Chapter 5

OPTIMAL OPERATION USING STRUCTURAL INFORMATION

This is the first of three chapters concerning specific methods for optimal operation of HENs. The method being discussed in this chapter utilizes the *structural* properties of the network. A control strategy is developed that, in addition to controlling the target temperatures, minimizes the utility consumption. The method results in a decentralized control structure with variable pairing. The procedure is based on an idea suggested by Mathisen *et al.* (1994) but in that paper no applications to validate the method are presented. The method is also described by Glemmestad *et al.* (1996), and the content of this chapter is, with the exception of some extensions, taken from that paper.

5.1 Introduction

This chapter concerns operation of a HEN with given structure and heat exchanger areas. In addition to structure and areas, the stream data (heat capacity flowrates, supply temperatures and target temperatures) are specified, and finally disturbances, such as variations in supply temperatures, flowrates and possibly in heat transfer coefficients are given. The goal is to find a control strategy that yields optimal operation. Optimal operaton was defined in section 2.3, and to recall, the control system should (1) satisfy targets at steady state, (2) minimize utility consumption and (3) give reasonable dynamic behavior.

The main rule for input/output pairing of HENs (Rule 2.2), is motivated from the needs of regulatory control (dynamic behavior). The method in this chapter aims to find a pairing that minimizes utility consumption instead, and this pairing may not always result in the best possible dynamic properties.

A prerequisite for optimization is that there are at least one degree of freedom in operation. As it was shown in section 2.4, most HENs have this feature (e.g. all pinch problems). In addition, optimum is often constrained meaning that for the operating state with minimum utility consumption, one or more manipulations are saturated (e.g. fully closed bypass). The location of optimum during operation for HENs is treated more thoroughly in section 5.3. The fact that optimum often is constrained is, however, very important when structural properies are utilized for optimal operation of a HEN. The idea of the method is the following:

Assume for simplicity a HEN with only one DOF that can be used for utility optimization. If one can find one manipulation that have to be saturated in optimum, then adjusting this manipulation to the saturation limit, there will be only one feasible solution for the remaining manipulations. That is, the number of remaining manipulations are equal to the number of targets. The optimal operating state of the HEN is achieved by using decentralized feedback control involving the remaining manipulations. In general, the method uses the structural properties of the HEN to find which manipulation should be saturated, and then feedback control is applied for the remaining system (with only one feasible solution).

The structural properties of the HEN are contained in *sign matrices*. These matrices describe how the manipulations affect outlet temperatures and utility consumption. The elements of the sign matrices are simply "+" and "–" etc. to denote whether an effect is positive or negative. The sign matrices are found from the HEN structure and simple physical insight. The procedure does not result directly in a particular manipulation that should be saturated, but in a *priority table* for the manipulations. This priority table is implemented in the control scheme and the optimal operating state will be found "automatically" during operation. The set of saturated manipulations may depend on the disturbances that are present, thus the control structure may change during operation. The method is introduced by an illustrating example where the idea is explained from simple physical insight.

5.2 An illustrating example

Based on the stream data in table 5.1, a pinch design with evolution can result in the HEN shown in figure 5.1. The design is based on a minimum heat recovery approach temperature of 20°K and the nominal value of 190°C in T_s^{H1}. The nominal stream data and the HEN is identical to the simple HEN used previously in the thesis except for the heat capacity flowrates which are reduced by a factor of one hundred (has no practical implications). The only disturbance is ±20°C in T_s^{H1} and its influence on the output temperatures should be completely rejected during steady state operation. Using the decomposition principle (Rule 2.1), we assume that T_o^{H1} and T_o^{C1} are perfectly controlled by the cooler and heater duties, respectively. The focus is on how to control the only bypass controlled temperature T_o^{C2}, using the bypass fractions u_I and u_{II}. Common engineering to control T_o^{C2} would be to increase the area of exchanger 2 and equip it with a bypass and a controller. This strategy would increase the capital cost of the HEN. Alternatively, one could avoid additional area of the process exchangers by increasing the heater and cooler duties which instead would increase the operating cost. We shall develop a procedure that maintains the target

temperatures and at the same time gives minimum utility consumption at steady state together with minimum added area.

