be done by executing mixed-integer linear programming (MILP) model which neglects the nonlinear terms of log mean temperature difference (LMTD) calculations. The average LMTD (ALMTD) is introduced to use instead of real LMTD. It is calculated by constructing composite curves for each period, calculating LMTD for every enthalpy intervals, and estimating the ALMTD by using Eq(2).

$$
ALMTD(i,j) = \sum_{N} q(i,j,n)\cdot LMTD(n) / \sum_{N} q(i,j,n) \qquad (2)
$$

Where i and j denotes hot and cold stream, respectively. The index n represents enthalpy interval while N is total number of intervals corresponding to the temperature range of match (i,j).

2.5 Validation by simulating on PRO/II

The best result is validated by using the commercial simulation software, PRO/II. Crude distillation process is simulated and the optimal HEN is applied in crude preheat train. It is assumed that the correction factor (FT) is equal to 1 and flow direction is countercurrent.

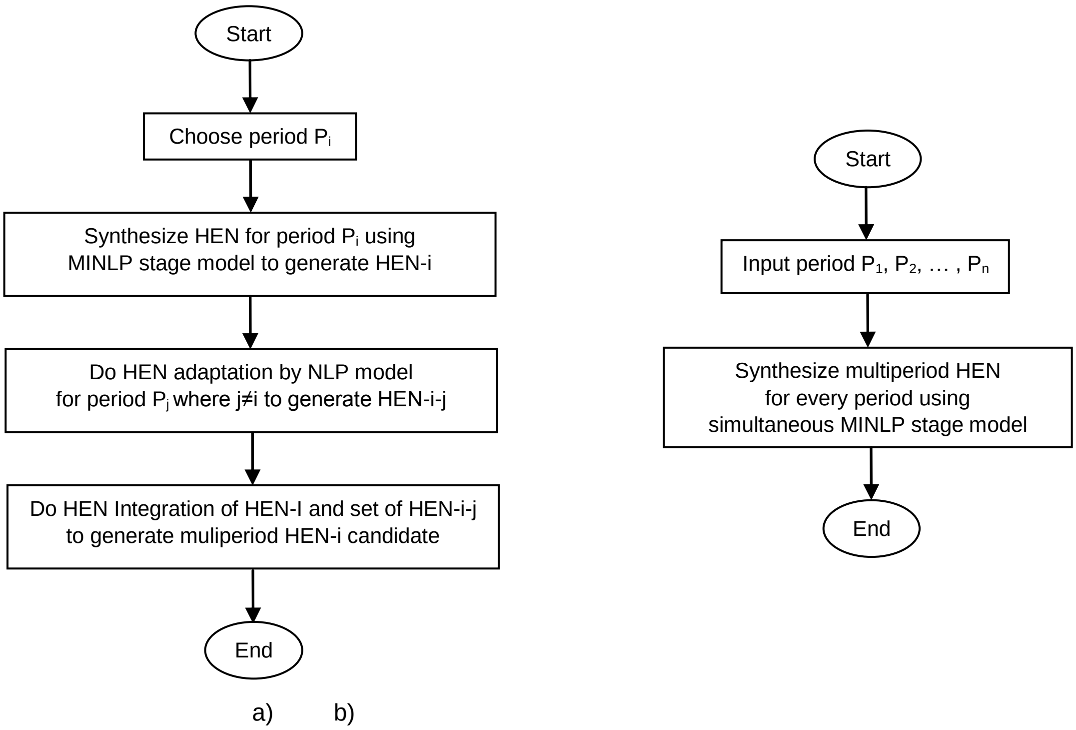


Figure 1: Algorithm of a) sequential and b) simultaneous approaches for multiperiod HEN synthesis

3. Case study

3.1 Simple case study

The case study adapted from Verheyen and Zhang (2006) is used to demonstrate the performance of both sequential and simultaneous methods. The problem involves vacuum gas oil (VGO) hydrotreater unit of an oil refinery. It consists of three hot streams and four cold streams. There is a catalyst being used in the hydrotreating reactor and will gradually loss its activity as time passes. Thus the inlet temperature to reactor has to be increased in order to compensate the loss of reaction rate. This causes not only changes of inlet and outlet temperature of reactor, but also the effluent compositions (heat capacity flowrates). The operational periods are classified into three periods: start-of-run (SOR), mid-of-run (MOR), and end-of-run (EOR). The stream data of each period is shown in Table 1. Note that the time duration for each period is assumed to be equal.

