Optimal operation of heat exchanger networks through energy flow redistribution

Karthika Mohanan and Sujit S. Jogwar
Department of Chemical Engineering, Indian Institute of Technology, Bombay, Powai, Mumbai, 400076, India *

Abstract

This paper presents a novel energy flow redistribution methodology to achieve optimal operation of heat exchanger networks (HENs). The proposed method aims to manipulate the propagation path of a disturbance through the network to reduce its impact on utility consumption. Specifically, an optimization problem is formulated to generate new duty targets for heat exchangers of the network when a disturbance is encountered. Subsequently, a feedback control system is designed to track these targets by manipulating bypasses around the process heat exchangers. The effectiveness of the proposed framework is illustrated with the help of three benchmark examples. The proposed approach can handle disturbances in inlet as well as target temperature, inlet flow and heat transfer coefficient of individual heat exchangers.

Introduction

Heat exchanger networks (HENs) allow for the implementation of plant-level energy integration, thereby improving energy efficiency of the overall process. A typical HEN design (synthesis) problem takes a set of hot and cold

*Correspondence concerning this article should be addressed to Sujit S. Jogwar at jogwar@iitb.ac.in

process streams, with the corresponding supply (inlet) and target (outlet) temperature and flow rate, as an input to generate a network of heat exchangers that optimizes an objective function (for example, minimum utility consumption, minimum number of exchangers, minimum total cost, etc.).[1] The steady state design of such optimal HENs has received a lot of attention over the last few decades,[2] resulting in the development of evolutionary synthesis approaches like pinch design method[3] and mathematical programming-based techniques.[4,5]

The operation of HEN is subjected to a variety of unanticipated or planned disturbances. As the HEN supply conditions are set by the operating conditions of upstream process units (such as a reactor or a distillation column), a disturbance can enter through the supply temperature or the flow rate when there is a process upset or an operating point change caused by an advanced controller. Similarly, the target temperature disturbance, typically planned, is introduced due to changes in the operating conditions of a downstream equipment. In a difference vein, fouling/scaling of a heat exchanger can result in a reduction of its heat transfer coefficient, thereby limiting the heat recovery achieved by the HEN. All these factors cause the HEN to operate sub-optimally or in the case of an extreme disturbance, result in infeasible operation (offset in target temperature). To address the issue of feasibility, design of a flexible HEN is pursued. Specifically, for a given bound on disturbances (mostly temperature and flow), a HEN is designed such that it can achieve optimal energy recovery for all the combinations of the considered disturbances. Broadly, these approach use sensitivity analysis,[6] resilience index,[7] flexibility analysis[8] or multi-period synthesis[9] (for details, refer to a comprehensive review of synthesis methods for flexible HEN design[10]).

On the other hand, to tackle these disturbances for an existing HEN, design of an optimal operation strategy is pursued. This approach combines target temperature regulation (through a feedback control system) with energy minimization (through offline or online optimization). Such an approach utilizes internal degrees of freedom (heat exchanger bypasses and/or stream split fractions) to achieve optimal operation in the presence of a disturbance. In the context of offline optimization, one of the approaches targets identifying a 'self optimizing' variable for a HEN with bypasses[11] or stream splits,[12] which when held constant using a feedback control system can result in optimal operation. Another approach aims at coordinating the use of internal degrees of freedom with external utility to optimize energy consumption by tracking optimality conditions. The resulting scheme is implemented in the form of a split-range configuration.[13–15] In the context of online optimization, one of the approaches aims at developing a reconfigurable HEN to optimize operation in the presence of time-varying availability and cost of utility.[16] Another approach optimizes a steady-state model of the HEN in the presence of a disturbance to obtain new targets for individual heat exchangers. These targets are then realized through a feedback control system.[17–19] The methodology presented in this paper belongs to this approach.

When a HEN encounters a disturbance, its energetic effect is propagated through the network along its natural path, and it eventually gets rejected through the utility heat exchangers. The proposed approach aims to redistribute this energetic effect in such a way that the total utility consumption can be minimized. For example, if inlet temperature of a hot stream entering the HEN increases above the design point, there is a net increase in the energy input of the HEN. This increased energy input can be directed towards one of the utility heaters, resulting in a corresponding reduction of the heating utility. Similarly, if performance (duty) of a heat exchanger deteriorates due to fouling, the reduced load can be shifted to the other heat exchangers so that the total heat recovery is not significantly affected. This manipulation of energy flow within the HEN is referred to as energy flow redistribution. Such a redistribution requires manipulation of duties of some of the heat exchangers in the network. Bypasses and stream splits can therefore be manipulated to achieve this redistribution. The proposed methodology provides a systematic way to formulate optimal operation problem of HEN using energy flow redistribution in the presence of key disturbances, including heat transfer coefficient, which has not been addressed so far by any of the existing approaches mentioned above. Furthermore, these approaches assume that bypasses are provided on all the heat exchangers, whereas the proposed methodology does not need such a practically limiting assumption.

The rest of the paper is organized as follows. A motivating example is considered to illustrate the concept and potential of energy flow redistribution. The proposed energy flow redistribution methodology is presented in the next section. This is followed by application of this approach to three benchmark example HENs to illustrate its features and benefits as compared to some of the existing approaches.

Motivating example

Let us consider an example HEN[20] with 3 hot and 3 cold streams, as shown in figure 1. Table 1 shows the stream data for this example. The network consists of seven process heat exchangers (PX1 through PX7), two heaters (UX1 and UX2) and 2 coolers (UX3 and UX4). Under nominal operating conditions, the HEN has a total utility requirement of 380 kW (100 kW heating duty and 280 kW cooling duty), which corresponds to a total heat recovery of 880 kW. During operation, it is considered that the duties of the utility exchangers can be manipulated to maintain target temperatures for steams H2, H3, C1 and C3. There is no constraint on the exit temperatures of streams H1 and C2.

Let us now consider that the supply temperature of hot stream H2 drops by -2.5^o C. This can happen due to an unanticipated or unplanned disturbance in an upstream process unit. This corresponds to a -10 kW disturbance in energy flow entering the HEN. Figure 2 shows the propagation path of the energy effect of this disturbance through the network. When the disturbance enters the system, it reduces the duty of heat exchanger PX3. This results in a corresponding reduction in PX3 outlet temperature. As the outlet streams of PX3 are inlets for exchangers PX4 and PX6, the operation of these exchangers is also affected. Thus the disturbance propagates through the network along its natural downstream path. Eventually, the disturbance reaches the exit point of streams H2 and C1. The corresponding target temperature controllers manipulate the duty of utility exchangers UX2 and UX3. This results in a 3.71 kW reduction in the duty of cooler UX3 and 1.74 kW increase in the duty of heater UX2. A fraction of the disturbance also exits along streams H1 and C2 (with no target temperature regulation). Overall the heat recovery of the system reduces to 875.19 kW.

Instead of relying on the natural propagation path, let us now engineer the disturbance propagation path to suit an objective of utility minimization. For an example, the energetic effect of the entire disturbance can be re-routed along cold stream C2 as shown (in red color) in figure 3. This requires reducing the duty of heat exchanger PX3 by 10 kW (3.86 kW extra compared to the natural reduction). The hot-side exit condition of PX3 thus remains the same as the nominal case and there is no disturbance propagation along stream H1. On the other hand, the cold-side exit of PX3 carries the entire energetic disturbance. Subsequently, if the duty of PX4 is maintained at its nominal value, the entire energetic effect of the disturbance exits along stream C2. As there is no utility exchanger and target temperature constraint for this stream, there is no change in the overall utility consumption. Alternatively, the energetic effect of the disturbance can also be re-routed along stream H2 as shown (in blue color) in figure 3. This requires maintaining duties of PX3 and PX6 to their nominal values and results in a 10 kW reduction in the utility of cooler UX3. It can thus be argued that an engineered disturbance propagation path (or energy flow redistribution) allows us to optimise utility consumption in the presence of a disturbance. It should be noted that such a redistribution requires that duties of PX3 and PX4 or PX6 be independently manipulated using a control system, and would require that these exchangers are over-designed and provided with a bypass stream.

Energy flow redistribution

In the previous section, we showed that energy flow redistribution can help achieve optimal operation. While such a redistribution can be performed manually for a simple disturbance in temperature, redistribution for a disturbance in flow or heat transfer coefficient is not straightforward. Furthermore, such redistribution also needs to account for process constraints, such as saturation of bypass or utility, non-availability of bypass, etc. Let us now develop a systematic framework for optimal energy flow redistribution to achieve a desired operational objective (for example, minimum utility consumption) in the presence of key operational disturbances (for example, supply or target temperatures, flow rate, heat transfer coefficient, etc.)