Stream	T_s [°C]	T_t [°C]	CP [kW/°C]
H1	190±20	30	1.0
C1	80	160	1.5
C2	20	130	0.5

Table 5.1 Stream data for illustrating example.

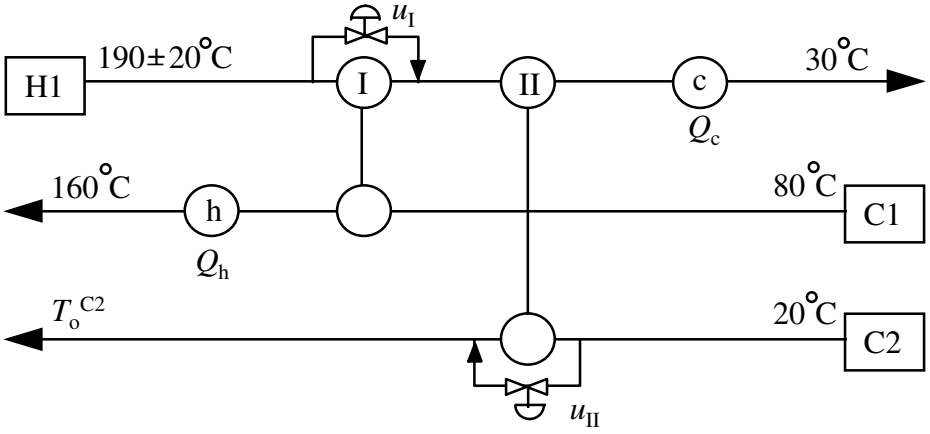


Figure 5.1 Network for illustrating example.

Assuming that bypasses (but no extra area) are placed across both heat exchangers, we have four manipulations (two bypass fractions and two utility duties) to control the three outlet temperatures. That is, there is one degree of freedom with respect to control and this degree of freedom will be used to minimize the utility consumption. T_o^{H1} and T_o^{C1} are perfectly controlled by utilities so we have two possible manipulations (u_I and u_{II}) to control the only bypass controlled target temperature T_t^{C2}.

First, assume that the outlet temperature T_o^{C2} is too low, for example due to a negative disturbance in T_s^{H1}. To increase the outlet temperature, u_I could be increased or u_{II} could be decreased. Increasing bypass u_I will increase downstream temperatures on stream H1 and decrease downstream temperatures in stream C1. To maintain the utility controlled target temperatures, the heat load has to be increased in the cooler as well as in the heater. Alternatively, decreasing u_{II} will give a desired increase in T_o^{C2} along with decreasing downstream temperatures in H1. This corresponds to a *reduction* in the utility consumption of the cooler. When the outlet temperature is too low we therefore prefer to reduce u_{II}. If this bypass is saturated at 0, we have to increase bypass u_I.

Next, assume that T_o^{C2} too high. A similar argument will imply that the preferred manipulation is to reduce u_I which at the same time will reduce utility consumption. If u_I is saturated, we must increase bypass u_{II} which also increases the utility consumption. Based on the arguments above, we will use the following control configuration for the HEN:

When T_o^{C2} is too high:
If $u_I > 0$, then pair T_o^{C2} and u_I in a SISO-controller and let $u_{II} = 0$,
else pair T_o^{C2} and u_{II} in a SISO-controller and keep $u_I = 0$.

When T_o^{C2} is too low:
If $u_{II} > 0$, then pair T_o^{C2} and u_{II} in a SISO-controller and let $u_I = 0$,
else pair T_o^{C2} and u_I in a SISO-controller and keep $u_{II} = 0$.

Figure 5.2 shows the result when this variable control structure is implemented. The controllers are simple PI-controllers with anti-windup. An important observation is that one of the manipulations u_I or u_{II} is always saturated at zero, and this implies that the optimal solution lies on the constraints of the feasible region. When u_I is used instead of u_{II}, the transient response becomes somewhat worse. We shall, however, not be too concerned about this since we assume that the process is continuos and that the setpoints and disturbances are fairly steady.