Table 1: Stream and economic data for simple case study

Stream	h (kW/m^2.°C)	SOR			MOR			EOR		
		T_{in} (°C)	T_{out} (°C)	FC_p (kW/°C)	T_{in} (°C)	T_{out} (°C)	FC_p (kW/°C)	T_{in} (°C)	T_{out} (°C)	FC_p (kW/°C)
H1	2	393	60	201.6	406	60	205.0	420	60	208.5
H2	2	160	40	185.1	160	40	198.8	160	40	175.2
H3	2	354	60	137.4	362	60	136.4	360	60	134.1
C1	1.5	72	356	209.4	72	365	210.3	72	373	211.1
C2	1.5	62	210	141.6	62	210	141.0	62	210	140.5
C3	2	220	370	176.4	220	370	175.4	220	370	174.5
C4	2	253	284	294.4	250	290	318.7	249	286	271.2

Annualization factor = 0.2, Exchanger capital cost = 8,333.3 + 641.7*(Area in m^2), Hot utility cost = $115.2/kW, Cold utility cost = $1.3/kW

Table 2: Stream and economic data for refinery case study

Stream	Light crude				Medium crude				Heavy crude			
	FC_p kW/°C	T_{in} °C	T_{out} °C	h kW/m^2.°C	FC_p kW/°C	T_{in} °C	T_{out} °C	h kW/m^2.°C	FC_p kW/°C	T_{in} °C	T_{out} °C	h kW/m^2.°C
H1	121.02	201.17	104.44	1.293	125.28	198.28	104.44	1.092	132.07	193.31	104.44	1.075
H2	69.91	274.71	148.89	1.318	71.80	271.63	148.89	1.235	74.03	267.77	148.89	1.221
H3	98.60	321.17	232.22	1.298	101.36	319.12	232.22	1.270	104.43	316.69	232.22	1.270
H4	105.22	32.22	30.00	1.058	91.92	32.22	30.00	1.253	70.57	32.22	30.00	1.309
H5	67.76	234.40	30.00	1.395	56.28	225.57	30.00	1.394	46.81	221.36	30.00	1.393
H6	49.64	273.17	30.00	1.423	34.77	269.78	30.00	1.431	29.33	263.57	30.00	1.438
H7	59.98	326.40	30.00	1.343	41.91	326.26	30.00	1.413	32.46	322.00	30.00	1.419
H8	135.33	341.73	30.00	0.892	210.12	357.39	30.00	0.888	268.65	353.52	30.00	0.826
C1	380.57	25.00	125.00	0.654	387.57	25.00	125.00	0.652	392.24	25.00	125.00	0.651
C2	434.32	125.00	170.00	0.632	443.70	125.00	170.00	0.630	449.76	125.00	170.00	0.630
C3	585.63	166.64	370.00	0.788	587.80	168.84	370.00	0.782	555.77	167.81	370.00	0.780
Exchanger capital cost = 26,460 + 389*(Area in m^2), Hot utility cost = $134/kW, Cold utility cost = $6.7/kW												

3.2 Refinery case study

A crude refinery process is simulated using PRO/II feeding three different types of crude, i.e., light, medium and heavy. Therefore, there are three periods operating 100, 150, and 100 days per year for each crude, respectively. Due to the different compositions of crudes, the design parameters such as temperatures and heat capacity flowrates are varied. The stream data are extracted as presented in Table 2. The problem consists of eight hot streams and three cold streams. Hereby, the average heat capacity flowrates are used and assumed to be constant for each stream. The project life time of 5 years is assumed with 10 % annual interest.

