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Multiple Modifications in Stepwise Retrofit of Heat Exchanger Networks

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This work considers improving the heat recovery of an existing heat exchanger network (HEN) while minimizing the total annualized cost of the retrofit design. The focus is on stepwise approaches that generate, starting from the base case network, a candidate retrofit HEN at each step in order to sequentially retrofit the HEN topology while permitting user intervention during the resolution procedure. Stepwise approaches which consider at most one new heat exchanger addition at each step sometimes fail to find a retrofit option that improves heat recovery. The present study addresses this problem by using the notion of bridge, a thermodynamic concept related to the creation of new heat paths in the network. A HEN superstructure is associated to each bridge and a MINLP model minimizing the total utility consumption is solved to obtain an explicit network topology corresponding to a chosen bridge. This new approach is illustrated on a milk processing case study where the network Pinch method fails to find a retrofit solution. For this example, the diagnosis stage of the network Pinch method cannot yield a retrofit project that improves the base case utility consumption. Using the concept of bridge and the proposed superstructure, an increase in heat recovery is achieved by adding two new process-process heat exchangers in a single step.

1. Introduction

As described by Furman and Sahinidis (2002) in the heat exchanger network (HEN) synthesis context, approaches to tackle the HEN retrofit problem usually fall in two broad categories: simultaneous and stepwise (or sequential) approaches. In simultaneous approaches, the HEN retrofit problem is addressed in one step and generally a superstructure of retrofit options is solved for minimum total annualized cost. On the other hand, sequential approaches aim to divide the retrofit problem into a sequence of sub-problems which are solved successively in order to decrease the computational complexity. Sreepathi and Rangaiah (2014) provide a literature survey of HEN retrofit approaches for the period from 1993 to 2014.

Certain retrofit considerations, such as safety, maintenance and piping costs, are difficult to quantify a priori (Zhu and Asante, 1999). To overcome this shortcoming, a category of sequential approaches has been proposed in which topological retrofit options are introduced in a stepwise fashion. Such methods offer the benefit of allowing user intervention at each step of the optimization procedure. The network Pinch approach (Asante, 1996) and its extensions, iterative method (Smith et al., 2010), and an step-by-step approach involving match penalty (Bakhtiari and Bedard, 2013), fall into this category. In order to limit both the size of the optimization problem and the number of network modifications, Asante (1996) and collaborators have proposed to introduce at most one topological HEN modification at each step. However, after load and area redistribution to minimize total utility consumption in the HEN, adding at most one new process-process heat exchanger may not result in the creation of a new cooler-heater heat path. As a consequence, this may render impossible any further improvement in heat recovery. In such cases, multiple new heat exchanger additions may be necessary in a single step.

In this work, to create such a cooler-heater path, the concept of bridge (Bonhivers et al., 2014) is used. For a given bridge, a superstructure is introduced in order to determine which process-process heat exchangers

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should be added to the HEN to improve heat recovery. This superstructure is optimized using a MINLP model minimizing the total utility consumption. If the resulting heat exchanger additions translate into a decrease of the total utility consumption with respect to the original network (after load and area redistribution), then an economic optimization can be carried out, otherwise the topological modification is discarded and a new bridge is evaluated.
In the next section, the notion of bridge is defined and illustrated on an example which highlights its link with the concept of cooler-heater path. In section 3, a superstructure and its corresponding MINLP model are introduced to determine which new process-process heat exchangers correspond to a given bridge. In section 4, the benefits of this new approach are illustrated on a milk processing example where the diagnosis stage of the network Pinch method fails in finding an option to improve heat recovery.

2. Bridges for heat recovery

In this section, the concept of bridge is defined and its relation to cooler-heater paths is explained. The bridge method for HEN retrofit was introduced by Bonhivers et al. (2014). This approach considers a partition of the cold and hot process streams into cold temperature intervals (called receptors, denoted by superscript r) and hot temperature intervals (called supplier, denoted by superscript s). This decomposition is based on the inlet and outlet temperatures of each process stream passing through heat exchangers in the network. Thus, to each process exchanger corresponds a supplier and a receptor, to each cooler corresponds a supplier and to each heater corresponds a receptor. Broadly stated, a bridge is a sequence of supplier-receptor pairs, termed matches, which starts from a cooler, passes through chosen process heat exchangers and ends with a heater. More precisely, if C and H denote a cooler and a heater (respectively) while HX_i denotes a process heat exchanger, then a bridge is defined as a set composed of a single match C^s-H^r or composed of a sequence of distinct matches of the form C^s-HX_1^r, HX_1^s-HX_2^r, HX_2^s-HX_3^r, …, HX_{n-1}^s-HX_n^r, HX_n^s-H^r. To illustrate this concept, a part of the HEN of an aromatic plant is shown in Figure 1. According to the previous definition, the set {$Cooler_1^s$-B^r, B^s-$Heater_2^r$} is a bridge in this network.