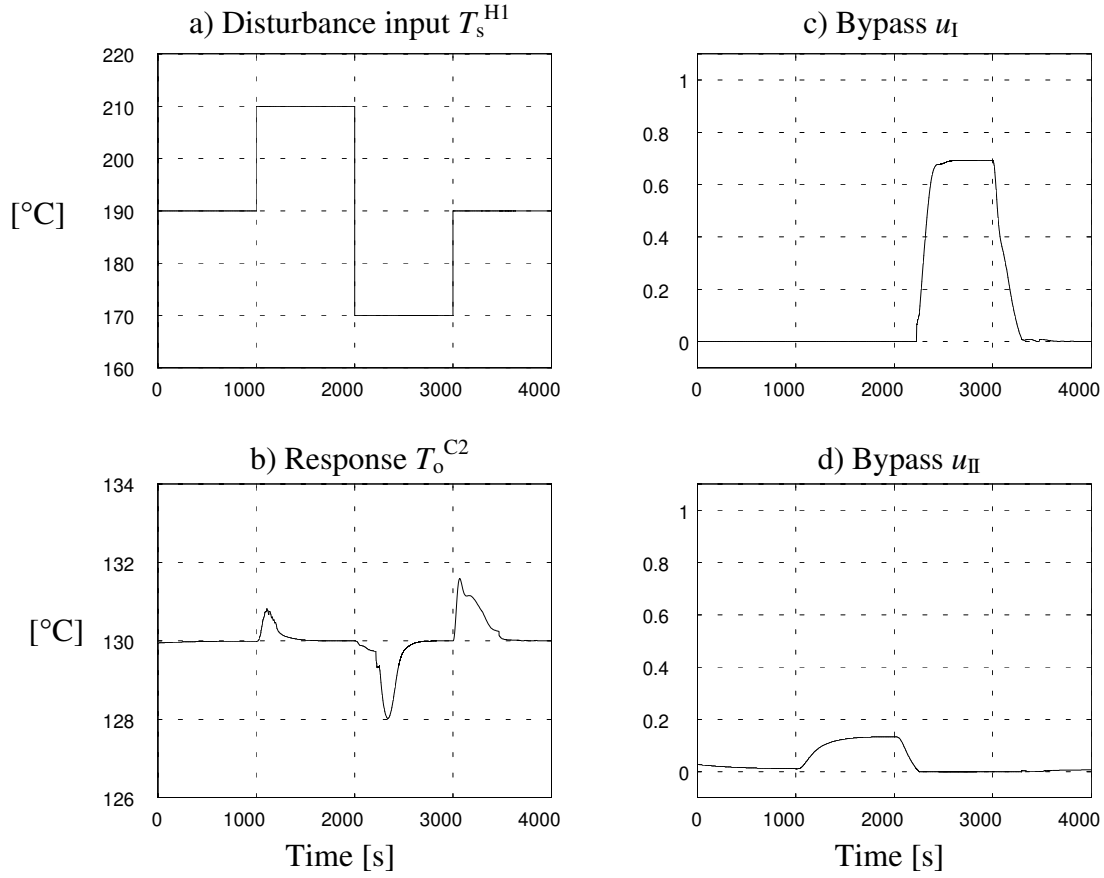


Figure 5.2 Simulation results for motivating example.
(a) Input disturbance T_s^{H1}. (b) Response in T_o^{C2}.
(c) and (d) Bypass fractions u_I and u_{II}.

In this example, a control strategy that minimizes utility consumption has been found from the *structural* properties of the HEN. In the following parts of this chapter, a systematic method to achieve optimal operation using structural information is developed.

To conclude this section, a remark regarding flexibility is given: As the example has shown, the variable control structure yield a controlled HEN with sufficient effective flexibility (recall definition 2.2). A fixed SISO control structure will result in *zero effective flexibility* if the areas are not increased. (Using u_{I} for control can only decrease $T_{\mathrm{o}}^{\mathrm{C2}}$ while u_{II} can only increase $T_{\mathrm{o}}^{\mathrm{C2}}$.) The flexibility can be increased by increasing the area of exchanger II and using u_{II} for control. However, an alternative way of making the controlled HEN more flexible (effective flexibility) is to *reduce* the area of exchanger I (or to bypass it constantly). This corresponds to increasing the utility consumption since the heat transferred in the path from the heater to the cooler is increased. Hence, the effective flexibility may be improved by reducing area.

The variable control strategy used in the example does not only minimize utility consumption, it also maintains the flexibility of the HEN itself, thus no area of process exchangers (compared to the nominal design) need to be added for flexibility.

