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Multi-Period Heat Exchanger Network Design Based on Periodic Heat Storage Approach

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Process hot and cold stream parameters in chemical processes and allied plants do change from time to time due to issues such as changes in environmental conditions, plant start-ups/shut-downs, changes in product quality demand or changes in feedstock quality supply, etc. These changes, which may be predictable or unpredictable, need to be catered for in the design of heat exchanger networks in a cost optimal and environment friendly manner. This paper presents an extension to existing methods in the literature for synthesizing multi-period heat exchanger networks by designing networks that make provision for periodic storage of heat for use in succeeding periods of operations. The first and second steps of the approach adopted in this paper entails synthesizing optimal networks for the individual periods of operations involved in the problem, so as to identify the potential amount of heat available for storage in each period. The identified heat is then included as a hot utility in succeeding periods of operations. In the next step, a sequential approach is adopted to ensure that optimally sized representative heat exchangers that would feasibly transfer heat, irrespective of the period of operation involved, and in the light of the stored heat, are designed for the final multi-period network. The proposed approach is applied to an example problem and the results obtained demonstrate the benefit of the technique.

1. Introduction

Energy consuming industries such as chemical and allied plants are facing increasing pressure concerning reduction in the use of fossil based energy sources such as coal, crude oil or even natural gas. One of the ways by which this reduction has been achieved is through the synthesis of heat exchanger networks (HENs) using either sequential or simultaneous based approaches. These synthesis methods have been used to accomplish simultaneous reductions in both energy and capital cost. However, it is worth stating that most of the methods that have been presented in the literature for heat exchanger network synthesis (HENS) have been based on single periods of operations, where it is assumed that process parameters such as supply/target temperatures and stream heat capacity flowrates are fixed. However, these parameters do change from time to time due to issues such as changes in environmental conditions, plant start-ups/shut-downs, changes in quality of product demand or quality of available feedstocks, process upsets, etc. Scenarios of this nature necessitates the need for a HEN that is able to adapt to the aforementioned fluctuations in a cost efficient and environment friendly manner. Just like the single period HENS methods, the two major approaches that have been adopted for the synthesis of multi-period HENs include sequential and simultaneous based approaches. The sequential based approaches include the method presented by Floudas and Grossmann (1986), which is a multi-period mixed integer linear programming (MILP) model where the minimum quantity of utility required in each period, together with the corresponding minimum number of units are targeted. Extensions to this method were further presented by Floudas and Grossmann (1987), where the automatic network generation method of Floudas et al. (1986) for single period problems, was extended to multi-period scenarios. This sequential based approach was again extended by Mian, et al. (2016a) where the positioning of utilities in the multi-period superstructure are not restricted to only the first and last intervals, as is the case in so many other synthesis methods for multi-period networks. This method, apart from being an extension of the multi-period minimum number of unit model of Floudas and Grossmann (1986), and the multi-period minimum investment cost model of Floudas and Grossmann (1987), also includes the multi-period utility integration and scheduling method of Marechal and

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Kalitventzeff (2003). The authors coupled the models using the derivative-free hybrid algorithm of Martelli and Amaldi (2014). Mian et al. (2016b) extended the work of Mian et al. (2016a) by including in their model, electrical and material storage. It is worth stating that since these methods are sequential in nature, where the network design in a second step is based on utility and number of unit targets in a first step, the interactions among the operating and capital cost may not be well optimized.

The simultaneous methods that have been used for the synthesis of multi-period heat exchanger networks include the approach of Verheyen and Zhang (2006) where the multi-period version of the stage-wise superstructure (SWS) of Yee and Grossmann (1990) was adopted. The technique used a maximum area approach in the objective function. Isafiade and Odejobi (2016) improved on existing multi-period SWS models by positioning utilities not only at the ends of the superstructure, but also within the intermediate stages. The authors also developed a sequential initializing technique for solving the resulting model. The method of Jiang and Chang (2013) is based on the time-sharing mechanism where exchangers are shared by different stream pairs in different periods of operations. Isafiade and Short (2016a) extended the optimisation of multi-period HENS to multi-objective scenarios where environmental impact is considered alongside economics as a second objective, while the method of Isafiade and Short (2016b) caters for changes in period durations that are unpredictable. The work of Short et al. (2016), which also used the SWS approach, developed a technique where detailed heat exchanger designs are embedded in multi-period HENs.

