Chapter 2

BASIC IDEAS AND CONCEPTS

This chapter includes the common basis required for the subsequent chapters, particularly for those chapters that concern operation of HENs. It will also give some further motivation why good operation and control of HENs is important for the overall process. Terms like flexibility, controllability and operability will be described, and the influence of the process structure will be discussed. The chapter starts with a quick summary of the design of the overall process and a brief overview of HEN synthesis, before the topics more related to operation are presented.

2.1 Decomposing the HEN from the rest of the process

A plant transfers raw materials into products by means of chemical reactions, separation steps etc. Often a plant comprises several feed streams being converted into a main product together with wanted or unwanted byproducts in a complex process structure. In addition, utility systems for thermal energy, mechanical and electrical energy, pneumatics and so on are required. In the subsequent, the term *utility* refers to thermal energy, i.e. addition and removal of heat.

The purpose of a plant is to manufacture the desired products as economically as possible. However, government regulations (e.g. regarding environmental pollution), safety and health demands also have to be fulfilled. Three tasks that have a major impact on the overall properties of a plant are the selection of:

1. Reaction path and reactor(s).
2. Recycle and separation network.
3. Heat exchanger network and utilities.

There are two essentially different approaches to process design (Smith, 1995, chapter 1):

1. Sequential development of a process structure.
In this approach, the designer starts by making decisions about the most important part of the process and then moves to less important parts. In process design the "onion model" described by Smith and Linnhoff (1988) is usually followed, see figure 2.1.

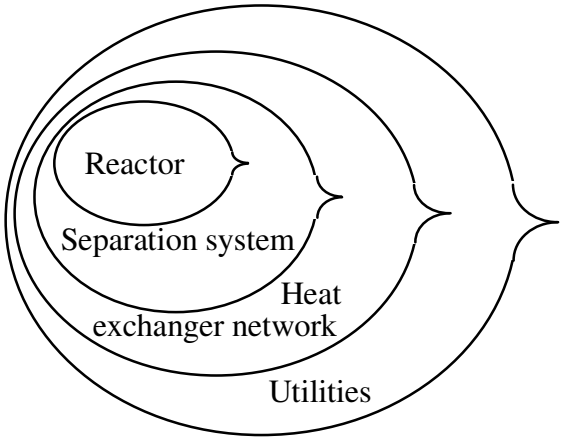

Figure 2.1 Onion diagram in process design.

The design starts with the "core" of the process which is the reactor. When reaction path and reactor have been selected, the designer can move outwards in the onion and make decisions on separation and recycle system, and so on. The flowsheet is developed sequentially and there is no guarantee that a series of optimal local decisions leads to an optimal overall process. For example, decisions made in the reactor and separation layers may give little potential for heat recovery in the outer layers. The designer may then go back to the inner layers and investigate other alternatives, hoping to find an overall solution at least close to the global optimum. Despite the danger of being trapped in local optima and the work required in investigating several alternatives, this approach also has advantages: The designer (or design team) interacts actively in the design process and can use his/her knowledge and experience. With the designer in command of the decisions taken a large variety of knowledge can be considered, but perhaps more important – the designer learns from the design process and will become a better designer in subsequent projects.

2. Simultaneous development of a process structure.
The second approach is based on a *superstructure* of the process. A superstructure (or hyperstructure) includes all process structures that will be considered. That is, the designer starts by setting up all possible reactors, all possible recycles and separators and so on. This results in a large number of candidate process structures and the design problem is formulated as a mathematical model which is solved by means of optimization. The approach usually result in an MINLP problem (see e.g. Grossmann, 1985) where the integer part represents discrete decisions such as whether a processing unit is present or not. (Note that the term "integer" in MILP or MINLP problems often actually refers to *binary* variables and not to integers). Logical propositions such as "*choose exactly one reactor*" *or* "*if reactor A is chosen, then separator D can not be chosen*" are formulated as mathematical constraints and included in the model.

This second approach will not be trapped in local optima due to sequential decisions as in the first approach. However, the second approach also have disadvantages: The optimal process structure may not be embedded in the superstructure given initially by the designer. Provided that the optimal structure *is* embedded within the superstructure, the numerical solution algorithm may fail to find the global optimum. In general such problems are non-convex and there is no guarantee that the global optimum will be found. Thus, this approach may also result in a local optimum. In addition, the combinatorial nature of such problems may impose severe limitations for the simultaneous approach when applied to medium or large size problems. The most serious disadvantage, however, is probably that the designer does not play an active role in the decision making. This means that topics like safety and health considerations or e.g. costs related to adaptation to existing infrastructure hardly will be considered in the conceptual design stage. Such considerations may be done by an experienced designer in early decisions of the sequential approach, but will be more difficult to implement in a optimization model required for the simultaneous approach. Also, the learning of the designer will be less prominent in the second approach.

Despite the fundamental differences between the sequential and simultaneous approaches, most practical designs will have elements of both. The difference between sequential and simultaneous methods may not only be applied to flowsheeting of a complete plant, it may be equally relevant for each subtask. In the next section, it will be clear that the main difference in synthesis of HENs is also between sequential and simultaneous methods. The rest of this section is devoted to decomposition of the HEN from the remaining parts of the plant and to explain why good operation and control of the HEN is important for the overall process. These issues are illustrated by an example. The example has been made as simple as possible while retaining the essential properties of a typical integrated plant.

Consider the plant in figure 2.2 where decisions regarding reaction path, reactors and separation have been made. The process does not have any material recycles.

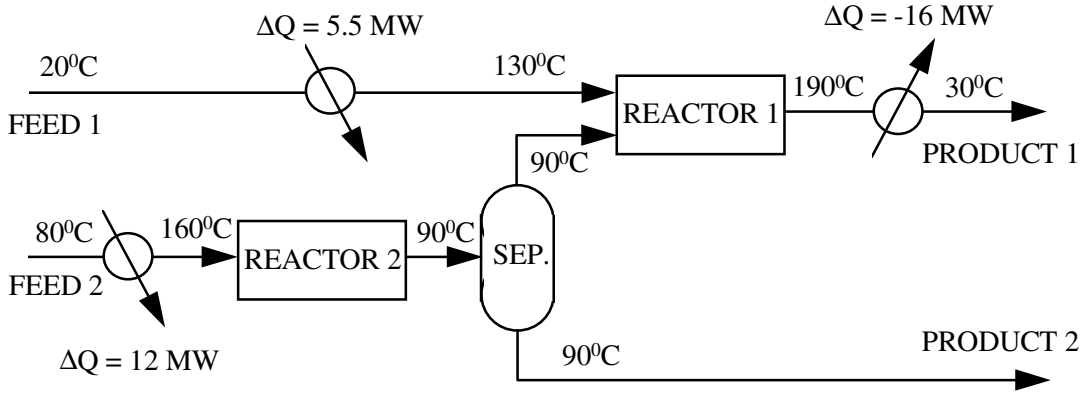

Figure 2.2 Simple process with two reactors and a separator.

The two feed streams requires heating and PRODUCT 1 requires cooling. Table 2.1 gives the data necessary for considering heat recovery between these three streams. Note that the

classification of hot and cold streams is based on whether a stream requires cooling or heating, it does not depend on temperature.

Stream name	Stream no.	T_s [°C]	T_t [°C]	CP [MW/°C]	ΔQ [MW]
PRODUCT 1	Hot 1 (H1)	190	30	0.10	16.0
FEED 2	Cold 1 (C1)	80	160	0.15	12.0
FEED 1	Cold 2 (C2)	20	130	0.05	5.5

Table 2.1 Thermal stream data for the simple heat recovery problem.

Using the data in Table 2.1, focus here is on the heat recovery problem only. The heat recovery problem has been decomposed from the rest of the process. An obvious way to satisfy the heating and cooling demands for this problem is to install two heaters and one cooler as shown in figure 2.3. The total heating and cooling duties are satisfied using external utilities (steam and cooling water) and the requirements are $Q_H = 17.5$ MW and $Q_C = 16.0$ MW for heating and cooling, respectively. This solution does not involve any heat recovery.

Figure 2.3 Trivial solution using external utilities only.

Figure 2.4 shows one possible HEN for the simple process. The countercurrent arrangement with hot streams on top from left to right and cold streams below from right to left (grid diagram) was introduced by Linnhoff and Flower (1978) and will be used throughout the thesis. In this simple HEN, two process-to-process heat exchangers (I and II) have been introduced and stream C2 does not need external heating. Compared to figure 2.3, the utility duties have been reduced to $Q_H = 8.0$ MW and $Q_C = 6.5$ MW while the number of heat transfer units has increased from three to four. Note that the reduction of *both* hot *and* cold utilities is equal to the total process-to-process heat transfer ($Q_I + Q_{II} = 9.5$ MW). This significant reduction in external energy consumption due to process integration is of course important. Linnhoff and Turner (1981) reports results from industrial applications where savings in both energy and capital costs have been achieved through heat integration.