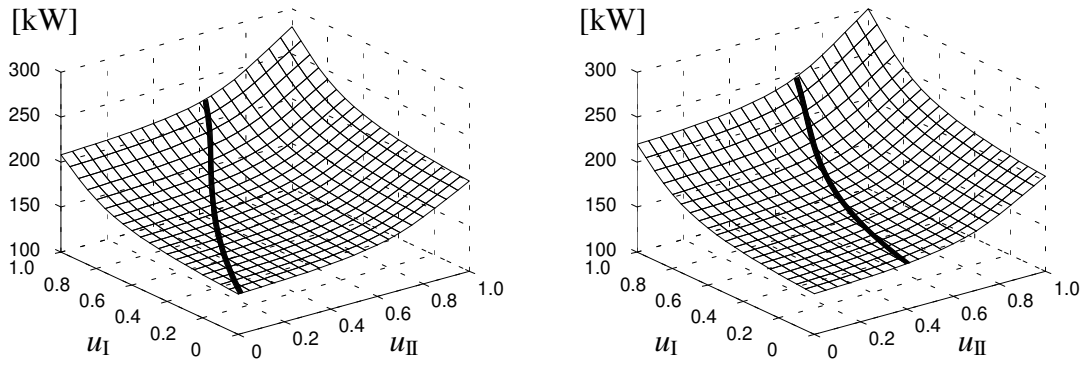
5.3 Location of optimum

As mentioned in the introduction to this chapter, an important feature of HENs in order to use structual information for operation, is that optimum often is located at the intersection of constraints.

Increasing the bypass fraction of a heat exchanger will monotonically decrease its duty and vice versa. This will give a monotonic increase or decrease of downstream temperatures and hence usually also the outlet temperatures and the utility duties. In a HEN, minimum utility consumption corresponds to maximum heat recovery between the process streams. In a HEN with degrees of freedom, this implies that some bypasses in most cases should be fully closed. These bypasses should only be used if this is the only way to meet the targets. This may happend if bypasses used for regulatory control are saturated. Hence, optimal operation of HENs normally corresponds to saturation of some manipulations.

An obvious exception is when a variable split fraction is used for utility optimization. In such cases, minimum utility consumption is obtained at some intermediate value of the split fraction, thus the optimal solution may not be located at constraints. Other exceptions are when there are independent downstream paths from both hot and cold side of a heat exchanger and to the same outlet temperature/utility exchanger (Mathisen, 1994). The effects from the hot and cold side of a bypassed heat exchanger will always have opposite signs. The net effect (positive or negative) can usually not be deduced from structural information, and optimal operation can not be guaranteed in such cases.

To illustrate the typical situation where optimum is constrained, total utility consumption for the HEN used in the illustrating example is plotted as a function of the two bypass fractions.



a) $T_{\mathrm{s}}^{\mathrm{H1}}$ is nominal (190°C). b) $T_{\mathrm{s}}^{\mathrm{H1}}$ is 20°K above nominal value.

Figure 5.3 Utility consumption as a function of u_{I} and u_{II}. Feasible line is also plotted.

Figure 5.3a (left graph) shows the utility consumption ($Q_{\mathrm{c}} + Q_{\mathrm{h}}$) when no disturbances are present. The line shows the combination of u_{I} and u_{II} that gives feasible operation, that is, all targets are met. As seen from the figure, feasible (but worst case) operation in the nominal case may be achieved with $u_{\mathrm{I}} = 1$ (fully open bypass) and $u_{\mathrm{II}} \approx 0.6$, while *optimal* operation is obtained for $u_{\mathrm{I}} = u_{\mathrm{II}} = 0$. The graph in figure 5.3b shows the same when the disturbance, $T_{\mathrm{s}}^{\mathrm{H1}}$ has its maximum value. For both cases the optimal solution is constrained. In addition, the results in figure 5.2 are confirmed.