Process heat exchanger

A HEN consists of an interconnection of multiple counter-current process heat exchangers. For each of these heat exchangers, heat gained by the cold stream is equal to the heat lost by the hot stream. This can be expressed mathematically as follows:

$$Q = CP_h \left(T_{h,in} - T_{h,out}\right) = CP_c \left(T_{c,out} - T_{c,in}\right) \tag{1}$$

where Q is the heat exchanger duty, T is the temperature and CP is the heat capacity flow rate (product of flow rate and heat capacity). The subscripts h and c represent the hot and cold stream, respectively. The duty of a heat exchanger can be related with its heat transfer coefficient by the following equation:

$$Q = UA\Delta T_{LM} \tag{2}$$

where U is the overall heat transfer coefficient, A is the heat transfer area and ΔT_{LM} is the logarithmic mean temperature difference. For a counter-current heat exchanger, Eq. (2) can be written as,

$$Q = UA\frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{ln\left(\frac{T_{h,in}-T_{c,out}}{T_{h,out}-T_{c,in}}\right)} \tag{3}$$

Using Eq. (1), the outlet temperature can be expressed in terms of the inlet temperature and the heat exchanger duty.

$$T_{h,out} = T_{h,in} - \frac{Q}{CP_h}$$

$$T_{c,out} = T_{c,in} + \frac{Q}{CP_c} \tag{4}$$

Substituting Eq. (4) in Eq. (3) and rearranging it gives the following equation relating the heat exchanger duty with its inlet temperatures.

$$Q = \frac{\phi - 1}{\left[\frac{\phi}{CP_h} - \frac{1}{CP_c}\right]} (T_{h,in} - T_{c,in}) \tag{5}$$

where $\phi = exp\left(UA\left(\frac{1}{CP_h} - \frac{1}{CP_c}\right)\right)$. Equation (5) enables us to compute duty of an exchanger in the presence of any disturbance. For example, let us consider the HEN and the disturbance case discussed in the previous section. For heat exchanger PX3, knowing the nominal cold side inlet temperature (120^o C) and the disturbed hot side inlet temperature (227.5^o C), the heat exchanger duty (263.86 kW) under the disturbance scenario can be computed.

For achieving energy flow redistribution, the duty of a heat exchanger should be independently manipulable. Let us therefore consider that a bypass is inserted on the cold side of a heat exchanger, as shown in figure 4. The heat capacity flow rate for the stream entering the cold side will be $CP_c(1-\beta)$, where β is the bypass fraction. Accordingly, Eq. (5) is modified as follows:

$$Q = \frac{\phi_c(\beta) - 1}{\left[\frac{\phi_c(\beta)}{CP_h} - \frac{1}{CP_c(1-\beta)}\right]} (T_{h,in} - T_{c,in}) = \Phi_c(\beta)\,(T_{h,in} - T_{c,in}) \tag{6}$$

where $\phi_c(\beta) = exp\left(UA\left(\frac{1}{CP_h} - \frac{1}{CP_c(1-\beta)}\right)\right)$ and $\Phi_c(\beta) = \frac{\phi_c(\beta)-1}{\left[\frac{\phi_c(\beta)}{CP_h} - \frac{1}{CP_c(1-\beta)}\right]}$.

Alternatively, if a bypass is inserted on the hot side of a heat exchanger, the corresponding heat exchanger duty can be computed by the following equation:

$$Q = \frac{\phi_h(\beta) - 1}{\left[\frac{\phi_h(\beta)}{CP_h(1-\beta)} - \frac{1}{CP_c}\right]} (T_{h,in} - T_{c,in}) = \Phi_h(\beta) (T_{h,in} - T_{c,in}) \tag{7}$$

where $\phi_h(\beta) = exp\left(UA\left(\frac{1}{CP_h(1-\beta)} - \frac{1}{CP_c}\right)\right)$ and $\Phi_h(\beta) = \frac{\phi_h(\beta)-1}{\left[\frac{\phi_h(\beta)}{CP_h(1-\beta)} - \frac{1}{CP_c}\right]}$. These equations help us include the effect of bypass fraction into energy flow redistribution. Let us again revisit the motivating example to illustrate this. Let us consider that the exchanger PX3 has a bypass on the hot side with a nominal bypass fraction of 0.2. Considering redistribution case depicted in blue color, in order to maintain PX3 duty at 270 kW, the corresponding bypass fraction should be reduced to 0.14. On the other hand, for the redistribution depicted in red color, the bypass fraction should be increased to 0.23 so that the exchanger duty drops to 260 kW.

In practice, there will be min/max constraints on the bypass fraction. For example, a high bypass fraction can lead to fouling, whereas a low bypass fraction can result in high pressure drop.[19] Let us consider that the bypass fraction can be varied between β_{min} and β_{max}. Accordingly, the lower and upper bounds on heat exchanger duty can be obtained as follows:

$$\begin{aligned} Q \geq Q_{min} = \Phi_{h/c}(\beta_{max}) (T_{h,in} - T_{c,in}) \\ Q \leq Q_{max} = \Phi_{h/c}(\beta_{min}) (T_{h,in} - T_{c,in}) \end{aligned} \tag{8}$$

According to the second law of thermodynamics, temperature crossing cannot take place inside any heat exchanger. This can be ensured by including the following constraints:

$$\delta T \quad \leq (T_{h,in} - T_{c,out})$$

$$\delta T \quad \leq (T_{h,out} - T_{c,in}) \tag{9}$$

where δT is a positive number. Representing the outlet temperature in terms of the inlet temperature and the heat exchanger duty through Eq. (4), we get the following constraints:

$$\begin{aligned} \delta T \quad &\leq (T_{h,in} - T_{c,in}) - \tfrac{Q}{CP_c} \\ \delta T \quad &\leq (T_{h,in} - T_{c,in}) - \tfrac{Q}{CP_h} \end{aligned} \tag{10}$$

Remark 1 *During the design stage, in order to achieve a trade-off between capital and operating cost, a minimum approach temperature (ΔT_{min}) is considered. During operation, such a conservative approach temperature is not required and a smaller value of the minimum approach temperature $\delta T < \Delta T_{min}$ can be implemented. Previously, it has been shown that such a condition results in a structurally resilient network.*[7]

Remark 2 *The analysis presented here considers that there is no phase change during heat transfer. In the case of phase change, the heat transfer corresponding to latent heat can be approximated, similar to most of the previous approaches, as sensible heat with a small temperature change and a large heat capacity flow rate. For example, if there is phase change on the hot side, considering $CP_h \gg 1$, $\phi \to exp\left(-\frac{UA}{CP_c}\right)$ and $\Phi \to CP_c(1-\phi)$. If both the hot and cold sides involve phase change (as in the case of a combined reboiler-condenser), the corresponding temperature driving force is constant and equal to $(T_{h,in} - T_{c,in})$. For this case, $\Phi = UA$.*

Temperature driving force is also constant for a case when $CP_h = CP_c$. For this case, it can be easily shown that $\Phi = \frac{UA}{(1+UA/CP)}$. Note that, in the case of phase change on both the sides, $CP \gg 1$ and $\Phi \to UA$, as mentioned *above.*

Remark 3 *This analysis can be easily extended to the cases where a bypass extends over multiple heat exchangers, as shown in figure 5. For such a case, for individual heat exchangers, Eq. (4) needs to include the bypass fraction. The expression for the final exit temperature (after mixing with the bypass), though, remains unchanged. It should, however, be noted that such a case offers less flexibility in terms of energy flow redistribution as there is a reduction in the number of degrees of freedom.*

Heat exchanger network

Let us now consider energy balance across the HEN. For any hot stream, as shown in figure 6, the total energy available is taken up, in parts, by each process heat exchanger along its path and the remaining heat, if any, is rejected via a cooler. Specifically, for a hot stream i, the energy balance is represented by the following equation:

$$CP_{h,i}\left(T_{supply,i} - T_{target,i}\right) - \sum_{k=1}^{N} Q_{k,i} - UC_i = 0 \tag{11}$$

where $Q_{k,i}$ represents duty of the k^{th} process heat exchanger on the hot stream i. UC_i represents the duty of the cooler on the hot stream i. Similarly, for a cold stream, as shown in figure 6, heat is added by process heat exchangers along its path and any additional heat required to reach the target temperature is supplied by a heater. Specifically, for a cold stream j, the energy balance is represented by the following equation:

$$CP_{c,j}\left(T_{target,j} - T_{supply,j}\right) - \sum_{k=1}^{N} Q_{k,j} - UH_j = 0 \tag{12}$$

where $Q_{k,j}$ represents duty of the k^{th} process heat exchanger on the cold stream j. UH_j represents duty of the heater on the cold stream j. These energy balance equations are written for all the hot and cold process streams.

