Design, Operation and Control of Resilient Heat Exchanger Networks

Knut W. Mathisen and Sigurd Skogestad[1]
Chemical Engineering
University of Trondheim - NTH
N-7034 Trondheim, Norway

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Abstract

Heat exchanger networks (HENs) constitute an important part of many industrial processes and has been an active area of research for the last 15 years. However, operational and control issues have largely been neglected, and the objective of this paper is to study the effect of these issues one the optimal design. First we formulate the control and on-line optimization problems. We then address bypass placement for control, and show how the controllability depends on the network structure. Then we discuss the flexibility or multiperiod problem To obtain optimal solutions it is necessary to avoid prespecifying the heat recovery level. Surprisingly, it is found for a design example, which has been extensively studied by Gundersen *et al*, (1991), that the size of the process heat exchangers are reduced when flexibility requirements are included, and that the simpler designs with less integration are favored. Controllability considerations also favor the simpler designs as they are easy to control at all operating points.

1 Introduction

The importance of the interactions between process design or process synthesis and process operation and control was first addressed by Ziegler and Nichols (1943) who introduced the term *controllability* as a link between these two areas. They point out that the controller and the process form a unit, and should by considered simultaneously. Perkins (1989), Morari (1992) and Wolff *et al* (1992) review present techniques and methods to address the interactions between process design and process control. Synthesis of heat exchanger networks (HENs) is generally recognized to be the most mature field within process synthesis (e.g., Gundersen and Naess, 1988). HENs are part of most chemical process and the synthesis problem is well-defined. Consequently, HENs is one of the few particular problems where synthesis methods that consider operation and control has been suggested. A number of author discuss design of flexible HENs. Calandranis and Stephanopoulos (1986, 1988) and Kotjabasakis and Linnhoff (1986) suggest an structural or heuristic approach. Floudas and Grossmann (1987) and Papalexandri and Pistikopoulos (1992) formulate the flexibility problem of HENs as a mathematical programming (MP) problem. Morari and coworkers (1982, 1984, 1989) and Cerda and coworkers, (1990a, 1990b, 1991) use a combination of heuristics or insights and mathematical programming. Georgiou and Floudas (1990) and Huang and Fan (1992) address automatic design of controllable HENs, but their approaches are structural, too. They try to design HEN without downstream paths from large (intense) disturbances to critical target. The main idea seems to be similar to breaking a downstream path suggested by Kotjabasakis and Linnhoff (1986). We will try to address both flexibility and controllability and illustrate how these considerations *quantitatively* affect design. Previous results from this research was presented at the Spring National meeting (Mathisen *et al*, 1992).

Importance of control and operation. The HEN is generally considered to be of secondary importance to overall process economics. This is reflected in the hierarchical process synthesis procedure of Douglas (1988) where decisions regarding the reactor and separation systems are taken at a higher level than decisions regarding the HEN. It is important to recognize that this is correct only as long as feasible operation is maintained. Consider, for example, the disastrous effects of overriding temperature safety constraints in nuclear power plants. Thus, it may be argued that operability ought to be the main concern on both operation and design of HEN, not the intensive search to find a new "global" minimum with a marginally lower annualized cost for the nominal operating point.

Organization of paper. In the rest of the paper the following 10 problems of design, operation and control of heat exchangers will be discussed:

I. Control/operation

1. *Control system design.* Find the best control system
2. *On-line optimization.* Find the optimal bypasses and split fractions that minimize the energy cost.

II. Design

3. *Bypass placement for flexibility.* Find the set of bypasses that minimizes the total annualized cost of bypass investment and energy when structure and area are given.
4. *Bypass placement for control.* Find the set of bypasses which is best from a control point of view when structure, area and disturbance ranges are given.
5. *Overall optimization of bypass placement.* Subproblems 3 and 4 are combined.
6. *Area optimization.* Find the optimal installed areas when the structure is given.
7. *Conventional HEN design problem.*
8. *Conventional HEN flexibility design problem.*
9. *Generalized HEN flexibility design problem* (with cost of bypasses).
10. *Overall HEN design.* Dynamic and control issues are included into subproblem 9.

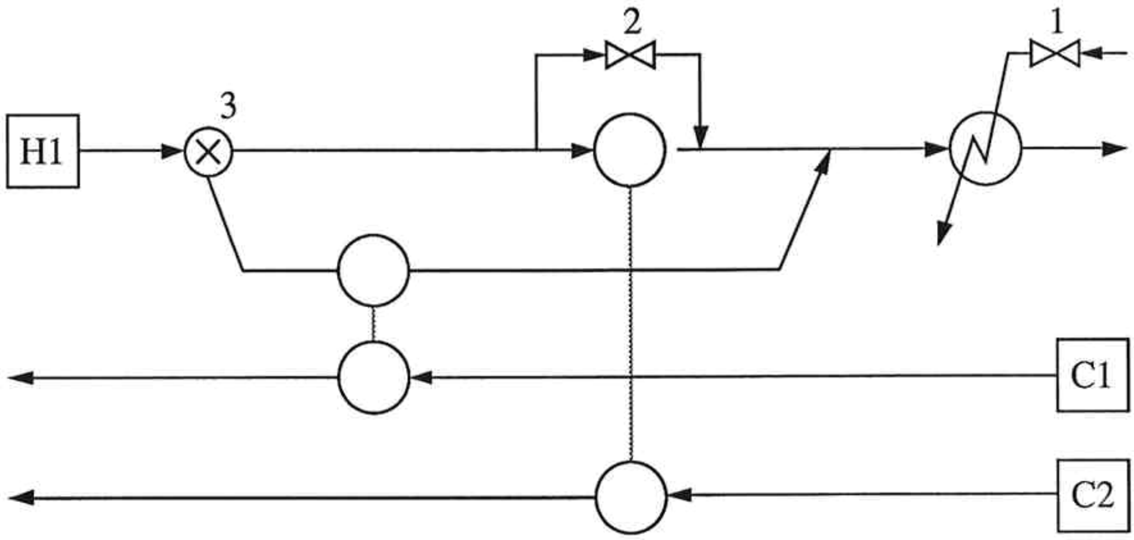

Figure 1: Most used manipulated inputs in HENs

The lists start from the control/operations issues (problem 1 and 2) where the plant (HEN with installed areas and bypass lines) is given and move towards the design issues (3-10) where plant is to be decided. Problem 10 is the appropriate integrated control and design problem. Because this problem is too difficult to solve directly the problems (3-9) are defined and studied to understand the subtasks.

2 Control and operation (problems 1-2)

In order to be able to address the trade-off between design and control in HEN, we will first consider the problems of control and operation. In this section it is assumed that process heat exchanger structure and area are given. Utility exchangers and bypass lines are also fixed.

Degrees of freedom. During operation, degrees of freedom or manipulated inputs are needed for control and optimization. The most usual manipulated inputs in HENs are:

1. Utility flowrates
2. Bypass fractions
3. Split fractions

These alternative manipulated variables are shown in Fig. 1.

The control and operation objectives in HENs. The controlled variables or outputs in HENs may be network outlet temperatures, intermediate temperatures or heat duties. The control and optimization objective will be to keep these outputs

- at their setpoints or targets,
- within a given range, *or*
- as close to a limit as possible (i.e. at maximum or minimum values)

Even when heat duties are to be controlled, the measured variables are stream temperatures. We assume that the control objectives are to keep the network outlet temperatures at their targets.

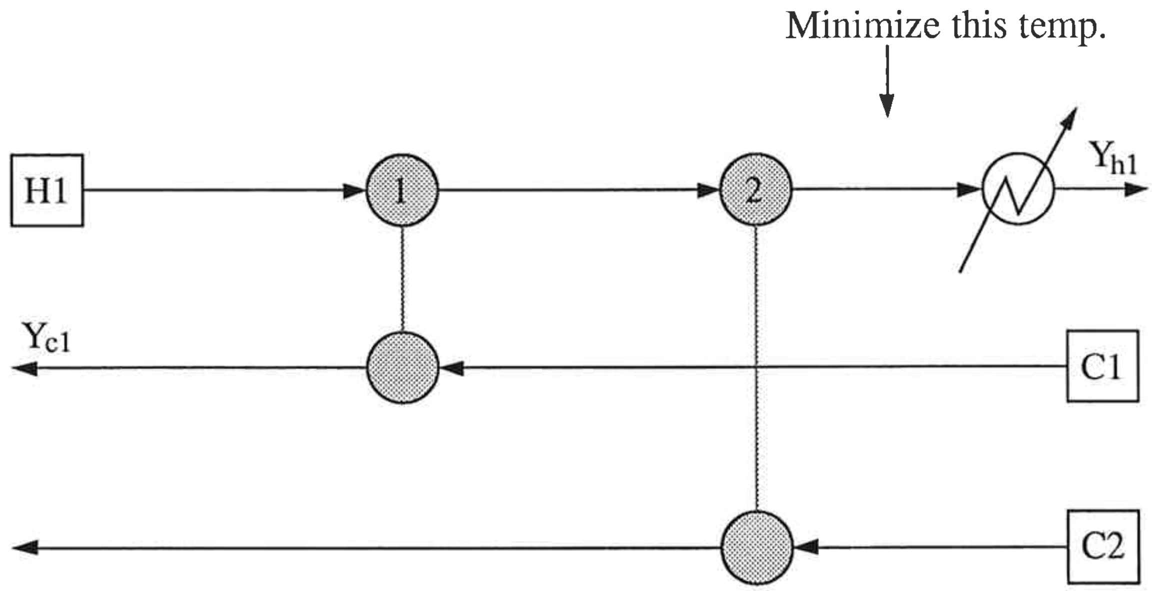

Figure 2: Control and optimization objectives in HENs

For energy optimization the temperatures upstream the utility exchangers are to be as close to the stream target temperatures as possible, see Fig. 2.

Control hierarchy. Decisions concerning control and operation of chemical processes are often taken in a hierarchical manner with 3 levels, (overall) steady-state process optimization, supervisory control and regulatory control. The interactions between the levels are illustrated in Fig. 3. For HENs temperature setpoints are mainly decided from the process optimization level.

The regulatory level manipulates utility flowrates and bypasses with fast effect on the controlled output, mainly to reject dynamic (short-term) disturbances. The regulatory control loops are usually decentralized. Controllability of HENs is the ability to perform efficient regulatory control. The supervisory level manipulates possible splitters and additional bypasses to reject long-term disturbances in an optimal manner (minimize utility consumption) and such that constraints are avoided at the regulatory level. An alternative definition of flexibility of HENs is the ability to perform efficient supervisory control. A resilient HEN must be both flexible and controllable.

Problem 1. Control system design: For a given network with exchangers and bypasses, find the best control system.

We will consider regulatory control with decentralized control loops. Issues are pairing of control loops and controller tuning. This problem is the conventional subproblem handed over from the process engineer to the control engineer. A block diagram is shown in Fig. 4. The disturbances **d** are usually inlet temperatures and flowrates of the process streams; the actuators **u** bypass or split fractions or utility flowrates and the outputs **y** stream temperatures.