5.4 The sign matrices

The method for optimal operation makes use of "sign matrices". These are used for storage of information that can be exctracted from the structure of the process. In general, a sign matrix is defines as

Definition 5.1 The sign matrix, *sign*(*A*).
Let A be a matrix of real numbers where the precise value of each element $a_{i,j}$ may not be known. The sign matrix *sign*(*A*) is defined as

$$sign(A)_{i,j} = \begin{cases} [+] & \text{if } a_{i,j} > 0 \\ [-] & \text{if } a_{i,j} < 0 \\ [0] & \text{if } a_{i,j} = 0 \\ [\pm] & \text{otherwise} \end{cases} \tag{5.1}$$

■

To avoid confusion with the operators for addition and subtraction, the elements in a sign matrix are enclosed by brackets also when single elements are addressed. Each entry in a sign matrix denote a scalar number, thus e.g. [+] denotes a number that we know is positive, but we may not necessarily know the specific value. In the example in the previous section, we concluded that increasing bypass u_{I} increases $T_{\mathrm{o}}^{\mathrm{C2}}$. This implies that the corresponding element in the (sign) transfer matrix is [+]. [0] simply denotes the number 0. [±] denotes a

number that may be both positive and negative (and zero) and occurs when there are opposing effects where we cannot conclude that the effects with a certain sign are the dominating.

The arithemic rules for signs (we only need addition and multiplication) follow the normal conventions for scalars. Examples are

$$[+] + [+] = [+]$$
$$[+] + [-] = [\pm]$$
$$[-] + [-] = [-]$$

$$[+] \cdot [+] = [+]$$
$$[+] \cdot [-] = [-]$$
$$[-] \cdot [-] = [+]$$

Further, all operations involving [±], except for multiplication by [0], results in [±].

Now, the relation of the sign matrices and optimal operation will be made. The following two systems for HENs are introduced:

$$y^{BP} = G^{BP}u \tag{5.2}$$
$$y^{U} = G^{U}u \tag{5.3}$$

Here, y^{BP} is a vector containing the bypass controlled output (target) temperatures and G^{BP} is the transfer function matrix from the input vector u (bypasses) to y^{BP}. In equation (5.3), G^{U} is the transfer matrix from u to the output vector y^{U} that contains the utility *consumption* for each of the utility controlled temperatures (assuming that the utility controlled outputs are perfectly controlled).

The procedure makes use of the two sign matrices $sign(G^{BP})$ and $sign(G^{U})$. Note that the definition of the sign matrix in this thesis is different from the sign matrix used by Mathisen *et al.* (1994) where the signs depend on whether a stream is hot or cold. Thereby, that method is useful only for HENs, while the method as presented in this thesis also may be applied to other processes. We will, however, assume a HEN in the presentation of the procedure.

The procedure is based on the following four observations for HENs:

1) A positive (negative) temperature change has a positive (negative) effect on all downstream temperatures.
2) Temperature disturbances are naturally dampened.
3) A flowrate increase of hot (cold) streams has a positive (negative) effect on all downstream temperatures.
4) Bypass increases propagate as a temperature increase from the hot side and temperature decrease from the cold side of the bypassed heat exchanger.

These observations are proven by Mathisen (1994, chapter 5), and they imply the following useful rules when constructing $sign(G^{BP})$:

- sign$(G^{BP})_{k,j}$ = [+] if all downstream paths are from the hot side of bypass j to bypass controlled target temperature k.
- sign$(G^{BP})_{k,j}$ = [–] if all downstream paths are from the cold side of bypass j to bypass controlled target temperature k.

Similarly, when constructing $sign(G^U)$, the following rules may be useful:

- sign$(G^U)_{i,j}$ = [+] if all downstream paths are from the hot (cold) side of bypass j to utility controlled target temperature i of a hot (cold) stream.
- sign$(G^U)_{i,j}$ = [–] if all downstream paths are from the hot (cold) side of bypass j to utility controlled target temperature i of a cold (hot) stream.

If there are no downstream paths from an input to an output, the corresponding element in the sign transfer matrix is [0]. If there are opposing effects, such as parallel downstream paths from a bypass, the corresponding element in the sign matrix is often [±]. There is, however, an important exception to this as given by the following observation which also is proven by Mathisen (1994, chapter 5):

5) Bypassing a heat exchanger immediately upstream a cooler (heater), increases the cold (hot) utility consumption, irrespective of any opposing effects.

This observation may be used to state that an element may be [+] or [–] even if it consists of opposing effects. In general, it is important to reduce the number of [±]-elements in the sign matrices as much as possible, since these elements do not indicate any specific information about the system.