Remark 4 *The framework considers that there is an utility exchanger at the exit of every process stream. Furthermore, it is considered that the corresponding target temperature constraint is strictly implemented for feasible operation. However, these conditions can be easily relaxed. For streams without any utility exchangers, duty terms UC_i and UH_j can be removed from Eq. (11) and (12), respectively. If there is no requirement of strict target temperature on a stream, the equality constraints in Eq. (11) or (12) can be replaced by inequality constraints. Using these constraints, a desired bound on the corresponding target temperature can be achieved.*

Optimization problem formulation

The equations presented in the previous two subsections can be solved to obtain a feasible operating point for the HEN. As these equations include all the potential disturbances for the HEN, we can solve these equations to optimize the performance of the HEN. To this end, the following optimization problem can be formulated:

$$\underset{Q_k, UH_k, UC_k}{\text{minimize}} \quad J = \sum_{k=1}^{N_{HX}} w_{Q,k} \left(Q_k - Q_{k,nom}\right)^2 + \sum_{k=1}^{N_{UH}} w_{H,k} UH_k + \sum_{k=1}^{N_{UC}} w_{C,k} UC_k$$

subject to

$$\begin{aligned}
&CP_{h,i}\left(T_{supply,i} - T_{target,i}\right) - \sum_{k=1}^{N} Q_{k,i} - UC_i = 0 \;\; \text{for each hot stream } i \\
&CP_{c,j}\left(T_{target,j} - T_{supply,j}\right) - \sum_{k=1}^{N} Q_{k,j} - UH_j = 0 \;\; \text{for each cold stream } j \\
&T_{h,out,k} = T_{h,in,k} - \frac{Q_k}{CP_{h,k}} \;\; \text{for each process heat exchanger } k \\
&T_{c,out,k} = T_{c,in,k} + \frac{Q_k}{CP_{c,k}} \;\; \text{for each process heat exchanger } k \\
&T_{h,out,mh} = T_{h,in,nh} \;\; \text{for each exchanger } nh \text{ downstream of hot side of exchanger } mh \\
&T_{c,out,mc} = T_{c,in,nc} \;\; \text{for each exchanger } nc \text{ downstream of cold side of exchanger } mc \\
&\Phi_{h/c,k}(\beta_{max})\left(T_{h,in,k} - T_{c,in,k}\right) \leq Q_k \;\; \text{for each process heat exchanger } k \\
&\Phi_{h/c,k}(\beta_{min})\left(T_{h,in,k} - T_{c,in,k}\right) \geq Q_k \;\; \text{for each process heat exchanger } k \\
&\left(T_{h,in,k} - T_{c,in,k}\right) - \frac{Q_k}{CP_{c,k}} \geq \delta T \;\; \text{for each process heat exchanger } k \\
&\left(T_{h,in,k} - T_{c,in,k}\right) - \frac{Q_k}{CP_{h,k}} \geq \delta T \;\; \text{for each process heat exchanger } k \\
&UH_{k,min} \leq UH_k \leq UH_{k,max} \;\; \text{for each utility heater } k \\
&UC_{k,min} \leq UC_k \leq UC_{k,max} \;\; \text{for each utility cooler } k
\end{aligned} \tag{13}$$

where N_{HX}, N_{UH} and N_{UC} represent the total number of process heat exchangers, utility heaters and utility coolers, respectively. $w_{Q,k}$ represents penalty for deviation of heat exchanger duty from its nominal value, whereas $w_{C,k}$ and $w_{H,k}$ represent the cost of cooling and heating utility, respectively. The first term of the objective function tries to maintain process heat exchanger duties close to their nominal values. This ensures that the redistribution algorithm, while minimizing utility consumption, does not push heat exchanger bypasses to their minimum/maximum values and loose flexibility of the system. The other two terms in the objective function try to force the energetic effect of a disturbance towards minimizing utility consumption. The relative contribution of these terms in the objective function allows for achieving a trade-off between flexibility and energy efficiency.

Remark 5 *The presented optimization framework is flexible with respect to the number of heat exchangers that participate in energy flow redistribution. If a subset of heat exchangers are not provided with any bypass, the* β_{max} *and* β_{min} *values for those exchangers can be set to 0. The algorithm will then compute the duty of these exchangers based on changes in their inlet temperature (caused by the effect of the disturbance).*

Implementation

The proposed methodology for optimal operation of HEN can be implemented as depicted in figure 7. When a disturbance in inlet temperature (T_{supply}), flow (CP), heat exchanger performance (U), target temperature (T_{target}) or a combination thereof is detected, the energy flow redistribution algorithm estimates a new set of heat exchanger duties required to ensure optimal operation. These are fed (as set points) to a feedback control system which manipulates the available bypass fractions. The feedback control system also includes regulatory temperature controllers to achieve the desired target temperature control by using utility exchanger duty.

Remark 6 *It is considered that the solution of energy flow redistribution is implemented with the help of duty controllers. Instead of this, one can also use conventional temperature controllers. Both these approaches are equiv-*

alent and require measurement of heat exchanger exit temperature. In the case of duty control, this measurement will be used to compute instantaneous value of duty. On the other hand, in the case of temperature control, the duty target from energy flow redistribution will be converted into temperature set point and will be subsequently tracked.

Remark 7 *The steady state network energy balance approach of the proposed methodology is similar to some of the previously published works in this area.[14, 17] The previous approaches do not explicitly include the effect of heat exchanger bypass on its duty (as considered in Eq. (8)). This can result in the optimizer requesting heat exchanger duty that saturates the bypass. The corresponding closed-loop system, therefore, cannot reach the optimal operating point. Our approach always computes duty targets which can be tracked by the closed-loop control system without any input saturation.*

Furthermore, both the above-mentioned approaches result in LP optimization and cannot handle disturbance in heat transfer coefficient, as it makes the formulation nonlinear. Linear formulation is required for implementation of the solution in a split-range configuration[14] as it is essential that the optimal solution lies at the intersection of active constraints.

Case studies

Let us now apply this methodology to some of the benchmark example HENs. For all the examples, each process heat exchanger dynamics are modelled by the following coupled PDEs.

$$\begin{aligned} \frac{\partial T_h}{\partial t} &= -v_h \frac{\partial T_h}{\partial z} - \frac{UA}{\rho C_{p,h} V_h}(T_h - T_c) \\ \frac{\partial T_c}{\partial t} &= v_c \frac{\partial T_c}{\partial z} + \frac{UA}{\rho C_{p,c} V_c}(T_h - T_c) \end{aligned} \tag{14}$$

$$
\begin{aligned}
T_h|_{z=0} &= T_{h,in} \\
T_c|_{z=L} &= T_{c,in}
\end{aligned}
$$

where v represents the fluid velocity, ρ is the fluid density, V is the volume and L is the length of the heat exchanger. These PDEs are discretized using orthogonal collocation and the resulting system of ODEs is solved in Matlab v9.7 (R2019b). The optimization problem of Eq. (13) is solved using CONOPT3 version 3.17L solver in GAMS (v32.2.0 2020). For closed-loop feedback control, PI controllers of the following form are used:

$$
u(t) = u_{nom} + K_C \left(\epsilon(t) + \frac{1}{\tau_I} \int_0^t \epsilon(\tau) d\tau \right) \tag{15}
$$

where u is the manipulated input, ϵ is the control error (difference between the set point and the current value), K_C is the proportional gain and τ_I is the integral time constant.

Network 1

Let us first apply the framework to the motivating example considered earlier. Let us initially consider that all the process heat exchangers are equipped with bypasses either on the hot or the cold side. The nominal operating conditions are listed in table 2. The parameters used for optimization and feedback control are given in the supplementary text.

Let us first consider the same disturbance scenario as the motivating example (2.5^o C drop in H2 inlet). Figure 8 compares the energy flow paths with and without energy flow redistribution. It can be seen that the optimal redistribution suggests distributing the energetic effect of the disturbance over the entire network, including the heat exchangers which were not affected during the natural propagation. The optimal redistribution results in a reduction of 7.16 kW in the heating utility and 13.01 kW in the cooling utility. This is better than the values obtained using manual redistribution which targeted only a small section of the network. To achieve this, the redistribution algorithm increases the duty of PX3 so that the effect of the disturbance is directed along H2, rather than C2. Subsequently, duties of PX1, PX5 and PX7 are increased such that the cold stream outlet temperature of PX7 is 3^o C hotter compared to the disturbed case, thus reducing the hot utility requirement. Figures 9 and 10 show the closed-loop profile of the HEN in response to this redistribution target. It can be seen that the controllers are able to track the required duty targets and maintain the target temperatures at their desired values. Only bypass for PX6 is at its minimum constraint and all the other bypasses are away from their operating limits. This is due to the first term of the objective function which ensures that, even after redistribution, the HEN retains its flexibility.

Let us now consider a disturbance in the target temperature. This represents a case when the operating point of a downstream unit is changed (typically by an advanced control system). A 5^o C increase in C1 target temperature is considered. It corresponds to a 10 kW extra outflow of energy from the system. Similar to the previous case, the energy flow redistribution algorithm optimises the heat exchanger duty allocation as shown in figure 11. In the absence of any redistribution, the entire increase in the energy has to be provided by the utility heater UX2. On the other hand, energy flow redistribution can compensate for this extra outflow of energy by adjusting the heat loads of the entire HEN. Specifically, heat loads of the upstream exchangers PX1 and PX7 on stream C1 are increased so that the required increase in the load of utility heater UX2 is reduced to 4.91 kW. This also necessitates changes in the other parts of the HEN to maintain the other target temperature constraints. Overall, net change in heating and cooling utility is +2.41 kW and −3.46 kW, resulting in the saving of 7% in hot utility and 1% in cold utility. Note that, even though PX6 is on the upstream path of C1, there is a net decrease in its duty. An increase in PX1 duty increases cold inlet temperature of PX6 and drops its duty to 9.77 kW. Even with the minimum bypass fraction of 0.05, this duty can only be increased to 9.84 kW (-0.16 kW deviation from the nominal value). The closed-loop responses for this case are included in the supplementary text.