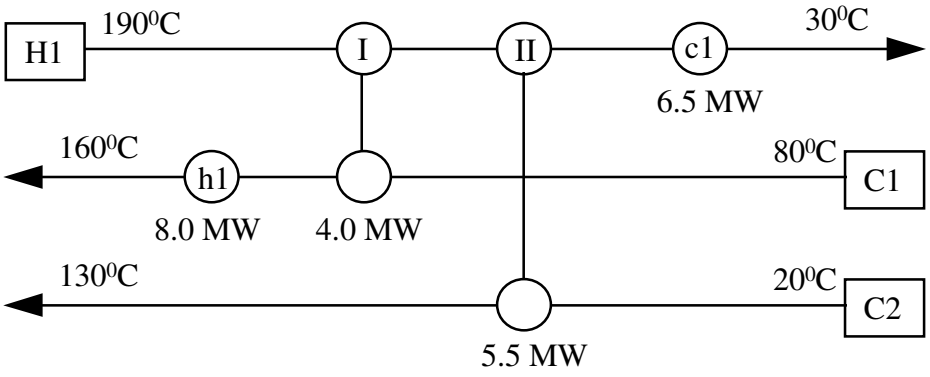

Figure 2.4 HEN for the simple process.

The HEN in figure 2.4 reduces utility consumption, however, it also introduces *interactions*. As an example, a disturbance in the supply temperature of stream H1 will not only affect the outlet temperature of the same stream but it will also affect the outlet temperatures of the two cold streams as this disturbance also will travel from hot to cold side of process-to-process heat exchangers. To see how these interactions in the HEN may influence the dynamics of the overall plant, the complete process including the HEN is drawn in figure 2.5.

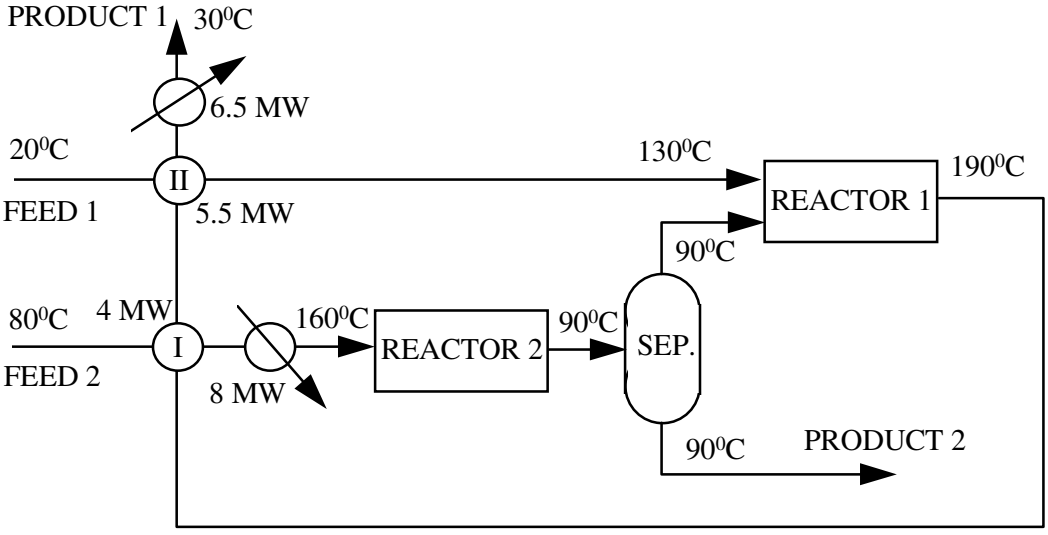

Figure 2.5 Complete plant with heat integration.

We see that the interactions in the HEN causes *feedback* in the plant, e.g. the exit temperature from REACTOR 1 will affect the inlet temperature of the same reactor through the heat exchangers. This may significantly change the overall plant dynamics, and may lead to slower response, increased sensitivity to disturbances and even instability. Of course, feedback may also give desired effects (e.g. feedback control). However, feedback introduced by heat integration makes it more difficult to deduce the plant dynamics from the dynamics of the individual plant units.

As illustrated by figure 2.4 and figure 2.5, a HEN can be considered from two different points of view:

Viewpoint 1. A HEN is a part of the process with its own properties such as heat recovery level and dynamic behavior, and it can be considered separately from the rest of the process.

Viewpoint 2. A HEN affects the overall plant properties as it connects the plant thermally. Consideration of the HEN as a separate unit has little interest.

The first point of view which focuses on the HEN as a separate unit is often employed in the synthesis of HENs. That is, the stream data is first selected from reactor, separation system and possibly recycle considerations (sequential approach). Then, the HEN is designed as a separate task even if it is clear that the optimal supply and target temperatures may change somewhat for the overall process.

Regarding the dynamics and control of an integrated plant, it could be easy to draw the conclusion that the second point of view has to be applied since it is the overall plant dynamics that is important. This conclusion is not quite true despite the fact that the dynamic behavior of the HEN itself may not be important. Consider an integrated plant where a separate control system has been designed for the HEN. Assume that the control system yields perfect control meaning that the outlet temperatures from the HEN are kept exactly at their target values (setpoints) also when disturbances are present. Now, the controlled HEN will *not* introduce any interactions or feedback in the overall plant. That is, if perfect control of the HEN is obtained, the overall plant dynamics will be as if heat integration was not present. However, the steady state benefit of heat integration in terms of reduced energy costs will be preserved. In practice, perfect control can not be achieved but we can conclude that "good" control of the HEN is desired as this will give "small" interactions and "small" effects of unwanted feedback in the overall plant. Good control of the HEN has a decoupling effect on the dynamics of the overall plant and will simplify control system design for the rest of the process. Of course, controlling the outlet temperatures from the HEN is also important since deviations from the target temperatures may affect for example reactor conversion or quality of separation in downstream units. In conclusion, dynamics and control of the HEN are important for the overall plant behavior.

2.2 HEN synthesis, a quick overview

The total design effort (on a systems level) required for a HEN typically involves the following three stages:

1. Nominal design. Synthesize one or more networks with good properties (regarding heat recovery and capital cost) for nominal stream data.
2. Flexibility and controllability. Investigate the networks with regard to flexibility and controllability, and possibly introduce some modifications (e.g. increased area) such that at least one HEN shows satisfactory results.
3. Operation. Design a control system to operate the HEN properly. This involves control structure selection and possibly some method for on-line optimization.

This section will briefly explain a few aspects related to the first of these points; synthesis of HENs for nominal stream data. HEN synthesis is often regarded as the most mature research field within process design, and progress during the last decades has been made in parallel by the two main "schools"; pinch technology and mathematical programming. A comprehensive and thorough review of HEN synthesis until the late 1980's is given by Gundersen and Næss (1988).

Despite being thoroughly investigated, the combinatorial aspects together with the non-convex nature of the HEN synthesis problem, make the search for the cost optimal HEN a challenging task, see e.g. Gundersen *et al.* (1991). The simple concepts described in this section is part of pinch analysis.

An important concept within pinch technology is the merge of all hot process streams and all cold process streams into one temperature/heat diagram, known as the composite curves. The stream data required to draw the composite curves for the simple problem used in the previous section is given in table 2.1, and the data will be used as a simple example. The composite curves for this example are shown in figure 2.6.

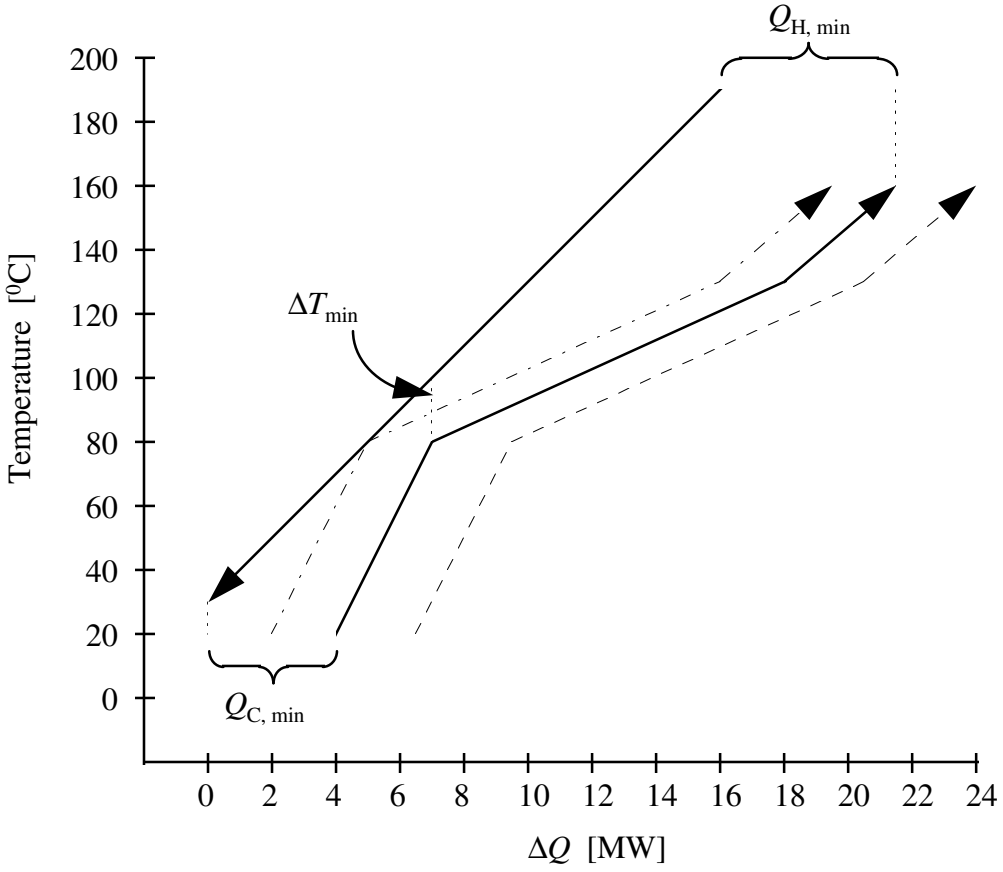

Figure 2.6 Composite curves for the simple heat recovery problem.