In the aspect of heat storage in heat integration studies, Nemet et al. (2012a) presented a method where options for heat storage are considered in the integration of solar thermal energy with batch process heat demand. In another study, Nemet et al. (2012b) developed the captured solar energy curve and the minimal capture temperature curve to establish the trade-off between the amount of solar energy captured and the actual amount of energy that the process receives. This was then applied to total site heat integration including heat storage. It is worth stating at this point that a key feature that is lacking in the papers reviewed so far, apart from the work of Mian et al. (2016b), is the investigation of possibility of periodic heat storage in multi-period HENS using a simultaneous synthesis approach. The work of Mian et al. (2016b), as previously discussed, used a sequential approach. Periodic heat storage in the context of multi-period HENS would mean that instead of releasing the heat from hot process streams which was not absorbed by cold process streams to cold utilities, the heat is stored in thermal storage tanks for possibility of usage in succeeding periods as hot utilities. Although it cannot be guaranteed that the use of periodically stored heat would satisfy all external heat required in subsequent periods of operations, however, the opportunity of satisfying some of the required heat demand should be explored. This approach is not only potentially economically beneficial, but it would have environmental benefits as well. The problem statement tackled in this paper is presented in the next section.

2. Problem statement

The problem investigated in this paper is stated as follows: Given a set of hot process HP streams to be cooled and cold process CP streams to be heated, with their supply and target temperatures (Ts and Tt) and heat capacity flowrates (FCP) at specified P periods of operations. Given also are a set of hot utilities HU and thermal storage fluid CU, where the hot utility can be used in any of the specified periods of operations to accomplish the required external heating while the thermal storage fluid can be used to absorb heat from hot process streams in specified periods for the purpose of storage and subsequent usage as hot utility in succeeding periods of operations. The aim is to synthesize a flexible network of heat exchangers capable of satisfying the heat demand of all process streams in all periods of operations in a cost-effective manner.

3. Methodology

The methodology adopted can be described as follows:

i. Extract process data for the first period and then synthesise its individual optimal HEN using the stage-wise superstructure (SWS) of Yee and Grossmann (1990), which is a mixed integer non-linear program (MINLP) for singe period operations. It should be known that in this paper the utility streams are made to participate in all intervals of the superstructure (except for the last interval) as presented by Isafiade and Odejobi (2016), (see Figure 1 for the adapted stage-wise superstructure). Note also that at this stage of the procedure, the heat not absorbed from hot process streams through process-to-process heat exchange, is released to a thermal storage fluid for use in succeeding periods of operations. In this first step, a conventional hot utility, e.g. high-pressure steam, is used to satisfy external heat demand by cold process streams, however contrary to existing multi-period models, no conventional cold utility is used, instead, a thermal storage fluid is used.
ii. In the second step, process data for the next period after the first is extracted and its individual optimal or near optimal HEN is again synthesised using the SWS approach. At this second stage, the stored heat of

the first period is included as additional hot utility, together with the conventional hot utility, that would satisfy external heat demand by cold process streams in the succeeding period. This process is repeated for all succeeding periods of operations. Note that the temperature of the stored fluid can be maintained constant by replenishing heat losses which may have occurred through the walls of the storage vessel or through its inflowing/outflowing fluid, through the addition of external heat. Such additional heat may be obtained from either renewable or non-renewable sources. However, such level of details is not included in the current model for the purpose of simplification, instead a cost is attached to the required additional heating. Ignoring the details associated with heat losses in this paper, especially for the example considered, is somewhat valid because it was observed that not all available heat in the storage vessel is absorbed by cold process streams due to other competing parameters that contribute to the optimality of a HEN. Such other parameters include temperature driving forces available in the stored fluid as compared to that of the conventional hot utility, cost items associated with heat storage as compared to cost of conventional hot utility, etc.