In the next simulation run, a disturbance in inlet flow rate is considered. While a disturbance in temperature causes a linear change in the heat exchanger duty, the effect of flow rate disturbance is non-linear (see Eq. (5)). Let us consider a 10% decrease (-0.3 kW) in the flow rate of stream H1. The corresponding response of the system, with and without energy flow redistribution, is shown in figure 12. Even though the energetic value of this disturbance is small, it has a strong impact on the energetics of the HEN. The duties of the three heat exchangers, PX4, PX5 and PX7, drop significantly, resulting in a 16.7 kW increase in the hot utility. Energy flow redistribution allows for improving the energetics by distributing the effect of the disturbance over the network. Specifically, duties of the other heat exchangers on cold streams C1 and C2 are reduced to lower the cold stream inlet temperatures for PX4 and PX7. This, along with pinching the corresponding bypass fraction, helps recover some of the duty reduction. However, this comes at the cost of increased cooling utility (which is cheaper). Overall, there is 8% reduction in the hot utility and 1.4% increase in the cold utility. The corresponding closed-loop responses are included in the supplementary text.

Lastly, let us consider a disturbance in heat transfer coefficient. Prolonged use of heat exchanger results in fouling and consequently the heat transfer coefficient (U) decreases. Similar to flow rate, the effect of U on the heat exchanger duty is also nonlinear (see Eq. (5)). Let us consider that the heat transfer coefficient of PX1 drops by 20%. The corresponding results are depicted in figure 13. This disturbance significantly drops PX1 duty. This directly increases the cooling utility UX4. On the other hand, the reduced cold inlet temperature of PX7 increases its duty and thus the increase in hot utility is limited. Energy flow redistribution, by exploiting the degrees of freedom available in the network, compensates for this disturbance and results in 4.4% and 2.2% reduction in the hot and cold utility, respectively. The corresponding closed-loop responses are included in the supplementary text.

It can thus be appreciated that the proposed approach aids optimal operation in the presence of key disturbances. The optimization problem takes about 0.06s (run-specific computation times are included in the supplementary text). Thus the proposed approach, as depicted in figure 7, is practically implementable.

Network 2

Let us now compare the performance of this framework with a similar approach proposed by Aguilera and Marchetti.[17] This example system has 2 hot and 2 cold streams, and the corresponding HEN consists of 3 process heat exchangers and 3 utility exchangers, as shown in figure 14. Under nominal conditions, the utility exchangers UX2 and UX3 are not active. The stream data for this system is given in table 3. The parameters for optimization and feedback control are given in the supplementary text.

The network is subjected to a series of disturbances in the inlet temperature. Initially, H1 inlet temperature is dropped by 10^o C. After 600 s, additionally H2 inlet temperature is increased by 10^o C and after 1200 s, C1 inlet temperature is increased by 10^o C, and all the three disturbances are maintained for the next 600 s. The comparison of performance of the proposed energy flow redistribution algorithm with the approach of Aguilera and Marchetti is summarized in table 4. The disturbance in H1 corresponds to a 500 kW decrease in the energy input of the HEN. Both the approaches reduce the duty of PX1 to direct the effect of disturbance towards utility cooler UX1. Due to explicit incorporation of bypass into the optimization formulation, our approach is able to push PX1 to its optimal limit (any further increase results in negative UX1). This results in extra saving of 15 kW in both the heating and cooling duty. The addition of H2 disturbance increases the energy input by 200 kW (still 300 kW less than the nominal case). Both the approaches propose maintaining PX3 duty at its nominal value. The earlier savings of 15 kW are still carried forward. Lastly, the disturbance in C1 causes an increase of 400 kW in the energy input (net effect being 100 kW extra compared to the nominal case). Both the approaches direct the energetic effect of the total disturbance towards utility cooler UX1 and result in the same hot and cold utility.

In the next case, a series of changes are requested in the target temperatures of C1, C2 and H2. Initially, C1 target temperature is dropped by 10^o C. After 600 s, additionally C2 target temperature is increased by 5^o C and after 1200 s, H2 target temperature is dropped by 10^o C, and all the three disturbances are maintained for the next 600 s. The comparison of performance of the proposed energy flow redistribution algorithm with the approach of Aguilera and Marchetti is summarized in table 4. For this scenario, both the approaches result in the same hot and cold utility requirement, albeit with different redistributed structure. Overall, the performance of the proposed approach is better or at par with the approach of Aguilera and Marchetti. The requested redistribution targets can be feasibly achieved using a feedback control system. The corresponding closed-loop responses are included in the supplementary text.

Network 3

Let us also compare the performance of the proposed approach with an offline optimization-based approach (self optimizing control[11]). The corresponding example network with 1 hot and 2 cold streams is shown in figure 15. There are two process heat exchangers, PX1 and PX2, each fitted with a bypass. The stream data for this system is given in table 5. Application of self optimizing control approach suggests controlling PX2 hot inlet temperature at 151.9^o C using bypass on PX1. The overall feedback control system consists of four temperature controllers; three target temperatures and one self optimizing variable. Two heat exchanger bypasses, and hot and cold utility are used as the manipulated variables.

The performance of this scheme is compared with the proposed approach. A series of disturbances in H1 inlet temperature and C2 flow rate, as shown in figure 16, are considered. Figure 16 depicts the dynamic response of the key network variables. It can be seen that both the approaches result in better energetic performance as compared to conventional operation. As compared to self optimizing control, the proposed approach results in lower utility consumption for the first two disturbance cases. For the other two disturbance cases, both the approaches result in the same utility consumption. The optimization problem can be solved in less than 0.1 s, enabling efficient implementation of the proposed framework.

Concluding Remarks

We presented a novel approach for achieving optimal operation of HENs. Utilizing some of the degrees of freedom (heat exchanger bypass fraction) available with the HEN, the energetic effect of a disturbance is distributed over the network to minimize utility consumption. This energy flow redistribution is computed by solving a nonlinear optimization problem. Starting with energy balance for a single heat exchanger, equality and inequality constraints are derived to relate the heat exchanger bypass fraction with the corresponding heat duty, temperature targets and utility requirement. The obtained duty targets are implemented in the HEN with the help of a feedback control system.

Some of the key distinguishing features of the proposed framework are as follows.

- The effect of bypass fraction on the heat exchanger duty is explicitly included in the framework to prevent bypass saturation during operation.
- There is no need to install bypass on each heat exchanger.
- A trade-off between optimality and flexibility of operation can be achieved.
- A disturbance in the form of heat exchanger performance deterioration can be optimally handled.

Through simulation case studies on three networks, it is shown that the proposed methodology is flexible in terms of types of disturbances it can handle and computationally quite efficient. It is also shown that the proposed methodology works at par or better than some of the existing approaches for optimal operation of HEN.

Acknowledgments

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Figures

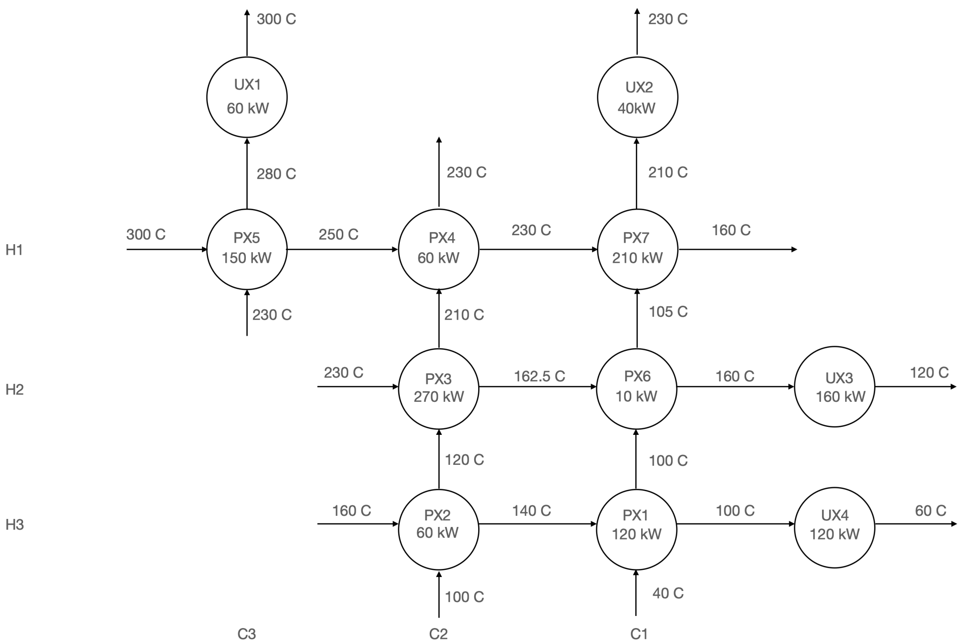


Figure 1: Example HEN with 3 hot and 3 cold streams[20]