In this simple example, there is only one hot stream and the hot composite curve (upper line) is trivial. Both of the cold streams are present in the temperature range from 80°C to 130°C, and the slope of the cold composite curve is 1/(0.15+0.05) = 5.0 [°C/MW] in this temperature

interval. The horizontal axis is *change* of heat, thus the horizontal positions of the curves are not unique. The vertical difference between the composite curves denote the driving forces for heat transfer. For the solid composite curves in figure 2.6, the smallest temperature difference between the curves, ΔT_{min}, is selected to 20°C. At the highest temperature, the process needs addition of hot utility Q_H (e.g. steam) and at lowest temperature the process needs removal of heat to cold utility Q_C (e.g. to cooling water). In the region along the horizontal axis where both curves are present, heat may be recovered between hot and cold process streams. The point where the composite curves are closest to each other is known as *the pinch*. With the smallest driving forces, the pinch represents the bottleneck for heat transfer. The pinch also decomposes the heat recovery problem into two subproblems; (1) above pinch where only hot utility is needed, and (2) below pinch where only cold utility is needed. Transferring heat across the pinch using process exchangers will increase *both* hot and cold utility accordingly ("double penalty") and should be avoided.

Before the pinch design method can be applied, a value of ΔT_{min} has to be selected. This specification actually trades off utility consumption (operating cost) against capital cost (e.g. heat exchanger area). It is thermodynamically feasible to let the composite curves touch at the pinch (dash-dotted cold curve in figure 2.6), yielding the lowest external utility consumption possible. With no driving forces at the pinch, however, infinite heat exchanger area is required and the resulting HEN is definitely not cost optimal. A reasonable value of ΔT_{min} can be found from optimizing the trade-off between utility consumption and capital cost. This is known as supertargeting, see Ahmad *et al*. (1990).

The pinch design method consists of three stages:

1. Targeting
2. Synthesis
3. Optimization.

These will now be described very briefly using the simple example.

Targeting

An important feature related to HEN synthesis is that it is possible to quantify *targets* for minimum utility consumption, minimum number of units and minimum area *ahead* of the actual synthesis stage. Minimum utility consumption ($Q_{H,min}$ and $Q_{C,min}$) can be found using e.g. the problem table algorithm or the heat cascade, or it may be found graphically from the composite curves (when they are aligned according to the specified value of ΔT_{min}). From figure 2.6, the targets for utility consumption are identified to $Q_{H,min} = 5.5$ MW and $Q_{C,min} = 4.0$ MW. The targets for utility consumption are constrained by the value of ΔT_{min}.

The target for number of units normally arises from the "*N*–1" rule: Minimum number of units (including utility exchangers) is equal to the number of streams (including utilities) minus one. This rule is based on graph theory – no thermodynamic considerations are made, and there are cases where the rule does not give a correct target value. A rigorous target value for minimum number of units may be found using mathematical programming. For the simple example, the target for number of units (for the complete HEN) is 3+2–1 = 4. Applying the *N*–1 rule below and above the pinch separately, the target for minimum number of units for the decomposed HEN is (3+1–1) + (2+1–1) = 5.

A target value for total area may be found assuming vertical heat transfer. This target, however, is not compatible with the target for minimum number of units. Cost optimal HENs often have close to minimum number of units, and the area will often deviate from the target.

Synthesis

In this step, a HEN that satisfies the target for utility consumption (maximum energy recovery) is designed. The design starts where the process is most constrained, at the pinch, and is carried out separately above and below pinch. ΔT_{min} is the agreed minimum approach temperature for each heat exchanger, and exchangers are placed between streams such that this requirement is fulfilled. To achieve this, stream splitting may be necessary. The duty of each heat exchanger is made as large as possible, constrained by the stream with the smallest heat demand. This "tick-off" rule minimizes the number of units in the design. Utility exchangers are placed on streams that do not meet the target temperatures when using only process exchangers. Figure 2.7 shows the maximum energy recovery HEN for the example and the pinch is shown by the dashed vertical line. The utility targets are met and the number of 5 units corresponds to the target for the decomposed HEN.

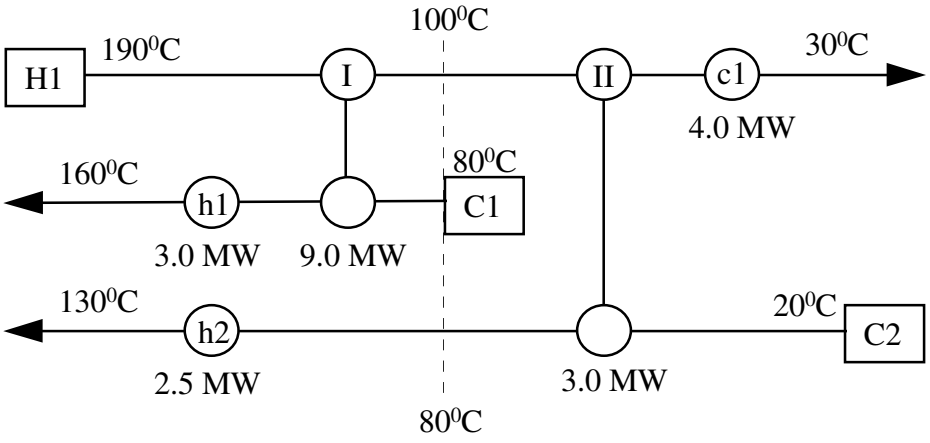

Figure 2.7 Maximum energy recovery network (ΔT_{min} = 20°C).

Optimization

In this stage, the maximum energy recovery HEN from the synthesis stage is improved in order to achieve a more cost optimal HEN. All pinch designs from the synthesis will have at least one unit more than the minimum number when the complete HEN is considered. Removing units may reduce the total HEN costs. The network in figure 2.7 has one unit above the target for the complete HEN, and excess units form *loops*. For this example, there is only one loop:

Units:	II h2 h1 I
Streams:	H1 — C2 — ST — C1 — H1

The units are physically connected by the streams as indicated above. To form a loop, the first and last stream must be identical. A loop always consist of an even number of units, and every second unit may increase and decrease its duty by the same amount of heat while maintaining the heat balance in the HEN. Manipulating a loop this way represents a degree

of freedom in the design stage, and it may be utilized to remove a unit. A heuristic rule in pinch design is to remove the unit with the smallest duty. Applied to the example, heater h2 is removed by reducing the duty to zero. This results in *increased* duties of 2.5 MW for heater h1 and exchanger II and the same *reduction* in exchanger I. Examining the resulting HEN, one will find that the constraint on ΔT_{min} is violated (hot side of exchanger I). ΔT_{min} is restored by exploiting *paths* in the HEN. In the example, there is a path from hot utility stream (ST) to the cold utility stream (CW, cooling water).

$$\begin{array}{ccccccc} & & \text{h1} & & \text{I} & & \text{c1} \\ \text{ST} & — & \text{C1} & — & \text{H1} & — & \text{CW} \end{array}$$

A path is manipulated similarly as a loop; every second unit is manipulated by opposite duties of equal magnitude. A path always comprises an odd number of units, meaning that the first and last unit (utility exchangers) are changed in the same direction. In the example, the hot outlet temperature of exchanger I is increased by reducing the duty of that exchanger. Hence, ΔT_{min} can be restored by reducing the duty of exchanger I which implies increased duties of the heater and cooler. In general, restoring a violation of ΔT_{min} implies that the duty of both utility exchangers in a path are *increased*. The completed HEN after ΔT_{min} is restored is shown is shown in figure 2.4. The composite curves for the finished HEN is shown in figure 2.6 (dashed cold line). Note that the smallest temperature difference between the composite curves are larger than the $\Delta T_{min} = 20°C$ at the hot end of exchanger I. The reason for this is that the completed HEN includes non-vertical heat transfer and heat is transferred across the pinch. This increases utility consumption but saves one unit.

In general when using pinch analysis, the designer is faced with a number of choices in the synthesis stage and particularly in the optimization stage. In practice, a number of alternative designs should be carefully investigated with respect to utility consumption, capital cost (e.g. area), operability aspects etc. before the final HEN design is settled.

The very brief and incomplete introduction to the pinch design method presented here was done without references to other works. It has mainly been included for readers without any prior knowledge about HEN synthesis More thorough introductions can be found elsewhere, see e.g. Linnhoff *et al*. (1982) or textbooks such as Douglas (1988) or Smith (1995). This thesis focuses on *operation* of HENs, and design is not emphasized. Some differences/similarities between design and operation can, however, already be pointed out with regard to the important terms presented above (composite curves, loops and paths). In operation of a given HEN, we want the utility consumption to be as small as possible. Control and operation of HENs are the main topics in the remaining sections of this chapter. The following relations between synthesis and operation can be given at this point:

Loops. Loops may be removed in the design stage, but the completed HEN design may still include one or a few loops. As it was clear from above, manipulating loops do not change the total utility consumption, hence we may expect that loops do not play any important role in operation. Loops (particularly those involving only process exchangers) introduces feedback internally in the HEN and this may change the dynamic properties of the HEN.