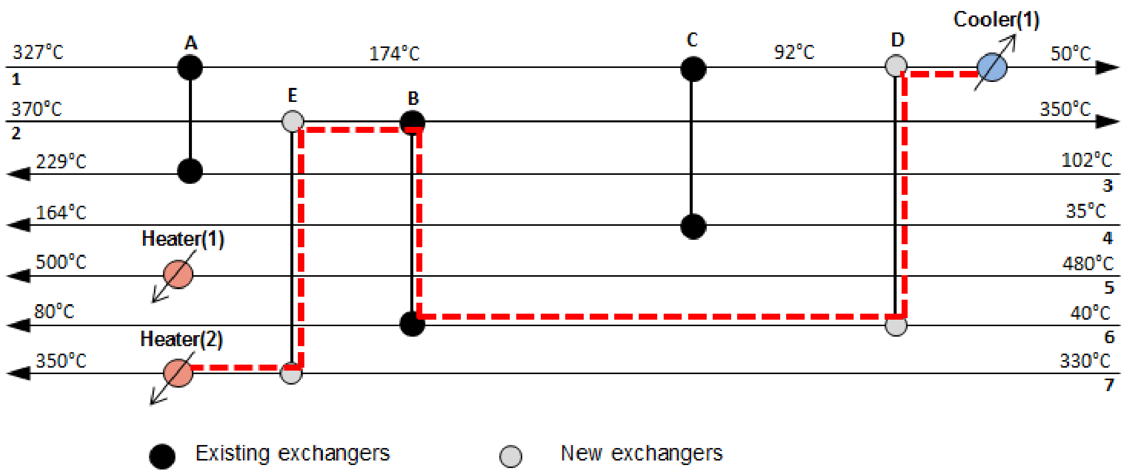

Figure 1: Two new heat exchangers associated to the bridge {$Cooler_1^s$-B^r, B^s-$Heater_2^r$}, dashed line: cooler-heater path

After load and area redistribution to minimize the total utility consumption in a given HEN, further heat recovery improvements require the creation of a new cooler-heater path (Linnhoff March, 1998). The simplest cooler-heater path in a HEN is created via the addition of a single new process-process exchanger connecting a cooler to a heater. In certain cases, a more complex path including multiple exchangers is needed to reduce the utility consumption. The bridge method identifies the possibility of adding new exchangers to a network by connecting its suppliers to its receptors, starting from a cooler and ending with a heater. For example, in Figure 1 the match $Cooler_1^s$-B^r represents a potential new exchanger (D), which can partially satisfy the duty of exchanger B. This results in the availability of heat from the supplier of exchanger B to be used in the next match B^s-$Heater_2^r$. Via new exchanger E, this second match enables the possibility of coupling the available heat in the supplier of exchanger B with the receptor of the $Heater_2$. By adding two new exchangers, this bridge creates a new cooler-heater path in the network, thus yielding potential for heat recovery increase.

The bridges of a HEN can be listed in an automatized fashion by applying the above definition for each possible match. For a given bridge, the location of new exchangers in the network topology is not uniquely determined. In particular, Figure 1 shows only one possibility for the bridge considered. In fact, multiple new exchanger locations may correspond to a single supplier-receptor match in a bridge. Consequently, in order to determine the location of the new exchangers associated to a bridge, a superstructure embedding all possible locations is defined in the next section.

