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Hybrid Synthesis Method for Multi-period Heat Exchanger Networks

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Developing a flexible heat exchanger network, that will remain operable in the face of potential variations in stream parameters, or variables, around some nominal values, especially for large problems, are difficult to solve simultaneously. A hybrid synthesis approach that systematically combines sequential and mathematical programming techniques may be more suitable to adopt. The proposed method presented in this paper entails firstly generating two representative single period networks using the Pinch Technology Stream Temperature versus Enthalpy Plot (STEP) approach and the multi-period stage-wise superstructure model for heat exchanger network synthesis. Streams for the representative network are obtained using the largest stream heat demand as criteria. The second stage of the proposed method entails generating a reduced multi-period stage-wise superstructure, using a combination of the matches obtained in the single period representative networks of the first step as initialising matches. The solution of the reduced superstructure of the second step, which is solved as a Mixed Integer Non-Linear Programming (MINLP) model, is then selected as the best multi-period network. The newly developed method of this paper is tested using an example from the literature. One of the solutions obtained is only 0.9 % higher, in terms of total annual cost, than the best solution presented in the literature but has the benefit of a fewer number of units.

1. Introduction

Most of the methods developed for heat exchanger network synthesis (HENS) have assumed constant stream supply/target temperatures and flowrates. These parameters may fluctuate due to issues such as changes in environmental conditions, changes in feed and product quality, process upsets. The few methods which did not assume fixed values for stream parameters, and which used mathematical programming, have shortcomings such as the inability to obtain globally optimal solutions due to the highly nonlinear nature of the model equations involved in HENS, especially for cases where detailed heat exchanger models are involved (Short et al., 2016). On the other hand, the use of sequential optimisation approaches, where the designer can influence the design process, such as Pinch Technology, does not adequately trade off competing variables in HENS, especially those involving multi-period profiles. Developing a flexible heat exchanger network (HEN), that will remain operable in the face of potential variations in stream parameters, especially for large problems, may be better suited to a hybrid synthesis approach that systematically combines sequential and mathematical programming techniques. Verheyen and Zhang (2006) adopted the stage-wise superstructure (SWS) model of Yee and Grossmann (1990), which was originally developed for single period networks, for the synthesis of multi-period networks. Verheyen and Zhang (2006) incorporated variability into the HEN design optimisation using the maximum heat exchanger area approach in the objective function. In this approach, heat exchangers are sized based on the maximum heat load available for same stream pairs in all periods. Isafiade and Odejobi (2016) also adopted the multi-period SWS model of Verheyen and Zhang (2006) in their work. The authors included the reduced superstructure synthesis approach where superstructures are initialised in a systematic way. The initialising approach adopted by Isafiade and Odejobi (2016) entails solving each sub-period's single period problem and then populating the reduced superstructure with the matches selected in the optimal solutions for the sub-periods. Kang et al. (2015) used a representative period method and a stepwise simplifying method for the synthesis of multi-period HENs.

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Solving large HENS problems using a simultaneous synthesis approach to global optimality in reasonable solution time is not a trivial task. The problem is compounded further for cases involving multi-period stream data due to increase in non-linearities. Pinch Technology, which is advantageous because the designer is involved in the synthesis process is also difficult to adopt for large HEN problems especially at the design stage where there are no explicit rules for pairing streams that are far from the pinch. The sequential nature of Pinch Technology makes it even more difficult to adopt for problems involving multi-period profiles. This is because, apart from the difficulty in identifying the pinch point, designing the heat exchangers to meet the operating and capital cost targets, while still ensuring optimal transfer of heat for stream pairs in all periods of operations, is not a trivial task. The work by Yoro et al. (2019) is among the few studies that have adopted pinch technology for synthesising multi-period networks. The approach of the authors did not include a robust capital cost targeting. This paper presents a hybrid approach for identifying initialisation matches that can be used to initialise a reduced simultaneous based superstructure for HENS involving multi-period profile. The proposed method of this paper makes provision for desirability features of HENS methods such as low total annual cost (TAC), minimum number of units and simple networks with few or no stream splits.

2. Problem statement

The problem of this paper is stated as follows: Given is a set of hot, HP, and cold, CP, process streams, including their supply, T^s, and target, T^t, temperatures and heat capacity flowrates. The streams, whose temperatures and flowrates can change from one period, P, to another, are to be cooled and heated. Given are sets of hot utilities (HU) and cold utilities (CU) which can be used in any of the operational periods to cool and heat the process streams. Other parameters given are stream heat transfer coefficients, (h), heat exchanger area and installation costs, and duration of each period of operation. The goal is to synthesise a multi-period HEN having a minimum TAC.