Paths. Manipulating a path changes the utility consumption, and manipulating paths for varying disturbances etc. to minimize utility consumption is important during operation.

Composite curves. While composite curves are fixed during design (when the heat recovery level is specified), they may change during operation due to variations in supply temperatures, heat capacity flowrates etc. In addition, the specification on ΔT_{min} (for trade-off between capital and operating costs) has no relevance during operation. The purpose during operation is to vary the manipulations in order to keep the composite curves as close to each other as possible when disturbances are present and change the shape of the composite curves.

In the remaining part of this section, the most important methods for HEN synthesis will be mentioned. A major difference of existing methods for HEN synthesis is between sequential and simultaneous approaches, as it was for the design of the overall plant. Methods for synthesis of HENs can be divided into four main categories.

1. Pinch design. Thermodynamic based sequential method.
2. Sequential approach based on mathematical programming.
3. Simultaneous approach based on mathematical programming.
4. Merge of approaches 1, 2 and 3.

In the pinch design method, the designer participates very interactively in the HEN design. Not only are the three stages (targeting, synthesis and optimization) carried out sequentially, but the synthesis stage itself is indeed sequential. The designer places the heat exchangers, one by one, starting at the pinch and moving away until the maximum energy recovery HEN is completed.

In the second category, the target for utility consumption is found using and an LP formulation. Using mathematical programming, constrained heat exchange such as forbidden matches (e.g. due to safety aspects or geographical distances) may be considered. With the target value from this first stage, rigorous targets for minimum number of units as well as the corresponding heat load distribution are found by solving an MILP problem, see Papoulias and Grossmann (1983). The actual network generation is formulated as an NLP problem (Floudas *et al*. 1986). The MILP problem may result in multiple solutions and networks may be generated for the most promising heat load distributions. The network generation (synthesis) is simultaneous in this approach. The approach is here denoted sequential since the HEN design is divided into three subtasks carried out in sequence. Each subtask is, however, performed simultaneously using mathematical programming. The introduction of the vertical MILP model for HEN synthesis (Gundersen and Grossmann, 1990) and the extended vertical MILP problem (Gundersen *et al.*, 1996) aims at improving this strategy so the MILP stage results in heat load distributions in the correct order. That is, the most promising heat load distribution should result in the HEN giving minimum total annual cost etc.

The third category includes truly simultaneous approaches using MINLP formulations. Available numerical algorithms may, however, fail to find the globally optimal HEN due to non-convexity. Further, combinatorial aspects may put severe limitations on the size of HEN synthesis problems that can be solved. In the model proposed by Yee and Grossmann (1990), only the objective function contains non-linearities and all constraints are linear. This model,

however, only allows for iso-thermal mixing, hence the globally cost optimal HEN may not be embedded in the superstructure. Examples of more recent research to overcome problems related to simultaneous HEN synthesis are convex under-estimators (Quesada and Grossmann, 1995) to overcome non-convexity problems, and reduction of the combinatorics problem using logic, see e.g. Floudas and Grossmann (1994). In addition, stochastic optimization methods such as simulated annealing and genetic algorithms are proposed in order to reduce the problem of being trapped in local optima. Despite the efforts to overcome the problems connected to simultaneous synthesis of HENs, the solution of the MINLP models still represents an obstacle that may be prohibitive at least to industrial sized problems.

At present, no existing method for HEN synthesis can guarantee to find the globally optimal solution. A new trend within HEN synthesis is to merge the best properties from the three approaches mentioned above. This forth approach involves use of pinch principles for screening of alternatives prior to the simultaneous method. Reducing the search space for the MINLP formulation in this way is described by Grossmann and Daichendt (1996). Another branch of this approach includes decomposing the composite curves into blocks and then applying simultaneous techniques for each block, see Zhu *et al*. (1995).

2.3 Introduction to operation and control of HENs

The control objective in a HEN is usually to control outlet temperatures to specified target values (setpoints, references). Target temperatures are denoted with subscript *t* and the actual (measured) outlet temperatures have subscript *o* (e.g. T_t^{H1} and T_o^{H1} are target and outlet temperatures for stream H1). The letters *r* for reference and *y* for measurement which are conventional notation in control literature will also be used. In some cases, there may be other control objectives as well. For instance, the reboiler or condenser in a distillation column may be integrated in the HEN, and the target in such case may be the heat duty of the unit. Another example is when some internal temperature has a maximum value e.g. to prevent decomposition. There may also be outlet temperatures without any specified target value (free outlet temperatures). If nothing else is specified, "targets" denote the setpoints for the outlet temperatures.

In addition to the regulatory control objective it is important that the utility cost is as small as possible. In order to have a concise understanding of what we want to achieve during operation of a HEN, the following definition is introduced.

Definition 2.1 *Optimal operation of HEN.*
For a HEN with given structure, heat exchanger areas, heat transfer coefficients and supply and target temperatures, the operation is optimal if the following three requirements are fulfilled:

- Primary goal: Target temperatures are satisfied at steady state.
- Secondary goal: Utility cost is minimized at steady state.
- Third goal: Dynamic behavior is satisfactory.

■

The secondary goal requires that there are extra degrees of freedom when manipulations have been dedicated for achieving the primary goal. As it will be clear from the next section, most HENs have degrees of freedom that can be used for utility cost minimization. The third goal is deliberately a bit more vague than the two first. It is certainly possible to define rigorous specifications on the dynamic behavior, but in many cases we will simply use hand rules and common sense to satisfy this third requirement. Of course, we want the controlled HEN to be stable and that the dynamics are not unnecessary slow or oscillatory. With this definition of optimal operation, where the two first goals apply at steady state, it is clear that it is assumed that the process is operated close to steady state most of the time and that the total operating costs are dominated by steady state performance rather than by transient responses.

To manipulate the outputs to meet the targets we differ between the following four categories of inputs:

1. Bypass fraction across one single heat exchanger
2. Bypass fraction across multiple heat exchangers
3. Duty of utility exchangers
4. Split fractions

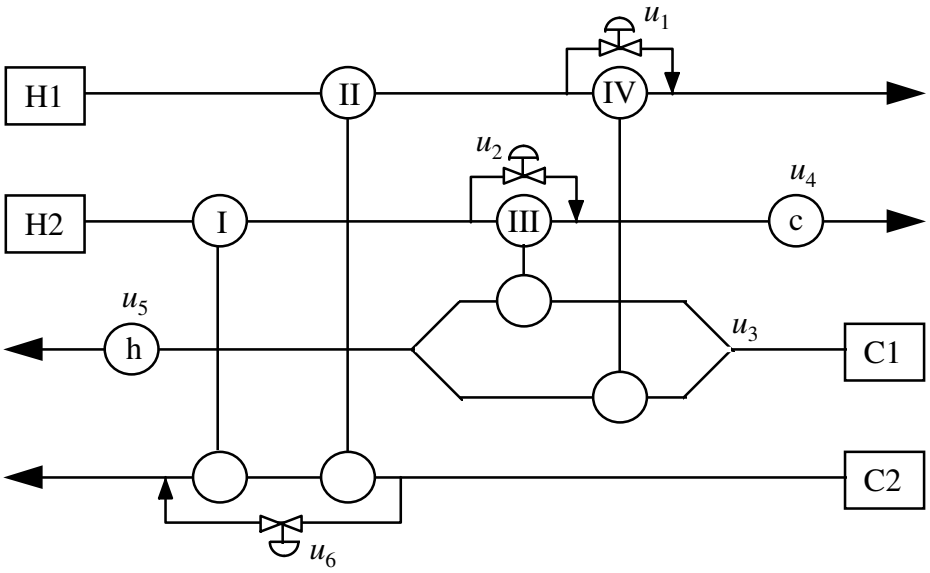

Figure 2.8 Different types of manipulations in a HEN. u_1 and u_2 are single bypasses, u_3 is a variable split fraction, u_4 and u_5 are utility duties and u_6 is a multi-bypass.

The network in figure 2.8 shows these four types of manipulations. For single bypasses (type 1) the input signal is assumed to be the bypass fraction directly. In practice, this may be implemented with a three-way control valve as the splitter, one flow transmitter in each of the two parallel streams and a flow ratio controller. Alternatively, one may install a regular control valve in the bypass stream (as indicated in figure 2.8) and perhaps a throttle in series with the heat exchanger combined with the low-level flow ratio control. (This alternative

solution will reduce the operating range and/or introduce additional pressure drop). In this thesis, the HEN will be viewed from a systems level, and the different practical realizations including the low-level flow control will not be considered in detail. We assume that the control signal is the split fraction directly (flow in bypass line divided by total flow in the stream). In practice, this signal may be the setpoint to the (fast) flow control.

Multi-bypasses may be considered in order to have a manipulation with a fast response in cases where single bypasses cannot affect all outputs directly (e.g. when both hot and cold outlet temperatures from a heat exchanger are controlled). Mathisen (1994, p.63) shows that a multi-bypass (type 2) may limit the operating range considerably compared to single bypasses, thus multi-bypasses may give serious problems with input constraints. In addition, a multi-bypass will reduce the driving forces on several heat exchangers. For these reasons, this category of manipulations will generally not be considered any further in this thesis.