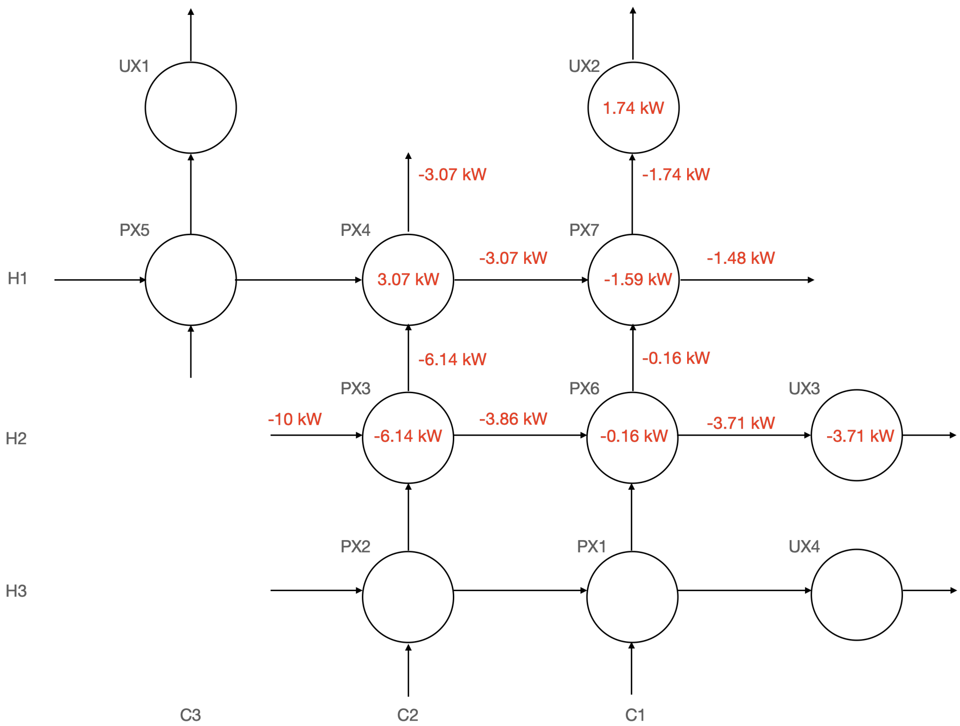


Figure 2: Motivating example - Disturbance propagation along its natural path (values denote deviation from the nominal operating point)

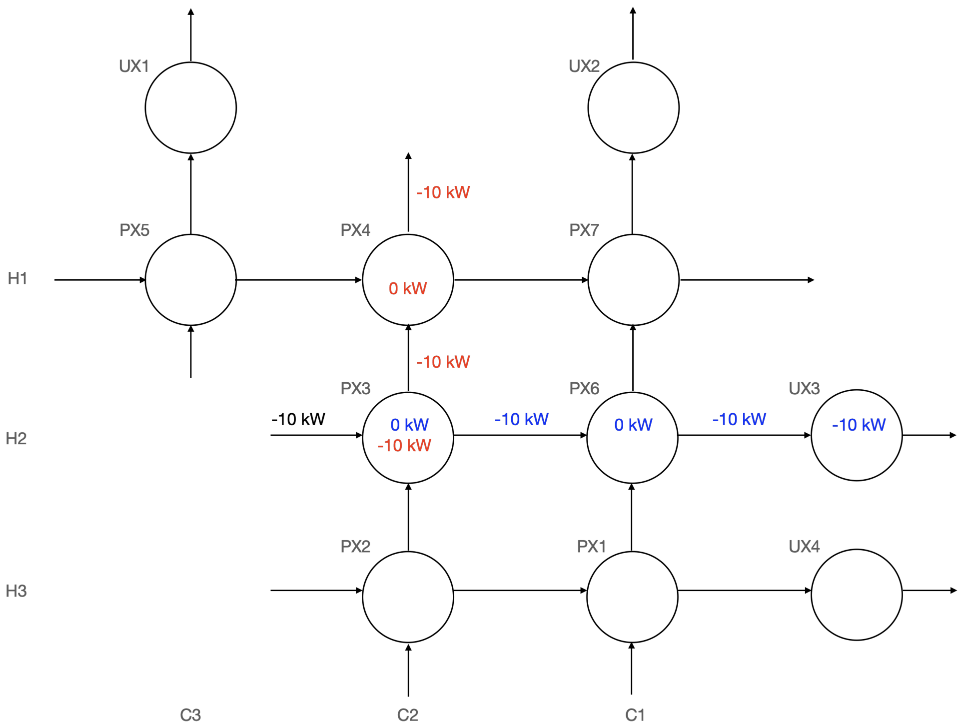


Figure 3: Motivating example - Disturbance propagation along an engineered path (values denote deviation from the nominal operating point) (blue and red color represent two different scenarios)

