Optimal Bypass Placement in Heat Exchanger Networks

Knut W. Mathisen, Sigurd Skogestad*and Truls Gundersen
Chemical Engineering
University of Trondheim - NTH
N-7034 Trondheim, Norway

Paper: 67e
Session: Plant-wide control
AIChE Spring National Meeting
New Orleans, March 29-April 2, 1992

Abstract

Heat exchanger networks (HENs) must be flexible (static resilient) and controllable (dynamic resilient) such that one is able to reject disturbances over a wide range of operating conditions. Degrees of freedom during operation needed for this include utility flowrates, bypass fractions and split fractions. Bypass placement affect flexibility, controllability, investment and operating cost. Thus, a four-way tradeoff exist even with fixed HEN structure and area. To deal with this tradeoff we suggest several appropriate optimization problems, and we propose to take controllability into account by adding constraints to the flexibility problem formulation. We derive a target for the number of bypasses. Further we argue that use of multi-bypasses may increase flexibility for a given number of bypasses and increase controllability when both outlet temperatures of one exchanger are controlled outputs. Therefore, the superstructure used in synthesis of optimal HENs ought to be extended to allow for multi-bypasses. It is known that prespecifying approach temperatures may give suboptimal solution to the standard HEN synthesis problem. In synthesis of flexible or multiperiod HENs it is especially important to simultaneously optimize approach temperatures, superstructure and area. The reason is that the optimal heat recovery approach temperature in one operating period greatly depends on the area requirements of the other operating points.

1 Introduction

Synthesis of heat exchanger networks (HENs) is generally considered to be the most mature field within process synthesis. Remarkable industrial results have been reported both for grassroot and retrofit projects. However, new results are still being reported frequently and the most recent review article (Gundersen and Naess, 1988) is already somewhat outdated.

---

*Address correspondence to this author. Fax: 47-7-594080, E-mail: skoge@kjemi.unit.no.

During the last decade the major part of the research has been done on the following subproblems:

- *Integration.* Research on integrating the HEN with the rest of the plant has especially focused on the utility system, the heat and power system and the separation system.
- *Synthesis.* Manual or interactive synthesis without pinch decomposition and restrictions on the approach temperatures and automated synthesis using mathematical programming for *simultaneous* optimization of heat recovery level, structure and area.
- *Assumptions.* Relaxation of the simplifying assumptions in the problem specification, especially constant inlet and outlet temperatures, constant heat capacity flowrates, constant heat transfer coefficients, negligible pressure drop and pure countercurrent heat exchange.

In this paper we will mainly consider the last problem, and in particular discuss the long-term (static) and short-term (dynamic) variations of temperatures, flowrates and heat transfer coefficients. Specifically, we assume that the HEN with exchanger areas is given and address how decisions about bypasses should be made in the design phase in order to ensure feasible steady-state operation for all operating points and fast rejection of dynamic disturbances. We further address how bypass fractions and split fractions should be manipulated during operation to minimize the operating cost.

Related work. Colberg and Morari (1988) give a comprehensive summary of the research on analysis and synthesis of flexible HENs. Since 1988 the most important result on flexibility of HENs is probably due to Cerda and coworkers (Cerda et al, 1990, Cerda and Galli, 1990 and Galli and Cerda, 1991). They define permanent and transient streams, the permanent streams being made up of the minimum flowrate and the minimum temperature range over all operating points. Consequently the transient streams are the part of the streams that only exist for some, but not all operating points. During synthesis, first priority is given to matching permanent streams, second priority to matching hot (cold) permanent streams and cold (hot) transient streams and third priority to matching transient streams. The method yields near-optimal networks. Cerda and coworkers also define dominant pinch points and show how these may be used to identify the worst-case operating points in networks with shift of the pinch generating stream and flowrate variations (non-convex networks). Other important works on flexibility and controllability of HENs are discussed in a previous paper (Mathisen et al, 1991).

2 Degrees of freedom during operation

Manipulated inputs. During operation, degrees of freedom or manipulated inputs are needed for control and optimization. Manipulated inputs in HENs may be:

1. Utility flowrates
2. Bypass fractions
3. Split fractions
4. Process stream flowrates
5. Exchanger area (e.g. flooded condenser)
6. Recycle (e.g. if exchanger fouling is reduced by increased flowrates)

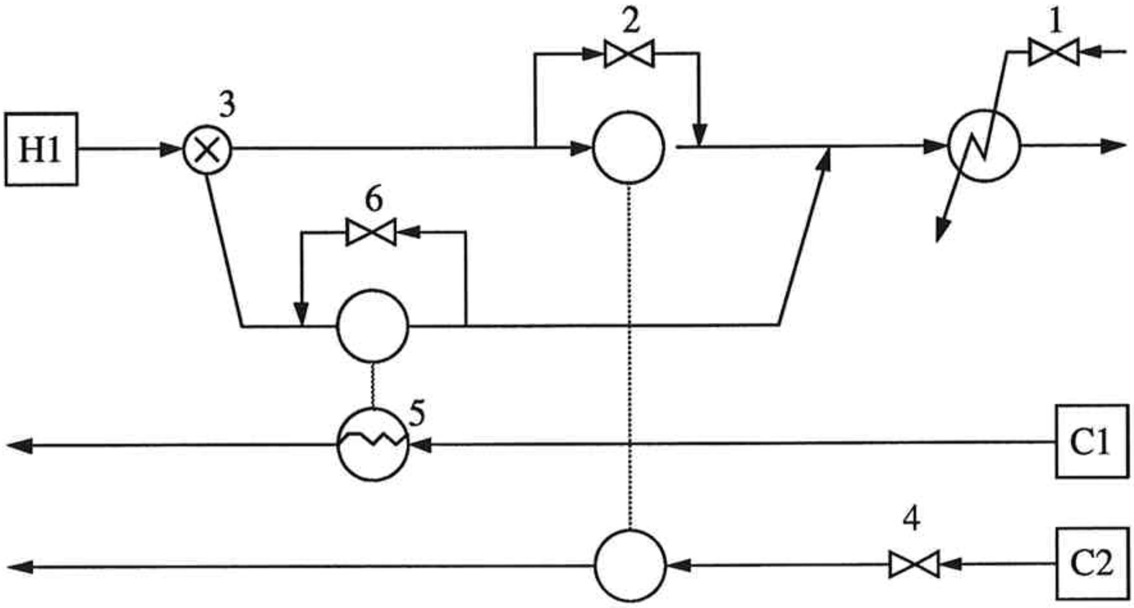


Figure 1: Possible manipulated inputs in HENs

The different possibilities are shown in Fig. 1. In this paper, we will consider bypasses and in some cases utility flowrates and splitters. Bypasses and splitters are denoted generalized splitters.

Control objectives. 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,
- below an upper limit or above a lower limit *or*
- as close to a limit as possible (i.e. at maximum or minimum values)

Like most authors, we assume that the control objectives are to keep the network outlet temperatures at their targets. For energy optimization the temperatures upstream the utility exchangers are to be as close to the stream target temperatures as possible. As it is sufficient to control either the hot or the cold utility consumption, and it is usually preferable to control the utility type with the fewer number of units (Marselle et al, 1982).

3 Bypass placement

Flexibility and controllability versus investment and operating costs of bypass lines and its control system are the main considerations when placing bypasses.

Flexibility. Static resiliency or flexibility is required to deal with both undesirable and desirable long-term changes. The former type may come from fouling of exchangers and other process equipment or catalyst deactivation in reactors. Such undesirable changes typically alter heat transfer coefficients and inlet temperatures in HENs continuously over a process campaign.

Desirable long-term changes originate from a change in the optimal operating conditions of the plant and are typically setpoint changes of the controlled outputs or step-like changes of the input temperatures and flowrates to a new operating point. An important objective when placing bypasses is to maintain feasible operation under these long-term changes. Colberg et al. (1989) suggest to differentiate between the flexibility problem, which they define as dealing with the discrete, desirable changes and the (static) resiliency problem, which is dealing with continuous, undesirable changes.

Controllability. Rejection of dynamic disturbances is the primary controllability consideration when placing bypasses. Dynamic disturbances (variations) must be rejected with sufficient speed of response for the set of operating points. If automatic on-line optimization is implemented, setpoints will be updated much more frequently and the relative importance of setpoint-tracking compared to disturbance rejection will increase.

Cost of bypasses. The overall reason for placing bypasses is of course to increase the plant profit. The costs of installing bypasses and control systems may be considerable. The costs include:

- Investment cost for bypasses including pipes, pipe junctions, manual valves, etc.
- Investment cost for control loops including measurements, control valves, display, software.
- Operating and maintenance cost of bypasses
- Operating and maintenance cost of control loops

The investment costs increase with pressure, temperature and corrosiveness (of the fluids) similar to the increase in cost of heat exchangers. In addition, the cost will increase with the pipe diameter and pipe length.