3. Bridge superstructure

A bridge usually begins with a cooler^s-process exchanger^r match and ends with a process exchanger^s-heater^r match. The exception occurs in the case of the shortest bridge, which consists in only one cooler^s-heater^r match. As mentioned in the preceding section, the possibility of adding a new exchanger between a supplier and a receptor occurs for each match.
Figure 2 illustrates the superstructure associated with each match type. As this figure shows, there is only one possible location for new exchanger addition associated to a cooler^s-heater^r match. Two possibilities occur for cooler^s-process exchanger^r matches, four for process exchanger^s-process exchanger^r and two for process exchanger^s-heater^r match.

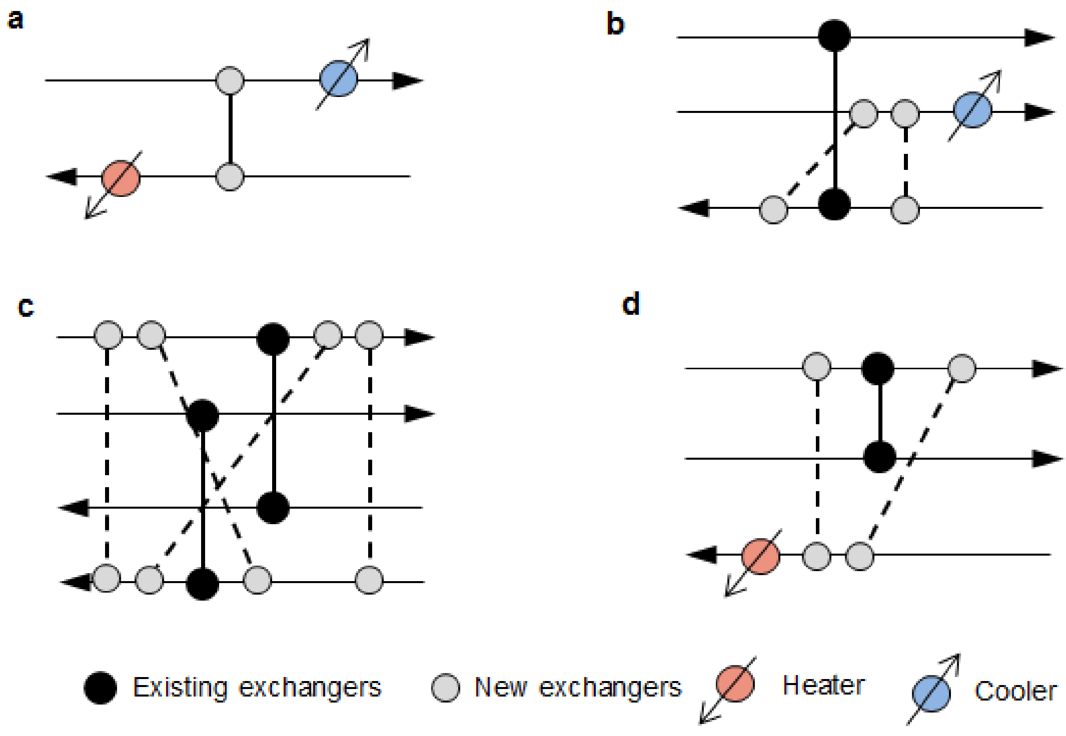

Figure 2: Superstructure associated to each match type: a) Cooler^s-Heater^r b) Cooler^s-Exchanger^r c) Exchanger 2^s-Exchanger 1^r d) Exchanger^s-Heater^r

For a given bridge, a superstructure is constructed by applying the rules described in figure 2 recursively for each match. The procedure of building the superstructure can be fully automatized.
Subsequently, a MINLP model is solved to determine which new process exchangers should be added in order to minimize the total utility consumption. For each heat exchanger, this model includes an energy balance, cold and hot stream mass balances as well as minimal approach temperature constraints. Splitters and mixers are modelled via mass and energy balances. Continuous variables correspond to duties, temperatures and split fractions while binary variables correspond to each new exchanger in the superstructure. Big-M constraints (Floudas, 1995) ensure that the duty of a new exchanger in the superstructure vanishes when it is not selected. The nonlinearities in the model arise in energy balances for mixers (i.e. when stream splits are present) and when specific heat capacities are non-constant with respect to temperature. Aiming to add as few new exchangers as possible, the objective function is a weighed sum of the total utility consumption and the total

number of new heat exchangers. Moreover, at most one new heat exchanger is chosen per bridge match. If this optimization results in a decrease of the total utility consumption with respect to the rebalanced (duties, areas) base case, then the retrofit HEN is optimized on an economical basis, otherwise it is discarded and a new bridge is considered.