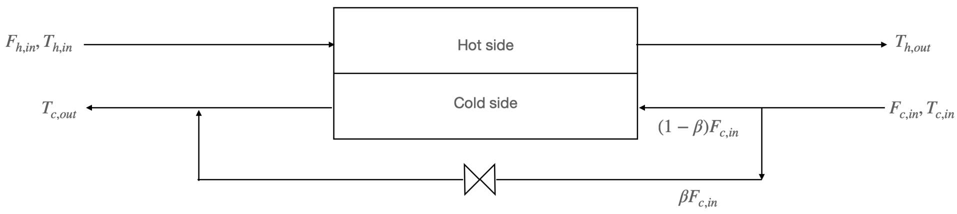


Figure 4: Counter-current heat exchanger with bypass on the cold side

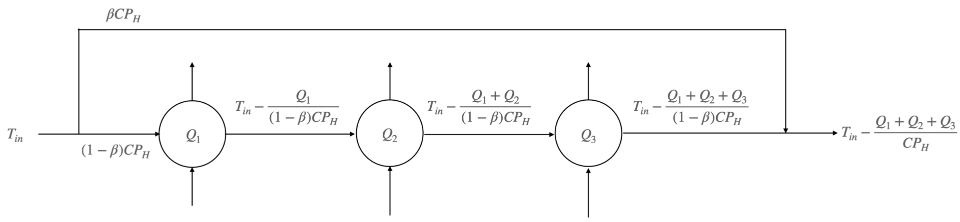


Figure 5: Bypass spanning multiple heat exchangers

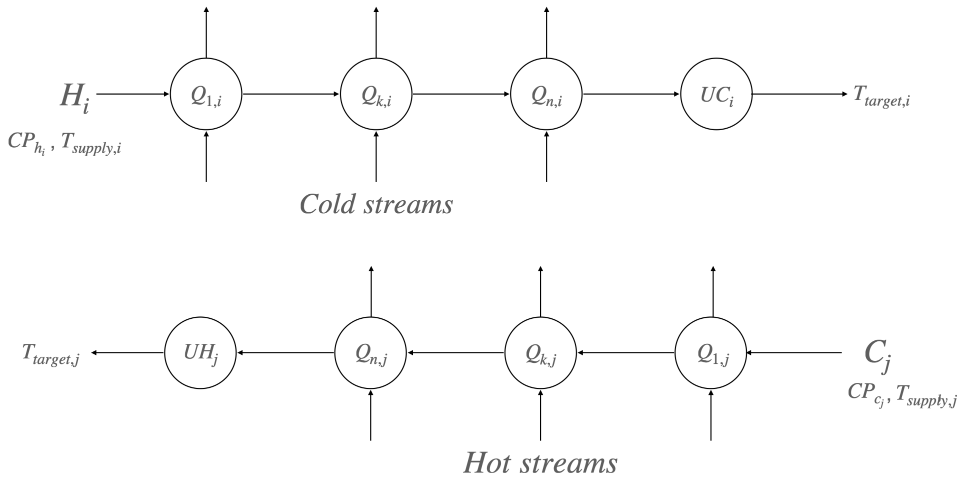


Figure 6: Energy flow along a hot and a cold stream

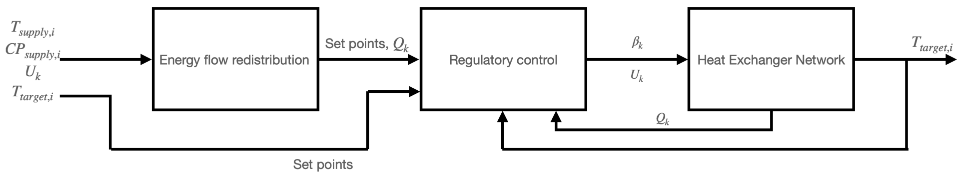


Figure 7: Implementation of energy flow redistribution for optimal operation

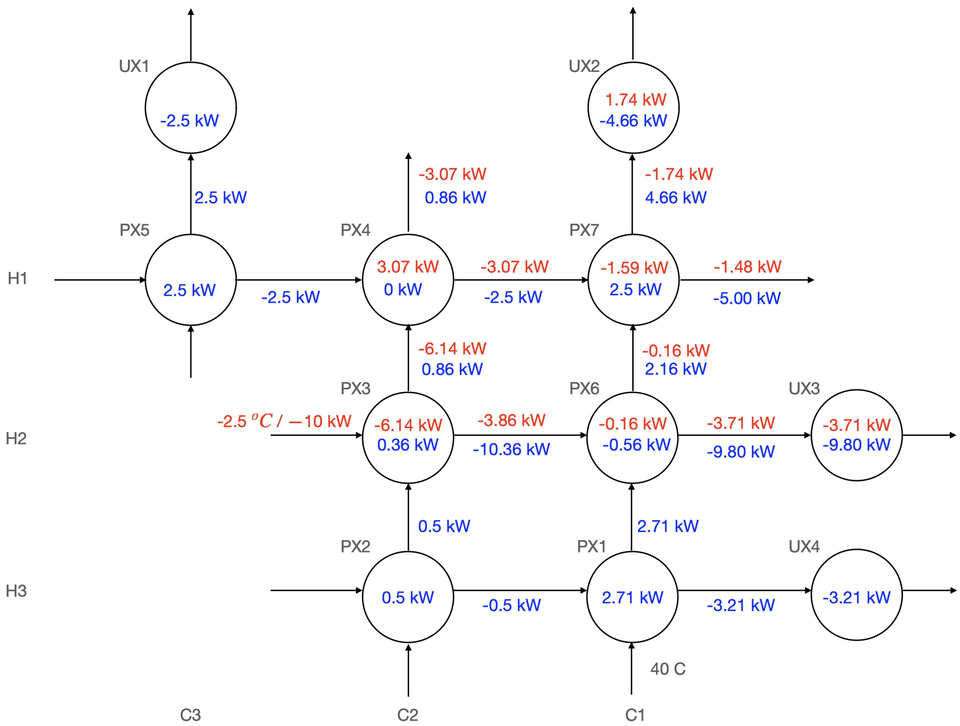
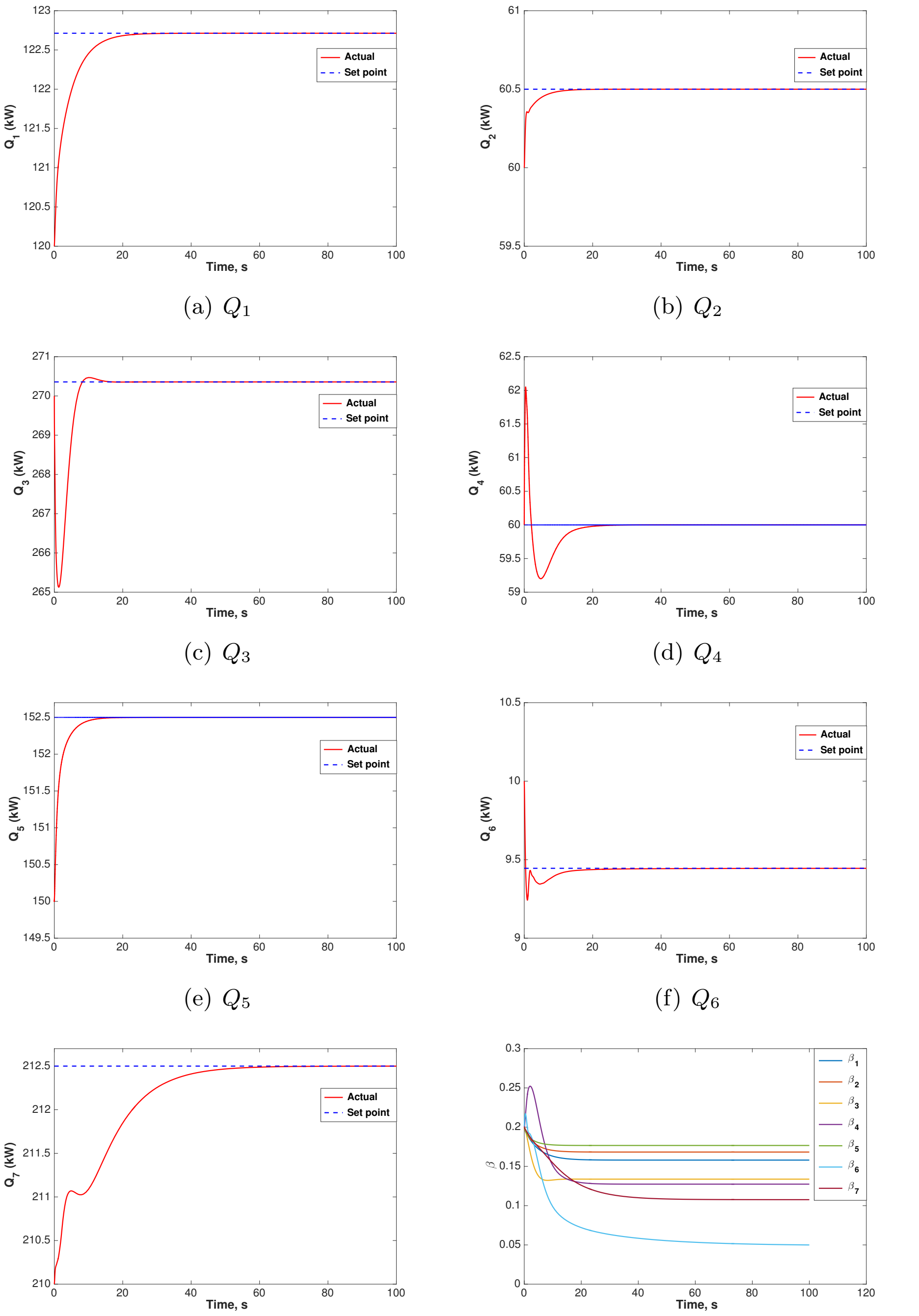


Figure 8: Network 1 - Comparison of energy flow with (blue) and without (red) energy flow redistribution for a -2.5^o C disturbance in H2 inlet (values denote deviation from the nominal operating point)



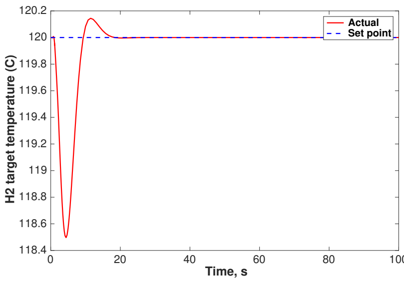
(a) Q_1 (b) Q_2

(c) Q_3 (d) Q_4

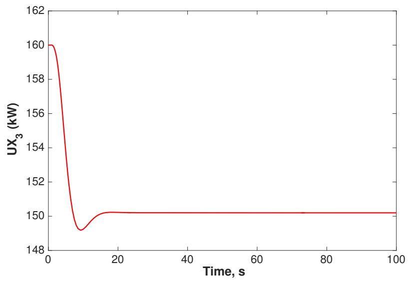
(e) Q_5 (f) Q_6

(g) Q_7 (h) bypass fraction

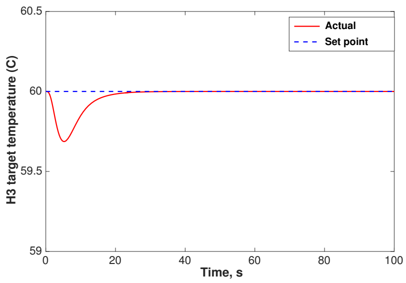
Figure 9: Network 1 - Closed-loop response of duty controllers for a -2.5^o C disturbance in H2 inlet



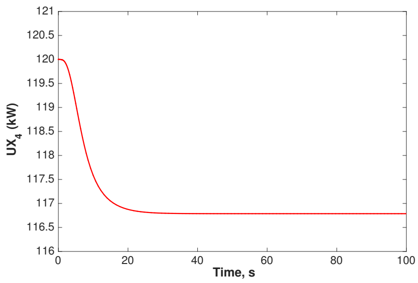
(a) H2 target



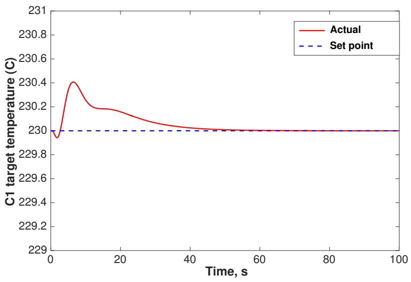
(b) UX_3



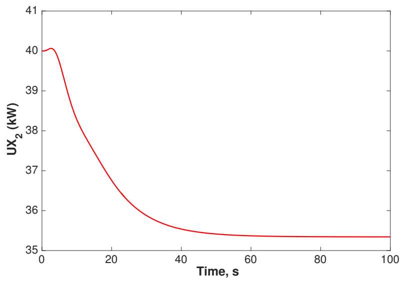
(c) H3 target



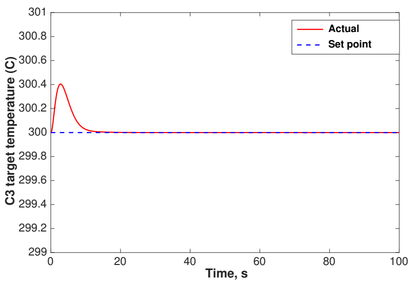
(d) UX_4



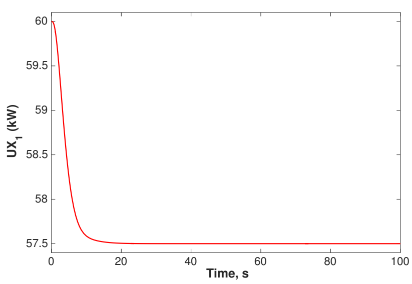
(e) C1 target



(f) UX_2



(g) C3 target



(h) UX_1

Figure 10: Network 1 - Closed-loop response of target temperature controllers for a -2.5^o C disturbance in H2 inlet