Possible bypass locations. "Bypass" is usually thought of as a pipeline around one side of a single process heat exchanger. Floudas and Grossmann (1987) formulates the multiperiod HEN synthesis optimization problem with superstructures that only allow single bypasses. Later Floudas and Ciric (1989) extended the superstructure to include all possible HEN flowsheets (i.e. the hyperstructure), but still only single bypasses are allowed. The reason for this is simply that when the installation cost of bypass lines and control loops are neglected and controllability is not considered, installation of bypasses over more than one exchanger will never be optimal. Furthermore, as bypass costs are omitted, it will often be optimal to explore all degrees of freedom in the HEN so that all process heat exchangers will be bypassed. Finally, at steady state bypassing the hot side of an exchanger is equivalent to bypassing the cold side so that bypass placement in practice is not part of the optimization problem at all. For flexibility it is usually equivalent to bypass the hot or the cold side, but this is not the case for control. Consequently, one needs to differ between these two cases. In addition to this several other types of bypasses need to be considered as they may be beneficial and are frequently used in practice. Bypasses may be divided into the following types:

1. Bypass around a single process heat exchanger ("single bypasses")
2. Bypass around multiple process heat exchangers ("multi- bypasses")
3. Bypass on the process side of a utility exchanger
4. (Multi-) bypass around process heat exchanger(s) *and* the process side of a utility exchanger.

Bypasses of type 3 and 4 do *not* improve flexibility, they are only used to get a faster speed of response, i.e. for controllability considerations. Using multi-bypasses may make it possible to install fewer bypasses and also simplifies the control system.

Number of alternative sets of bypass selections. When N_{byp} number of bypasses is to be placed in a HEN with N_{hx} process heat exchangers, the number of alternative sets *with exclusively single bypasses* is:

$$2^{N_{byp}} \frac{N_{hx}!}{N_{byp}!(N_{hx} - N_{byp})!} \tag{1}$$

where it is assumed that there cannot be more than one bypass per heat exchanger. Even this simplified bypass placement problem is a fast-growing combinatorial problem. In practice, one may also use multi-bypasses and the number of bypasses may be any number of bypasses between zero and well above the number of process heat exchangers. Equations for computation of the number of alternative bypass sets in the general case together with a numerical example can be found in Appendix 1. Even for small examples with only 4 streams and 6 units, the number of alternative sets may be above 2000. Therefore, one needs insight and/or effective search algorithms.

4 Problem formulation

Even for a given HEN structure a number of interesting optimization problems may be formulated. Before considering these, let us introduce the following definitions:

An operating point: An operating point is a set of steady-state operating conditions with given stream inlet temperatures and flowrates and with given performance specifications and heat transfer coefficients. The performance specifications are usually zero target temperature deviation and the heat transfer coefficients being constant or some simple function of flow, temperature and/or pressure.

A set of operating points: This may either be a continuous set defined as one nominal operating point with a given static disturbance range ("resiliency" or "parameter range" formulation), or it may be a discrete set consisting of finite number of operating points with given durations ("multiperiod" or "multiple base case" formulation). A continuous set is most useful when considering feasibility (i.e. can the worst case operating point(s) be handled?), whereas a discrete set is most useful when performing an economic evaluation (e.g., minimizing yearly energy cost).

A disturbance range: The disturbance range is the union of the inlet temperature ranges, and flowrates ranges of all the process streams. It may be dynamic or static.

Flexibility or static design resiliency: The HEN design is flexible or static resilient if all target temperatures can be met for the set of operating points by adjusting the bypass fractions between 0 and 1 (so that the effective exchanger areas vary between the installed areas and 0) with specified utilities.

Controllability or dynamic design resiliency: The HEN design is controllable or dynamically resilient if the performance specifications (allowed dynamic target temperature deviations) can be met for the specified dynamic disturbance range by use of feedback control.

The optimization problems are listed below, starting with the control/operations issues and moving towards the design issues.

1. *Control of a given HEN.* For a given network with exchangers and bypasses, find the best control system. Main issues are pairing of control loops and controller tuning.

2. *On-line static optimization of a given HEN.* For a given (steady-state) operating point, find the optimal bypass and split fractions that yield the desired target temperatures and minimize the energy cost, or some other economic objective. By definition the HEN is infeasible if this optimization problem has no solution.

3. *On-line overall optimization of a given HEN.* The subproblem above is extended to take dynamic variations around the steady-state operating point into account. For a steady-

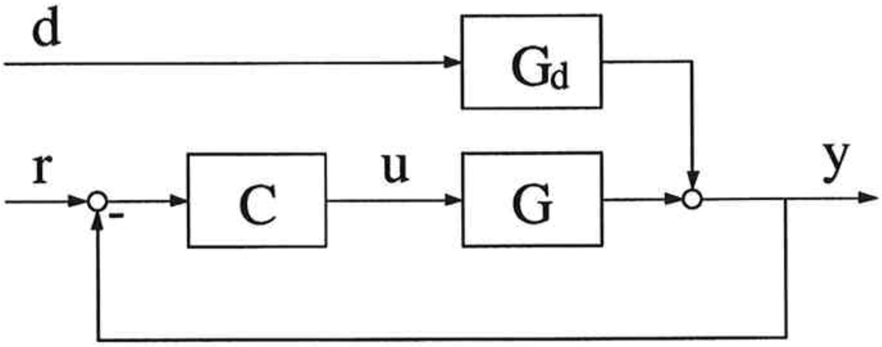


Figure 2: Block diagram

state operating point and a given dynamic disturbance range, find the optimal bypasses and split fractions that minimize the energy cost and fulfills the given dynamic performance specifications (response times and allowed dynamic deviations).

4. *Bypass placement for flexibility.* For a given network with fixed exchanger areas, a given set of possible steady-state operating points, and a given number of bypasses, find the set of bypasses that minimizes energy cost. This may give a trade-off between the number of bypasses and energy. Alternatively one may minimize total annualized cost (TAC). In this case the cost of bypasses must be included, otherwise one may simply place bypasses on all exchangers. Also note that subproblem 2 is embedded into this optimization.
5. *Bypass placement for control.* For a given network (areas given), a given operating point, a given dynamic disturbance range, and given specifications with respect to response times and allowed dynamic deviations, find the set of bypasses which is best from a control point of view.
6. *Bypass placement for minimization of fouling.* Heat exchanger fouling is an important issue in most chemical processes. Kotjabasakis and Linnhoff (1987) discuss how this problem may be addressed as a special case of the problem of bypass placement for flexibility.
7. *Overall optimization of bypass placement.* This combines the two above subproblems for control and flexibility. We propose to minimize the TAC for a specified control performance (one may generate tradeoff curves by varying the performance level), but other approaches are also possible, for example, by treating control deviations directly in terms of cost or by adding simple rules (constraints) to include the control issues.
8. *Optimization of installed areas for a given network structure.* This optimization may be for one operating point or for a given set of operating points (flexibility). It may also be generalized to include bypass placements.

5 Control and on-line optimization

5.1 Control of a given HEN (Problem 1)

This problem is the conventional subproblem handed over from the process engineer to the control engineer, where both HEN structure, areas and bypasses are given. It may be the final subproblem in a completely sequential design procedure, or it may be part of a retrofit project. The retrofit project may be started because the existing control system is outdated, the plant shows unwanted dynamic variations, or to increase flexibility or controllability. A block diagram is shown in Fig. 2. The disturbances **d** are usually inlet temperatures and flowrates of the process streams.

Selection of measurements. In most cases this is straightforward in HENs because the controlled outputs are all stream temperatures. Temperature measurements are inexpensive, reliable and easy to maintain. In some cases it may be desirable to control the heat duty, e.g. when the heat exchanger is a reboiler or a condenser. In that case additional flow measurements are needed, and where to place the measurements often becomes an issue, too.

Selection of actuators, pairings and controller tuning. Utility flowrate of heaters and coolers or bypass fractions are usually the actuators or manipulated inputs in HENs. The main rule is that controlled outputs (target temperatures) downstream utility exchangers are to be controlled with the utility flowrate and controlled outputs that are *not* downstream utility exchangers are controlled with bypasses with a direct effect. However, in this case one is restricted to use the existing bypasses. A stepwise procedure for analyzing controllability of HENs based on linear controllability measures and some heuristic rules on how to select manipulated inputs and pairings were presented at a previous AIChE meeting (Mathisen et al, 1991). Our experience is that a decentralized control configuration can be used in most cases, at least when the manipulators have direct effects on the controlled output. The control loops can be tuned using established linear methods.

5.2 On-line optimization (Problems 2-3)

In practice, the results of this optimization are implemented by sending setpoints to the control system. One may also combine the two levels by using, for example, a model predictive controller.

Problem 2: On-line static optimization of a given HEN. For a given HEN with installed areas and heat transfer coefficients and a steady-state operating point with given inlet temperatures, target temperatures (controlled outputs) and heat capacity flowrates, find the optimal bypasses and split fractions that minimize the energy cost.

Previous work with specified heat recovery. In the past, the conventional HEN flexibility problem has been solved assuming specified heat recovery levels for the various operating points. For example, Floudas and Grossmann (1987) use a uniform heat recovery approach temperature (HRAT) to set the utility requirement for all operating points. However, this constraint may make it impossible to utilize the installed area fully at all operating points. For instance, consider the "optimal" solution for example 2 from Floudas and Grossmann (1987) shown in fig. 3 where the exchangers in parallel are bypassed in period 3 to get the specified heat recovery. The reason is simply that the area requirements for period 3 is lower than for period 1. The HRAT specification is equivalent to specifying the temperature of stream $C1$ into the parallel exchangers at 450^oC (10^oC lower than the target temperature of stream H1). With this temperature of the cold stream into the parallel exchangers, there is more area available than what is needed, so the parallel exchangers must be bypassed. By relaxing the HRAT specification, the temperature of stream $C1$ into the parallel exchangers may be increased to 454^oC. The bypass around the parallel exchangers must then be closed in order to achieve the target temperatures of H1, H2 and H3. By closing the bypass, the utility cost of period 3 is reduced from $\$77.85h^{-1}$ (Floudas and Grossmann, 1987) to $\$74.72h^{-1}$ (new formulation). In fact, for this problem the bypass should be closed for all operating points, i.e. it should simply be removed.