4. Case study

The proposed method is illustrated on a milk processing case study. The simplified process flow diagram (PFD) of this process is presented in Figure 3-a. In this process, raw milk flows through heat exchanger Hx(1) to reach a specified temperature. It then passes into the cream separator unit where the cream is removed to be used in other departments. Skim milk then flows through Heater(1) where steam is used to heat it up. Hot skim milk then flows through the holding tube where it is maintained at 74 °C for a predetermined duration to complete the pasteurization process. Hot pasteurized milk is cooled down in Hx(1) while heating the raw milk. It is then sent to other processes. Cooler(1) is used to cool down the whey from the cheese process located just aside of the pasteurization line using glycol as the cooling medium. In this simplified process, there is one process-process heat exchanger, one heater and one cooler. The process consumes 559 kW of hot utility and 1,530 kW of cold utility. Figure 3-b represents the grid diagram of this process. Using 5 °C as the minimum approach temperature, the minimum heating and cooling requirements are found to be 164 kW and 1,135 kW respectively.

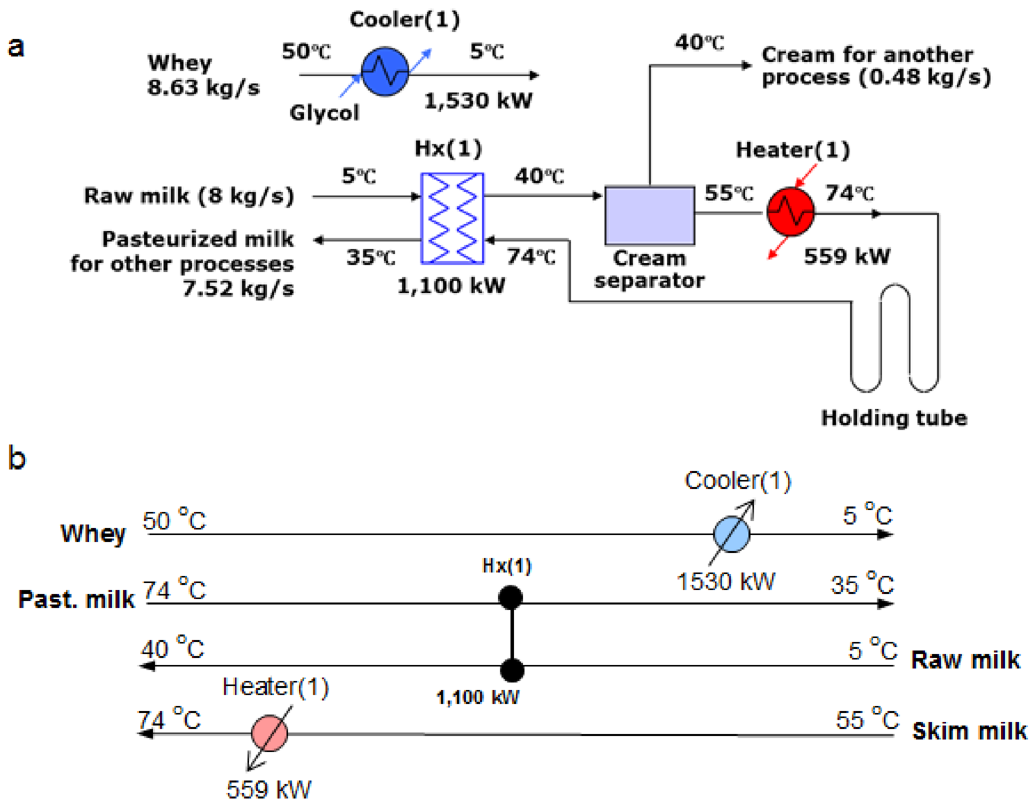

Figure 3: Milk pasteurization plant; a) simplified process flow diagram; b) grid diagram

In this example, the network Pinch method fails to find a retrofit project. This is due to the fact that two modifications (new exchangers) should be added in the first step in order to create a cooler-heater path and thus reduce the utility consumption. As shown below, the proposed approach yields a cooler-heater path in one single step.