Utility heat exchangers (type 3) are manufactured in various types and many different control strategies are being used. Again, since the HEN is considered from a systems level, we will not consider the implementation details and simply assume that the duty of the utility exchangers are manipulated directly. A utility exchanger is usually located as the final unit in a stream and therefore affects only the outlet temperature of this stream and no other temperatures in the network.

For networks with stream splits, the split fractions may be fixed or variable. A variable split fraction can be used as the manipulated input to control a target temperature. Often, however, a variable split fraction will be used for optimization purposes rather than for regulatory control.

As a general rule in this thesis, it is assumed that a single bypass is (or can be) placed across any heat exchanger and that utility exchangers (if present) always control the outlet temperature of that particular stream. Whether a split fraction is used as a manipulated input or not will be explained in each case. To summarize, the two most important types of manipulations are single bypasses and utility exchanger duties and this gives origin for dividing the targets into the following categories:

- **Bypass controlled targets.** Target temperatures controlled by a bypass across a process-to-process heat exchanger.
- **Utility controlled targets.** Target temperatures normally controlled by the duty of a final utility exchanger.

For problems with multiple hot or cold utilities there may be cases where a utility exchanger is located *internally* in the HEN. While internal utility exchangers may occur for industrial HEN problems, they are not considered very frequently in the academic literature. Utility controlled targets refers to outputs controlled by a *final* utility exchanger. Internal utility exchangers are not considered any further in this thesis. Thus, the term “utility exchanger”, actually refers to a final utility exchanger.

Since a utility exchanger only affects one outlet temperature, all exit temperatures from utility exchangers normally are utility controlled while the other target temperatures usually are bypass controlled. Using the HEN in figure 2.4 as a simple example, T_o^{H1} and T_o^{C1} are utility

controlled while T_o^{C2} is bypass controlled. This division into bypass controlled and utility controlled targets will be utilized in the methods presented in later chapters. The two categories of outputs can also be used to decompose HENs into a certain general structure. To do this, first split the targets (outputs) into y_U and y_{BP} for utility and bypass controlled targets as above. Then split the manipulated inputs into utility duties u_U and bypass fractions u_{BP}. Now the transfer function G from the inputs to the outputs can be divided into the following block structure:

$$\begin{bmatrix} y_U \\ y_{BP} \end{bmatrix} = \begin{bmatrix} G_{11}^{diag} & G_{12} \\ 0 & G_{22} \end{bmatrix} \begin{bmatrix} u_U \\ u_{BP} \end{bmatrix} \tag{2.1}$$

G_{11}^{diag} will always be diagonal since each final utility exchanger only affects the exit temperature of the corresponding stream, and therefore we also have $G_{21} = 0$. The first set of outputs is given by

$$y_U = G_{11}^{diag} u_U + G_{12} u_{BP} \tag{2.2}$$

Assuming that y_U are controlled by SISO feedback controllers from u_U, the last term in equation (2.2) can be considered as a disturbance. If the control of some utility controlled targets are critical, the diagonal feedback control may be combined with feedforward control from u_{BP}. Note that it *may* be possible to use bypass fractions for control of utility controlled outputs, but one must ensure that there are enough bypasses left for control of the bypass controlled outputs y_{BP} (since $G_{21} = 0$, meaning that u_U can not control y_{BP}). It is important to note that while y_U may be affected by u_{BP}, y_{BP} is *not* affected by u_U since we simply have

$$y_{BP} = G_{22} u_{BP} \tag{2.3}$$

Now, if we assume that y_U is *perfectly* controlled by u_U the following rule for decomposition of HENs can be stated.

Rule 2.1 *Decomposition of HENs.*
Assume that utility controlled targets are perfectly controlled using duties of utility exchangers, and that the utility exchangers are not saturated. Then, studying the utility consumption for the complete HEN and the dynamics of the bypass controlled targets are equivalent to study G_{22} together with a steady state expression for the duty of each utility exchanger. That is, G_{11} and G_{12} in equation (2.1) do not need to be addressed. ■

The expression for the steady state utility duty Q_U for each utility exchanger is

$$Q_U = \Delta T_U \, CP \tag{2.4}$$

where CP is the heat capacity flowrate of the process stream and ΔT_U is the positive temperature difference between the target temperature and the temperature at the inlet of the utility exchanger. The fact that dynamic models for utility exchangers may not be needed can be exploited to greatly simplify dynamic simulations of HENs as it will be done in chapter 3. An important point concerning optimization of a HEN during operation, is that there are no degrees of freedom associated with G_{11} since it is diagonal. The degree(s) of freedom (which

is a prerequisite for optimization) is associated with G_{22} (which usually has more columns than rows). Therefore, methods for optimal operation often focus on this transfer function together with simple expressions for utility consumption as in equation (2.4).

The pairing between inputs (manipulations) and outputs for regulatory control is usually rather straightforward. This is partly due to the structure in equation (2.1) which makes the pairing of u_U and y_U trivial since G_{11} is diagonal and partly because the "main rule" for pairing in HENs often can be used for the other outputs. The main rule for pairing can be stated as

Rule 2.2 *Main rule for input/output pairing in a HEN.*
For each outlet temperature that have a target value, prefer a manipulation which has a direct effect on this temperature. ■

This rule can be found several places in the literature and it is a frequently used hand rule for designers. See e.g. Mathisen (1994, chapter 4), where a number of other rules for bypass placement are stated as well. In cases where both hot and cold outlet temperatures from a heat exchanger have target values, the main rule for pairing cannot be applied and other pairings or a multivariable controller has to be used.

The pairing problem often assumes a quadratic plant, i.e. same number of inputs as outputs. This is usually not the case for HENs and when a manipulation has been assigned to each target temperature there are often extra manipulations left. How these extra manipulations are utilized may be important for other features than control such as for example energy consumption. It is important to keep in mind that rule 2.2 originates from the needs of regulatory control. Other pairings may be preferred if dynamic requirements are relaxed, and utility consumption is considered more important. Hence, there is a trade-off between dynamics and steady state performance. This interesting trade-off is important for the methods for optimal operation proposed in chapters 5, 6 and 7.

As it has been evident from this section, the methods for control of HENs presented in this thesis will be based on decentralized control. That is, SISO controllers will be used even if it is clear that the plant itself is multivariable. One might ask why not use a centralized controller that uses all measurements and computes all manipulations using dynamic optimization that simultaneously accounts for regulatory control as well as optimizing issues. Today, more and more plants have modern control systems that allow for such centralized control. At least the hardware conditions are fulfilled by means of data acquisition where all measurements are available for a computer which also can apply manipulations to the process. Despite this, most plants are based on decentralized control and some reasons for this are:

- Decentralized plant. Often a large part of the plant is trivially decentralized, or at least a pairing that gives relatively small interactions can be found.
- Easy to understand. The operation of SISO control loops (using PI or PID controllers) are fairly well understood by operators and others involved in the plant operation, and the control structure is often relatively easy to understand.
- Maintenance and modifications. Maintenance of a centralized control system (software) may be complex since it would have to comprise a complete model of the

plant together with optimization algorithms, equation solvers etc. In a decentralized control system, the different parts of the software can more easily be maintained or modified as long as the interactions from the plant to other control loops are taken into consideration.

- Modeling effort. A centralized controller requires a dynamic model of the complete plant and a considerable amount of work is normally required to obtain such a model. In a decentralized control system, the individual loops are usually tuned without any (mathematical) model at all. In practice, the tuning of a complete plant during start-up is often done in a hierarchical manner starting with the fast and low-level loops, inner loops of cascade structures etc. and moving on to more slow loops with the faster loops closed.

Regarding the first point, it was argued in section 2.1 that process integration increases plant interaction, but it should also be recalled that good control of the HEN has a decoupling effect on the overall plant.

There is a trend towards increased use of multivariable controllers such as MPC, and in many cases these are implemented in addition to (not instead of) conventional (SISO) controllers such that the MPC provides setpoints for the SISO control loops. The methods for optimal control that are proposed in this thesis are based on a decentralized control structure.

2.4 Degrees of freedom in design and operation

In section 2.2 it was demonstrated that a loop in a HEN represents a degree of freedom (DOF) that can be used to optimize the *design* by shifting the duties of the heat exchangers. In a loop, one exchanger may be removed by choosing the duty equal to zero and this breaks the loop. A HEN without any loops has no such degrees of freedom in the design phase. In *operation*, however, the situation is different. During operation we assume:

- Fixed network structure.
- Fixed installed heat exchanger areas where the effective area can be varied between zero and the installed area by manipulating a bypass.
- Specified supply and target temperatures and heat capacity flowrates of process streams.

The perhaps most fundamental difference between design and operation regarding degrees of freedom is that in design there has to be a mechanism that trades off energy cost against capital cost. This fact is rather obvious, since if only energy consumption is considered during design, the result would be a HEN with infinite area and thus infinite capital cost. In the pinch design method, the trade-off between energy and capital cost is taken care of by the specification of $\Delta T_{\min}$ (heat recovery level).

In operation, on the other hand, the trade-off between energy and capital cost is completely irrelevant. Since the HEN structure and installed areas are fixed, the capital costs are fixed as well. The only issue that matters is to exploit the installed heat exchanger areas as efficiently as possible (minimized energy cost) while maintaining the targets. Some earlier works prohibits violation of $\Delta T_{\min}$ for a HEN to be announced operable, see e.g. Calandranis and

Stephanopoulos (1986). This view is not adopted in this thesis. The inapprioprate problem formulation of constraining ΔT_{min} in flexibility/operability analysis is also pointed out by Mathisen (1994, chapter 9). Since the trade-off between capital and energy cost (e.g. by specifying ΔT_{min}) represents a constraint in design and not in operation, this is one example of differences in degrees of freedom in design and operation.