3. Methodology

The method adopted in this paper also involves generating a reduced superstructure, similar to that of Isafiade and Odejobi (2016). The key difference is that the approach of this paper uses a hybrid technique to identify the set of matches that would be used to initialise the reduced superstructure. The hybrid technique entails adopting the Stream Temperature Versus Enthalpy Plot (STEP) and Heat Allocation and Targeting diagram (HEAT) of Wan Alwi and Manan (2010), on one hand to generate a set of potential matches and using a representative single period SWS model to identify another set of potential matches on the other hand. The two sets of potential matches are then systematically used to initialise a reduced multi-period superstructure that is solved as a mixed integer non-linear (MINLP) model. The STEP method, rather than the traditional Pinch Technology approach, is adopted in the hybrid synthesis model of this paper because it establishes utility targets, and designs to meet these targets, in a single step. This is advantageous for reasons such as easy identification of direct potential one-to-one hot-cold stream matches without the need for stream splitting. This is unlike the traditional Pinch Technology approach where the process of establishing stream matches that meet utility and heat exchanger area targets require stream splitting because streams are represented as composites and not as individual streams. Figure 1 is a summary of how the proposed method of this paper works.

The details of how the STEP and HEAT diagrams are generated for single period HENS problems can be found in Wan Alwi and Manan (2010), while the details of the mathematical model equations can be found in the works of Verheyen and Zhang (2006) and Isafiade and Short (2016). The expression for the maximum heat exchanger area approach and objective functions, are both shown in Eq(1) and Eq(2).

$$A_{i,j,k} \geq \frac{q_{i,j,k,p}}{(LMTD_{i,j,k,p})\ (U_{i,j})} \tag{1}$$

$$\begin{aligned} min\left\{\sum_{p\epsilon P}\left(\frac{DOP_p}{\sum_{p=1}^{NOP} DOP_p}\sum_{i\epsilon HP}\sum_{j\epsilon CU}\sum_{k\epsilon K} CUC_j \cdot q_{i,j,k,p} + \frac{DOP_p}{\sum_{p=1}^{NOP} DOP_p}\sum_{i\epsilon HU}\sum_{j\epsilon CP}\sum_{k\epsilon K} HUC_i \cdot q_{i,j,k,p}\right)\right\} \\ + AF\left(\sum_{i\epsilon H}\sum_{j\epsilon C}\sum_{k\epsilon K} CF_{ij} \cdot z_{i,j,k} + \sum_{i\epsilon H}\sum_{j\epsilon C}\sum_{k\epsilon K} AC_{ij} \cdot A_{i,j,k}^{ACI}\right) \quad \forall\ i\epsilon HP, j\epsilon CP, k\epsilon K, p\epsilon P \end{aligned} \tag{2}$$

In Eq(1), $q_{i,j,k,p}$ represents the quantity of heat (kW) exchanged between hot stream i and cold stream j in interval k of the SWS and operational period p, $U_{i,j}$ represents overall heat transfer coefficient between hot stream i and cold stream j (0.1 W/m^2°C), $LMTD_{i,j,k,p}$ represents the logarithmic mean temperature difference (°C) between hot stream i and cold stream j in interval k of the SWS and operational period p, while $A_{i,j,k}$ represents heat exchanger area (m^2) transferring heat between hot stream i and cold stream j in interval k of the superstructure. In Eq(2), DOP_p and NOP represent duration of operational period p and number of periods, CUC_j and HUC_i represent cost per unit of cold and hot utility (1.3 \$/(kW·y) for cold utility and 115.2 \$/(kW·y) for hot utility), AF (0.2) represents annualisation factor, $CF_{i,j}$ (8,333.3 \$) represent heat exchanger installation cost, $z_{i,j,k}$ is a binary variable which is used to indicate the existence, or otherwise, of a heat exchanger between hot stream i and cold stream j in interval k of the superstructure, $AC_{i,j}$ (641.7 \$/m^2) represents cost per unit heat exchanger area while ACI is heat exchanger area cost exponent.