The pairing problem in HENs. The main bypass placement rule for control is to manipulate the exchanger duty immediately upstream the controlled temperature. This may done by changing the utility flowrate if the controlled temperature is downstream a cooler or a heater or by changing the bypass flowrate if the controlled temperature is downstream a process heat exchanger. For faster dynamic response the controlled stream should be bypassed. With this rule the pairing

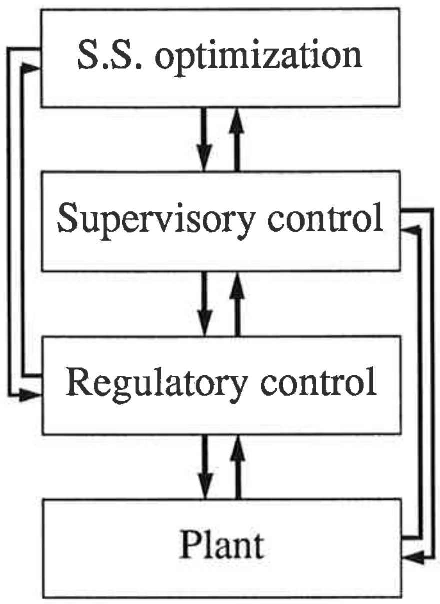

Figure 3: Control hierarchy showing the process optimization, supervisory control and regulatory control levels and the interactions between the levels.

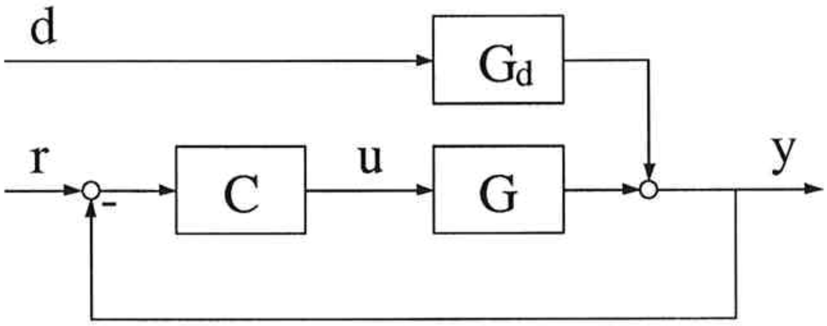

Figure 4: Block diagram

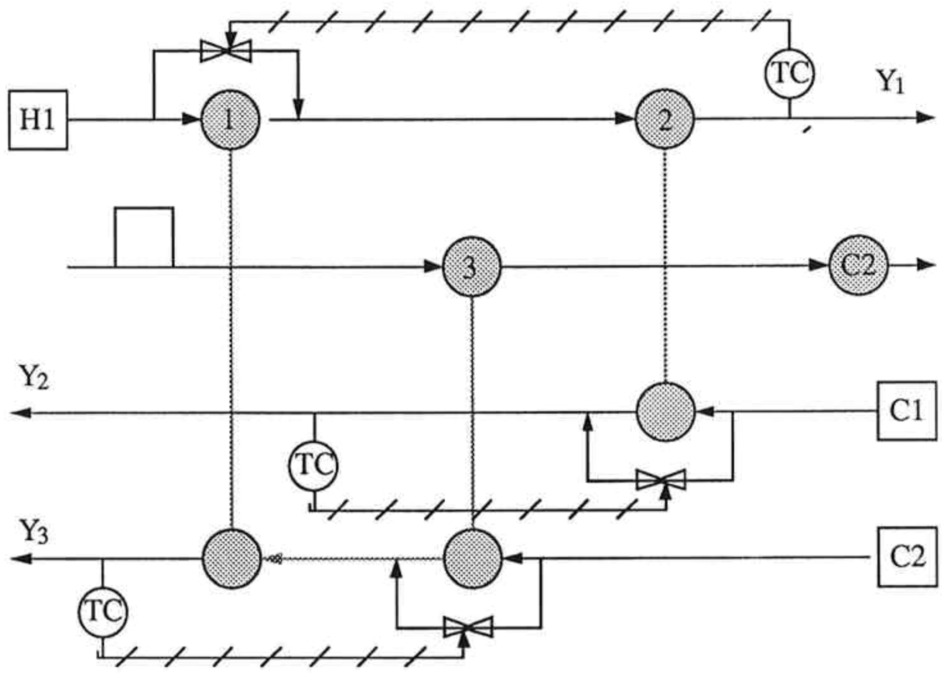

Figure 5: Heat exchanger structure from Saboo and Morari (1984) yielding a difficult 3×3 pairing problem even if all process heat exchangers may be bypassed. One possible single-loop control structure is shown

problem for control is rather simple in most cases. However, in this case one can only manipulate the process heat exchangers with bypass lines so this has important implications for the bypass placement problem discussed later. Furthermore, in some cases it may be structurally impossible to adhere to the main rule even if all process exchangers are bypassed. Such cases yield difficult 2×2 pairing problems (Mathisen *et al*, 1991, 1992).

HENs may also give 3×3 pairing problems, consider for example Fig. 5 from Saboo and Morari (1984). Because both outputs of exchanger 2 are controlled outputs, exchanger 3 must be manipulated although this exchanger have no immediate downstream effect on any of the 3 outputs. Computation of the frequency-dependent relative gain array (RGA) (Bristol, 1966) can be used to decide the pairings for this problem. The main RGA rule is to pair on elements which are close to 1 at high frequency, and to avoid pairings that give negative RGA at steady-state. The appropriate pairings with problem data from Saboo and Morari (1984) are to control output y_1 by manipulating exchanger 1 (on the hot or the cold side), output y_2 with exchanger 2 and output y_3 with exchanger 3. Note that this gives two pairings which are not consistent with the main bypass placement tule. The elements of the RGA for these preferred pairings are plotted as a function of frequency in Fig. 6.

The most important point with this example is however input constraints. The problem with inputs constraints is partly due to problem parameters, but also due to the structure. With the preferred pairings only one of the 3 bypasses have a direct effect so that the G becomes small. The required manipulations for perfect control computed as row sums of $G^{-1}Gd$ are shown in Fig. 7. Since all the variables have been scaled to be in the interval -1 to 1, we see that the required change in bypass for rejecting the disturbances is more than 10 times larger than what is allowed. It is interesting to note that Saboo and Morari (1984) used this example to demonstrate non-convex behavior of HENs. We note that HENs where both outputs of one exchanger are controlled outputs tend to have flexibility problems as well as controllability problems.

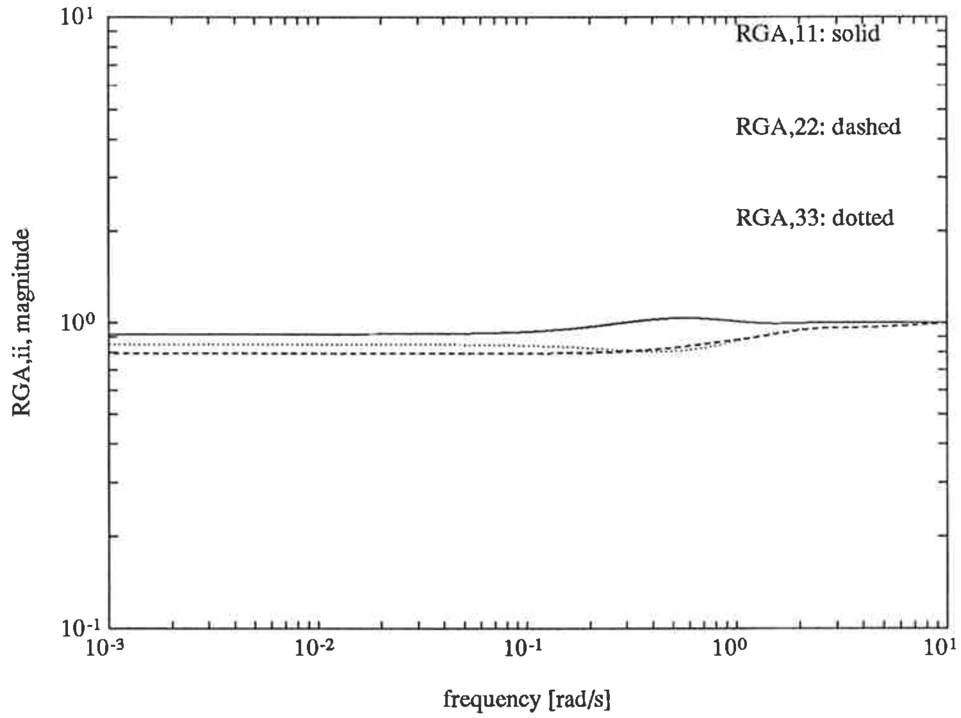

Figure 6: 3×3 pairing problem. Data from example given by Saboo and Morari, (1984). Elements of the RGA for preferred pairings

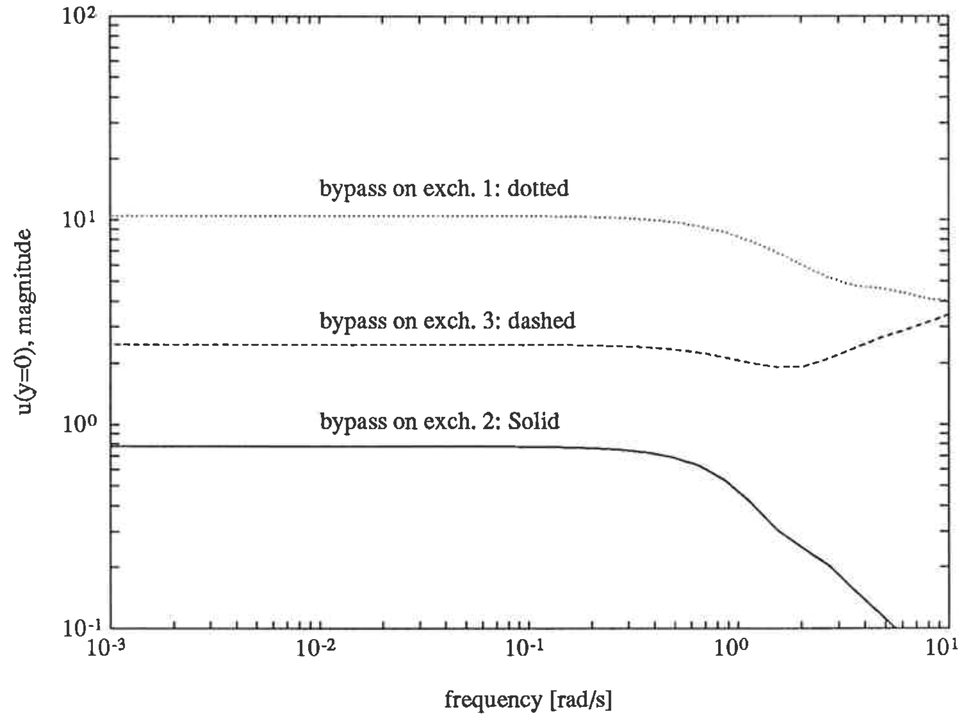

Figure 7: 3×3 pairing problem. Data from example given by Saboo and Morari, (1984). Required manipulations for perfect control; u(y=0) computed as row sums of $G^{-1}Gd$

Problem 2. On-line optimization: For a given HEN and a given (steady-state) operating point with specified outlet temperatures, find the optimal bypasses and split fractions that minimize the energy cost.