4. Results and discussion

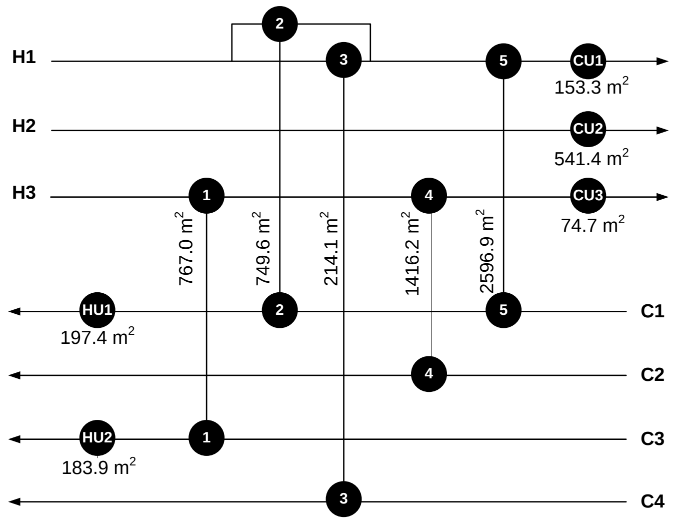
The mathematical model was implemented on GAMS 21.4 with DICOPT2x-C (CONOPT3 and CPLEX 9.0) as MINLP solver. The computer platform is a Lenovo Y450 with Intel® Core 2 Duo T6400 CPU at 2.0 GHz. Table 3 shows the comparison of the results between sequential and simultaneous approaches. Grid diagrams of each method are shown in Figure 2 and 3. It can be seen that the simultaneous approach generates HEN design better than the sequential approach as it has the lower TAC. This is because the solution obtained from the sequential approach might fall in sub-optimal solution since there were several optimizing steps, while the simultaneous method solved the problem at a time. Furthermore, the result of simultaneous method has less complexity than another one because there is no stream splitting.

Table 3: Summary result of sequential and simultaneous approaches from case study

Parameter	Sequential approach	Simultaneous approach
No. of heat exchangers	10	10
Total area (m^2)	6,894	6,900
Fixed cost ($/yr)	16,667	16,667
Area cost ($/yr)	884,840	885,515
Utility cost ($/yr)	1,831,833	1,811,172
TAC ($/yr)	2,733,340	2,713,354

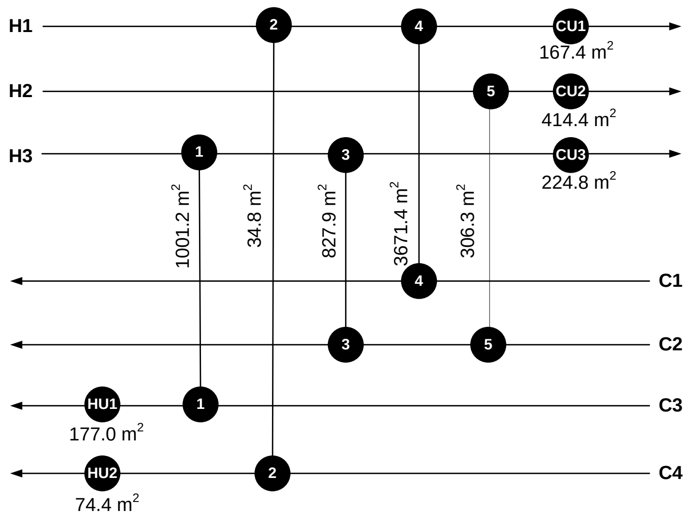
Table 4: Summary result of HEN with and without initialization for refinery case study

Parameter	Without initialization	With initialization
No. of heat exchangers	29	25
Total area (m^2)	15,029	16,079
Fixed cost ($/yr)	202,578	174,636
Area cost ($/yr)	1,543,422	1,651,209
Utility cost ($/yr)	7,395,913	7,304,782
TAC ($/yr)	9,141,913	9,130,627



Q(kW)	Period 1	Period 2	Period 3
CU1	5,070.5	5,555.4	5,654.3
CU2	22,212.0	23,856.0	21,024.0
CU3	2,566.3	2,550.5	2,124.2
HU1	6,533.7	8,991.3	4,169.8
HU2	9,587.5	8,535.7	8,863.2

Figure 2: Grid diagram of HEN from sequential approach



Q(kW)	Period 1	Period 2	Period 3
CU1	5,228.6	5,747.5	6,332.7
CU2	12,510.3	14,019.5	11,476.8
CU3	11,705.3	11,800.6	11,260.0
HU1	9,024.8	7,949.3	8,451.8
HU2	6,691.8	9,183.4	4,848.2

Figure 3: Grid diagram of HEN from simultaneous approach

Based on the comparison of two methods, the simultaneous approach was selected to apply with the refinery case study in order to ensure its performance when dealing with larger problem. It was found that the simultaneous model needed significant amount of time to solve the refinery case. Therefore, an initialization technique was adopted to help reduce the computational time.