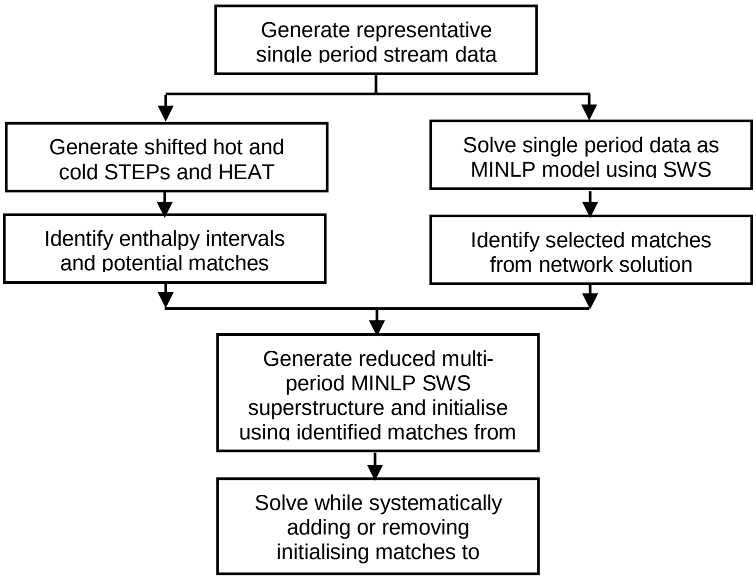

Figure 1: Structure of solution procedure of proposed methodology

4. Case study

The example used in this paper to illustrate the proposed synthesis method is the popular 3 hot streams and 4 cold streams multi-period HEN problem which was first presented by Verheyen and Zhang (2006). The problem, which has been solved by several authors, involves 3 periods of operations of equal durations. The stream data for the 3 operational periods is shown in Table 1. Applying the first step of the solution procedure shown in Figure 1 gives the representative streams shown in Table 2.

Table 1: Stream data of case study for start of operation, middle of operation and end of operation

Streams	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)
H1	390	60	201.6	406	60	205.0	420	60	208.5
H2	160	40	185.1	160	40	198.8	160	40	175.2
H3	354	60	137.4	362	60	136.4	360	60	134.1
C1	72	356	209.4	72	365	210.3	72	373	211.1
C2	62	210	141.6	62	210	141.0	62	210	140.5
C3	220	370	176.4	220	370	175.4	220	370	174.5
C4	253	284	294.4	250	290	318.7	249	286	271.2
HU	500	450		500	450		500	450	
CU	0	10		0	10		0	10	

Note that the representative stream data are obtained by identifying a fictitious stream to represent streams in all operational periods. As an example, the fictitious stream representing hot stream 1 in periods 1, 2 and 3, is a stream having the largest heat load. This is determined from Table 1 by identifying the following, the highest supply temperature (420 °C in period 3), the lowest target temperature (60 °C, same for all periods) and the largest heat capacity flowrate (208.5 kW·°C in period 3). The same procedure is adopted for the cold streams, where the highest supply temperature, the lowest target temperature and the largest heat capacity flowrates are also identified. Doing this for all streams results in the data shown in Table 2. The second step of the solution procedure involves the generation of the STEP and HEAT diagrams on one hand, and the generation of an

SWS based network solution on the other hand. In both cases, the representative stream data of Table 2 are used. The resulting STEP diagram is shown in Figure 2. In this figure, the red lines represent the hot STEP while the green lines represent the cold STEP.

Table 2: Representative stream data

Stream	T^s (°C)	T^t (°C)	F (kW·°C)
H1	420	60	208.5
H2	160	40	198.8
H3	362	60	137.4
C1	72	373	211.1
C2	62	210	141.6
C3	220	370	176.4
C4	249	290	318.7

The HEAT diagram, which is not shown here, is used to match streams on a one-to-one basis within each temperature interval. It is worth stating that future studies will involve the use of the HEAT diagram to set targets for heat exchanger design parameters such as pressure drop, number of shells and tubes. Such targets will then be used to initialise a reduced superstructure. In this paper, only the matches identified in the STEP diagram of Figure 2 are used as initialising matches for the reduced superstructure. In the STEP method, each enthalpy interval corresponds to a heat exchanger. In Figure 2, there are 20 enthalpy intervals, of which some involve direct overlap between the hot and cold STEPs, with the hot STEP being at a higher temperature interval compared to the cold. These intervals correspond to the region of process-to-process heat transfer. Other enthalpy intervals have either only the hot STEP, or even both hot and cold, but the cold STEP is at a higher temperature interval compared to the hot, while one interval has only the cold STEP. Intervals having only the hot STEP will be matched with cold utilities while regions having only the cold STEP will be matched with hot utilities. The shifted stream pinch temperature in the STEP diagram is 230 °C.