Alternatively some other economic objective than energy cost may be used. The optimization may be static or take dynamic disturbances into account.

On-line static optimization. This optimization may be implemented at the supervisory control level. Static optimization of HENs with a single hot and a single cold utility type is a mathematically well-defined problem. Most degrees of freedom will be used to keep the controlled outputs at their setpoints. The remaining degrees of freedom may be exploited by the supervisory control system for on-line optimization. The main tasks for the supervisory control system are resetting of the regulatory control loops to handle constraints and minimization of utility consumption. It is important be aware of the fact that soft targets in design (i.e. the outputs are allowed to vary within a given range) often become hard targets during operation in order to save energy. The optimization problem may be formulated as (Marselle *et al*, 1982; Mathisen *et al*, 1992):

$$\min_{u} \quad (T_{hi}^{t-1} - r_{hi})w_{hi} \quad \text{(minimize hot utility)} \tag{1}$$

subject to

$$T_{hj}^{t} - r_{hj} = 0 \quad \text{(hot and}$$

$$T_{cj}^{t} - r_{cj} = 0 \quad \text{cold target temperatures)}$$

$$r_{hi} - T_{hi}^{t-1} \leq 0 \quad \text{(positive duty coolers}$$

$$T_{ci}^{t-1} - r_{ci} \leq 0 \quad \text{and heaters)}$$

$$-u \leq 0 \quad \text{(bypass and split fractions above 0}$$

$$u - 1 \leq 0 \quad \text{and below 1)}$$

where w is heat capacity flowrate, the T^t's are the temperatures at the network outlet, r_{hi} is the set of hot target temperatures (setpoints) downstream coolers, r_{hj} the set of hot targets r_{ci} the cold targets downstream heaters, r_{cj} the cold targets and u are the manipulated split and bypass fractions. Note that only hot utility is included in the cost function as the cold utility will be given from an energy balance. No upper bound on the utility exchangers are included, but this constraint may easily be added.

Although the task is well-defined mathematically, it may be difficult to implement the proper control strategy to ensure minimum utility consumption without a process model. Marselle *et al* (1982) points out that the utility type (hot or cold) with the fewer units is to be included in the cost function to simplify the optimization.

On-line optimization including regulatory control (dynamic disturbances). For this problem, the performance specifications in terms of response times and allowed dynamic deviations are also given. The problem is then to find the optimal bypass and split fractions that minimize the energy cost and fulfills the performance specifications. A simplified approach is to consider it mainly as a static problem at supervisory control level and take into account that a minimum bypass flow, u_{reg}^{min}, is needed to reject dynamic disturbances at the regulatory control level. The dynamic disturbances are then handled by the regulatory control level. One approach is that the supervisory level resets the regulatory controls (i.e. bypass fractions) to their ideal resting value (IRV).

The optimization problem can then be stated as:

$$\min_{u} \quad (T_{hi}^{t-1} - r_{hi})w_{hi} \tag{2}$$

subject to

$$T_{hj}^{t} - r_{hj} = 0$$
$$T_{cj}^{t} - r_{cj} = 0$$
$$r_{hi} - T_{hi}^{t-1} \leq 0$$
$$T_{ci}^{t-1} - r_{ci} \leq 0$$
$$-u_{sup} \leq 0$$
$$u_{sup} - 1 \leq 0$$
$$u_{reg}^{min} - u_{reg} \leq 0$$
$$u_{reg}^{min} + u_{reg} - 1 \leq 0$$

where w is heat capacity flowrate, the T^{t}'s are the temperatures at the network outlet, r_{hi} is the set of hot target temperatures (setpoints) downstream coolers, r_{hj} the set of hot targets, r_{ci} the cold targets downstream heaters, r_{cj} the cold targets, u_{sup} the split and bypass fractions used for supervisory control and u_{reg} the split and bypass fractions used for regulatory control. The last constraints give $u_{reg}^{min} \leq u_{reg} \leq 1 - u_{reg}^{min}$. The problem above is defined as an open-loop optimization problem. In practice, one should use a problem formulation that allows for feedback, for example, about the actual values of u_{reg}, which are determined by regulatory feedback control loops. In addition, this optimization problem will often be non-unique (extra degrees of freedom). One may then enforce the requirement $u_{reg} = u_{reg}^{IRV}$, i.e., exploit the extra degrees of freedom to reset the regulatory bypass fractions to their ideal resting values (IRV).

A typical open loop disturbance transfer function for HENs is given in Fig. 8. From the figures it is seen that the disturbance gains get close to the steady-state values at frequencies around $10^{-2} rad/s$. Because the supervisory control system is usually slower than this, this means that the regulatory control system must reject almost the full effect of the disturbances. This is especially true for gas streams where the typical dwell times are approximately an order of magnitude less than for liquid streams. Thus, steady-state considerations and expected magnitude of the dynamic disturbances may be used to compute the minimum bypass needed u_{reg}^{min}.

3 Design

Ideally, one should use an integrated approach to design where all factors such as capital costs, operation, control, bypass placement etc. are considered simultaneously. An integrated design approach may be compared with the traditional approach:

1. Perform a conceptual HEN design for the nominal or expected worst case operating point.

   Select heat recovery level

   Derive a superstructure or a pinch design

   Derive the network structure

   Optimize the exchanger areas and split fractions

2. Perform detailed heat exchanger calculations.

   Heat transfer coefficients are updated

   Exchanger driving forces are updated (no. of shells per exchanger, no of tube passes per shell pass)

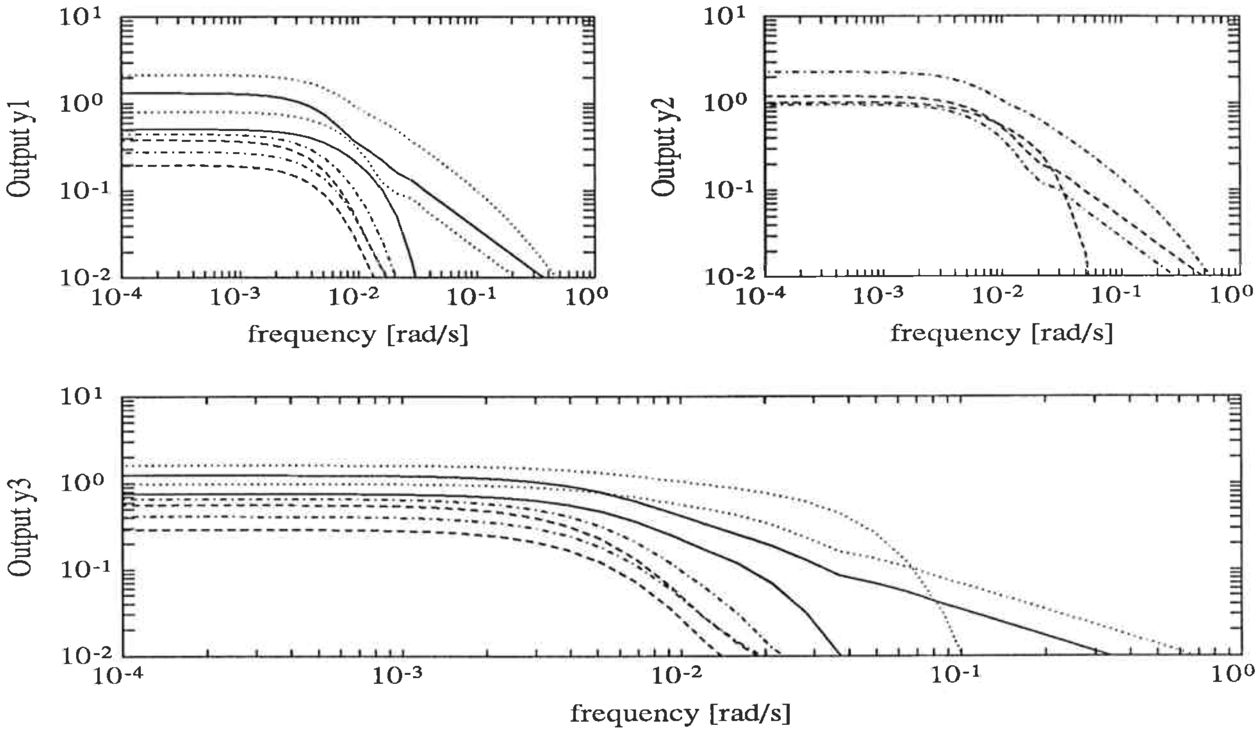

Figure 8: Typical open loop disturbance transfer function for HEN (elements of G_d). Data from example 3.2 by Townsend and Morari (1984). Disturbances are the the four inlet temperatures and the four flowrates

3. Consider operability

   Add area on heat exchangers that are to be bypassed and used for control.

   Add area on heat exchangers and/or utility exchangers to fulfill flexibility requirements (including start-up).

The resulting design from this sequential approach may be far from the overall optimal design. Jegede (1990) has made an important contribution towards integrating conceptual HEN design and detailed heat exchanger calculations. We will discuss the implications of adding flexibility and controllability requirements during conceptual design in the rest of the paper.

If we return to our list of 10 problems in the introduction, then problem 10 is the "integrated approach". However, because a completely integrated approach seems unrealistic, and because we need to better understand the trade-offs involved, we will also consider the subproblems 3-9 given in our list.

3.1 Bypass placement and area optimization (problems 3-6)

A target for the number of bypasses (Mathisen *et al*, 1992). Consider a general HEN with

- N_{hx} process heat exchangers
- N_s controlled outputs ("hard" targets)
- N_u utility exchangers
- N_{spl} splitters
- N_u' utility exchangers where the duty drop to zero for some operating point

An upper bound on the number of bypasses will usually be the given by the number of process exchangers as there cannot be more than one degree of freedom per exchanger. If utility exchangers and splitters are used as manipulated variables wherever possible, one needs at least $N_s - N_u + N'_u - N_{spl}$ bypasses to be able to control the rest of the outputs. The number of bypasses N_{byp} will then be:

$$N_s - N_u + N'_u - N_{spl} \leq N_{byp} \leq N_{hx} \tag{3}$$

where the lower bound is the target number of bypasses.

Problem 3. Bypass placement for flexibility: For a given network and for a given set of possible steady-state operating points, find the set of bypasses that minimizes the total annualized cost (TAC). The cost of bypasses must be included otherwise one may simply place bypasses on all exchangers.

The flexibility of HENs increase with the number of bypasses installed. Installation of bypasses (and control loops) may however be expensive, and we would like to point out that installing extra area of an upstream exchanger or increase operating cost may be an alternative to installing bypasses without decreasing flexibility (Mathisen *et al*, 1992). This may be desirable, because it may make it possible to only install bypasses for control, i.e., to use the same bypasses for control and flexibility.