New formulation. The appropriate formulation of the on-line optimization is therefore:

$$minimize \quad (T_{hi}^{t-1} - y_{hi})w_{hi} \tag{2}$$

subject to

$$T_{hj}^{t} - y_{hj} = 0 \tag{3}$$

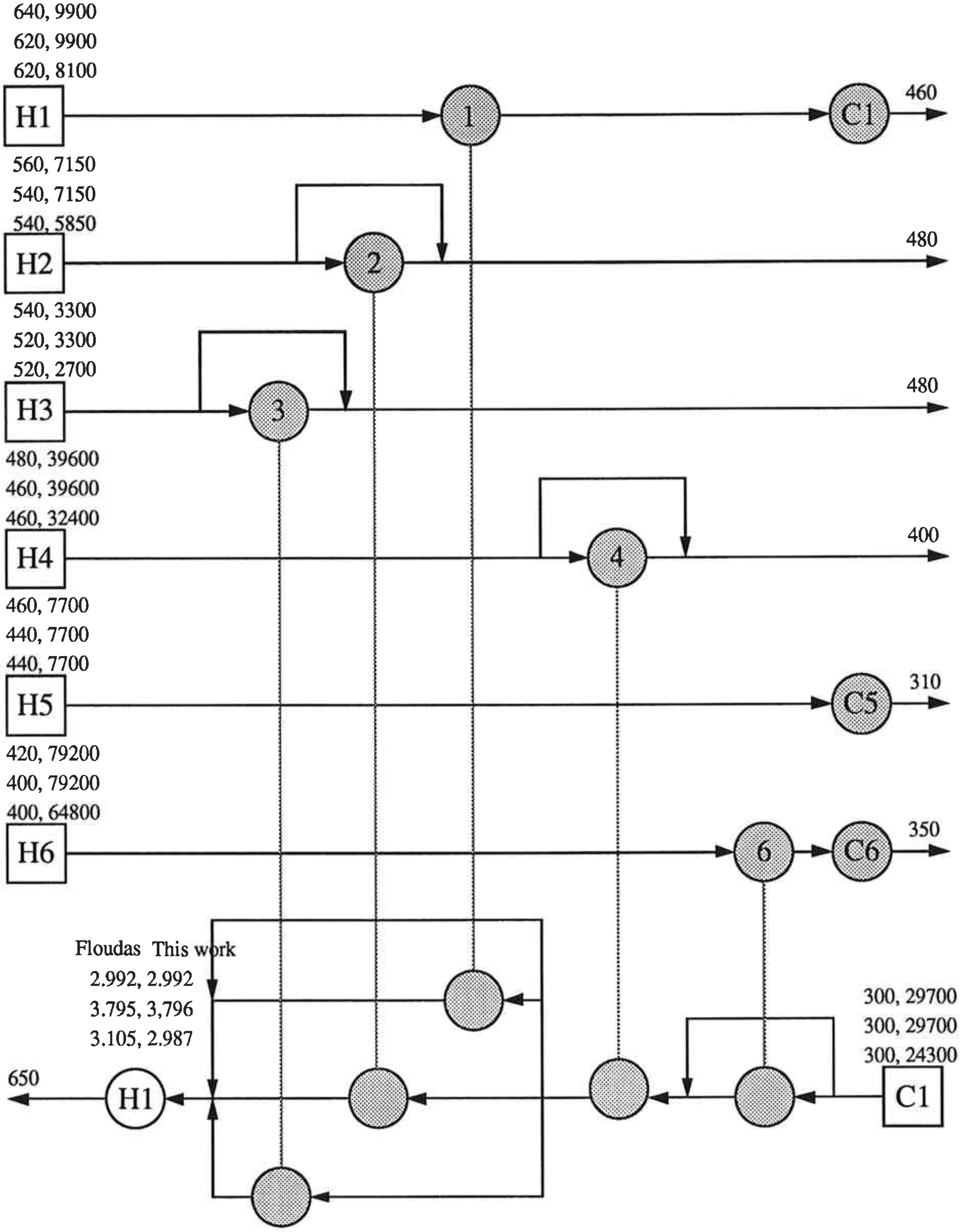


Figure 3: Flexible HEN design from Floudas and Grossmann (1987) used to illustrate the unwanted restrictions imposed by specifying the heat recovery.

$$T^{t}_{cj} - y_{cj} = 0 \tag{4}$$

$$y_{hi} - T^{t-1}_{hi} \leq 0 \tag{5}$$

$$T^{t-1}_{ci} - y_{ci} \leq 0 \tag{6}$$

$$-u \leq 0 \tag{7}$$

$$u - 1 \leq 0 \tag{8}$$

where w is heat capacity flowrate, the T^t's are the temperatures at the network outlet, y_{hi} is the set of hot target temperatures (setpoints) downstream coolers, y_{hj} the set of hot targets *not* downstream coolers, y_{ci} the cold targets downstream heaters and y_{cj} the cold targets *not* downstream heaters. We assume no limitation on the duty of the utility exchangers, but one may alternatively assume given areas and maximum flowrates.

Problem 3: On-line overall optimization of a given HEN (including control). 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. The steady-state optimal operating point for HENs will as in most chemical process problems be at the intersection between constraints (Marselle et al, 1982). The faster the response to dynamic disturbances, the closer to the intersection one is able to operate. In case of slow response and large dynamic disturbances, it may be optimal to operate close to another process constraint intersection. One may define a "hard" target as a temperature that must be controlled with a utility exchanger or a bypass with a direct effect. One may further introduce as a constraint that the primary manipulator is able to reject the dynamic disturbance to within the allowed dynamic deviation for all "hard" targets. For the other "soft" targets, it is not required to reject dynamic variations. One may then calculate how close to the constraints one may operate, i.e. decide the nominal bypass fractions and utility duties.

The dynamics and controllability considerations can in this way be taken into account by adding more constraints to the steady-state optimization problem. This approach is usually preferable to including the costs of dynamic deviations, because such costs are very problem-specific and often difficult, time-consuming and expensive to obtain.

6 Optimal bypass placement

6.1 A target for the number of bypasses

Consider a general HEN with

- N_{hx} process heat exchangers
- N_s controlled outputs ("hard" targets)
- N_u utility exchangers

If utility exchangers are manipulated wherever possible, one needs at least $N_s - N_u$ bypasses to be able to control the rest of the outputs. 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. We know of industrial examples where more bypasses than the process exchangers are implemented. However analysis of controllability and flexibility indicate that the number of bypasses could be reduced in these cases. The number of bypasses N_{byp} will then be:

$$N_s - N_u \leq N_{byp} \leq N_{hx} \tag{9}$$

Four additional factors influence the number of bypasses:

1. Cooler/heater duty. The duty of some utility exchangers may drop to zero for some operating points. This is favorable and should be encouraged, but it requires one extra bypasses for each utility exchanger duty that drops to zero. The number of extra bypasses needed is denoted N'_u.
2. Process exchanger duty. The duty of process exchangers may also drop to zero for some operating points, although this occur more seldom. This may require extra bypasses, but sometimes multi-bypass can be used.
3. Stream splits. If there are splitters in the HEN, it is favorable to manipulate split fractions instead of bypasses for flexibility. N_{spl} may be exchanged.
4. The process pinch. It may be necessary to reduce the duty of exchangers upstream the pinch with bypasses, but this is not favorable and should be avoided if possible.

From the above argumentation, factors 1 and 3 (but not factors 2 and 4) are used get an improved lower bound. This lower bound is the target number of bypasses:

$$N_{byp}^{target} = N_s - N_u + N'_u - N_{spl} \tag{10}$$

6.2 Bypass placement for flexibility (Problem 4)

Consider again the example from Floudas and Grossmann (1987). This HEN has six process heat exchangers, three coolers and one heater, (two units more than minimum). Assuming that the utility exchangers are used to control four of the seven target temperatures, at least three bypasses are required. These bypasses may be placed on the hot side of exchangers 2, 3 and 4, see Fig. 3. A fourth bypass is needed because cooler $C1$ is not used in period three. This makes it necessary to control the hot outlet of exchanger one, too. Since we already have argued that one of the five bypasses in the network generated by Floudas and Grossmann should be removed, this could be the end of the story. However, in addition to the bypasses there are two splitters. From energy recovery considerations it will always be advantageous to manipulate split fractions instead of bypass fractions if possible. The split fractions may be manipulated to control two of the three hot outlet temperatures of the parallel exchangers, reducing the minimum number of bypasses to two. This is the target number of bypasses for this example. Due to the pinch (Factor 4) and with with the installed areas of exchangers 4 and 6 a third bypass around exchanger 6 is needed. One might think that a multi-cold bypass around exchangers 4 and 6 may be used instead of the two single bypasses, but this is not possible. The reason why this is not a good idea is that we then place the multi-bypass towards the pinch point, ruining the performance of exchanger 4. The optimal bypass placement for flexibility are shown in Fig. 4

6.3 Bypass placement for control (Problem 5)

For a given network (fixed exchanger areas), a given operating point, a given dynamic disturbance range, and given specifications with respect to response times and allowed dynamic deviations, find the set of bypasses which is best from a control point of view. As stated above the main rule is to manipulate the exchanger immediately upstream of the controlled output.