iii. The third stage of the synthesis procedure entails generating a flexible multi-period network having heat exchangers that would feasibly transfer heat in all participating periods of operations in a cost-efficient manner. It is worth stating that the existing multi-period versions of the SWS model may not be directly applicable in this case due to the fact that the number of available utilities are not the same in all periods of operations. This is a feature that is hardly found in existing multi-period models for HENs, i.e. most models have assumed that all utilities are available for use in all periods of operations. The approach adopted in this paper involves synthesising the final flexible network, through evolution, from the individual optimal networks of each of the periods previously synthesised in the first and second steps above. The approach entails identifying the most critical/constrained period of operation not necessarily in terms of heat load, but in terms of required number of heat exchangers. The identified number of heat exchangers and their associated areas, are then used as a guide to systematically adjust the representative heat exchangers of the final flexible network. The resulting network is then tested to check whether it is able to feasibly transfer heat in all periods of operations with the integrated periodic heat storage. It should be known that based on this approach, some exchangers may not serve all periods, and such exchangers will need to be bypassed in the final multi-period network. The details of how the methodology works is illustrated using an example.

3.1 Model equations

Some of the model equations adopted in this paper are those of the SWS model of Yee and Grossmann (1990). For the purpose of simplicity, the details of the SWS model are not shown in this paper. Other model equations used which are unique to this paper for the context considered are discussed next. Eq(1) illustrates the storage vessel size.

$$VTS_{i,j,k} \geq \frac{q_{i,j,p,k}}{C_p \rho \left(T_j^s - T_j^t\right)} \tag{1}$$

In Eq(1), C_p (4.2 kJ/(kg·°C)) is the specific heat capacity of the thermal storage fluid, ρ (1,000 kg/m^3) is its density, T_j^s and T_j^t and (20 °C and 155 °C) are the supply and target temperatures of the storage fluid in the storage vessel, while $q_{i,j,p,k}$ (kW) is the quantity of heat released by hot process stream i to storage fluid j in period p and interval k of the superstructure. Eq(2) shows the overall objective function. In Eq(2), the objective function comprises a sum of the annualised capital cost and annual operating cost where the capital cost comprises cost of process and utility heat exchangers and cost of storage vessel. The annual operating cost comprises cost per unit of conventional hot utility and heat replenishment for the storage vessels. In Eq(2), DOP_p is the average time duration of each period of operation, NOP is the number of periods, CUC_j and HUC_i are cost per unit of cold utility j (10.3 \$/(kW·y)) and hot utility i (150 \$/(kW·y)), AF_{HE} and AF_{ST} are the annualisation factors for heat exchangers and thermal storage vessels (both 0.2), $AC_{i,j}$ is the cost per unit area for heat exchangers (641.7 \$/m^2), $ACTS_{i,j}$ is cost per unit volume for thermal storage vessel (20 \$/m^3), $A_{i,j,k}^{ACE}$ is area of heat exchangers having area cost exponent as ACE, $CF_{i,j}$ is cost of installing each heat exchanger (8,333.3 \$), $y_{i,j,k}$ is the binary variable illustrating the existence or otherwise of a heat exchanger in the superstructure, $VTS_{i,j,k}$ is volume of thermal storage tank.

4. Example

The example considered in this paper comprises three periods of operations with equal durations (2,860 h for each period). The details of the stream data are shown in Table 1. It should be known that for all periods including period 1 both HU1 and HU2 are used. The thermal fluid that holds the stored fluid is modelled as HU2 when it releases heat to cold process steams while the same fluid is modelled as CU1 when it receives heat from hot process streams in the storage tank. HU2 comprises the stored heat that is carried over from a preceding period.