Problem 4: Bypass placement for control: Find the set of bypasses which is best from a control point of view when structure, area and disturbance ranges are given.

Appropriate bypass placements for control. As mentioned above in the discussion of the control problem, the main bypass placement rule for control is to place (single) bypasses such that they have a direct effect. This rule adhere with general recommendations on selection of control configuration (Morari *et al*, 1980), specific recommendations for HENs (Calandranis and Stephanopoulos, 1988) as well as results from structural approaches (Georgiou and Floudas, 1990; Daoutidis and Kravaris, 1992). In particular it is undesirable to control "horizontally across" an exchanger, e.g. bypass an exchanger upstreams the exchanger where the outlet temperature is to be controlled, see Fig. 9. The considerable deadtime in heat exchangers make fast control impossible. Comparison of these bypass placements cannot be done without a dynamic model.

Not adhering to the main bypass placement rule may result in undesired properties (singularities) as outlined below.

Parametric singularity I: Multiple downstream paths. For the case with multiple downstream paths from the manipulated exchanger to the controlled output stream inverse response may occur (Mathisen *et al*, 1991). Also for some intermediate operating point the steady-state gain may become zero.

Structural singularity I: Bypasses on both hot and cold side. One cannot place single bypasses on both sides of a heat exchanger because G becomes singular (i.e. only one degree of freedom per exchanger). For example, placing single bypasses on both sides of exchanger 2 in Fig.5 must be disallowed.

Parametric singularity II: Two controlled outputs on one exchanger. In cases where both outputs of one heat exchanger are controlled outputs, the structure of the process heat exchangers make it impossible to adhere to the main rule for bypass placement. For such structures, it is recommended that at least one of the inputs bypasses the exchanger. Otherwise we get a system with the general structure shown in Fig. 10. In practice this is equal to controlling the outlet temperatures by manipulating the inlet temperatures, and this yields a 2×2 system that become singular at steady-state (Reimann, 1986) when the outlet temperatures are equal.

Structural singularity II: Two controlled outputs on one exchanger. Above, we explained how not bypassing a heat exchanger with two outputs yield singularity for some operating point. Not

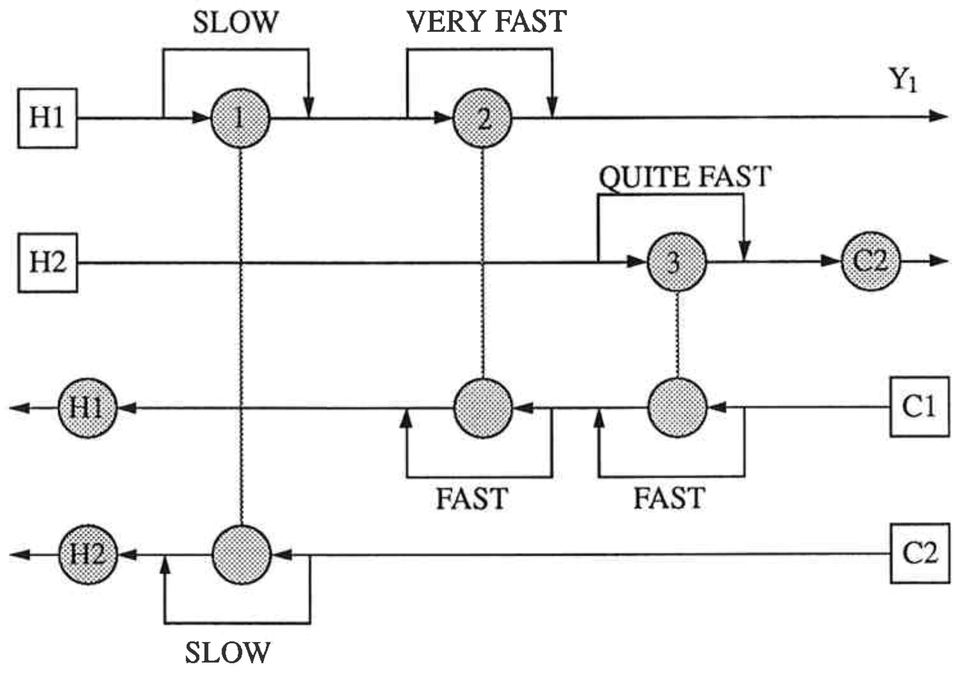

Figure 9: Desirable (very fast), possible (fast or quite) and undesirable (slow) bypass placements for control.

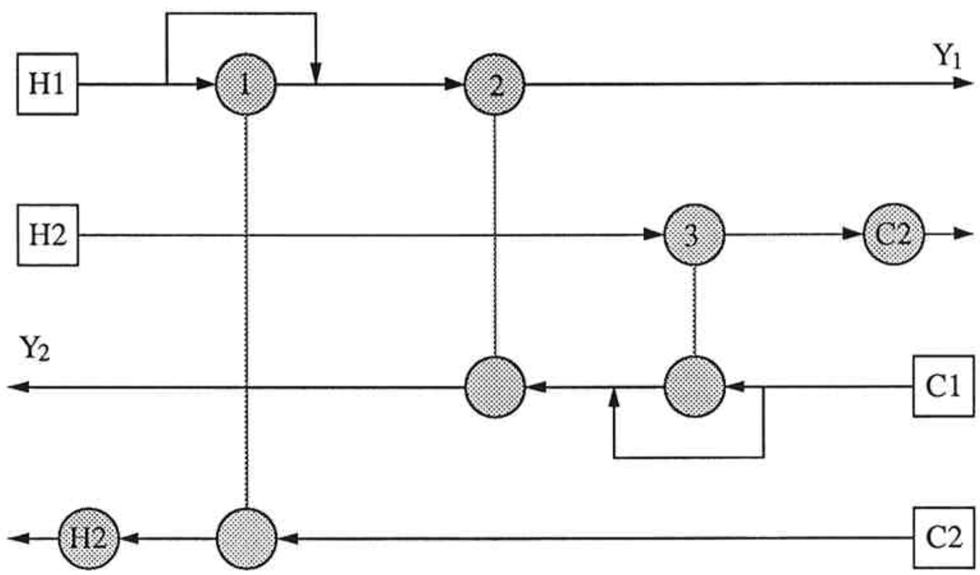

Figure 10: Parametric singular system (for $y_1 = y_2$) when both outlet temperatures of one exchanger are controlled and this exchanger is not bypassed.

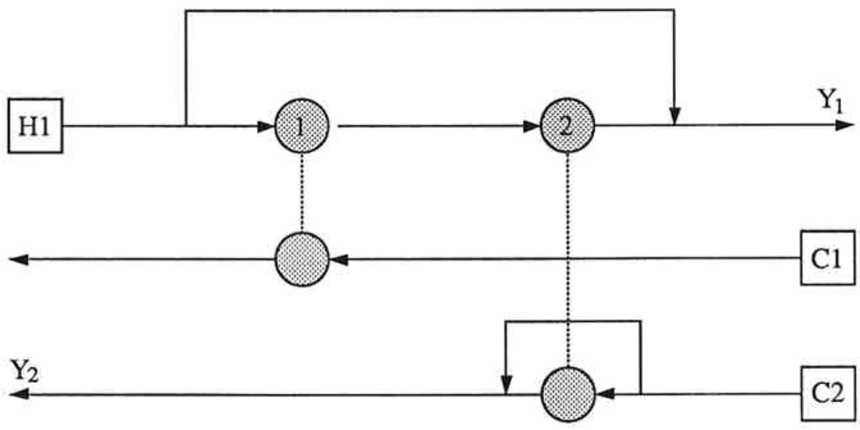

Figure 11: Multibypass may be used to comply with main bypass placement rule

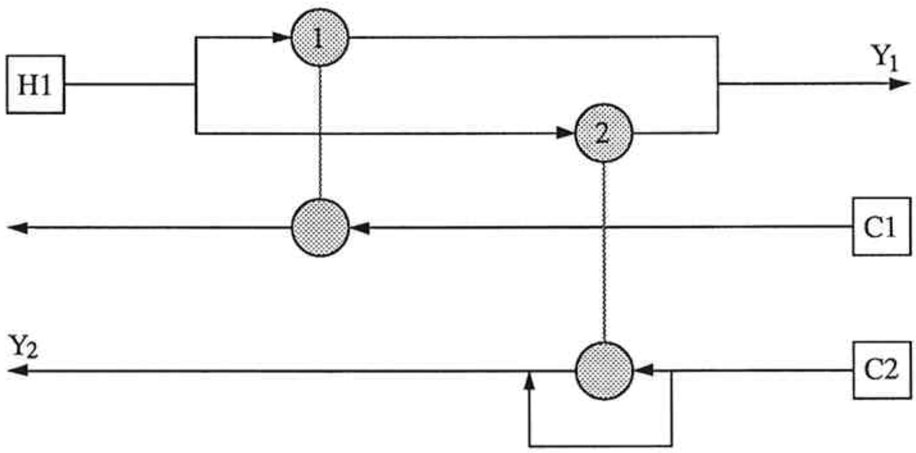

Figure 12: Example split design

bypassing a heat exchanger where both outlets are to be controlled give a *structural* singular system if both manipulated variables affect the outputs through the same downstream path (Mathisen *et al*, 1991).

Parametric singularity III: Multibypass. When both temperatures out of one heat exchangers are controlled outputs, multibypass may always be used to comply with main bypass placement rule. System approaches singularity as duty of exchanger 1 is decreased compared to duty of exchanger 2, see Fig.11. Installation of multibypasses will always make it possible to get a direct effect and a fast response, but cannot reduce problems with input constraints.

Parametric singularity IV: Splitters as manipulated inputs. Split fractions may be used as manipulated inputs instead of bypass fractions. In general, split fractions should be used for static optimization (flexibility) and should be avoided for control. As an example consider the network in Fig. 12. The split fractions may be used to control output y_2, but not output y_1 because of the competing effects of the two branches. For operating points where the split fraction is optimized to yield minimum outlet temperature, the response may be inverse, see Fig. 13. Thus, for some intermediate operating point the steady-state gain will become zero.