An important question regarding operation of HENs is whether optimization is possible or not. A prerequisite for doing any optimization is that there are degrees of freedom left when manipulations are used for regulatory control. The most crucial question is not how *many* degrees of freedom (DOFs) the HEN has, but simply *whether* we have zero DOFs (optimization is not possible), or one or more DOFs (optimization is possible).

Degrees of freedom of HENs during operation is discussed more thorougly in chapter 4. A simple rule to quickly conclude whether a HEN may be optimized or not, is presented. It will be distinguished between DOFs that may be utilized for utility optimization and DOFs that only can be used to shift duties internally in the HEN (without affecting the utility cost). In many cases, adding extra manipulations will not contribute to the number of DOFs that can be exploited for optimization. It will be shown that most HENs have DOFs that can be used for optimization, and a quantitative expression for the number of DOFs will be derived.

2.5 Flexibility and controllability

Operability of a plant includes all aspects related to the operation of it such as flexibility, safety and reliability, controllability, startup, shutdown etc. This section briefly introduces the two terms, flexibility and controllability.

Flexibility
Flexibility is the ability of a plant to maintain feasible steady state operation for the varying disturbances and operating points that may be encountered during operation. In a HEN, the targets should be met when supply temperatures and flowrates vary within specified regions, and also the targets themselves may be subject to changes during operation. In the case of fouling, the design should also take varying heat transfer coefficients into consideration. Finally, the error of the HEN *model* used for flexibility evaluation compared to the *real* HEN should be considered to ensure that not only the HEN model, but also the real HEN is flexible. Two important problems within flexibility analysis are the *flexibility test problem* and the *flexibility index problem*, see Biegler *et al*. (1997). The flexibility test problem aims to find an answer (yes or no) to whether a design is feasible for a given set of parameter variations. In the flexibility index problem, an index that quantifies the flexibility is introduced (Swaney and Grossmann, 1985). This index of flexibility is equal to one if the design just fulfills the flexibility requirements, above one if the flexibility exceeds the requirements, and below one if the design is infeasible somewhere within the specified uncertainty region.

The flexibility index only quantifies the flexibility for the worst case parameter (or worst case *direction* of parameter combinations). For instance, a flexibility index of 0.8 indicates that for the worst case parameter (or combination of parameters), the plant becomes infeasible when the parameter value is 80% of its nominal value. It does not give any information about

the other parameters (or directions), which also may yield infeasibility just above 80% of the nominal values, or they may have plenty of flexibility.

For HENs, flowrate variations may yield non-convexities as shown by Saboo and Morari (1984). This may give a design which is feasible for two different flowrate values and infeasible for some intermediate value. In flexibility analysis, this implies that the critical parameter values may *not* correspond to the extreme values (corner points) of the parameters. Variations in supply temperatures, however, cannot give any non-convexities due to linear responses, and the critical points corresponds to the corner points. Halemane and Grossmann (1983) show that the computation of the flexibility index is greatly simplified if the critical points in the analysis corresponds to the corner points. For HENs, this implies that variations in supply temperatures can be analyzed by checking the corner points, whereas flowrate variations may yield non-convexities and the critical points may be in the interior of the uncertainty region, see e.g. Floudas and Grossmann (1987). It should be noted that even the corner point check may not be trivial if there are many independent parameters.

Kotjabasakis and Linnhoff (1986) suggest a three-way trade-off between energy, capital cost and flexibility in HEN synthesis. While this may be a suitable view for many problems, it is not adopted in this thesis. Here, it will normally be required that the HEN is feasible for the specified region of disturbances and parameter variations. It is assumed that the variations stay within this region during operation, and therefore no extra money should be spent (or wasted) on making the HEN more flexible than needed.

The term *structural flexibility* in HENs refers to the flexibility of a given network structure when the approach temperature of the heat exchangers are allowed to be zero, that is, areas can be infinitely large. The actual flexibility will be limited by the installed area of some heat exchanger and therefore the achievable flexibility will be less than the structural flexibility.

While flexibility certainly is dependent on the network structure, the flexibility of a given structure can be modified by adjusting the heat exchanger areas. This problem of area optimization is considered by e.g. Mathisen (1994, chapter 9) and Papalexandri and Pistikopolous (1994). In this thesis, it will be assumed that the HENs to be operated have been designed with sufficient flexibility and that the issue is to achieve optimal operation for this given HEN. Problems such as designing for flexibility or area optimization is not considered.

It is important to be aware that the actual flexibility of a HEN during operation may be *limited by the control strategy*. Even if a HEN has capability of being sufficiently flexible, there is no guarantee that the control strategy will adjust the manipulations such that the full flexibility of the HEN is maintained. In the literature, this point seems to have been neglected, or it has been implicitly understood that the control system will not deteriorate the flexibility. While flexibility is a property of the HEN alone, we define *effective flexibility* as follows:

Definition 2.2 *Effective flexibility of HENs.*
The effective flexibility is the ability of a *controlled* HEN to maintain feasible steady state operation for the varying disturbances and operating points that may be encountered during operation. Effective flexibility is a property of the HEN and the control strategy. ■

In control structure design it is important to ensure that the control structure preserves sufficient flexibility such that the controlled HEN fulfills the requirement for effective flexibility.

Controllability

While flexibility concerns steady state properties, *controllability* is related to more short term responses and dynamic properties. In this thesis, the term controllability will usually be used in a loose sense simply meaning how easy the plant is to control. E.g. a manipulation with a "fast" and "large" effect on a controlled output may be preferred compared to a manipulation with a "slow" and "small" effect for controllability reasons. Such qualitative considerations is the basis for the main rule for input/output pairing in HENs.

Controllability is a property of the plant itself, irrespective of the controller. However, manipulations and measurements are defined to be a part of the plant, and the selection of these may strongly affect the controllability. Concerning control and operation of HENs, e.g. Marselle *et al.* (1982), it is often implicitely understood that a variable bypass is placed across each heat exchanger and that all outlet temperatures are measured. In this thesis, it is assumed that a bypass *is or may* be placed across each heat exchanger. In addition, extra measurements (internally in the HEN) may be utilized for improved controllability. The actual choice of manipulations and measurements results in different controllability properties and it is considered as different plants concerning controllability, despite it is the same HEN (same structure, areas etc.) within the synthesis terminology.

Quantitative analysis of controllability aims to find what control performance can be expected, or whether a specified closed-loop performance can be achieved. The closed-loop performance may be specified in the time domain (overshoot, settling time etc.) or in the frequency domain (e.g. bandwidth). A comprehensive description of quantitative controllability analysis (or performance targeting) in the frequency domain is given by Skogestad and Postlethwaite (1996). Control limitations in HENs, such as RHP-zeros, are thoroughly treated by Mathisen (1994, chapter 3), and will not be emphasized in this thesis. In chapter 6 of this thesis, it will be necessary to apply a quantitative measure of controllability in order to find a pairing that is acceptable also from a control point of view. This measure of controllability will be based on the *relative gain array* (RGA) of a linear model of the HEN. The RGA for a square plant (transfer matrix) G is defined as

$$\mathrm{RGA}(G) = G \times (G^T)^{-1} \tag{2.5}$$

where $\times$ denotes element-by-element multiplication. The RGA was introduced by Bristol (1966) as a measure of (two-way) steady state interactions in MIMO systems. The RGA, and particularly the frequency dependent $\mathrm{RGA}(G(j\omega))$, has a number of interesting control properties, see Skogestad and Postlethwaite (1996, chapters 3 and 10). Using the RGA is often a efficient tool since it does not have to be recomputed for different pairings of the same plant. One property of the steady state RGA is the ability to test if a plant is *decentralized integral controllable* (DIC), and this property will be utilized in chapter 6 of this thesis. The DIC was introduced by Skogestad and Morari (1988), and will be defined and explained in chapter 6.

Most HENs have more manipulations than targets and this yields a transfer function with more columns than rows. Even HENs (pinch problems) with *no* loops have one manipulation

in excess. As stated in Mathisen (1994, chapter 3), most HENs without loops only have one-way interaction and this corresponds to transfer function that is upper or lower triangular (with proper ordering of inputs and outputs). The pairing of a square plant that is triangular is trivial since RGA(G) = I. However, this is *not* the case for non-square plants and pairing is not trivial. As an example, consider the transfer function for the HEN in figure 2.4 that will have the form

$$\begin{bmatrix} T_o^{H1} \\ T_o^{C1} \\ T_o^{C2} \end{bmatrix} = \begin{bmatrix} g_{11} & 0 & g_{13} & g_{14} \\ 0 & g_{22} & g_{23} & 0 \\ 0 & 0 & g_{33} & g_{34} \end{bmatrix} \begin{bmatrix} u_{c1} \\ u_{h1} \\ u_{I} \\ u_{II} \end{bmatrix} \tag{2.6}$$

From equation (2.1), we recognize G_{11} = diag([g_{11}, g_{22}]) and using the trivial decomposition rule for HENs (rule 2.1), the remaining system becomes

$$T_o^{C2} = \begin{bmatrix} g_{33} & g_{34} \end{bmatrix} \begin{bmatrix} u_{I} \\ u_{II} \end{bmatrix} \tag{2.7}$$

The RGA of G_{22} = [g_{33} g_{34}] is a 1×2 matrix with row sum equal to one, and the pairing is not trivial. In chapter 6 where the RGA is used to find the pairing, the square system when one (or more) manipulations is assumed unused is considered. This requires the RGA to be recomputed for the possible selections of unused manipulations.