In the case of period 1, it was assumed that some stored heat was available for use. This stored heat may be a starting stored heat for the process or heat carried over from the last period of the previous cycle of operation. Depending on the specific case at hand, additional heat may need to be added to the stored heat not only to replenish its lost heat but also to ensure that the temperature of the stored heat is high enough to provide large temperature driving forces for heat exchange. For this example, additional heat (at a cost of 50 \$/(kW·y)) was added to the stored heat at each period so as to increase the storage fluid temperature to 285 °C. Applying the first and second steps of the synthesis procedure gives the set of matches selected, which are listed in Table 2, for each of the periods. Applying the third step gives the final flexible network shown in Figure 2. The network has an annualised capital cost of 10,275,889 \$. This cost comprises cost of the two tanks and cost of the eleven heat exchangers shown in Figure 2. The annual operating cost for periods 1, 2 and 3 are 2,359,426 \$; 2,426,150 \$ and 2,211,502 \$. In the solution network, HU2 is used to satisfy the heat demand by cold process streams CP1 and CP2 in periods 1, 2 and 3. HU2 is also used to satisfy the heat demand by CP3 in period 1. This heat is transferred to the cold streams through heat exchangers 1, 2 and 3. On the other hand, heat exchangers 9, 10 and 11 release process heat from hot streams HP1, HP2 and HP3 to the thermal storage fluid in periods 1, 2 and 3.

$$\begin{aligned} min & \left\{ \left\{ \sum_{p\epsilon P} \left[\left(\frac{DOP_p}{\sum_{p=1}^{NOP} DOP_p} \cdot \sum_{i\epsilon HP} \sum_{j\epsilon CU} \sum_{k\epsilon K} CUC_j \cdot q_{i,j,p,k} \right) + \left(\frac{DOP_p}{\sum_{p=1}^{NOP} DOP_p} \cdot \sum_{i\epsilon HU} \sum_{j\epsilon CP} \sum_{k\epsilon K} HUC_i \cdot q_{i,j,p,k} \right) \right] \right\} \right. \\ & + \left[AF_{HE} \left(\sum_{i\epsilon HP} \sum_{j\epsilon CP} \sum_{k\epsilon K} CF_{i,j} \cdot y_{i,j,k} + \sum_{i\epsilon HP} \sum_{j\epsilon CP} \sum_{k\epsilon K} AC_{i,j} \cdot A_{i,j,k}^{ACE} \right) \right. \\ & \left. \left. + AF_{ST} \left(ACTS_{i,j} \cdot VTS_{i,j,k} \right) \right] \right\} \\ & \forall \; i\epsilon HP;\; j\epsilon CP;\; p\epsilon P;\; k\epsilon K \end{aligned} \tag{2}$$

Table 1: Problem data for the example considered

Period 1				Period 2				Period 3			
Streams	FCP kW/°C	T^s °C	T^t °C	Streams	FCP kW/°C	T^s °C	T^t °C	Streams	FCP kW/°C	T^s °C	T^t °C
H1	151.6	193	60	H1	155.0	206	60	H1	152.0	205	60
H2	110.0	160	40	H2	98.8	160	40	H2	100.0	160	40
H3	120.4	374	60	H3	100.4	362	60	H3	102.0	360	60
C1	109.4	10	56	C1	110.3	12	65	C1	101.1	8	60
C2	131.6	10	100	C2	141.0	12	110	C2	140.5	14	120
C3	76.4	20	270	C3	75.4	20	270	C3	64.5	20	270
C4	194.4	143	384	C4	198.7	150	390	C4	191.2	150	386
HU1	∞	500	450	HU1	∞	500	450	HU1	∞	500	450
CU1	∞	20	155	CU1	∞	20	155	CU1	∞	20	155