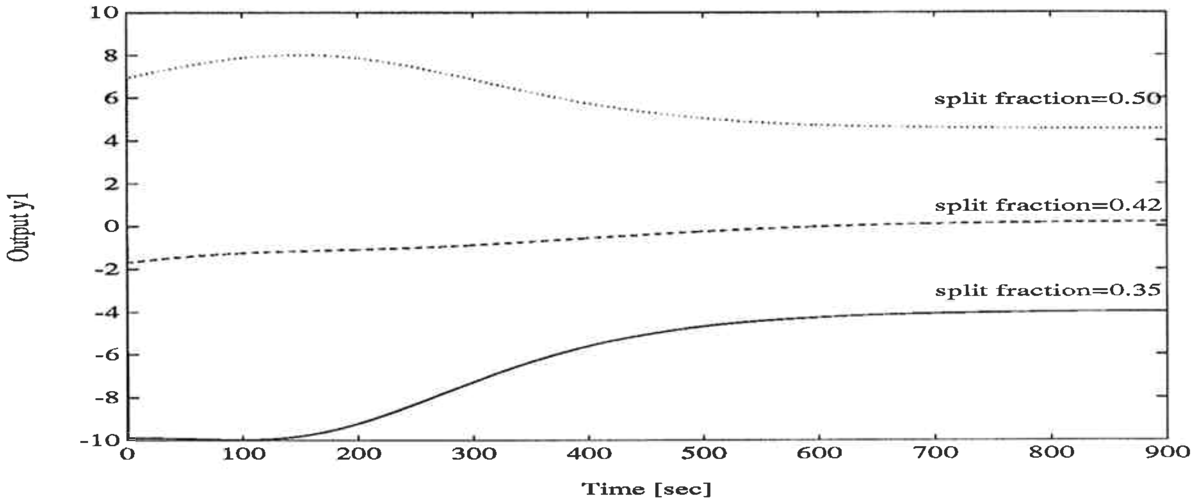

Figure 13: Sign of gain dependent on operating point. Intermediate operating point gives inverse response.

Comment: The structural approach of Georgiou and Floudas, (1990) may be used to avoid bypass placements that give structural singularity, but cannot detect parametric singularities.

Problem 5. Overall optimization of bypass placement: Find the optimal bypass placement for a given network considering both control and flexibility.

This problem combines subproblems 3 and 4 above. The bypasses for (regulatory) control are usually single bypasses with direct effects on the corresponding outputs (decentralized control system assumed). The best bypass placement for flexibility may however quite often be to bypass an exchanger further upstream the controlled output. Fig. 11 was previously used to illustrate how multibypass may be used to adhere to main bypass placement rule for control when both outlet temperatures of one heat exchanger are controlled outputs. If only the hot outlet of exchanger 2 was to be controlled the bypass placement for control would be to put a bypass on the hot side of this exchanger. However, if exchanger 1 is large compared to exchanger 2, bypassing exchanger 1 will usually be preferable to bypassing exchanger 2 from flexibility considerations. In such cases a multibypass may be good solution.

So, usually it is possible to obtain separately the best bypass set for flexibility and the best bypass set for controllability. The difficulty arises when these (usually different) sets are to be combined. There are at least three different approaches:

1. The outer union of the two optimal sets, i.e. the bypass placments for flexibility and control are combined directly.

2. The minimum outer union of all possible sets, i.e. generate all possible bypass sets for flexibility and all possible sets for control and select the sets with maximum overlap.

3. Find the best overall sets by simultaneous consideration of both flexibility and controllability. This approach requires that the relative importance of flexibility versus controllability is quantified.

The necessary number of bypass placements for control and flexibility (e.g. computed as in approach 1) may be used to discriminate between alternative HEN designs. Designs with the number of bypasses equal to the target number of bypasses are preferred. Designs that are flexible by only manipulating the direct effect bypasses for control and possible splitters are desirable.

Problem 6. Area optimization: Find the optimal exchanger areas and split and bypass fractions for a given heat exchanger structure.

In subproblems (3-5) bypass placement was considered assuming that both network structure and installed area was fixed. In practice the bypass placement influence the optimal distribution of area in the network. Bypass placement and area optimization should therefore be considered simultaneously.

One (steady-state) operating point. Conventional HEN synthesis for one (nominal) operating point yields a well-defined area optimization problem when the structure is given:

$$\min_{A_{hx},u} \quad C_{hx} + C_{uhx} + C_{util} \quad \text{(minimize capital and operating cost)} \tag{4}$$

subject to

$$\begin{aligned}
T^t_{hj} - r_{hj} = 0 &\quad \text{(hot and} \\
T^t_{cj} - r_{cj} = 0 &\quad \text{cold target temperatures)} \\
A_{hx} - Q_{hx}/(U\Delta T_{lm}) = 0 &\quad \text{(countercurrent process heat exchangers)} \\
A_{uhx} - Q_{uhx}/(U\Delta T_{lm}) = 0 &\quad \text{(countercurrent utility exchangers)} \\
-Q_{hx} \leq 0 &\quad \text{(positive duty process heat exchangers)} \\
r_{hi} - T^{t-1}_{hi} \leq 0 &\quad \text{(positive duty coolers} \\
T^{t-1}_{ci} - r_{ci} \leq 0 &\quad \text{and heaters)} \\
A_{hx} - A^{max}_{hx} \leq 0 &\quad \text{(max process heat exchanger size)} \\
A_{uhx} - A^{max}_{uhx} = 0 &\quad \text{(max utility exchanger size)} \\
-u \leq 0 &\quad \text{(split fractions above 0} \\
u - 1 \leq 0 &\quad \text{and below1)}
\end{aligned}$$

where A_{hx} is the process heat exchanger areas, u the split factors, the T^t's are the temperatures at the network outlet, r_{hi} is the set of hot target temperatures (setpoints) downstream coolers, r_{hj} the set of hot targets r_{ci} the cold targets downstream heaters and r_{cj} the cold targets. C_{hx} is the annualized capital cost for the process heat exchangers, computed as $(C_1 + C_2 * A^m_{hx}) * F_{install} * F_{payback}$ where C_1, C_2 and m are constants, $F_{install}$ is installation factor and $F_{payback}$ the inverse of the payback time. C_{uhx} is the annualized capital cost for the utility exchangers, computed similarly. C_{util} is the annual utility cost computed as $(C_{HU} * Q_{HU} + C_{CU} * Q_{CU}) * F_{online} * 8760$ where C_{HU} and C_{CU} and Q_{HU} and Q_{CU} are the unit costs and duties of hot and cold utility, respectively. F_{online} is the online factor which multiplied by hours per year (8760) gives the number of operating hours per year. Note that there is no constraint on the heat recovery level.

Even though the problem is well defined, obtaining the minimum cost solution may be difficult due to non-convexities arising from the use of logarithmic mean temperature differences (countercurrent heat exchange) and economy of scale exchanger capital cost laws (the exponent m is less than unity).

A discrete set of (static) operating points. This correspond to the multiperiod or multiple base case formulation. A discrete set of operating points typically arises from feedstock changes and changes in product specifications. As a result inlet and outlet temperatures and flowrates of the streams vary. The optimization problem is formulated similarly as Eq. 4, but the utility cost is computed in proportion to the operating time at each operating point, and bypasses around the process heat exchangers are included. The setpoints or target temperatures r and split and bypass fractions u may vary with operating point and becomes matrices.

We use this problem formulation below in design illustration 2.

A continuous set of (static) operating points. A continuous set of operating points typically arises from catalyst deactivation and exchanger fouling. In order to formulate an optimization problem, some sort discretization or simplification is necessary. We propose 3 alternative ways:

1. Select a discrete set of operating points equally distributed throughout the operating parameter space and compute operating cost as the sum of the individual contributions. Suitable if all operating points are approximately equally probable, for example through a linear degradation of heat transfer coefficient(s). Operating cost accuracy and problem complexity grow with the number of discrete operating points so there is a trade-off.

2. Compute operating cost from the most probable operating point. Suitable if the operating costs vary little throughout the parameter range and/or operating periods far away from the nominal operating point are short.

3. Compute operating cost from the worst case operating point. Suitable if it is unknown or uncertain where in the parameter space one will be operating.

Generalization to include bypass placements. This generalization extend the area optimization to include subproblem **??**. In the problems described above the cost of the heat exchangers are associated with the installed area only. Usually, many exchangers in HEN are equipped with bypass lines to increase operability. The capital and installation cost of bypass lines may be significant compared to exchanger cost. When the cost of bypass lines is included, there will be an incentive to minimize the number of bypasses.

Generalization to include controllability. This generalization extend the area optimization to include the on-line (dynamic) optimization problem defined by Eq. 2.

3.2 Design problems including the network structure (problems 7-10)

Traditionally, the design or synthesis of heat exchanger networks is involve three sequential tasks, selection of heat recovery level, selection of network structure and optimization of area distribution. The tasks are interdependent and should be considered simultaneously to ensure overall optimality. Even with fixed problem parameters, the simultaneous optimization number of units, heat recovery level, heat load distribution and network structure yields a difficult, combinatorial problem. When flexibility and controllability requirements are included the complexity is prohibiting except for very simple example problems.

Problem 7. Conventional HEN design problem: For a given steady-state operating point, find the optimal network structure and installed areas that minimize TAC.

This problem is very-well stated and studied extensively in academia, a recent review (Gundersen and Naess, 1988) include several hundred papers. The global optimal solution is still difficult even for small literature examples due to topology traps (when using the Pinch Design Method) or non-convexities (when using mathematical programming), see Gundersen *et al* (1991).

Problem 8. Conventional HEN flexibility design problem: For a given set of steady-state operating points, find the optimal network structure and installed areas that minimize TAC.

The set of operating points may be discrete set (multiple base cases or multiperiod formulation) or continuous set (parameter range or resiliency formulation). This problem was first formulated by Marselle *et al*, 1982.

Problem 9. Generalized HEN flexibility design problem: Cost of bypasses and control loops are included into subproblem 8.

Cost of bypasses and control loops may be high and ought to be taken into consideration at an early stage. The cost depend on labour cost, layout, stream characteristics (different composition, flowrate, pressure and temperature requires different materials of construction and dimensions). It may be included by using different cost equations or different installation factors. We recommend to use different cost equations because the most important cost factor for heat exchangers are materials of construction and pressure class. In addition to this it is possible to relate the bypass cost to the installed area, and larger heat exchangers will usually be more expensive to bypass.

Problem 10. Overall HEN design problem: For a given set of steady-state operating points with specified dynamic disturbances and performance requirements and utilities, find the optimal network structure, installed areas and control configuration that minimize total annualized cost of investment and operating costs.

Dynamic and control issues are included into subproblem 9. The investment cost should include heat exchangers, piping (bypasses and splitters) and control system. Operating cost include cost of utilities and possibly maintenance of control loops.

3.3 Design illustration 1: Controllability of flexible designs

Consider Design 1, 2 and 3 of Problem 4 from Townsend and Morari (1984) in Fig. 14 who concluded from a flexibility point of view that either design 2 or design 3 are acceptable (they used the term resilient). the control problem is that all target temperatures are to be kept constant under disturbances in inlet temperature of cold stream 2. Assuming that utility exchangers are used as manipulated inputs throughout the operating range, at least 2 bypasses must be installed as degrees of freedom during operation. Previous experience make it possible to select appropriate single bypass placements for regulatory control as shown in Fig. 14. With these bypasses, the ability to reject dynamic disturbances of the three designs are compared. The necessary input for perfect control are shown in Fig. 15 whereas the infinity norm of the closed-loop disturbance gains (Hovd and Skogestad, 1992) are shown in Fig. 16.

Conclusion: Controllability of design 1 is worse than designs 2 and 3 from input constraints. The result from the linear tool $G^{-1}G_d$ is similar to the result from the non-linear computation of flexibility by Townsend and Morari (1984). Controllability of design 2 is better than design 3 from the CLDG. The difference is due to the structure of design 2 making it impossible to install bypasses with direct effects. The important point with this illustration is that flexible design may have quite different control characteristics.