We consider again the example from Floudas and Grossmann shown in Fig. 3. The structure of this design makes it possible to implement a control configuration where all outputs are controlled by manipulating the exchanger immediately upstream. However, assume that the bypass fractions are optimized on-line to minimize energy consumption. For period 1, most bypass valves should then be closed making it impossible to reject dynamic disturbances so that the optimal static solution cannot be quite achieved in ptractice. For period 2 (and/or 3) control of the outlet temperature for stream $H1$ using cooler $C1$ is impossible since the duty of the cooler drops to

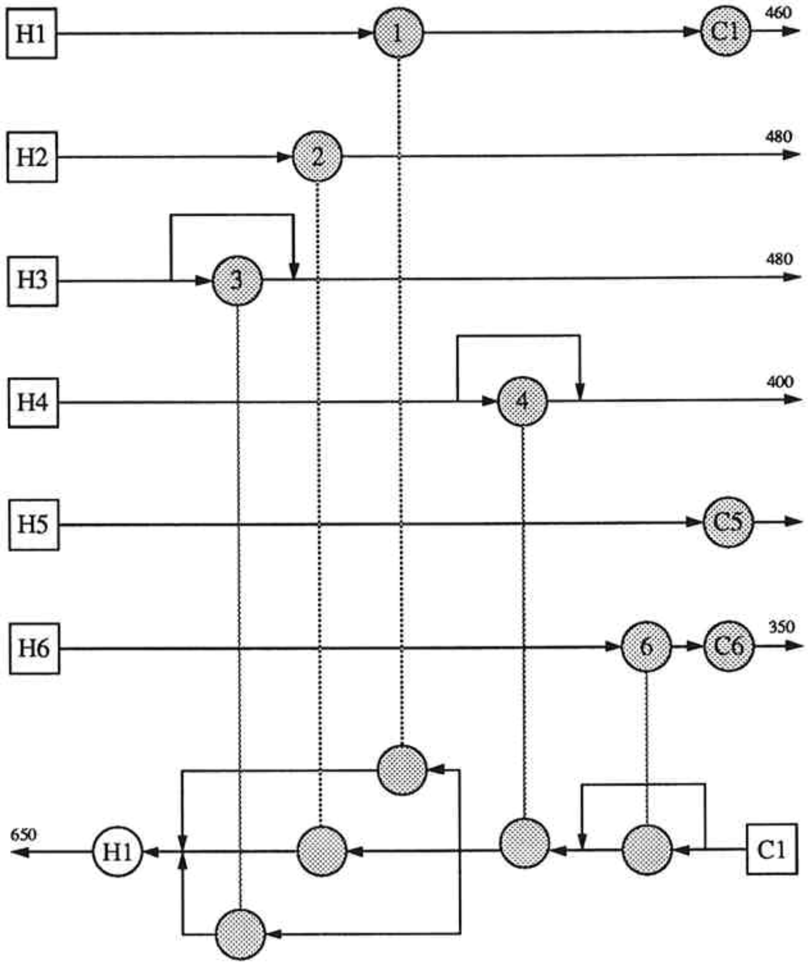


Figure 4: Example from Floudas and Grossmann (1987). Suggested bypass placement for flexibility.

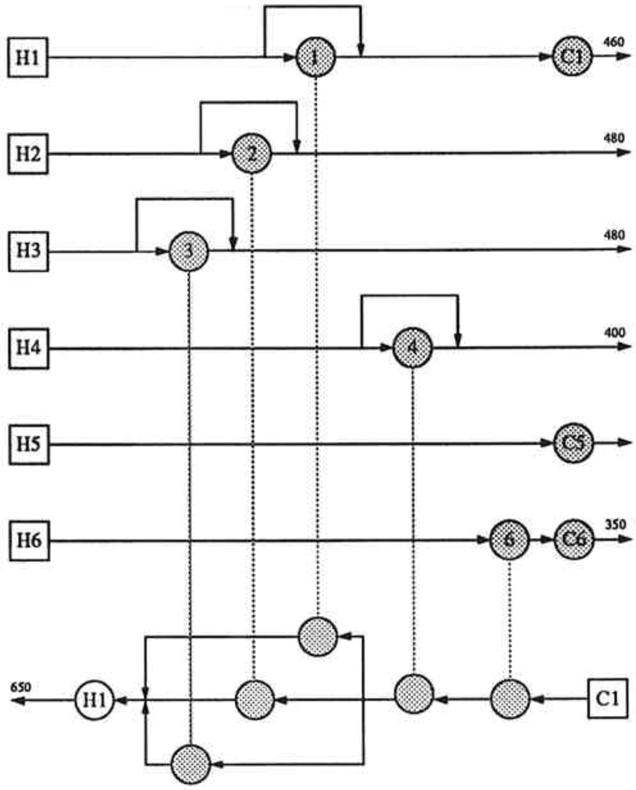


Figure 5: Suggested bypass placement for control

zero. Structurally this creates a new target temperature, the hot outlet of heat exchanger 1. One may adjust this temperature by manipulating the splitter on stream $C1$. However, this will upset heat exchanger 2 and/or 3 (depending on the implementation of the three-way splitter of stream $C1$), and due to the countercurrent nature of the heat exchangers, these upsets will be difficult to reject. The resulting control system gets more complicated with higher investment and operating costs, and the overall process will have poorer controllability for this operating period. As a consequence of this, one will probably in practice prefer to install a bypass on the hot side of exchanger 1 and the recommended bypass placement for control may be as shown in Fig. 5. Thus, the bypass on exchanger 1 may be needed for controllability reasons although it should not be used for flexibility reasons. An alternative solution in cases like this (and such cases are often encountered in practice) is to install a multi-bypass of the process stream (in this case stream H1) around the process exchanger (HX 1) and the utility exchanger (C1). This will increase the area requirements of the involved exchangers, but simplify operation and control.

6.4 Overall optimization of bypass placement (Problem 7)

The suggested bypass placement for control and flexibility may be combined directly. However, the bypass around exchanger 6 can be omitted without making control more difficult. To maintain feasibility for period 3 without this bypass, an area increase of $58.9m^2$ on exchanger 4 is required. Even though this results in a 15% area penalty for exchanger 4, the investment cost may be lower. Furthermore, in order to make control simpler it may be desirable to extend the hot bypass on exchanger one to include the cooler. The structure after these changes are shown in Fig. 6.

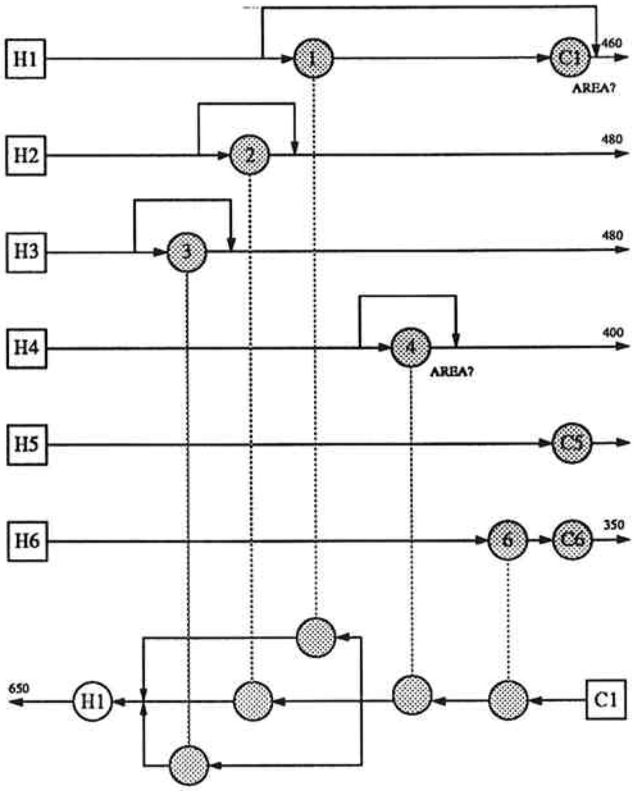


Figure 6: Suggested bypass placement for control and flexibility

7 Other issues when placing bypasses

7.1 Multi-bypass

One multi- versus one single bypass. The main rule for bypass placement for control is to exclusively select bypasses with a direct effect on the corresponding controlled output. The example network shown in Fig. 7 has a structure where such a desirable control configuration is impossible using single bypasses. This potential controllability problem is always encountered when both outlet temperatures of a heat exchanger are controlled outputs. The problem has been thoroughly discussed in another paper (Mathisen et al, 1992), but for completeness we will state the conclusions. If it is assumed that both controlled outputs are critical targets, one needs to install a double bypass as shown in fig. 7 to get a fast response. Still, there may be problems with input constraints, which are independent of whether one chooses to install two single bypasses or one single and one double bypass. Thus, for cases like this installation of a multi-bypass improves controllability, but leaves the flexibility unchanged.