The stored heat obtained in period 3 can be reintegrated with period 1 in the next operation cycle. The first column in Table 3 shows the set of exchangers, alongside their areas, for the final network that would serve all periods of operations. The third, fourth and fifth columns show the set of exchangers that would be active when any of periods 1, 2 or 3 is active. This implies that when period 1 is active, none of the exchangers will be bypassed since all exchangers of the final network are required by in this period. When period 2 is active, all exchangers of the final flexible network will be active except exchanger HU2, CP3, 3. The same scenario plays out when period 3 is active. The thermal storage tanks that will serve the network have capacities 867,340 m^3 (for heat stored in period 1 and used in period 2) and 730,660 m^3 (for heat stored in period 2 and used in period 3). These values are very large due to the quantity of heat demand by the process streams. In Figure 2 only tank 1 (TK1 is shown), although it's shown twice. In period 1, TK1 (867,340 m^3) which is connected to exchangers 9, 10 and 11 receives heat from HP1, HP2 and HP3 for the purpose of storage. At the point of switchover to period 2, the heat stored in TK1 from period 1 is then released to cold process streams CP1, CP2 and CP3 through exchangers 1, 2 and 7 as shown in Figure 2. The process is repeated for tank 2 (TK3).

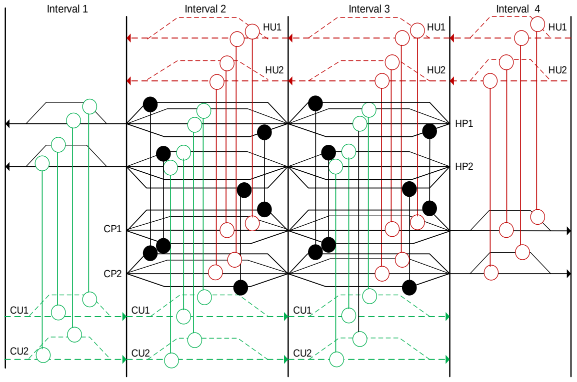

Figure 1: Schematic of the SWS model used in this study (adapted from Isafiade and Odejobi (2016))

Table 2: Selected matches for individual periods

Period 1	Period 2	Period 3
HU1, CP3,1	HU1, CP3,1	HU1, CP3,1
HU1, CP4,1	HU1, CP4,1	HU1, CP4,1
HU2, CP1,1	HU2, CP1,1	HU2, CP1,1
HU2, CP2,1	HU2, CP2,1	HU2, CP2,1
HU2, CP3,3	HP1, CP3,2	HU2, CP3,3
HP1, CP3,2	HP1, CU1,4	HP1, CP4,3
HP1, CU1,4	HP2, CU1,4	HP1, CU1,4
HP2, CU1,4	HP3, CP3,3	HP2, CU1,4
HP3, CP3,3	HP3, CP4,2	HP3, CP4,2
HP3, CP4,2	HP3, CU1,4	HP3, CU1,4
HP3, CU1,4		