5.5 The procedure

The procedure aims to combine the elements in $sign(G^{BP})$ and $sign(G^U)$ in order to find the preferred manipulation for reduction of a control error. A manipulation that decreases the control error and at the same time decreases the utility consumption is desired. If no such manipulation exist (or it is saturated) one may be forced to use a manipulation that increases utility consumption.

As a shorthand notation in the remaining of this chapter, we will not write "*sign*" every time an individual element of a sign matrix is accessed, e.g. $g^U_{i,j}$ is the shorthand notation for $sign(G^U)_{i,j}$.

The elements in $sign(G^U)$ denote the effect of the manipulations (bypasses) on each of the utility exchangers. Instead of adressing each individual utility unit, we want to minimize the total utility consumption. To do this, a sign vector $sign(g^U)$ is constructed from the $sign(G^U)$ matrix. Each entry of the row vector $sign(g^U)$ is simply the sum of the corresponding column of $sign(G^U)$, i.e.

$$g^U_j = \sum_i g^U_{i,j} \tag{5.4}$$

Here, g_j^{U} is an element of the vector $sign(g^{\mathrm{U}})$ while $g_{i,j}^{\mathrm{U}}$ is an element of the matrix $sign(G^{\mathrm{U}})$. Using the conventional arithmetics for adding sign elements, $sign(g^{\mathrm{U}})$ can be found from the following rule:

$$g_j^{\mathrm{U}} = \begin{cases} [+] & \text{if } \left(g_{i,j}^{\mathrm{U}} = [+] \text{ or } g_{i,j}^{\mathrm{U}} = [0]\right) \forall i \quad \text{(at least one } [+]\text{)} \\ [-] & \text{if } \left(g_{i,j}^{\mathrm{U}} = [-] \text{ or } g_{i,j}^{\mathrm{U}} = [0]\right) \forall i \quad \text{(at least one } [-]\text{)} \\ [0] & \text{if } g_{i,j}^{\mathrm{U}} = [0] \quad \forall i \\ [\pm] & \text{otherwise} \end{cases} \tag{5.5}$$

Each element in $sign(g^{\mathrm{U}})$ is easily found from the corresponding column of $sign(G^{\mathrm{U}})$. As an example the following $sign(G^{\mathrm{U}})$ result in the vector $sign(g^{\mathrm{U}})$ written below.

$$sign(G^{\mathrm{U}}) = \begin{bmatrix} + & 0 & 0 & 0 & + & 0 \\ + & + & 0 & 0 & + & 0 \\ 0 & - & - & 0 & \pm & + \\ 0 & 0 & 0 & 0 & 0 & + \end{bmatrix}$$

$$sign(g^{\mathrm{U}}) = \begin{bmatrix} + & \pm & - & 0 & \pm & + \end{bmatrix}$$

The vector $sign(g^{\mathrm{U}})$ denotes the effect from each manipulation on the total utility consumption. Note that there are cases where physical insight may override the arithmetics. Observation 5 in last section is an example where the sum of [+] and [–] may result in [+] *or* [–] since we may conclude that one of the effects always is larger than the other. Another important example is in the calculation of $sign(g^{\mathrm{U}})$ for HENs where all outlet temperatures have targets. To fulfill the total energy balance of the HEN it can be concluded that

$$\begin{aligned} g_j^{\mathrm{U}} = [+] \quad \text{if} \quad & \left(g_{i,j}^{\mathrm{U}} = [+] \text{ or } g_{i,j}^{\mathrm{U}} = [0]\right) \quad \text{for } i \in H \quad \text{(at least one } [+]\text{)} \\ \text{or} \quad & \left(g_{i,j}^{\mathrm{U}} = [+] \text{ or } g_{i,j}^{\mathrm{U}} = [0]\right) \quad \text{for } i \in C \quad \text{(at least one } [+]\text{)} \end{aligned}$$

where H is the set of all hot process streams and C is the set of all cold process streams.

The procedure consists of the following four steps:

Step 1. Initialization.
Initialize bypasses that have increasing or zero effect on utility consumption to zero. Bypasses with decreasing effect on utility consumption is initialized to one.

$$u_j = 0 \text{ if } g_j^{\mathrm{U}} = [+] \text{ or } [0] \tag{5.5a}$$

$$u_j = 1 \text{ if } g_j^{\mathrm{U}} = [-] \tag{5.5b}$$

From step 2, start with the first bypass controlled output ($k = 1$).