One multi- versus several single bypasses. Consider the HEN structure shown in Fig. 8. Feasible operation for three different operating points is required. At the nominal operating point (denoted operating point 1) all bypasses closed. For operating point 2, it is necessary to reduce the heating of stream C1 more than what is possible through a single bypass on exchanger 1. Then one may either use two single bypasses (around exchangers 1 and 4) or use one double bypass. For operating point 3 one needs to *increase* the duty of exchanger 1 compared to operating point 1. Since the bypass around exchanger 1 is zero for operating point 1, the only way to achieve this is to increase the driving forces by increasing the hot inlet temperature. Thus an exchanger upstream exchanger 1 on the hot side must be bypassed. If the necessary temperature increase is large, it may be necessary to either put single bypasses around both exchanger 2 and 3 or install

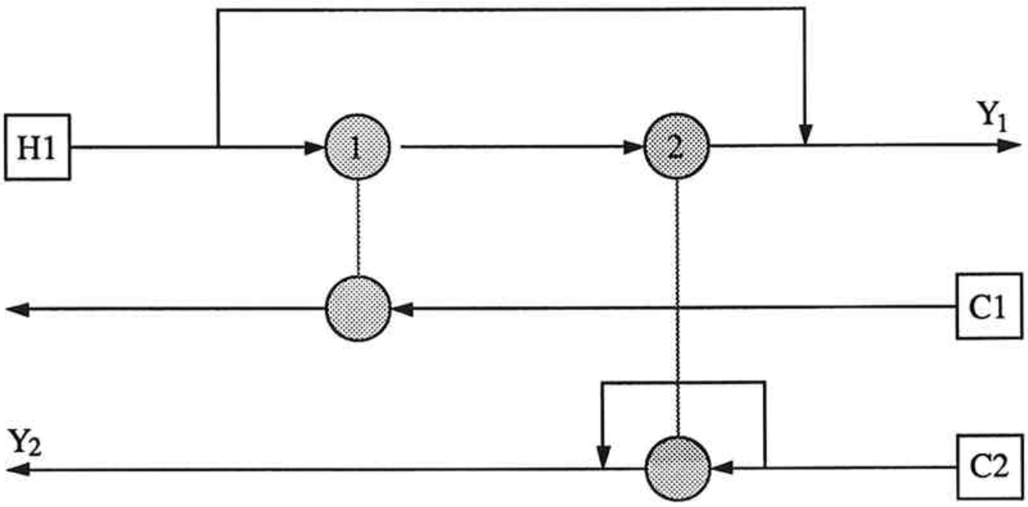


Figure 7: HEN where both temperatures out of exchanger 2 are controlled outputs

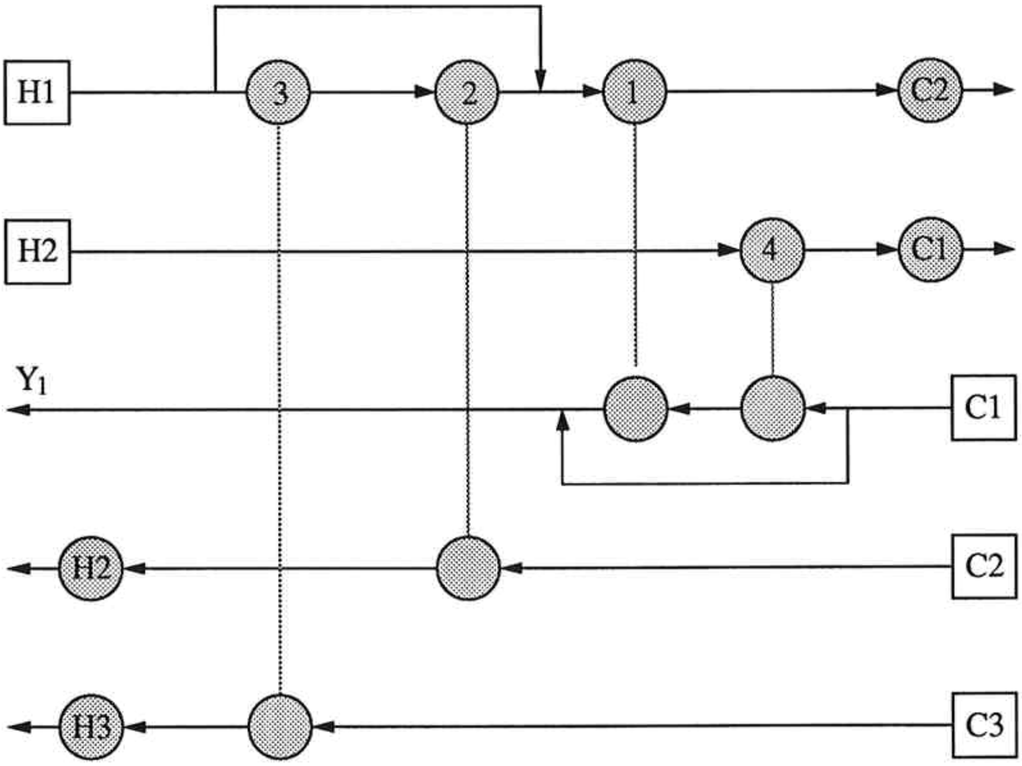


Figure 8: Example of HEN structure where installation of multi- bypasses may be preferred to single bypasses

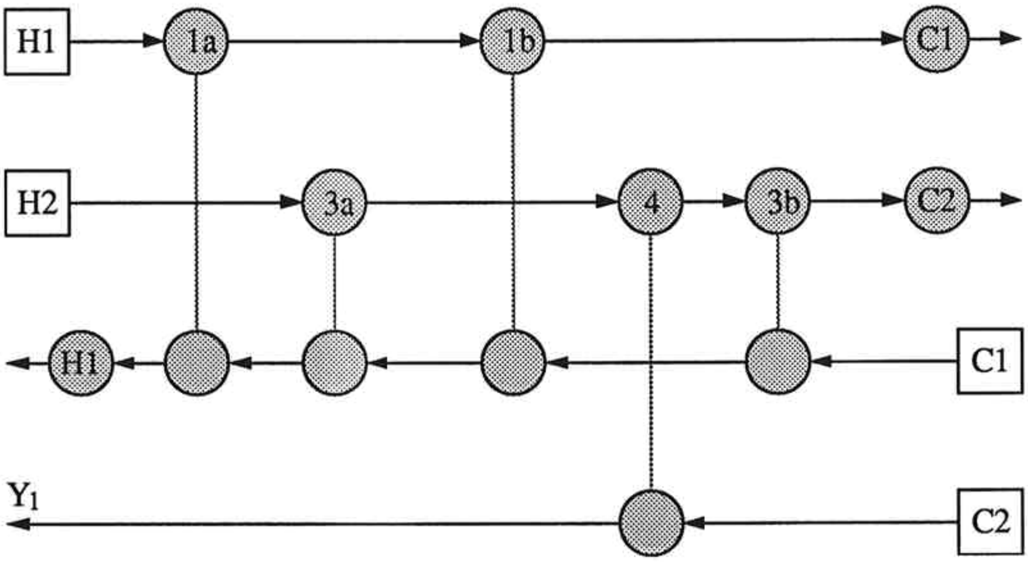


Figure 9: Example 2.2 from Townsend and Morari with the only two possible bypass placement for disturbance rejection

one double bypass as shown in Fig. 8. In summary, this example illustrates that there may be a trade-off between several single bypasses in series single and one multi-bypass. Installation of a multi-bypass improves flexibility (as compared to one single bypass) or simplifies control (as compared to two or more single bypasses). Further, the example illustrates that bypasses may be used to *increase* the duty of a downstream exchanger.

7.2 Trade-off between the number of bypasses and energy

To illustrate that there also may be a trade-off between number of bypasses and energy, we consider the network in Fig. 9 which is example 2.2 (example 2 design 2) from Townsend and Morari (1984). we have changed the problem into a multiperiod problem by having two possible targets for each of the outlet temperatures for streams $H1$, $H2$ and $C1$. For operating period 1 the target temperature of stream H1 is increased by 40^oC, for operating period 2 the target temperature of stream H2 is increased by 40^oC and for operating period 3 the target temperature of stream C1 is decreased by 40^oC. For each of these cases the change in target corresponds to having zero duty in the corresponding utility exchanger. For example, the target temperature of stream $H1$ in period 1 corresponds to zero duty on cooler $C1$. Feasible operation for all the three operating periods is possible by using only two bypasses as shown in Fig.10. Somewhat simplified, the single bypass around exchanger 4 is used to control the target temperature of stream C2 for all operating points whereas the *triple* bypass around exchangers 3b, 1b and 3a is used to control target H1 in period 1 target H2 in period 2 and target C1 in period 3. This cannot be done without a large utility consumption penalty. If one allows to install a third bypass the utility requirements drop. In this case three single bypasses are used. If one allows four bypasses the hot utility consumption for the best bypass sets drop to $560MWh$ per year, which is the minimum. Four is the target number of bypasses for this problem. The optimal bypass placement in this