2.6 Process structure affects operability

It is rather evident that the structure of a process affects the operability. This section will first recall some results from linear systems theory to demonstrate this point. Then, it will be shown by a few simple examples that process structure may significantly change the operability of the HEN as well as for the overall process.

Let g denote the transfer function for a SISO system. That is, g is a frequency dependent complex rational function that can be written as

$$g(s) = k_g \frac{\prod_{i=1}^{i=N_{gz}} (s - z_{gi})}{\prod_{i=1}^{i=N_{gp}} (s - p_{gi})} \tag{2.8}$$

where z_g and p_g are the zeros and poles, and N_{gz} and N_{gp} denote the number of zeros or poles of the system g. k_g is a constant. Similarly, let h be a transfer function written in a similar way.

$$h(s) = k_h \frac{\prod_{i=1}^{i=N_{hz}} (s - z_{hi})}{\prod_{i=1}^{i=N_{hp}} (s - p_{hi})} \tag{2.9}$$

Introduce the short-hand notation n_g and d_g for the numerator and denominator of g in equation (2.8), and similarly n_h and d_h for h. Now, the zeros and poles of the total system when g and h are connected in a *series*, *parallel* or *feedback* structure can easily be found.

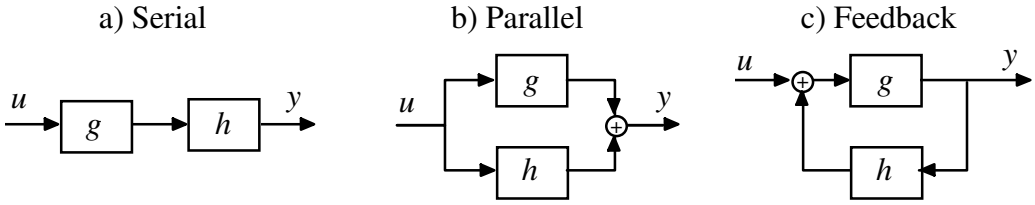

Figure 2.9 Series, parallel and feedback connection.

The transfer function for series connection is

$$\frac{y}{u}(s) = g(s)h(s) = \frac{n_g n_h}{d_g d_h} \tag{2.10}$$

which implies that the zeros and poles for the connected system simply are the zeros and poles of the individual parts (g and h). Series interconnection is typical for plants without integration and as mentioned in previous sections the dynamics of the overall plant can be predicted quite intuitively from the individual units since no new zeros or poles are introduced. Note that even if series interconnection cannot move or introduce new zeros or poles, they may be canceled. For parallel interconnection the overall transfer function becomes

$$\frac{y}{u}(s) = g(s) + h(s) = \frac{n_g d_h + n_h d_g}{d_g d_h} \tag{2.11}$$

The poles of the new system are the poles of the individual elements, meaning that connecting stable systems in parallel cannot yield an unstable overall system. The "plus" in the nominator of equation (2.11) implies that parallel interconnection gives an overall system with *new zeros*. This *may* significantly change the operability of the plant as it may introduce RHP-zeros. A RHP-zero typically occurs when a fast response with small steady state effect counteracts a slow response with large steady state effect, such that the overall step response will start moving away from the final value, yielding an inverse response. Note that while RHP-zeros often are associated with inverse response for SISO systems, an *even* number of RHP-zeros may not necessarily imply inverse response behavior. However, RHP-zeros represent a fundamental control limitation (perfect control cannot be achieved) for both SISO and MIMO systems, see Rosenbrock (1970). Effective control is only possible at low frequencies *or* at high frequencies. In process control applications, good control is usually required at low frequencies and therefore RHP-zeros imply an upper bound on the bandwidth.

If a bypassed heat exchanger has a downstream path from both hot and cold side to a controlled outlet temperature, this represents a parallel connection and the two effects will always have opposite directions. Therefore, such parallel downstream paths may result in RHP-zeros and control limitations. As the following explanation shows, such parallel paths may also give singularity at steady state. Assume that the net effect is small and that a change

in the heat transfer coefficient in one of the parallel paths (e.g. due to fowling) changes the sign of the net effect (at steady state). At some intermediate value of the heat transfer coefficient the two parallel effects will exactly cancel each other at steady state which gives a parametric singularity. For parameter values where the faster of the two opposing effects also is largest at steady state, RHP-zeros would not be expected. When the parameter passes the value that gives steady state singularity (sign changes) and the slower effect becomes dominating at steady state, a RHP-zero may occur. This illustrates that there is a connection between steady state properties (parametric singularity) and control properties (RHP-zeros). A temperature disturbance in a HEN will be dampened at steady state and it will also become slower as it traverses more heat exchangers. Therefore, the parallel path that is shortest, normally gives a response that is both fastest and largest, and this suggests that RHP-zeros may not occur very frequently in practice for HENs. Also, a manipulation that may give singularities is usually not preferred for control. In general, however, parallel paths often occur in HENs and other parts of the plant, and they may result in RHP-zeros and hence in fundamental control limitations as well as modified steady state performance.

The last of the three basic interconnection types, feedback, may perhaps give the most dramatic change of the overall plant dynamics. From figure 2.9c we may write $y = gu + ghy$ which yields the transfer function

$$\frac{y}{u}(s) = \frac{g}{1-gh} = \frac{n_g d_h}{d_g d_h - n_g n_h} \tag{2.12}$$

The zeros of g do not move, but the poles in h become additional zeros in the overall transfer function. The interconnected system will have new poles and this may dramatically affect the operability of the plant. Feedback interconnection of systems that are individually stable may yield an unstable overall system. On the other hand, an unstable plant may be stabilized by feedback control. As shown in section 2.1, feedback interconnections frequently occur in integrated processes.

In addition to these three basic interconnection types, one fourth configuration is presented where there are two sets of inputs (u_1 and u_2) and two sets of outputs (y_1 and y_2). We want to focus on the transfer function from the primary input (u_1) to the primary output (y_1) when feedback is introduced between the secondary output and input, see figure 2.10.

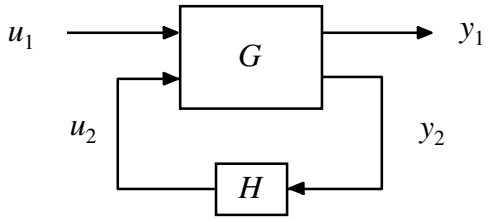

Figure 2.10 Feedback of secondary variables.

Partitioning G into four block matrices where the dimensions match the two sets of inputs and outputs, we can write:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} G_{1,1} & G_{1,2} \\ G_{2,1} & G_{2,2} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{2.13a}$$

$$u_2 = H\, y_2 \tag{2.13b}$$

From equation (2.13) the transfer function from u_1 to y_1 (lower linear fractional transform of G and H) is given by

$$y_1 = \left[G_{1,1} + G_{1,2} H \left(I - G_{2,2} H \right)^{-1} G_{2,1} \right] u_1 \tag{2.14}$$

Assume a scalar transfer function, and introde the notation $n_{i,j}$ and $d_{i,j}$ for the numerator and denominator of $g_{i,j}$ and similarly n_h and d_h for the the numerator and denominator of h. Then, the zeros and poles of the resulting system are given by the zeros and poles of the individual transfer functions:

$$\frac{y_1}{u_1}(s) = \frac{n_{1,1} d_{1,2} \left(d_h d_{2,2} - n_h n_{2,2} \right) d_h d_{2,1} + d_{1,1} n_{1,2} d_h d_{2,2} n_h n_{2,1}}{d_{1,1} d_{1,2} \left(d_h d_{2,2} - n_h n_{2,2} \right) d_h d_{2,1}} \tag{2.15}$$

While this expression is more complicated than for the three previous interconnection types, it is evident that feedback in the secondary variables changes both the poles and zeros of the resulting transfer function of the primary variables. It is often stated that feedback moves the poles but not the zeros. This is true for the input and output directly involved with the feedback loop, but feedback may move the zeros for other transfer functions. As a simple example, consider a case where $g_{1,1} = \frac{1}{s+1}$, $g_{1,2} = \frac{1}{s+2}$, $g_{2,1} = \frac{2}{s+3}$, $g_{2,2} = \frac{2}{s+1}$ and $h = 1$. All elements are stable and there are no zeros, but the resulting transfer function has both one RHP-pole and a RHP-zero ($\frac{y_1}{u_1}(s) = \frac{(s-0.71)(s+1.81)(s+3.90)}{(s-1)(s+1)(s+2)(s+3)}$). This type of interconnection may indeed occur in practice, see Jacobsen (1997) where a reactor-separator system with recycle is investigated. In that paper, sufficient conditions for the existence of RPH-zeros for the connection in figure 2.10 also is given.