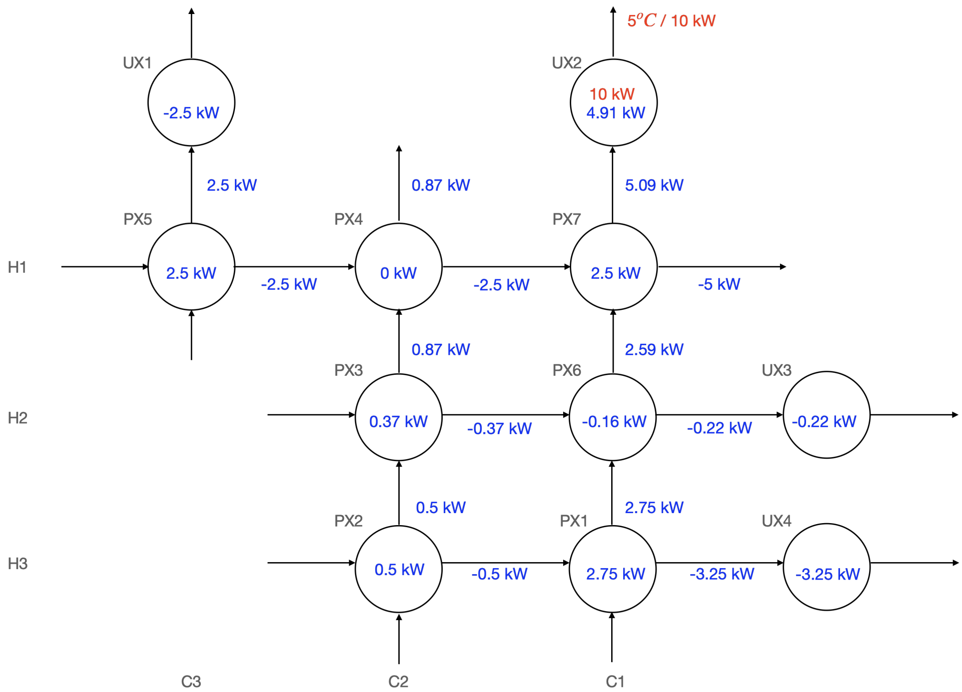


Figure 11: Network 1 - Comparison of energy flow with (blue) and without (red) energy flow redistribution for a 5^o C disturbance in C1 target temperature (values denote deviation from the nominal operating point)

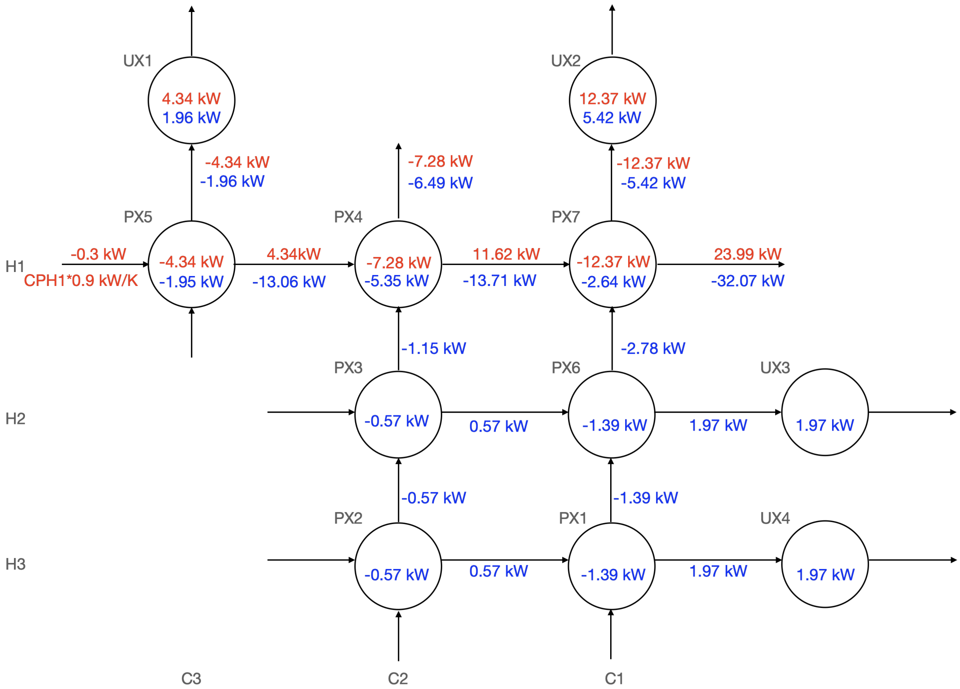


Figure 12: Network 1 - Comparison of energy flow with (blue) and without (red) energy redistribution for a -10% disturbance in H1 flow rate (values denote deviation from the nominal operating point)

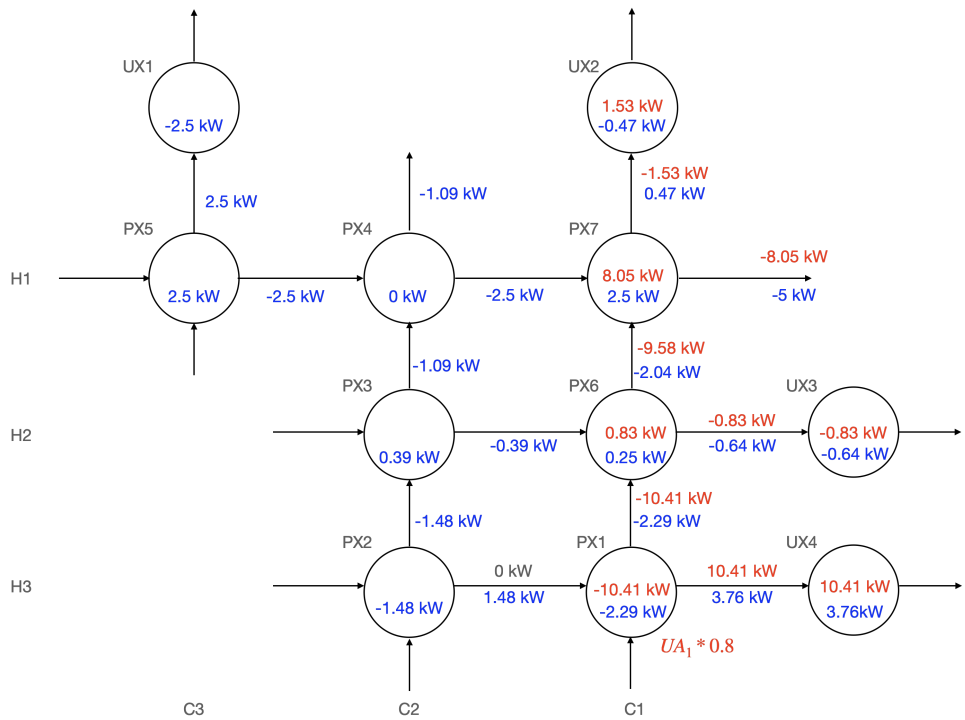


Figure 13: Network 1 - Comparison of energy flow with (blue) and without (red) energy redistribution for a -20% disturbance in HX1 heat transfer coefficient (values denote deviation from the nominal operating point)