Step 2. Give priority to the manipulations j from the sign matrices in the following order:

i. Bypasses that affect bypass controlled output k and reduce utility consumption. For each manipulation j, priority i is given if the following is fulfilled:

$$e_k^{\mathrm{BP}} \cdot g_{k,j}^{\mathrm{BP}} \cdot g_j^{\mathrm{U}} = [+] \tag{5.6}$$

ii. Bypasses that affect bypass controlled output k and have zero or mixed influence on utility consumption. That is, priority *ii* are given to bypasses with $g_{k,j}^{\mathrm{BP}} \neq [0]$ which are not included in priorities *i* or *iii*.

iii. Bypasses that affect bypass controlled output k and increase utility consumption. For each j, priority *iii* is given if the following is fulfilled:

$$e_k^{\mathrm{BP}} \cdot g_{k,j}^{\mathrm{BP}} \cdot g_j^{\mathrm{U}} = [-] \tag{5.7}$$

Step 3. Use heuristics to choose among equal priorities from step 2.

a) Among bypasses with the same priority, choose the one closest to the bypass controlled output.

b) Among bypasses with the same priority, disregard bypasses that may have mixed influence ([±]) on the bypass controlled output k.

Step 4. Increase k to next bypass controlled output and repeat from step 2.

The priorities given in step 2 are crucial and the result is summarized in a priority table. The following example shows in detail how the procedure is applied to the HEN in the illustration example and how the priority table is generated.

Example 5.1 *Application of the procedure to the illustrating example.*
First we define the input and output vectors of the systems in equations (5.1) and (5.2): $u = [u_{\mathrm{I}}\ u_{\mathrm{II}}]^T$, $y^{\mathrm{BP}} = T_{\mathrm{o}}^{\mathrm{C2}}$ and $y^{\mathrm{U}} = [Q_{\mathrm{c}}\ Q_{\mathrm{h}}]^T$, where Q_{c} and Q_{h} are the cooler and heater duties when $T_{\mathrm{o}}^{\mathrm{H1}}$ and $T_{\mathrm{o}}^{\mathrm{C1}}$ are perfectly controlled by the cooler and heater, respectively. Using the rules given above to find the two sign matrices for the network structure in figure 5.1 we get

$$sign(G^{\mathrm{BP}}) = [+\ -] \quad \text{and} \quad sign(G^{\mathrm{U}}) = \begin{bmatrix} + & + \\ + & 0 \end{bmatrix}$$

This G^{U} gives $sign(g^{\mathrm{U}}) = [+\ +]$. There is only one bypass controlled output, and the procedure gives:

Step 1. Initialize $u_{\mathrm{I}} = u_{\mathrm{II}} = 0$ since both elements in $sign(g^{\mathrm{U}})$ are [+].

Step 2. Both elements in G^{BP} satisfies $g_{1,j}^{\mathrm{BP}} \neq [0]$ so both bypasses affect the only bypass controlled output. With $k = 1$, priority i is given to a manipulation when the conditions in (5.6) are fulfilled and priority *iii* is given when (5.7) is fulfilled. For bypass u_{I} ($j = 1$) we get

$$e_1^{BP} \cdot g_{1,1}^{BP} \cdot g_1^{U} = e_1^{BP} \cdot [+] \cdot [+] \quad \Rightarrow \begin{cases} \text{Priority } i & \text{when } e_1^{BP} > 0 \\ \text{Priority } iii & \text{when } e_1^{BP} < 0 \end{cases}$$

and for bypass u_{II} ($j = 2$) we get

$$e_1^{BP} \cdot g_{1,2}^{BP} \cdot g_2^{U} = e_1^{BP} \cdot [-] \cdot [+] \quad \Rightarrow \begin{cases} \text{Priority } i & \text{when } e_1^{BP} < 0 \\ \text{Priority } iii & \text{when } e_1^{BP} > 0 \end{cases}$$

In this example, there are no cases where priority *ii* are given.

Step 3. No bypasses are given the same priority (for the same value of e_1^{BP}) so no heuristics are needed.

Step 4. There is only one bypass controlled output ($k = 1$), hence no repetitions can be made.