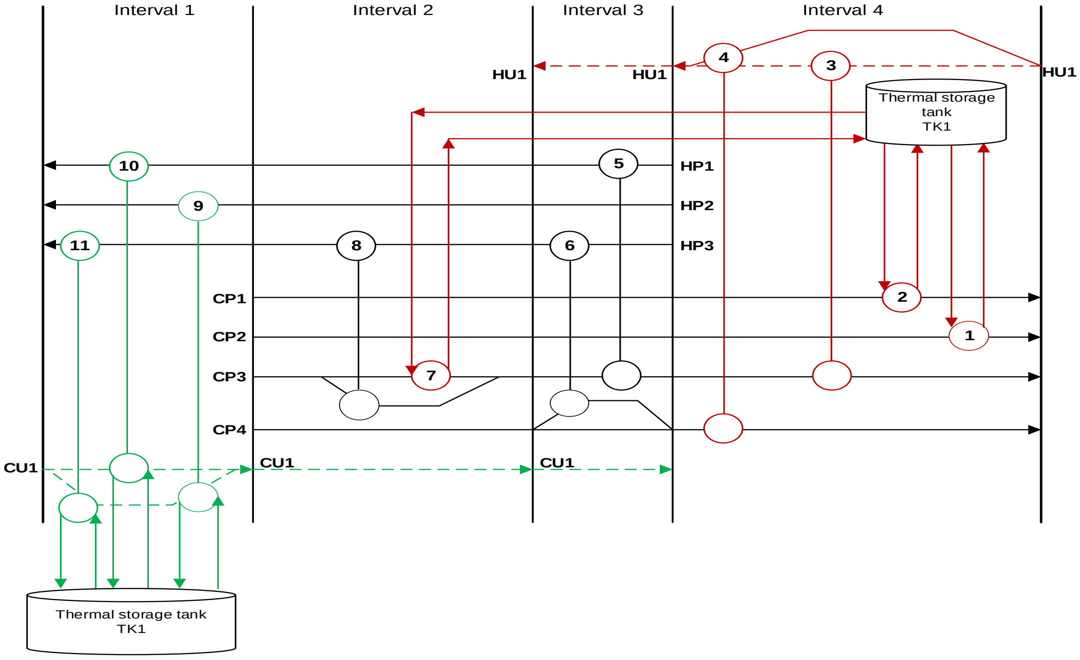

Figure 2: Final flexible multi-period network integrated with periodic heat storage for the example considered

Table 3: Representative heat exchanger areas for final flexible network

Flexible network Area (m^2)		Period 1	Period 2	Period 3
HU1, CP3,1	337.5	HU1, CP3, 1	HU1, CP3, 1	HU1, CP3, 1
HU1, CP4,1	2,052.2	HU1, CP4, 1	HU1, CP4, 1	HU1, CP4, 1
HU2, CP1,1	405.8	HU2, CP1, 1	HU2, CP1, 1	HU2, CP1, 1
HU2, CP2,1	1291.8	HU2, CP2, 1	HU2, CP2, 1	HU2, CP2, 1
HU2, CP3,3	121	HU2, CP3, 3		
HP1, CP3,2	768.7	HP1, CP3, 2	HP1, CP3, 2	HP1, CP3, 2
HP1, CU1,4	6,542.7	HP1, CU1, 4	HP1, CU1, 4	HP1, CU1, 4
HP2, CU1,4	12,544	HP2, CU1, 4	HP2, CU1, 4	HP2, CU1, 4
HP3, CP3,3	321.7	HP3, CP3, 3	HP3, CP3, 3	HP3, CP3, 3
HP3, CP4,2	1,479.8	HP3, CP4, 2	HP3, CP4, 2	HP3, CP4, 2
HP3, CU1,4	4,254.9	HP3, CU1, 4	HP3, CU1, 4	HP3, CU1, 4

5. Conclusions

This paper has presented an extension to existing multi-period heat exchanger network synthesis models by including in the synthesis process the storage of heat in each period of operation for use in succeeding periods. The example considered, which involves three periods of operations where stream process parameters vary from one period to another, has a total annual operating cost of 17,272,967 $. This cost is about 16 % higher than the solution that would have been obtained if the conventional multi-period HENS approached had been used. For this example, the higher cost is mostly due to the cost of storage tanks. However, the method is beneficial in that it has the possibility of helping to reduce environmental impact associated with hot and cold utility generation. In order to keep the approach presented in this paper as simple as possible, and due to the fact that this work is a preliminary study, a host of issues that are critical to getting an optimal network were not considered. These issues include heat losses during storage, the dynamics associated with the process of heating and cooling of fluid in a tank, comparison of the periodic heat storage integrated approach and the non-integrated approach using detailed and realistic cost, environmental issues, generation of the final flexible multi-period network using a simultaneous approach, rather than the sequential approach adopted in this paper, etc. It is hoped that these issues will be considered in future studies.

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