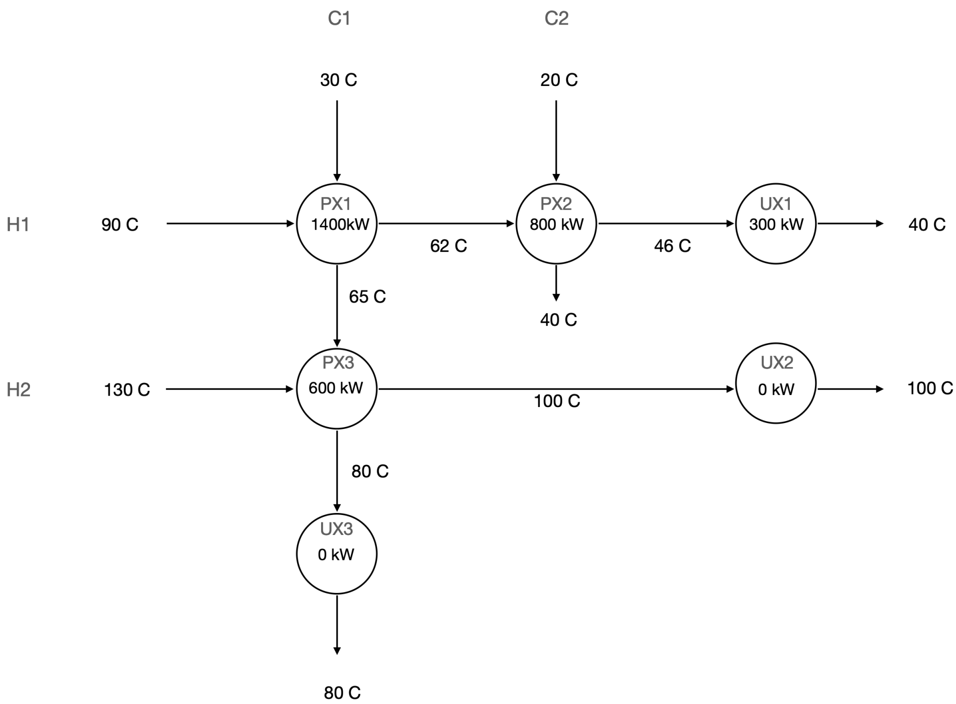


Figure 14: Example network 2 with 2 hot and 2 cold streams

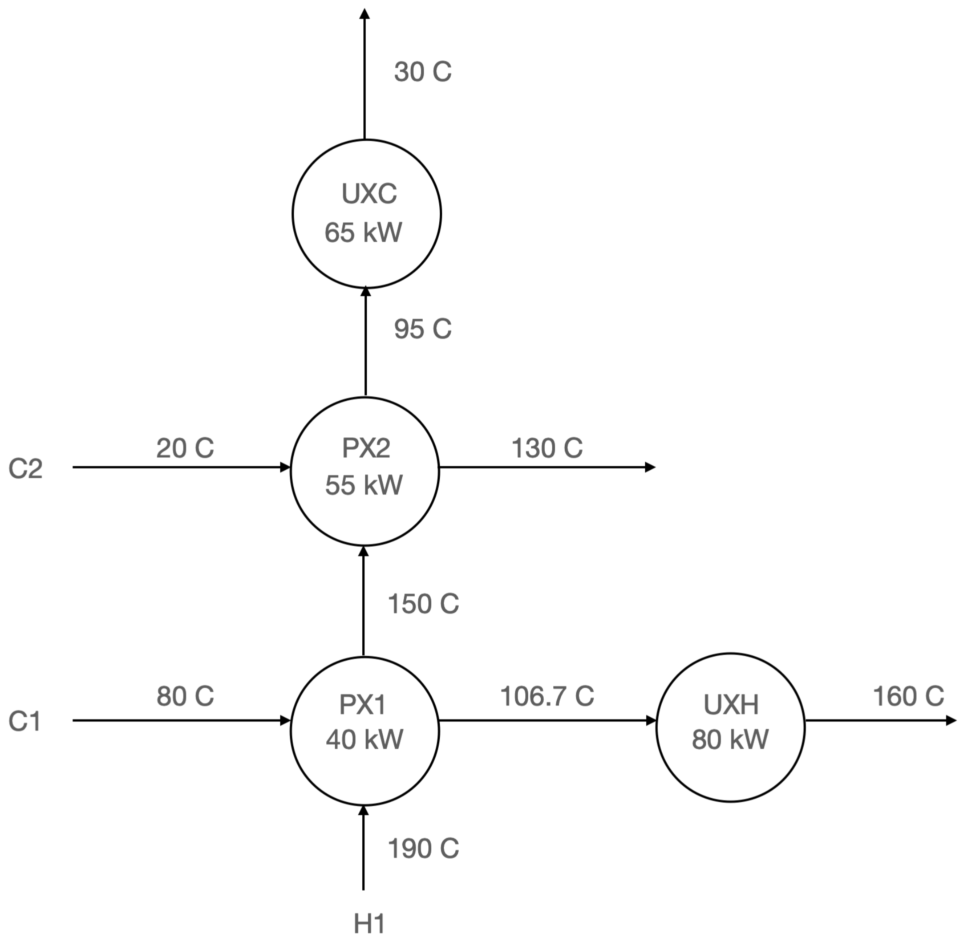
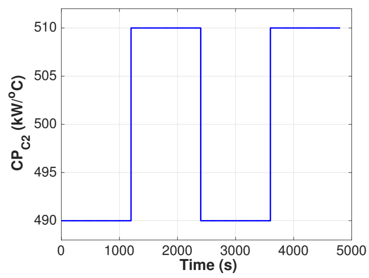
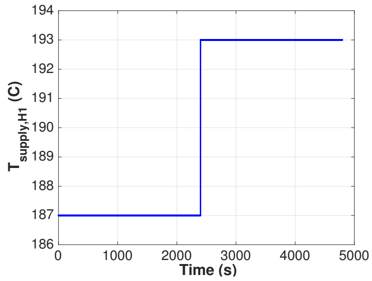


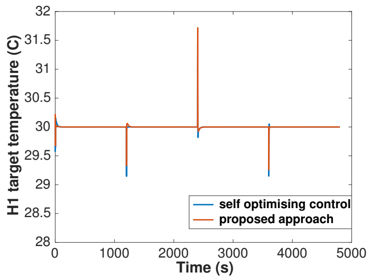
Figure 15: Example network 3 with 1 hot and 2 cold streams



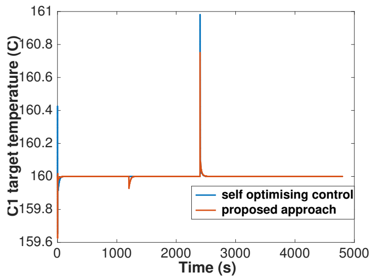
(a) C2 Flow



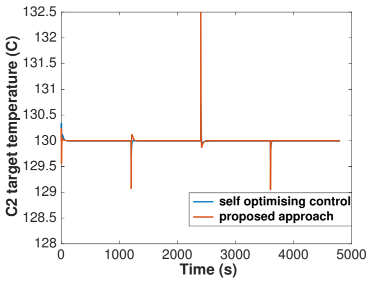
(b) H1 Inlet temperature



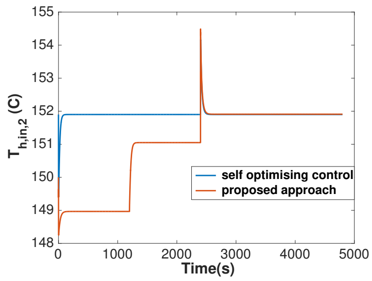
(c) H1 target



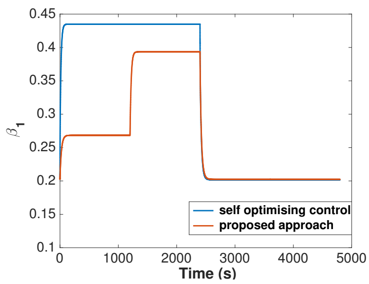
(d) C1 target



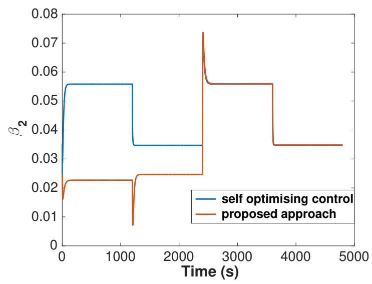
(e) C2 target



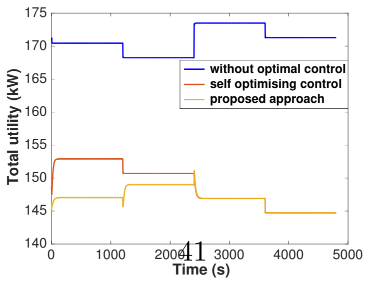
(f) $T_{h,in,2}$



(g) β_1



(h) β_2



(i) Total utility

Figure 16: Network 3 - Dynamic response for a series of disturbances in inlet temperature and flow

Tables

Table 1: Stream data for motivating example with 3 hot and 3 cold streams (CP: heat capacity flow rate)

Stream	CP (kW/°C)	T_{supply} (°C)	T_{target} (°C)
H1	3	300	160
H2	4	230	120
H3	3	160	60
C1	2	40	230
C2	3	100	230
C3	3	230	300

Table 2: Nominal operating point for network 1

Heat Exchanger	Q (kW)	β	$T_{h,in}$ (°C)	$T_{h,out}$ (°C)	$T_{c,in}$ (°C)	$T_{c,out}$ (°C)
PX_1	120	0.2	140	100	40	100
PX_2	60	0.2	160	140	100	120
PX_3	270	0.2	230	162.5	120	210
PX_4	60	0.2	250	230	210	230
PX_5	150	0.2	300	250	230	280
PX_6	10	0.2	162.5	160	100	105
PX_7	210	0.2	230	160	105	210
UX_1	60	-	-	-	280	300
UX_2	40	-	-	-	210	230
UX_3	160	-	160	120	-	-
UX_4	120	-	100	60	-	-

Table 3: Stream data for network 2 (CP: heat capacity flow rate)

Stream	CP ($kW/^oC$)	T_{supply} (^{o}C)	T_{target} (^{o}C)
H1	50	90	40
H2	20	130	100
C1	40	30	80
C2	40	20	40

Table 4: Comparison of optimal operation results for network 2 (AM: Aguilera and Marchetti's approach, ERM: proposed approach)

Disturbance	Approach	Duties (kW)						Hot utility (kW)	Cold utility (kW)
		Q_1	Q_2	Q_3	UC_1	UC_2	UH_3		
No	-	1400	800	600	300	0	0	300	0
H1	AM	1185	800	600	15	0	215	15	215
	ERM	1200	800	600	0	0	200	0	200
H1 & H2	AM	1185	800	800	15	0	15	15	15
	ERM	1200	800	800	0	0	0	0	0
H1, H2 & C1	AM	800	800	800	400	0	0	400	0
	ERM	800	800	800	400	0	0	400	0
C1	AM	1172	800	428	528	172	0	700	0
	ERM	1051	800	549	649	51	0	700	0
C1 & C2	AM	1000	1000	600	500	0	0	500	0
	ERM	1010	1000	590	490	10	0	500	0
C1, C2 & H2	AM	972	1000	628	528	172	0	700	0
	ERM	800	1000	800	700	0	0	700	0

Table 5: Stream data for network 3 (CP: heat capacity flow rate)

Stream	CP ($kW/^oC$)	T_{supply} (^{o}C)	T_{target} (^{o}C)
H1	1.0	190	30
C1	1.5	80	160
C2	0.5	20	130