To conclude, series interconnection does not usually introduce any unexpected dynamic behavior, parallel interconnection moves the zeros (may introduce RHP-zeros), and feedback interconnection moves the poles (may introduce RHP-poles and hence instability). In addition to these three basic interconnection types, introducing feedback (e.g. recycle) in one part of a plant may move both poles and zeros in other parts of the plant. It should perhaps be mentioned that *real* plants have neither poles nor zeros, since these are mathematical terms that apply for rational functions. However, it is assumed that the results for the linearized transfer functions also capture the essence of the behavior of the real plants. Non-linear effects and constraints in real plants (or more rigorous models) may certainly result in much more complex behavior.

From these results for interconnection of linear systems, a few practical examples will now be shown, where the process structure affects the operability in some other ways than pointed out above. Figure 2.11 shows two heat exchangers that may be a part of a larger HEN. Assume that the annual cost from nominal steady state considerations is only marginally different for the two alternatives.

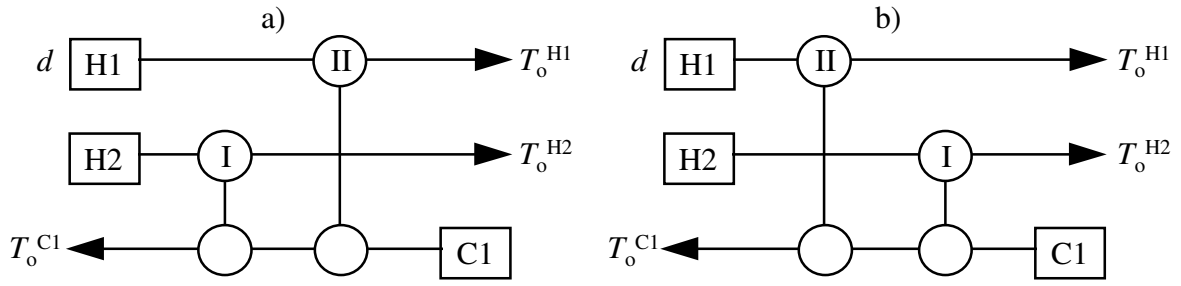

Figure 2.11 Two alternative orders for heat exchangers

We shall consider the two alternatives in the figure for two different cases.

Case 1 Disturbance rejection.
Assume that T_s^{H1} may vary considerably (indicated with d in the figure) and that it is critical to have accurate control of T_o^{H2}. In alternative A, the disturbance will affect the controlled output since there is a downstream path from d to T_o^{H2} through the two heat exchangers. There is no such downstream path in alternative B, and the disturbance will not affect the critical target at all. Alternative B is clearly preferred in this case. ■

Case 2 "Good" control.
Assume that it is critical to have good control of T_o^{H1} and T_o^{C1} when there may be various disturbances in all three supply streams. In alternative A, the main rule for input/output pairing can be used. Bypassing II on the hot side and I on the cold side yield direct (or at least fast) effect on both outputs and only one-way interaction (u_I does not affect T_o^{H1}). The main rule for input/output pairing can not be applied to alternative B (when single bypasses are used), since bypassing both side of the same heat exchanger can not control two temperatures independently at steady state. Bypassing II on the hot side and using a multi bypass across both I and II on the cold side give direct effect on both outputs, but may give problems with input constraints. With one single bypass on each heat exchanger, this structure will give two-way interactions and they may be strong, see Mathisen (1994, chapter 4). For this case, alternative A is clearly preferred. ■

The figures 2.12 and 2.13 show an example where different HEN structures give different overall plant properties. The HEN is integrated with two reactors, R1 and R2. In figure 2.12 there are thermal feedback loops from the outlet to the inlet of each reactors. The outlet temperature of reactor R1 affects the inlet temperature through only one heat exchanger (II), while the outlet temperature of reactor R2 affects the inlet through two heat transfer units (I and h).

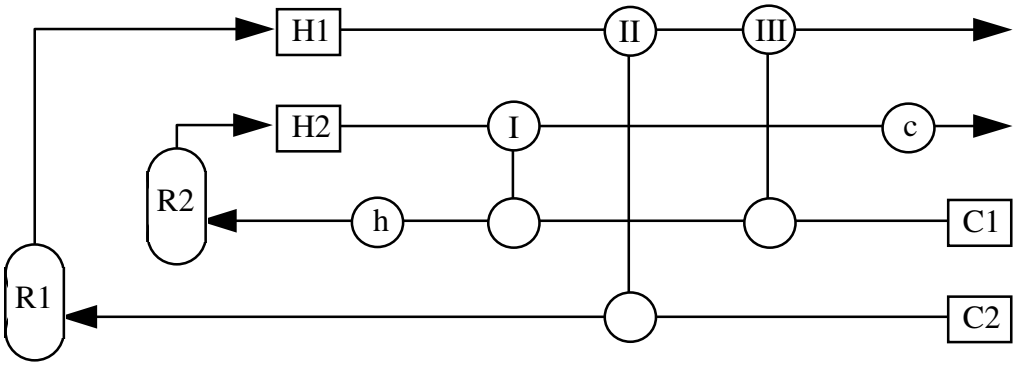

Figure 2.12 Overall plant structure.

In figure 2.13, there are also feedback loops, however, the reactor outlet temperature (from both reactors) have to traverse three heat transfer units before it reaches the inlet of the same reactor. For reactor R2, the disturbance also has to traverse R1. This *indicates* that the structure in figure 2.13 yields weaker feedback loops, and that it *may* be preferred compared with the structure in figure 2.12 due to possible improved overall plant dynamics. While no clear conclusions can be drawn for this example, it should be clear that the two structures give different properties for the total plant.

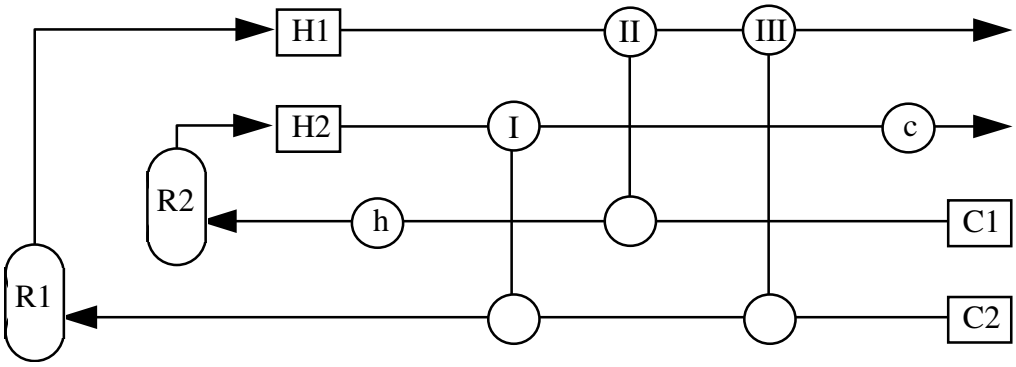

Figure 2.13 Modified overall plant structure.

Finally in this chapter, it is emphasized that the structure may *change during operation*. If a bypass should saturate it would normally be at zero (fully closed bypass pipe and full duty of heat exchanger). This makes the bypass inactive since it cannot be manipulated. This changes the *control structure* and if the bypass fraction was controlling a target temperature, a new bypass will have to be assigned for this purpose, if possible. The saturation of a bypass at zero will not change the structural properties of the HEN regarding propagation of temperature effects. As an example, consider the bypass across heat exchanger II in figure 2.4 being saturated at zero. Still, the bypass on heat exchanger I can by used for control of the bypass controlled target.

A utility exchanger may be saturated at zero duty, and this should be encouraged since utility consumption should be as low as possible. An upstream manipulation has to be assigned if the outlet temperature of the utility exchanger still needs to be controlled. Saturation of utility exchangers may also change the problem type from a pinch problem to a threshold problem. This implies that the HEN cannot be optimized (any *further*) at this operating

condition. It is already operated optimally, since a bad control strategy may turn it back to a pinch problem with an unnecessary large utility consumption.

While saturation at zero does not change the network structure (only the control structure), this is not the case when a heat exchanger is completely bypassed (saturation at one). This corresponds to removing the heat exchanger. If for instance heat exchanger I in figure 2.4 is completely bypassed, this HEN is divided into two subnetworks (and both are threshold problems). It is evident that when a bypass is fully closed, the outlet temperature of this exchanger can not be controlled by any upstream effects on the opposite side. It may be of more practical interest to note that when a bypass fraction increases, the upstream effect traversing to the opposite side decreases. This may be good for disturbance rejection, but makes control more difficult.

In this section, it has been shown that the structure of a process (or HEN) may considerably affect how easy it is to operate. Also, the operation of a process may change not only the control structure, but may also also change the process structure itself, e.g. by bypassing a heat exchanger completely.

Notation

CP	Heat capacity flowrate
d	Denominator
G	Transfer function
k_g	Constant in transfer function g
k_h	Constant in transfer function h
n	Numerator
N	Number of, e.g. N_z is number of zeros.
N_{DOF}	Number of degrees of freedom
N_{target}	Number of targets
N_{units}	Number of units
p	Poles (in a transfer function).
Q_{C}	Cold utility consumption
Q_{H}	Hot utility consumption
Q_{in}	Energy flow in
Q_{out}	Energy flow out
T	Temperature
T_{o}	Outlet temperature
T_{s}	Supply temperature
T_{t}	Target temperature
y	Output or measurement
y_{BP}	Bypass controlled outputs
y_{U}	Utility controlled outputs
u	Input/manipulation
u_{BP}	Bypass fractions
u_{U}	Utility duties
z	Zeros (in a transfer function)
ΔT_{min}	Minimum temperature difference

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