3.4 Design illustration 2: Operability of nominally optimal designs

We consider a simple four-stream example studied by Gundersen *et al* (1991). The stream and cost data are given below:

Stream	$T_{in}[^oC]$	$T^t[^oC]$	$w[kW/^oC]$	$h[W/m^2,^oC]$
$H1$	150	60	20	100
$H2$	90	60	80	100
$C1$	20	125	25	100
$C2$	25	100	30	100

Annualized cost of process heat exchangers (C_{hx}) and utility exchangers (C_{uhx}):

$$(C_1 + C_2 * A_{hx}^m) * F_{install} * F_{payback} = 8600 + 670A_{hx}^{0.83}) * 3/3$$

Cost of utilities (C_{util}):

$$(C_{HU} * Q_{HU} + C_{CU} * Q_{CU}) * F_{online} * 8760 = (3e{-}5 * Q_{HU} + 3e{-}6 * Q_{CU}) * 8600$$

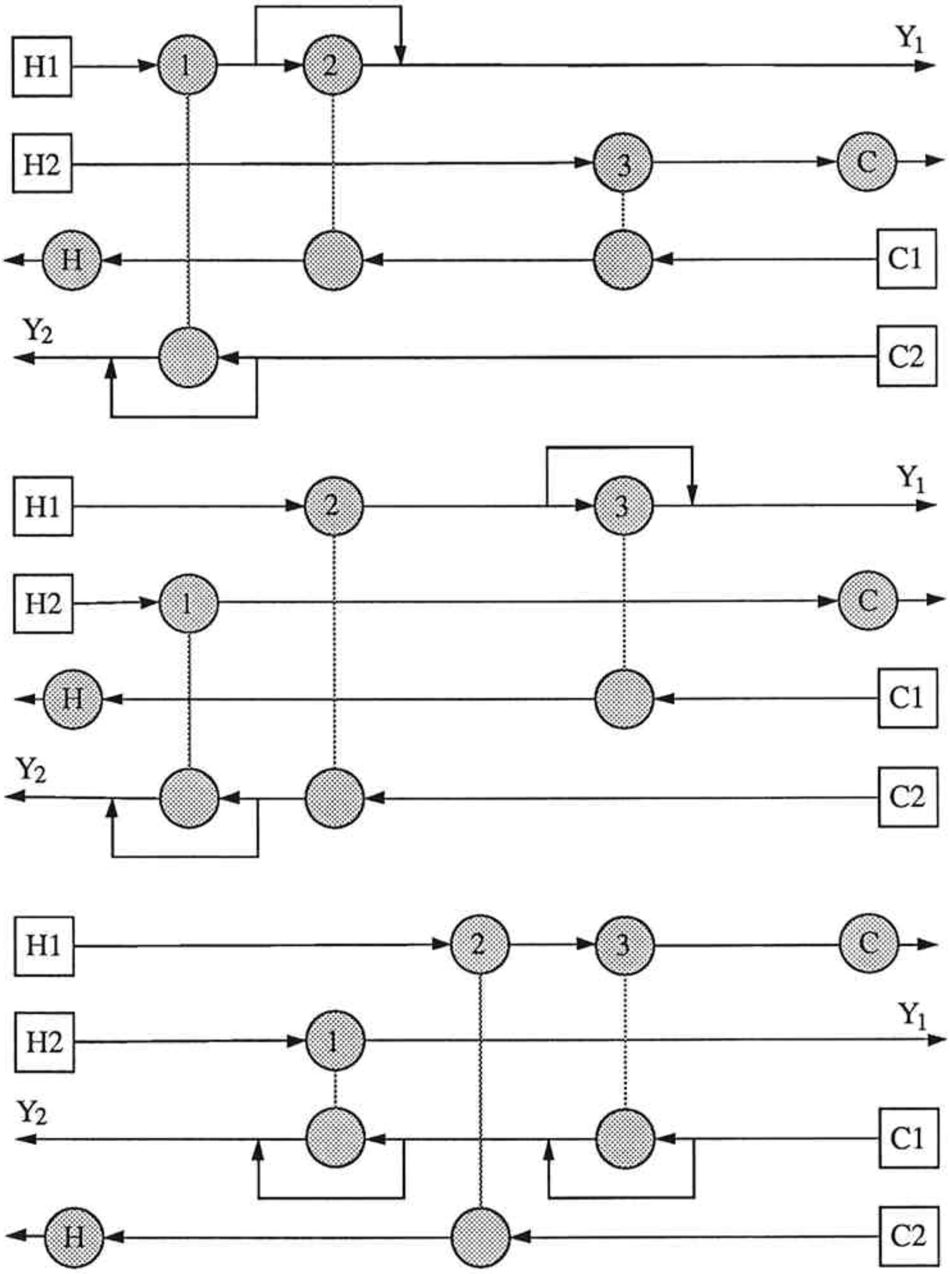

Figure 14: Design 1 (non-resilient) and designs 2 and 3 (resilient) of Problem 4 in Townsend and Morari (1984).

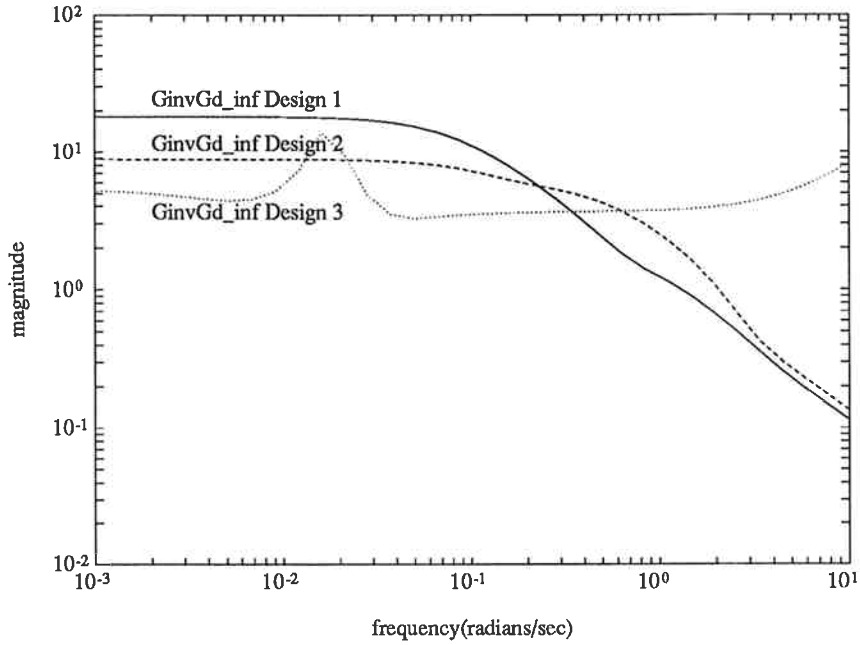

Figure 15: Design 1 (non-resilient) and designs 2 and 3 (resilient) of Problem 4 in Townsend and Morari (1984). The necessary input for perfect control computed as $(G^{-1}G_d)_{\text{inf}}$.

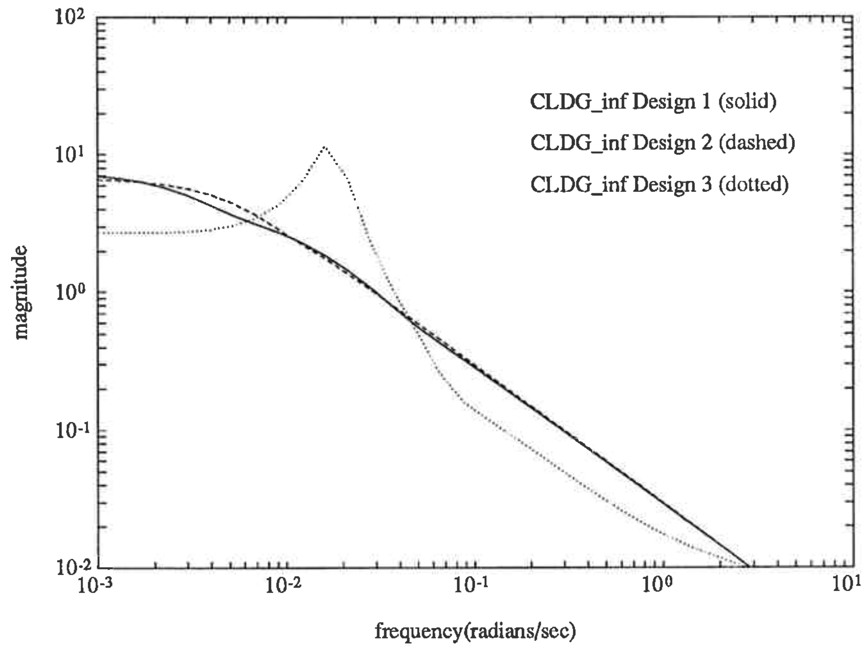

Figure 16: Design 1 (non-resilient) and designs 2 and 3 (resilient) of Problem 4 in Townsend and Morari (1984). The infinity norm of the closed-loop disturbance gains, $(G_{diag}G^{-1}Gd)_{\text{inf}}$

Gundersen *et al* (1991) considered a number of alternative heat load distributions and network structures varying both the heat recovery level and the number of units. Nominal stream parameter values are given in Fig. 17, where the best nominal designs with four, five and six units are shown. We will use this example to address some questions concerning flexibility and controllability of nominally optimal or near-optimal designs:

Are nominally near-optimal designs approximately equally easy to control?
Are nominally near-optimal designs approximately equally flexible?
Are the nominally near-optimal designs sensitive to low load operation.
Can flexible designs be derived from nominally near-optimal designs?
Are these flexible designs optimal?
Are these flexible designs sensitive to operation time at each operating point?
Are these flexible designs sensitive to including flow-dependent heat transfer coefficients?
Are the results sensitive to the number of bypasses installed?
Are these flexible designs easy to control (at all operating points)?

Nominal designs. Let us first study the best four, five and six unit designs given by Gundersen *et al* (1991). The four unit design is a threshold solution, the five unit design was obtained by exhaustive search and the six unit design from mathematical programming based on the stage-wise superstructure by Yee and Grossmann (1990). The following structural similarities are recognized:
1) All designs have 3 process heat exchangers 2) All designs have one process heat exchanger on stream $H1$ and two on $H2$
3) No cooler on stream $H1$
The designs are denoted 4P134, 5S234 and 6S143, where the first digit gives the total number of units, the letter indicate parallel or serial structure and the three final digits are the process heat exchanger numbers, ordered from left to right in the grid diagram. By convention exchanger 1 match stream $H1$ and $C1$, exchanger 2 $H1$ and $C2$ and so on. Process heat exchanger cost C_{hx}, utility exchanger cost C_{uhx} and operating cost C_{util} for the three designs are given in Tab. 1 below

	1	2	3	4	5	6	7
Design	4P134	5S234	6S143	6P134	5S14	5S23	6S21S43
C_{hx}	856.5	535.6	595.9	591.5	434.4	400.6	629.1
C_{uhx}	511.7	148.3	139.8	142.9	207.1	222.2	122.2
C_{util}	174.2	314.2	266.8	273.0	402.1	441.2	258.4
TAC [$k$$]	1081.8	998.1	1002.4	1007.4	1043.7	1064.0	1009.7

Table 1: Cost for nominal designs. Example from Gundersen *et al*, (1991).