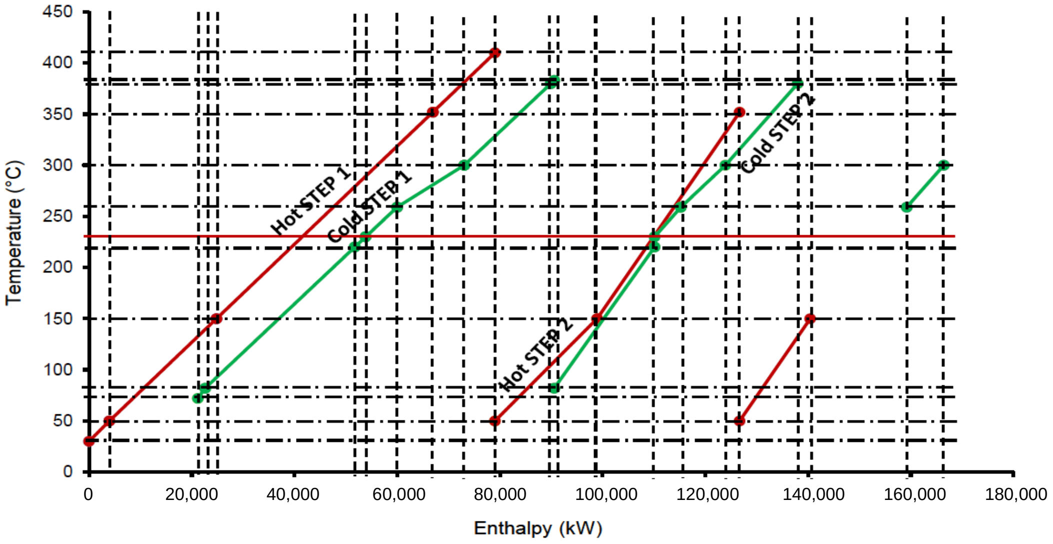

Figure 2: STEP diagram for the case study

Figure 3 shows the mapping of the targeted matches in the STEP diagram onto the stage-wise multi-period superstructure. Some targeted exchangers in the enthalpy intervals of the STEP diagram have been combined and represented as a single match in Figure 3. This is done to reduce the number of intervals from 20 in Figure 2 to 10 in Figure 3. The second aspect of step 2 of the synthesis procedure shown in Figure 1 involves generating an additional set of potential matches that will be used to initialise the reduced superstructure. This additional set of matches are obtained by solving the representative streams in Table 2 using the single period SWS model. The SWS at this stage is also solved using 10 intervals to ensure consistency with the 10 intervals of the STEP grid structure in Figure 3.

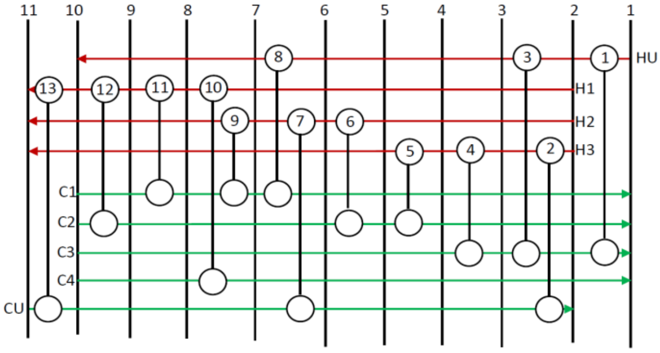

Figure 3: STEP matches populated in the stage-wise multi-period superstructure

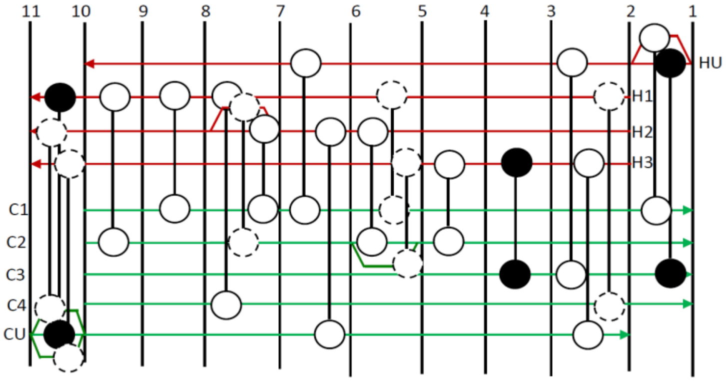

Figure 4: Reduced stage-wise multi-period superstructure comprising a combination of matches from the STEP and conventional single period SWS model.