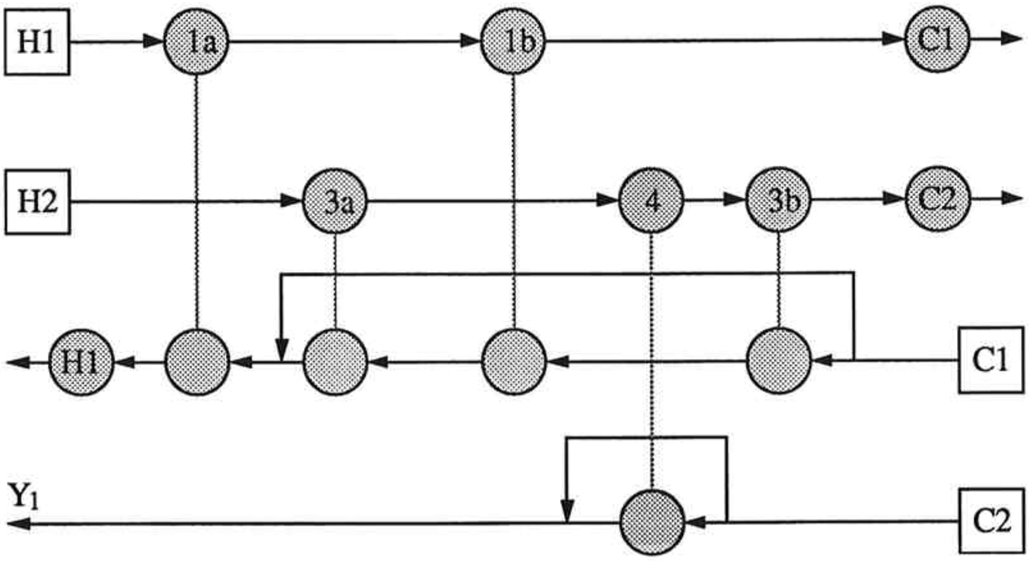


Figure 10: Example 2.2 from Townsend and Morari with large target temperature variations. Bypass placement when only two bypasses are allowed.

case is shown in Fig. 11.

No of bypasses allowed	Hot utility consumption
0 bypasses:	infeasible
1 bypass :	infeasible
2 bypasses:	1384 MWh/yr
3 bypasses:	1064 MWh/yr
4 bypasses:	560 MWh/yr
5 bypasses:	560 MWh/yr

Note that nothing is gained by installing a fifth bypass. The table shows that the strict performance specifications (hard targets) result in a severe energy penalty if fewer bypasses than four (the target) is installed. In Fig. 12 it is illustrated how flexibility, controllability, investment and operating cost (utility and maintenance) may vary as with number of bypasses in the general case.

Investment cost increases with number of bypasses. The investment cost per bypass is high for the first bypasses because multi-bypasses must then be used to achieve feasible operation. If more bypasses than process heat exchangers are installed, the investment cost per bypass is equally high because these bypasses will be multi-bypasses as there already will be single bypasses on all exchangers. The operating cost is large with few bypasses because of the large energy penalty. The operating cost increases when a lot of bypasses are included due to increased maintenance cost and constant energy cost. Controllability and flexibility both increases with number of bypasses, but maximum flexibility will generally be achieved with fewer bypasses than maximum controllability. With a lot of bypasses installed, the controllability deteriorates because the control system becomes complicated.

Use of heaters/coolers as manipulators. Note that an alternative to using bypass is to add

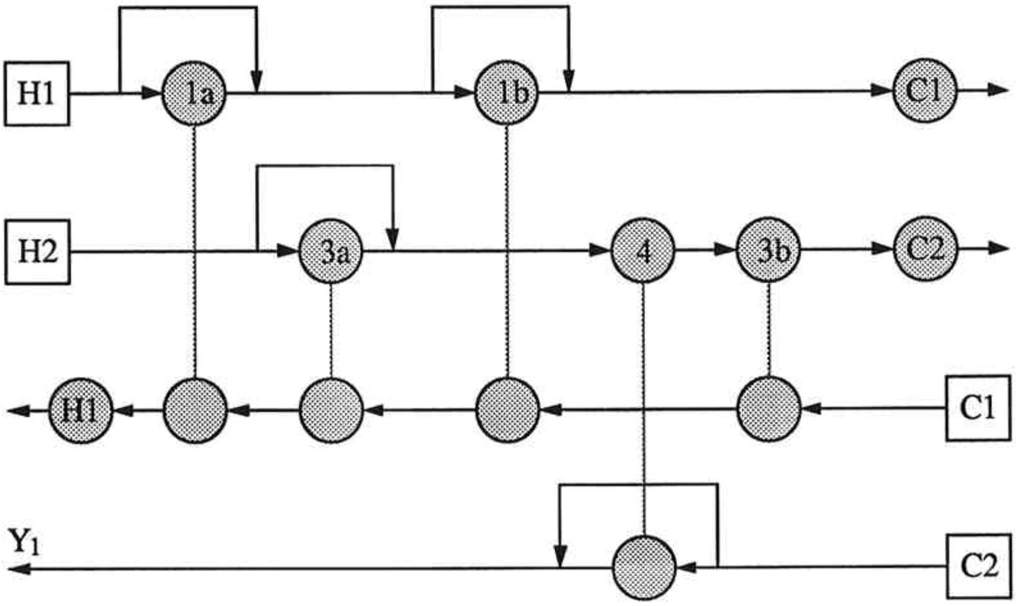


Figure 11: Example 2.2 from Townsend and Morari with large target temperature variations. Optimal bypass placement when 4 bypasses are allowed.

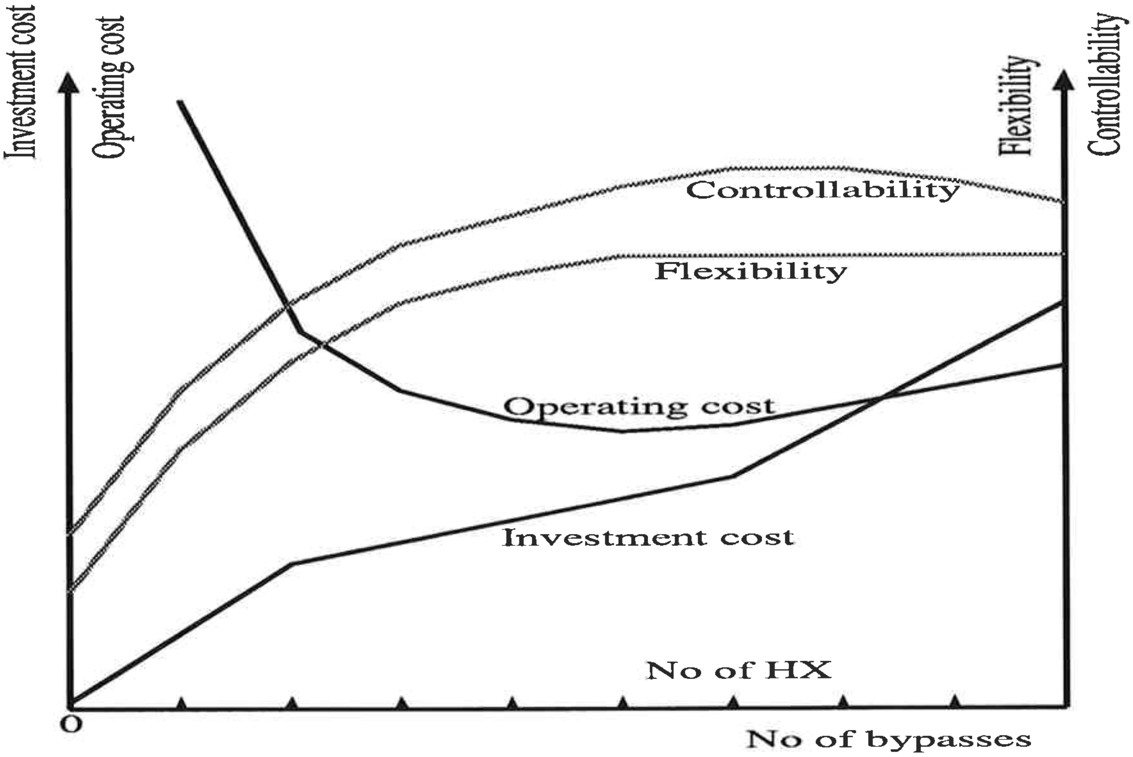


Figure 12: Flexibility, controllability, investment and operating cost (utility and maintenance) as function of number of bypasses (qualitatively!)

heaters or coolers. specifically if we for the above example allow both heaters and coolers on all streams, but use no bypasses, the utility consumption is $756 MWh/yr$. if we allow for use of bypasses in addition, the utility consumption drops, and reaches for four bypasses the same value of $560 MWh/yr$ as found above. This illustrates that if feasible operation can be achieved by use of bypasses, then nothing is gained by adding more utility coolers or heaters.

8 Optimization of installed area (Problem 8)

This optimization may be for one operating point or for a given set of operating points (flexibility). It may also be generalized to include bypass placements and dynamic disturbances.

Optimization of installed exchanger areas for one operating point. Without dynamic disturbances and performance specifications this problem is very well stated and straightforward to solve. In automated HEN synthesis using mathematical programming this problem is embedded into the overall optimization problem. Therefore, one will always get the optimal area distribution among the heat exchangers in the network provided the optimization does not fall into local optima. These local optima are present because economy of scale for investment cost and enthalpy balance equations for the heat exchangers yield a non-convex model. When HEN synthesis is performed with manual methods, one should always finish the task by optimizing the split fractions and installed areas.