In Tab. 1 we have also included four other network structures. Among the other possible designs with three process heat exchangers, we consider design $6P134$, which is a variation of design $6S143$ with exchangers 3 and 4 in parallel. We also consider two very simple designs with only two process heat exchangers, $S14$ and $S23$. These designs may have been the result if one did not use pinch technology or mathematical programming. Finally, we have included one of the designs with 4 process heat exchangers. i.e. $6S21S43$.

The threshold solution $4P134$ requires large process heat exchangers (C_{hx} is large), and is the most expensive design in terms of total annualized cost (TAC). The simple designs with 2 process heat exchangers (i.e. $5S14$ and $5S23$) are less expensive, but still not near-optimal because of higher cost of utility exchangers (C_{uhx} and larger utility consumption (C_{util}) than

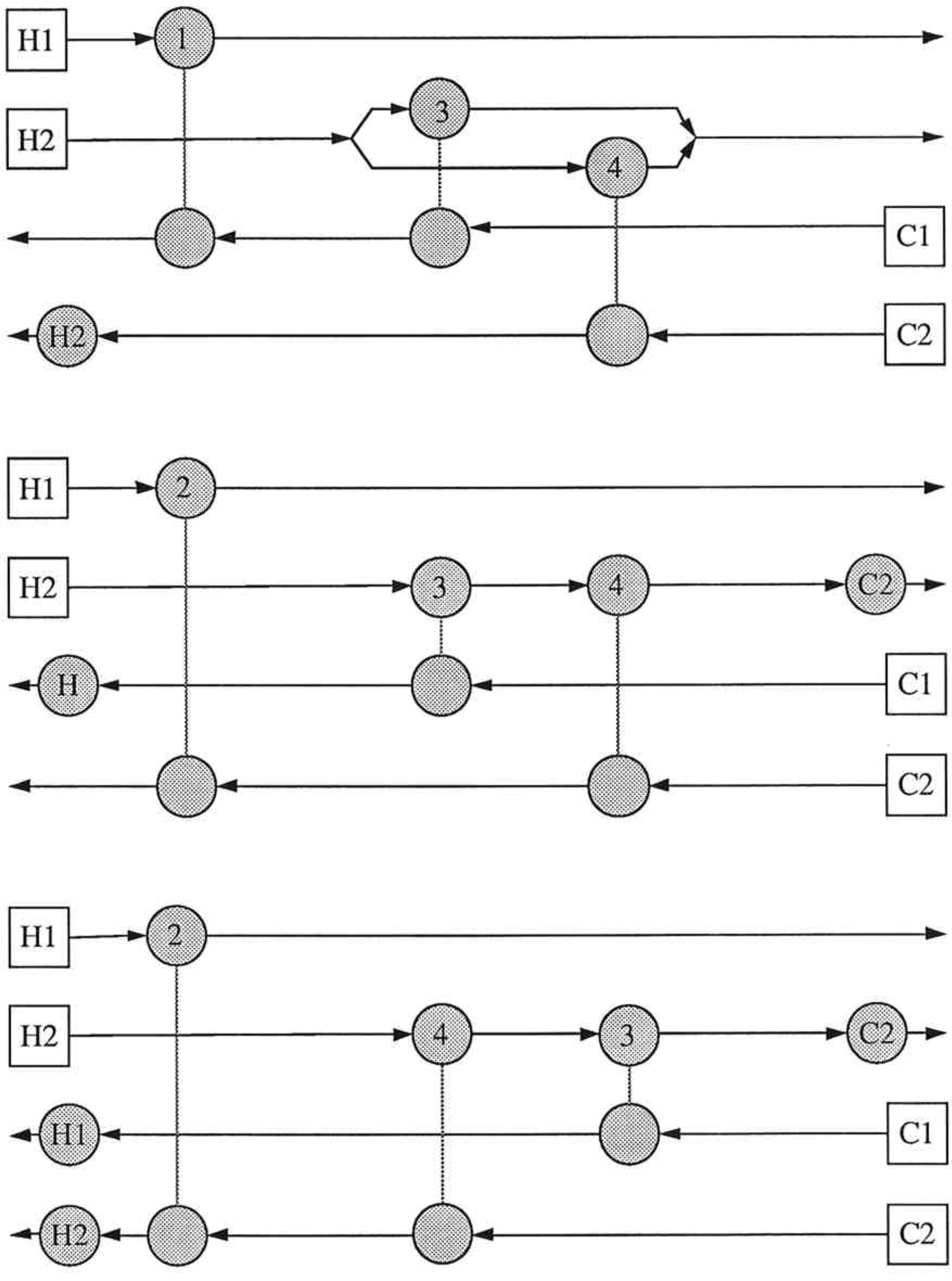

Figure 17: The best designs with four, five and six units from Gundersen *et al* (1991)

the best designs. The other four designs have a better trade-off between capital cost and utility consumption resulting in "near-optimal" TAC (within 1%).

Are nominally near-optimal designs approximately equally easy to control? No. For example, design $6S143$ with three utility exchangers is easy to control, whereas designs $5S234$ and $4P134$ are very difficult to control. The latter designs are difficult to control because both outputs of one exchanger are controlled outputs and this exchanger straddles pinch. For this problem (as for most practical problems) there are several designs which only differs marginally in cost, and it can be recommended to use controllability to choose between nominally near-optimal designs. Preferably controllability should be analyzed as suggested in a previous paper (Mathisen *et al*, 1991) but a simpler qualitatively comparison of near-optimal designs may be performed as follows:

1. Avoid designs where both outlets are controlled outputs

2. Prefer designs with many utility exchangers

Are nominally near-optimal designs approximately equally flexible? The answer is obviously "no" in general, and the answer is also no for this example where the controllable designs are more flexible than the uncontrollable. A resiliency (flexibility) index can be calculated as described by Saboo *et al* (1985), and may be used to differentiate between near-optimal designs.

Are the nominally near-optimal designs sensitive to low load operation? To check the sensitivity of running the plant at low load we selected 7 operating points, where all the heat capacity flowrates are decreased to 100, 95, 90, 80, 70, 60 and 50% of the nominal load, respectively. Inlet and outlet temperatures are kept constant, and plant operation is assumed to be equally distributed over all 7 operating points.

Design	6S143	5S14	6S21S43
C_{hx}	510.1	394.7	550.4
C_{uhx}	173.5	220.3	150.8
C_{util}	214.9	312.6	208.3
TAC	898.6	927.6	909.4

From the table above, it is clear that the relative difference between the total annualized cost between these three designs and the same designs at the nominal operating point remains approximately constant.

Flexibility (multiperiod) problem. Now we include flexibility requirements to the problem studied by Gundersen *et al*, (1991). The disturbance range is selected to $\pm 10K$ in inlet temperatures and $\pm 20\%$ in the flowrates. Then six additional operating points are specified. The first three correspond to maximum hot utility, maximum cold utility and maximum area requirement (Marselle *et al*, 1982) with a disturbance range of $5K$ of the inlet temperatures and 10% of the flowrates. The other three operating points are similarly selected but with the full disturbance range (i.e., $10K$ and 20%):

$$T_{in}[^\circ C] = \begin{array}{lccccccc} Op.point & Nominal & 1 & 2 & 3 & 4 & 5 & 6 \\ StreamH1 & 150. & 145. & 155. & 155. & 140. & 160. & 160. \\ StreamH2 & 90. & 85. & 95. & 95. & 80. & 100. & 100. \\ StreamC1 & 20. & 15. & 25. & 15. & 15. & 30. & 15. \\ StreamC2 & 25. & 20. & 30. & 20. & 15. & 35. & 15. \end{array}$$

$$w[kW/K] = \begin{array}{lccccccc} Op.point & Nominal & 1 & 2 & 3 & 4 & 5 & 6 \\ StreamH1 & 20. & 18. & 22. & 22. & 16. & 24. & 24. \\ StreamH1 & 80. & 72. & 88. & 88. & 64. & 96. & 96. \\ StreamC1 & 25. & 27.5 & 22.5 & 27.5 & 30. & 20. & 30. \\ StreamC1 & 30. & 33. & 27. & 33. & 36. & 24. & 36. \end{array}$$

Even though these temperature and flowrate disturbances are no larger than what might be expected in chemical process plants, none of the network structures given in Tab. 1 and in fact none of structures presented by Gundersen *et al* (1991) can ensure feasible operation at all operating points even with infinite areas on all exchangers. The following question is then important:

Can flexible designs be derived from nominally near-optimal designs? Yes, from nominal designs it will always be possible to derive flexible designs by increasing existing utility exchangers and installing new utility exchangers. For example, to the nominally best 5 and 6 unit designs ($5S234$ and $6S43$) one may add utility exchangers and get 7 units designs denoted $7S143$ and $7S234$. With these process heat exchangers, utility exchangers must be placed on all streams to fulfill the flexibility requirements. Similarly, nominal design 6P134 may be made into the flexible design $7P134$.

Are these flexible designs optimal? To check whether these designs are optimal we have derived and compared most of the possible alternatives with 2, 3 or 4 process heat exchangers. However, here we will include results only on those designs that can be derived by adding utility exchangers to the designs in Tab. 1. We get the following numbers where the numbers 1 to 7 refer to Tab. 1.

	1 and 4	2	3	5	6	7
Design	7P134	7S234	7S143	6S14	6S23	8S21S43
C_{hx}	439.5	373.2	438.3	398.9	364.0	442.1
C_{uhx}	463.5	490.4	468.8	471.0	466.4	467.9
C_{util}	478.7	568.0	486.0	518.8	568.2	493.3
TAC	1381.7	1431.6	1393.0	1388.7	1422.6	1403.3

With 2 process heat exchangers, utility exchangers must be included on all streams to fulfill the flexibility requirements, and this gives designs $6S14$ and $6S23$. For the nominal design $6S21S43$ it also beneficial to place utility exchangers on all streams, and this gives design $8S21S43$.

Comments:

1. All designs are similar in terms of TAC.

2. The nominally best design $5S234$ yields the worst flexible design $7S234$, whereas the best flexible design $7P134$ has the process heat exchanger structure of the nominally expensive threshold solution $4P134$.

3. Design $6S23$ and especially design $6S14$ give very good results.

4. Since $S14$ and $S23$ give such good results, the more complicated structures have similar area distributions to either design $S14$ or $6S23$ (i.e., the area of the additional process heat exchangers of these designs are close to zero). This explains why the designs are similar in terms of TAC. Indeed, if one allows exchanger area to go to zero, there are only three different designs to consider; $7P134$, $6S14$ and $6S23$.