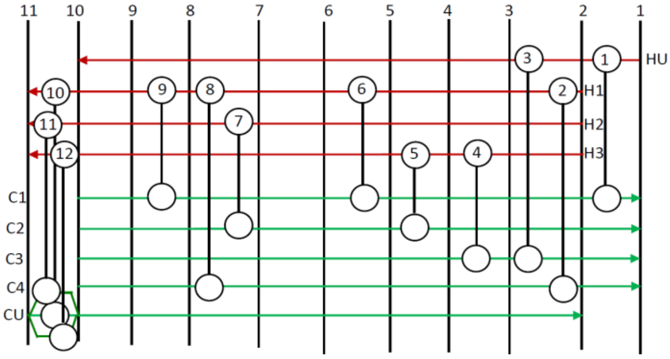

Figure 5: Final optimal solution network

It is worth stating that the solution of the network, whose structure is not shown here, has a TAC of 6,364,069 $/y. Figure 4 represents the third step of the synthesis procedure of Figure 1, which involves the generation of the reduced superstructure. The reduced superstructure comprises a combination of the matches obtained in the STEP diagram and the single period conventional SWS. In Figure 4, the matches represented with dark shaded circles are those that are common to both the STEP grid structure of Figure 3 and the solution of the SWS single period model. The matches represented with thick lined circles are those that are only common to the STEP grid structure, while those represented with broken circles are only common to the single period SWS model solution structure.

The matches in Figure 4 are then used as the initialising matches in the reduced superstructure which comprises the multi-period stream data of Table 1. The superstructure was solved as an MINLP model. Solving the model as a reduced superstructure is beneficial, as presented by Isafiade et al (2015), as it has shorter solution time due to the model having fewer binary variables. Using the STEP diagram as one of the structures from which promising matches are obtained is beneficial in that when the resulting solution network of the STEP diagram is converted to potential matches in the SWS, the ensuing superstructure will have many intervals and no stream splits. This is evident in Figure 3 where there are no stream splits. Networks without stream splits are preferable to those with stream splits because they are less complex in terms of layout and controllability. Also, other features of heat exchangers, such as pressure drop, number of shells and tubes, can be targeted at the STEP diagram stage, and then exported to the multi-period SWS model as initialising parameters. This is planned as follow-up work to this paper. Figure 5 shows the final solution obtained in this paper for the case study. The TAC of the solution which has 12 units is 6,268,587 $/y. This TAC comprises an annual operating cost of 3,079,861 $/y and an annualised investment cost of 3,188,726 $/y. It is worth noting that in the network of Figure 5, no matches are in intervals 6 and 9. The solution can be improved not in terms of TAC but in the number of units in the optimal solution by excluding the initialising matches present in these intervals in the reduced superstructure of Figure 4 and then solving the updated reduced superstructure. Doing this gives a solution having a TAC of 6,277,254 $/y and 11 units. This second, solution, which is just 0.14 % higher than the solution of Figure 5 in terms of TAC, would be preferred due to the fewer number of units. The best solution, in terms of TAC, presented in the literature is that of Pavao et al. (2018). Their solution, which is just 0.9 % lower than the second solution of this paper, has 13 units.

5. Conclusions

This paper has presented a hybrid approach to identifying potential initialising matches for solving the multi-period HENS problem using a reduced SWS model. The method is beneficial in that promising initialising matches are obtained from the STEP method and SWS model for single period HENS problems. The result obtained from the case study considered compares favourably with those reported in the literature in that, apart from having a relatively low TAC, it also produces a simple network with no stream splits. The motivation for adopting the hybrid approach in this paper is that the STEP diagram serves as a good basis from which not only utilities and heat exchanger areas can be targeted and designed, but estimates for other heat exchanger design parameters such as pressure drop, number of shells and tubes, can be obtained and then exported to the reduced multi-period HENS SWS model as initialising parameters to solve the problem. Also, solving large-scale HENS problems is not a trivial task. The difficulty is compounded further for large-scale HENS problems involving multi-period profiles due to an increase in non-linearities. It is hoped that these issues will be addressed in future studies using an extended version of the methodology of this paper.

Acknowledgments

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