Dynamic disturbances. If dynamic disturbances are considered one *may* need to install bypasses and/or extra area to fulfill the performance specifications. It is important to be aware of the possibility that installation of bypasses may be unnecessary. Examples are

- The controlled outputs that are not downstream utility exchangers are soft target temperatures or are to be maximized (cold streams) or minimized (hot streams).
- The control range of utility exchangers controlling the hard targets are large compared to the dynamic disturbances.

If bypasses still are needed, it is desirable to use only one bypass for all possible sets of dynamic disturbances. For example, if a certain single bypass cannot reject the disturbances, consider using a multi-bypass instead of two single bypasses.

Optimization of installed exchanger areas for a given set of operating points. "A set of operating points" may be a nominal operating point with a given disturbance range ("resiliency" formulation), or it may be a finite number of operating points with given durations ("multiperiod" or "multiple base case" formulation). In the resiliency formulation, one may optimize TAC for the worst case (area of utility exchangers and operating cost taken from the worst combination of disturbances), or alternatively optimize TAC for the nominal case while requiring feasible operation for all combinations of disturbances (area of utility exchangers taken from the worst combination of disturbances, but operating cost from the nominal operating point). In most cases the multiperiod formulation seems most reasonable.

For illustration, consider again example 2 from Floudas and Grossmann (1987). By leaving out the restrictions on HRAT, this structure may be optimized from a TAC of $k\$1374$ (Floudas and Grossmann, 1987) to $k\$1217$ (this work), i.e. an 11.4% reduction (Assuming 8400 operating hours equally distributed over the 3 operating periods). The optimized areas and utility cost are shown in the table below.

		Floudas & Grossmann (1987)	This work
Process HX area $[m^2]$	HX 1	94.68	55.12
	HX 2	72.75	43.33
	HX 3	35.58	20.95
	HX 4	385.88	234.65
	HX 6	142.34	116.15
Utility cost $[\$h^{-1}]$	Period 1	91.64	102.22
	Period 2	95.15	100.37
	Period 3	77.85	79.33
TAC $[k\$]$		1374	1217

The reduction is due to lower investment, but also to more equal weight on all operating periods in the optimization. Now consider bypass placement for these two alternatives. Recall that for the exchanger areas found by Floudas and Grossmann (1987) at least three bypasses (around exchangers 4 and 6 and either 1, 2 or 3). Interestingly, for the exchanger areas in this work the bypass on heat exchanger 6 is not included. After area optimization, the number of bypasses drops to 2 which is equal to the target!

9 Discussion

Cost of bypasses. We have argued that investment cost as well as operating and maintenance cost of bypasses and control loops may be considerable. If one simply assumed that the cost of bypasses generally is a constant fraction (e.g. 20%) of the cost of the heat exchangers, it would be relatively easy to take these costs into account already during network design.

Bypasses for control Due to both investment and operating cost it is desirable to have a simple control system, that is a decentralized control system with few controlled outputs. It is an additional advantage if the same set of bypasses can cope with desirable and undesirable long-term changes (flexibility) and dynamic variations (controllability). When a simple control system cannot be implemented, it may often be advisable to either tolerate that the plant cannot fulfill all the flexibility or controllability requirements or redesign the entire HEN.

Effect of flowrates on heat transfer coefficients. Note that reducing the flow through an exchanger instantaneously reduces the heat transfer coefficient. This makes bypass control easier, a desired heat duty reduction will be achieved with smaller manipulations. However, when considering flexibility of split-designs, this is a negative effect, because the heat transfer coefficient of exchangers in parallel will decrease in the same way. In a design with two exchangers in parallel, both must be designed for maximum flow (i.e. maximum allowed pressure drop), and this will correspond to different operating points. Thus, both exchangers cannot be operated optimally (with maximum heat transfer coefficient) at the same operating point.

Minimization of fouling. Heat exchanger fouling is an important issue in most chemical processes. Fouling decreases the optimal length of the process campaigns and requires cleaning. Both reduced flowrate or increased temperature through an exchanger, even for a short period of time, may give a considerable degradation of exchanger performance for the rest of the campaign. Therefore, fouling may be an important argument for HEN structures without splitters, and fouling may be important both for flexibility and control. The HEN must be flexible so that the target temperatures can be met throughout the campaign, i.e. the HEN must be able to cope with this undesirable long-term change. For minimization of fouling, additional intermediate temperatures must be controlled and some exchangers should not be bypassed. In some cases it may even be appropriate to install a recirculation stream around a fouling exchanger to keep the flowrate high during low plant load or use a recycle as an alternative to a bypass for reducing the heat duty of the exchanger without reducing the flowrate through the exchanger.

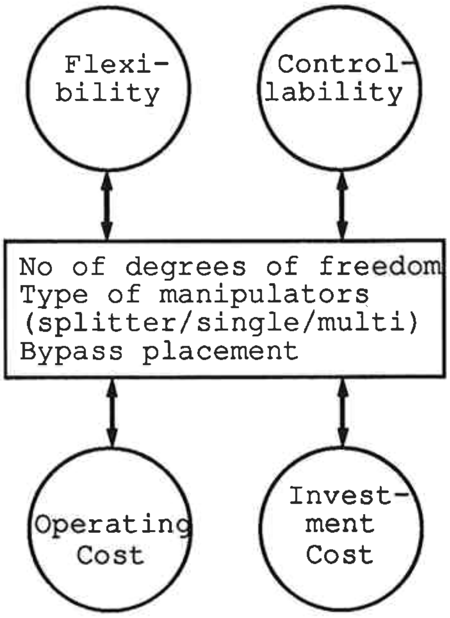


Figure 13: Four-way tradeoff

Pressure drop. The pressure drop in HENs may be important for design as well as operation, especially for gas streams. The heat transfer coefficient generally increases with pressure drop, but the plant power requirements increases, too, so a trade-off exists. Due to pressure drop considerations, heat exchangers with multiple tube passes are often used. The temperature driving force decreases when the flows no longer are countercurrent. This increases area requirements, and is unfavorable for flexibility. However, the apparent dead-time of the exchanger is decreased, so control is favored in cases where an exchanger not immediately upstream the output is used as a manipulator.

Controller tuning/use of linear tools. Several authors (e.g. Alsop and Edgar, 1989) have emphasized the non-linearity of heat exchangers, and used a heat exchanger to illustrate advantages of non-linear or adaptive control methods. These authors use a "utility exchanger", i.e. one of the flowrates is used as manipulated input. In practice many utility exchangers and all process heat exchangers are manipulated by adjusting the bypass fraction. This makes the system less non-linear and established powerful linear methods for controller tuning can be applied.

10 Conclusions

A number of practically interesting optimization problems may be formulated, even with HEN structure and *areas given*. There is a four-way trade-off between flexibility (static performance specifications) controllability (dynamic performance specifications) operating cost (utility requirement and control system maintenance), investment cost (installation of bypasses and control system). Decision variables are no of bypasses, type of bypasses and bypass placement. The tradeoff is illustrated in Fig. 13.

Splitters, single bypasses or multi-bypasses may be used as manipulated variables in HENs. For control multi-bypasses are best, single bypasses second best and splitters the worst. Multi-bypasses are preferred due to the possible control range and (sometimes) speed of response as compared to single bypasses. Splitters are worst due to possible problems with unwanted side-effects of the control actions and the slower speed of response. For flexibility, splitters are best, single bypasses second best and multi-bypasses are worst, ie the order is reversed. Splitters are preferred because the installed areas are utilized completely for all operating points. From an area-utilization point of view single bypasses are better than multi-bypasses.

Bypasses are placed to increase controllability or flexibility (increase the feasible range of operation) or reduce energy cost. There is a trade-off between number of bypasses (investment cost) and energy. Often minimum energy requirement may be achieved without bypasses on all process exchangers. Optimal resilient HENs have a number of bypasses that is equal to or slightly above the target number of bypasses suggested in this paper.

Use of multi-bypasses may decrease the number of bypasses needed to fulfill flexibility requirements by a) decreasing the number of bypasses needed to control one output, and b) controlling different outputs at different operating points. This will typically occur when the duty of the final exchanger on a controlled stream is small compared to the static disturbance loads (provided that additional upstream exchangers exist). Multi- bypasses may increase the speed of response, that is increase the controllability. This will typically occur when both outputs of one exchanger are to be controlled.

Prespecification of approach temperatures ought to be avoided in synthesis of resilient HENs. Instead of focusing on achieving maximum energy recovery for the set of operating points one should address feasibility and area-utilization. Dynamic and control considerations should be taken into account already in the design phase. Because the cost of dynamic variations are difficult to quantify for most chemical processes, it may be preferable to take controllability into account by adding constraints to the synthesis problem formulation.