5. **IMPORTANT!** The sizes and investment cost of the process heat exchangers *decrease* compared to the nominal design in all cases. This is opposite of what has previously been believed(e.g., Marselle *et al.* The reason is that area cannot be exploited as efficiently in the flexibility case because the process heat exchangers will be bypassed for some of operating points. Increased criss-crossing (i.e. non-vertical heat transfer) may also decrease the efficiency. Therefore, the flexibility designs tend to have less installed process heat exchanger area. This will favour designs with less area installed at the nominal operating point and may explain the fact that design $S14$ becomes second-best when flexible requirements are included.

Conclusions. Based on these and other optimizations of designs with 2, 3 and 4 process heat exchangers it seems that the process heat exchanger structure of the nominally near-optimal designs give quite good results.

Are these flexible designs sensitive to operation time at each operating point? We considered the effect of changing operating hours for the the different cases by changing the operation time at the nominal operating point. The nominal operating point is used for 14.29% (as in flexibility cases above), 50%, 99% and 100% (i.e. operation at nominal operating point only) of the total operating hours. The remaining operating hours are equally distributed over the six other operating points.

Design $7S143$:

% at nom. op. point	14.29%	50%	99%	100%
C_{hx}	438.3	456.3	461.0	595.9
C_{uhx}	468.8	465.1	464.7	139.8
C_{util}	486.0	433.7	374.9	266.8
TAC	1393.0	1355.0	1300.6	1002.4

Comment: Cost is only decreasing slowly with increasing operation at the nominal operating point. The flexibility requirements are very costly even as the operation time away from the nominal operating points approaches zero. The main reason is that much larger utility exchangers must be included to make all operating points feasible.

Design $6S14$:

% at nom. op. point	14.29%	50%	99%	100%
C_{hx}	398.9	395.9	399.4	434.4
C_{uhx}	471.0	472.4	472.0	207.1
C_{util}	518.8	484.8	431.0	402.1
TAC	1388.7	1353.1	1302.5	1043.7

Comment: The results for this design and other designs are similar as fro design $7S143$. Note that the optimal installed process heat exchanger area is considerably less for the flexibility case even when 99% of the operation time is at the nominal operating point.

Conclusions: The results are not sensitive to the operating time at the nominal operating point. However, actually requiring feasible operation for a specified disturbance range has a large effect on the result.

Are these flexible designs sensitive to including flow-dependent heat transfer coefficients? So far heat transfer coefficients are assumed to be constant and equal to $100W/m^2K$ for all streams. In practice, the stream heat transfer coefficients will vary with flowrate as $h \sim v^m$ where $0.6 \leq 0.8$. This becomes important for flexibility designs because the flowrate through the exchanger vary with operating point. Inclusion of this flowrate-dependence and assuming that the specified nominal heat transfer coefficients can only be achieved at maximum heat capacity flowrates over operating points (i.e. when $w_{H1} = 24$, $w_{H2} = 96$, $w_{C1} = 30$ and $w_{C2} = 36kW/K$ for the serial or no-split-designs) increases TAC with approximately 3%. The results can generally be said to be insensitive to including flow-dependent heat transfer coefficients. It is interesting to note that introduction of flow-dependent heat transfer coefficients increase the cost of the flexibility designs, because flow-dependent heat transfer coefficients have positive effect on bypass control because gains will increase. Thus, smaller control action is needed to achieve a desired output change.

Are the results sensitive to the number of bypasses installed for flexibility? The three different flexible designs $7P134$, $6S14$ and $6S23$ we bypasses on 2 of the process heat exchangers in order to obtain the optimal operation in all operating points. Intuitively, one expects that the number of bypasses cannot be reduced without a large increase in TAC. However, for design $7P134$, one of 2 bypasses (i.e. bypass on exchanger 4) is only utilized at one operating point, and the other

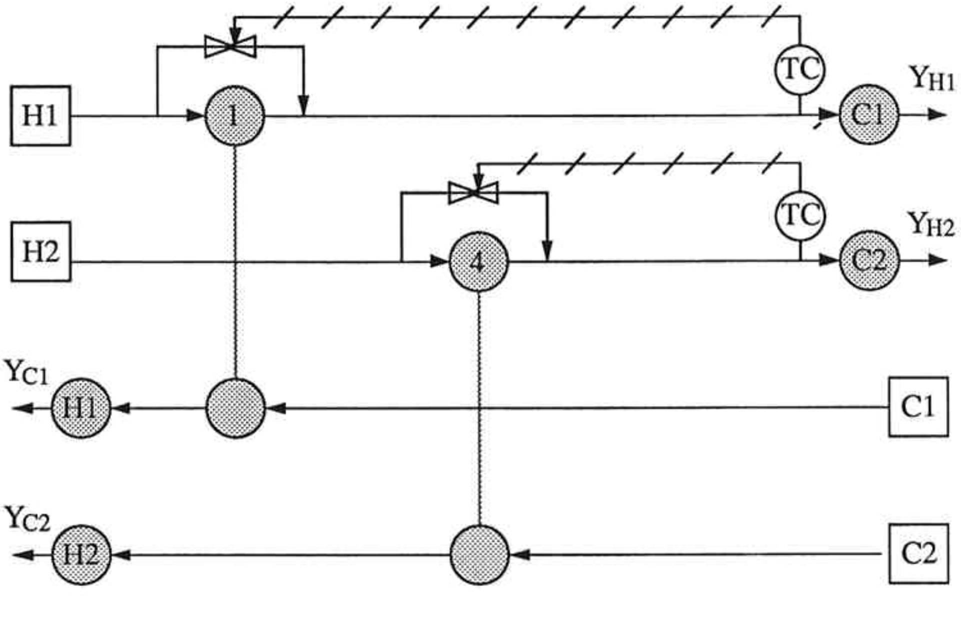

Figure 18: The global optimal solution when operability considerations are included

bypass (i.e. bypass around exchanger 1) is only utilized at 2 operating points. For design $6S14$ the bypass around exchanger 4 is utilized for 2 operating points.

Design	7SP134	7SP134	7SP134	6S14	6S14
No. of bypasses	2	1	0	2	1
TAC	1381.7	1398.8	1438.5	1388.7	1403.6

Omitting the bypass around exchanger 4 only increases TAC with 1.2% (to 1398.8k\$). Also omitting the bypass around exchanger 1 increases the TAC with additional 2.8% (to 1438.5k\$). For design $6S14$ the bypass around exchanger 4 is utilized for 2 operating points, and omitting this bypass only increases TAC with 1.1% (to 1403.6k\$). The cost penalties are surprisingly low, so for this problem the results are not sensitive to the number of bypasses installed.

Are these flexible designs easy to control (at all operating points)? Because the designs include utility exchangers on all streams, one would immediately assume that controllability is not a problem. However, for some operating point one or several of the utility exchanger duties drop to zero. Bypasses around process heat exchangers must then be used as manipulated variables. For design $S14$ the duty of the coolers drop to zero for some operating points whereas the duty of the heaters does not. Thus, it is easy to control this design, by placing the bypasses on the hot side of the process heat exchangers they can be used to control the hot target temperatures with a direct effect for the operating points where the duty drops to zero. For design $6S23$ control will be a bit more complicated because both the coolers and the heater on stream $C2$ drop to zero for some (but not the same) operating point. Adhering to the main bypass placement rule for control becomes impossible, the bypass around exchanger 3 must be used to control stream $H2$ for one operating point and stream $C1$ for another operating point. For design $7P134$ both coolers and the heater on stream $C1$ drop to zero for some operating point. For control one would either have to use the same bypass to control two different outputs (at different operating points) or use the splitter. Neither solution adhere to the main bypass placement rule for control.

Conclusions: Design $6S14$, see Fig. 18 yields the desired control configuration where all outputs are controlled either by a utility exchanger or a single bypass with a direct effect at all operating points. Control interactions will also be small because the HEN consists of two separate subsystems.

Conclusions from design illustration 2

1. Flexibility designs have less installed heat exchanger area than nominal designs, and less heat integrated nominal designs are favored.
2. The optimal design changes dramatically if we require feasibility for certain operating points, and does not depend strongly on how much time is spend at each operating point.
3. Use of flow-dependent heat transfer coefficients make parallel designs less favorable compared to serial designs.
4. Design $6S14$ with only two process heat exchangers can be regarded as the global optimal solution for this four stream problem because it is simple, low in capital cost and easy to control.

Nomenclature

A_{hx} - Process heat exchanger area $[m^2]$
A_{uhx} - Utility exchanger area $[m^2]$
C_{CU} - Cost of cold utility $[\$/Wh]$ C_{HU} - Cost of hot utility $[\$/Wh]$ C_{hx} - Annualized investment cost of process heat exchangers, $(8.6 + 0.67 * A_{hx}^{0.83}) * F_{install} * F_{payback}[k\$]$
C_{uhx} - Annualized investment cost of utility exchangers $[k\$]$
C_{util} - Annual operating cost $[k\$]$
$d(s)$ - vector of disturbances
$F_{install}$ - Installation factor $[-]$
F_{online} - On-line fractional time $[-]$
$F_{payback}$ - Inverse of the payback time
$G(s)$ - Process transfer function matrix
$G_d(s)$ - Disturbance transfer function matrix
h - Stream heat transfer coefficient $[W/m^2K]$
N_{byp} - No of bypasses in HEN
N_{hx} - No of process heat exchangers in HEN
N_s - No of controlled outputs
N_{spl} - No of splitters in HEN
N_u - No of heaters and coolers in HEN
N_u' - No of heaters and coolers in HEN that drops to zero for at least one operating point
$r(s)$ - vector of reference signals (setpoints)
Q_{HU} - Duty of heater $[W]$
Q_{CU} - Duty of cooler $[W]$
Q_{hx} - Duty of process heat exchanger $[W]$
U - Overall heat transfer coefficient $= h_h h_c/(h_h + h_c)[W/m^2K]$
T_{hi}^t - temperature of hot stream without cooler at network outlet
T_{hj}^{t-1} - temperature of hot stream with final cooler at cooler inlet
T_{ci}^t - temperature of cold stream at network outlet
T_{cj}^{t-1} - temperature of cold stream with final heater at heater inlet
$u(s)$ - Vector of manipulated inputs.
u_{sup} - Inputs manipulated by the supervisory control level
u_{reg} - Inputs manipulated by the regulatory control level
u_{reg}^{min} - Minimum bypass fraction for regulatory control level

u_{reg}^{IRV} - Ideal resting values for u_{reg}
$y(s)$ - vector of outputs
r_{hi} - setpoint for hot target temperature not downstream cooler
r_{hj} - setpoint for hot target temperature
r_{ci} - setpoint cold target temperature not downstream heater
r_{cj} - setpoint cold target temperature
w_h - heat capacity flowrate of hot stream $[kW/K]$
w_c - heat capacity flowrate of cold stream $[kW/K]$
ΔT_{lm} - logarithmic mean temperature difference $[K]$

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