The only existing bridge in this network is {Cooler(1)^s-Hx(1)^r, Hx(1)^s-Heater(1)^r}. Figure 4 depicts the superstructure associated with this bridge. The exchangers labelled as New Hx(1) in this figure represent the potential new exchangers related to the first match Cooler(1)^s-Hx(1)^r. The exchangers labelled as New Hx(2) represent the potential new exchangers related to the match Hx(1)^s-Heater(1)^r.

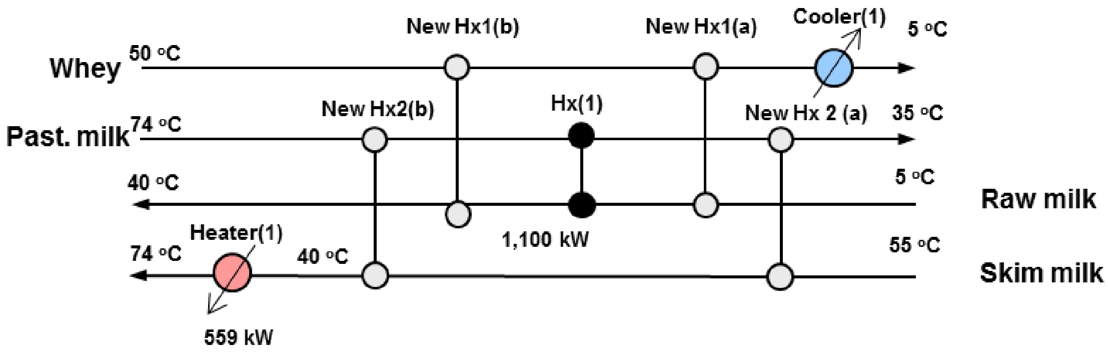

Figure 4: Superstructure associated to the bridge {Cooler(1)^s-Hx(1)^r, Hx(1)^s-Heater(1)^r}. New Hx(1) corresponds to the first match while New Hx(2) corresponds to the second match of the bridge

The MINLP model described in the previous section is solved in order to minimize the total utility consumption. Note that for this example the model is in fact linear (no stream splits, constant heat capacities). The optimization results are shown in Figure 5. The cold and hot utility consumption targets are reduced by 25.8 % and 70.7 % respectively.

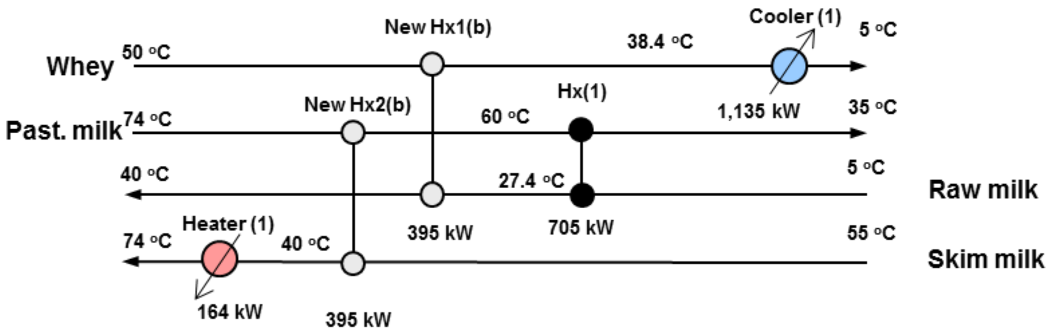

Figure 5: Topology associated to the bridge {Cooler(1)^s-Hx(1)^r, Hx(1)^s-Heater(1)^r} after optimization

5. Conclusion

Stepwise approaches for HEN retrofit may terminate when introducing at most one topological modification to the network yields no improvement in heat recovery. Based on the thermodynamic notion of bridge, a method to overcome this limitation is presented. For a given bridge, a superstructure for new exchanger addition and a MINLP model minimizing its utility consumption are defined. For a case study where the Network Pinch fails to find a heat recovery improvement, the proposed approach is shown to find a heat recovery improvement by adding two new heat exchangers in a single step. The new method can be used as a stand-alone approach or inside existing approaches (e.g. Network Pinch) to bypass cases where premature termination is encountered. Future work includes defining rules to select which bridges should be evaluated (and in which order) as well as establishing a termination criterion for bridge evaluation. The possibility of associating new stream splits to a bridge is also envisioned as subsequent work.

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