Nomenclature

a_i - Number defined in appendix 1
$d(s)$ - vector of disturbances
$G(s)$ - Process transfer function matrix
$G_d(s)$ - Disturbance transfer function matrix
j_i - index for number of multi-bypasses over i heat exchangers in HEN
k - index for number of bypasses in HEN
m_i - Number defined in appendix 1
N_{byp} - No of bypasses in HEN
N_c - No of cold process streams in HEN
N_h - No of hot process streams in HEN
N_{hx} - No of process heat exchangers in HEN
N_i - No of multi-bypasses over i heat exchanger 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 (or period)
$r(s)$ - vector of reference signals (setpoints)
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 without heater at network outlet
T_{cj}^{t-1} - temperature of cold stream with final heater at heater inlet
$u(s)$ - Vector of manipulated inputs.
$y(s)$ - vector of outputs
y_{hi} - setpoint for hot target temperature not downstream cooler
y_{hj} - setpoint for hot target temperature downstream cooler
y_{ci} - setpoint cold target temperature not downstream heater
y_{cj} - setpoint cold target temperature downstream heater
w_h - heat capacity flowrate of hot stream $[W/K]$

w_c - heat capacity flowrate of cold stream $[W/K]$

References

[1] Alsop, A.W. and T.F. Edgar (1989). Nonlinear heat exchanger control through the use of partially linearized control variables. *Chem. Eng. Comm.*, 75, 155-170.

[2] Cerda, J., Galli, M.R., Camussi, N. and M.A. Isla (1990). Synthesis of Flexible Heat Exchanger Networks - I. Convex Networks. *Comput. Chem. Engng.*, 14, 197-211.

[3] Cerda, J. and M.R. Galli (1990). Synthesis of Flexible Heat Exchanger Networks - II. Nonconvex Networks with Large Temperature Variations. *Comput. Chem. Engng.*, 14, 213-225.

[4] Colberg, R.D. and M. Morari (1988). Analysis and Synthesis of Resilient Heat Exchanger Networks. In: *Advances in Chemical Engineering* (J. Wei, Ed.), 14, 1-93.

[5] Colberg, R.D., M. Morari and D.W. Townsend (1989). A Resiliency Target for Heat Exchanger Networks. *Comput. Chem. Engng.*, 13, 821-837.

[6] Floudas, C.A. and I.E. Grossmann (1987). Automatic Generation of Multiperiod Heat Exchanger Networks Configurations *Comput. Chem. Engng.*, 11, 123-142.

[7] Galli, M.R. and J. Cerda (1991). Synthesis of Flexible Heat Exchanger Networks - III. Temperature and Flowrate Variations. *Comput. Chem. Engng.*, 15, 7-24.

[8] Gundersen, T. and L. Naess (1988). The synthesis of Cost Optimal Heat Exchanger Networks. An Industrial Review of the State of the Art. *Comput. Chem. Engng.*, 12, 503-530.

[9] Kotjabasakis, E. and B. Linnhoff (1987). Better System Design Reduces Heat Exchanger Fouling Costs. *Oil & Gas J.*, 85, 49-56.

[10] Marselle, D.F., M. Morari and D.F. Rudd (1982). Design of Resilient Processing Plants - II. Design and Control of Energy Management Systems. *Chem. Eng. Sci.*, 37, 259-270.

[11] Mathisen, K.W., S. Skogestad and E.A. Wolff (1991). Controllability of Heat Exchanger Networks. Paper 152n at *AIChE Annual Mtg.*, Los Angeles, USA.

[12] Mathisen, K.W., S. Skogestad and E.A. Wolff (1992). Bypass Placement for Control of Heat Exchanger Networks. Paper at *ESCAPE-1.*, Elsinore, Denmark (to appear in special issue of *Comput. Chem. Engng.*

[13] Townsend, D.W. and M. Morari (1984). Resiliency of Heat Exchanger Networks: An objective compatible with minimum cost. Paper at *AIChE Ann. Mtg.*, San Francisco.

Appendix 1

The number of bypasses N_{byp} may vary between zero (all hard targets are controlled by utility exchangers) and the number of process heat exchanger N_{hx}. The number of alternative sets of bypass selections with exclusively single bypasses (Eq. 1) must then be replaced by the following sum:

$$\sum_{k=0}^{Nhx} 2^k \frac{N_{hx}!}{k!(N_{hx}-k)!} \tag{11}$$

where the summation (with index k) is over the number of bypasses.

If bypasses over two exchangers in series is allowed, the structure of the network must be known to decide the number of alternative sets of bypass selections. Suppose N_i is the number different i exchangers in series in the HEN, $i \geq 2$. One is to take the utility exchangers into consideration. If N_{byp} bypasses are to be placed and single and double bypasses are considered, the number of alternative sets of bypass selections is:

$$\sum_{j_2=0}^{max(0,min(N_{byp},N_2))} 2^{N_{byp}-j_2}\frac{N_{hx}!}{(N_{byp}-j_2)!(N_{hx}-N_{byp}+j_2)!}\frac{N_2!}{j_2!(N_2-j_2)!} \tag{12}$$

where the summation (with index j_2) is over the number of double bypasses. Suppose that the largest number of units (process heat exchanger and utility heat exchangers) are n and that all possible multi-bypasses is to be considered. One needs $n-1$ summations, and their indices are denoted $j_2, ..j_i, ..j_n$. If a_i is defined as $j_n + j_{n-1} + .. + j_{i+1}$ and $m_i = max(0, min(N_{byp} - a_i, N_i)$ the number of different bypass sets may be expressed as:

$$\sum_{j_n=0}^{m_n}\sum_{j_{n-1}=0}^{m_{n-1}} .. \sum_{j_2=0}^{m_2} 2^{N_{byp}-a_1}\frac{N_{hx}!}{(N_{byp}-a_1)!(N_{hx}-N_{byp}+a_1)!}\frac{N_2!}{j_2!(N_2-j_2)!}\frac{N_3!}{j_3!(N_3-j_3)!}..\frac{N_n!}{j_n!(N_n-j_n)!} \tag{13}$$

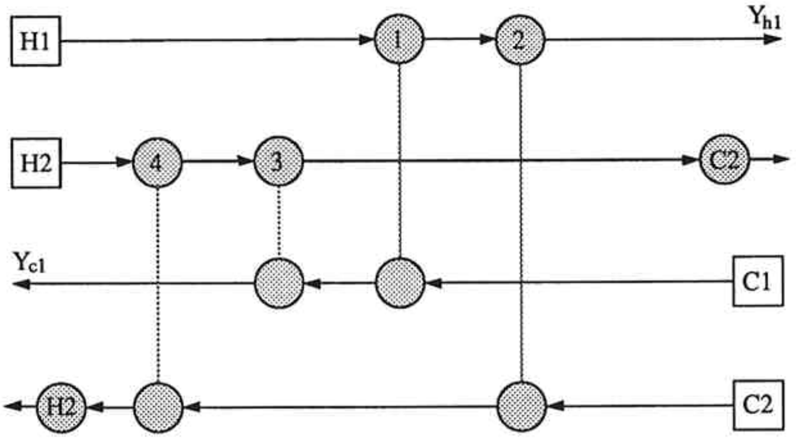
If one allow any number of bypasses up to the number of process heat exchangers, but only single and double bypasses, the number of alternative sets of bypass selections is:

$$\sum_{k=0}^{N_{hx}}\sum_{j_2=0}^{max(0,min(k,N_2))} 2^{k-j_2}\frac{N_{hx}!}{(k-j_2)!(N_{hx}-k+j_2)!}\frac{N_2!}{j_2!(N_2-j_2)!} \tag{14}$$

where the first summation (with index k) is over the total number of bypasses and the second summation (with index j_2) is over the number of double bypasses as before. If the meaning of m_i is slightly altered $m_i = max(0, min(k - a_i, N_i)$ Eq (5) above may be generalized as Eq (3):

$$\sum_{k=0}^{Nhx}\sum_{j_n=0}^{m_n}\sum_{j_{n-1}=0}^{m_{n-1}} .. \sum_{j_2=0}^{m_2} 2^{k-a_1}\frac{N_{hx}!}{(k-a_1)!(N_{hx}-k+a_1)!}\frac{N_2!}{j_2!(N_2-j_2)!}\frac{N_3!}{j_3!(N_3-j_3)!}..\frac{N_n!}{j_n!(N_n-j_n)!} \tag{15}$$

An example using a HEN from Townsend and Morari (1984) is given below:



$N_{hx} = 4, N_2 = 6, N_3 = 2$: $N_{byp} = 2$ and only single bypasses: 24 alternatives $0 \leq N_{byp} \leq N_{hx}$ and only single bypasses: 81 alternatives $N_{byp} = 2$ and single or double bypasses: 87 alternatives $N_{byp} = 2$ and single or double or *triple* bypasses: 116 alternatives $0 \leq N_{byp} \leq N_{hx}$ and single or double bypasses: 1159 alternatives $0 \leq N_{byp} \leq N_{hx}$ and single or double or triple: 2073 alternatives

An approximate value of the number of possible double bypasses (N_2) can be calculated from the number of streams and exchangers, i.e. without knowing the exact network structure: $N_2 \approx 2N_{hx} + N_u - (N_h + N_c + N_{spl}$ where N_u is the number of utility exchangers, N_h hot streams, N_c cold streams and N_{spl} stream splits. $N_3 \approx 2N_{hx} + N_u - 2(N_h + N_c + N_{spl})$ $N_i \approx 2N_{hx} + N_u - (i-1)(N_h + N_c + N_{spl})$

For the example from Townsend and Morari, $N_u = 2$,$N_h = 2$, $N_c = 2$ and $N_{spl} = 0$ which gives $N_2 = 6$ and $N_3 = 2$. Consequently, the approximate formula is an exact formula in this case.