After using the initialization technique, the computational time decreased substantially by over 70 %. Moreover, from Table 4, the obtained solution was more preferable than that without initialization. Finally, simulation of the best HEN design was carried out by using PRO/II to see its functionality in the real process. It was found that some modification had to be made because the outlet temperature of the process streams, which do not have utility exchangers installed at the end, did not reach the desire temperatures. Hence, some exchanger areas had to be changed and one utility exchanger was added in the process. The final applicable HEN is illustrated in Figure 4.

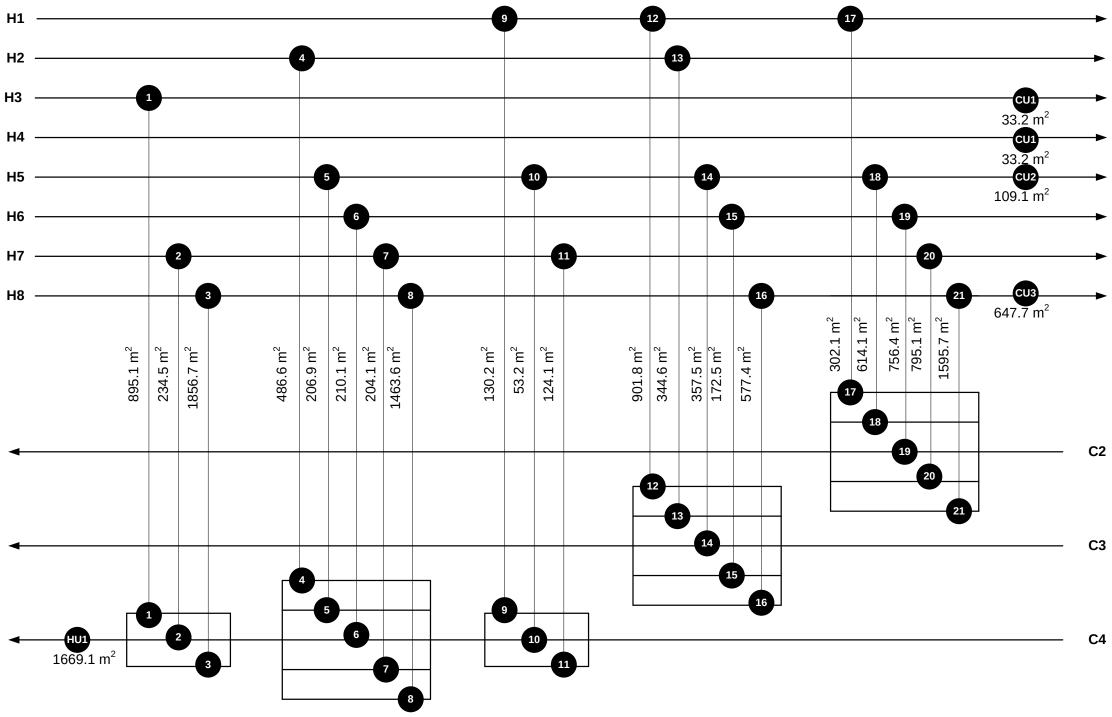


Figure 4: Grid diagram of validated HEN from simultaneous method with initialization for crude refinery process

5. Conclusions

In this study, the sequential and simultaneous methods have been developed for multiperiod HEN synthesis. The three-step sequential method composes of HEN synthesis, HEN adaptation, and HEN integration. The simultaneous approach is carried out using simultaneous MINLP model for multiperiod which solves in one step. It has been shown in this work that the simultaneous approach can perform better than the three-step sequential approach by giving lower TAC. Moreover, the simultaneous MINLP model is quite rigorous since no initial feasible solution is needed for both of two case studies. But, as the problem size increases, the computational time required is also increased substantially. An initialization technique is hence applied to find an initial feasible solution. This can help reduce the time resource; moreover, it can improve the solution of HEN design.

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