The bypass priorities found by the procedure can be summarized as: When $e_1^{BP} > 0$, use u_I as the primary manipulated input. If u_I is saturated, use u_{II} as secondary input. When $e_1^{BP} < 0$, use u_{II} as the primary input. If u_{II} is saturated, use u_I as secondary input. From the given bypass priorities (*which* bypass to adjust) and the values in $sign(G^{BP})$ (*how* to adjust), we can now construct a priority table for the bypass manipulations:

	Primary manipulation	Secondary manipulation
$e_1^{BP} > 0$	Reduce u_I ($u_I \downarrow$)	Increase u_{II} ($u_{II} \uparrow$)
$e_1^{BP} < 0$	Reduce u_{II} ($u_{II} \downarrow$)	Increase u_I ($u_I \uparrow$)

Table 5.2 Priority table for example.

The control structure suggested by this priority table is identical to the one used in the illustration example. This control strategy will be the same for all networks with this structure, and it will "automatically" find the bypass fractions that give minimum utility consumption together with meeting the target demands at steady state (provided that the HEN is feasible and the SISO-controllers do not give any steady state control error). ■

To construct the sign matrices for networks that include loops, inner matches (process/process heat exchangers with downstream process/process exchangers on both sides) as well as split manipulations, some additional observations for HENs are given in Mathisen *et al.* (1994). These are mainly derived from the four observations given above and may be used to convert some [±] elements in the sign matrices to [+] or [–].

5.6 Parallels to split-range control

The control structure found for the illustrating example in this chapter is very similar to split-range control which is a commonly used control configuration. Figure 5.4 shows a typical

example which is taken from Loe (1993). The process is a utility system with three steam pressure levels. Each level may have several suppliers and consumers (not shown) with varying demands. The objective is to control the pressure of the MP-steam by supplying HP-steam (using u_2) to increase the pressure, or by delivering steam to the LP-level (using u_1). This is obtained using a pressure transmitter (PT) and a pressure controller (PC) for control of the two valves. The signal from the controller is splitted such that both valves are fully closed when the signal is 50%. Valve u_2 opens when the control signal exceeds 50%, and valve u_1 opens when the control signal is leass than 50% (see figure 5.4b which shows the valve positions as a function of the control signal). This is an example of split-range control, and it allows two actuator devices to be controlled by one single controller.

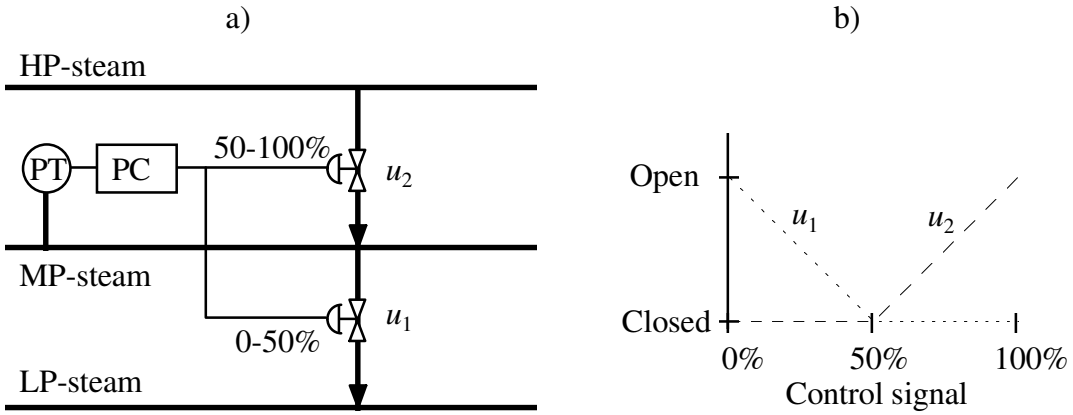


Figure 5.4 Example of split-range control for a steam supply system.

In practice, spilt-range control may be implemented without the use of any swithes: Assume that the physical control signal is electrical current in the range 4 – 20 mA which is supplied to both valves. Scaling valve u_2 to be open at 4 mA and closed at 12 mA, and valve u_1 to be closed at 12 mA and open at 20 mA, the split-range control will work. A perhaps more updated implementation is to perform the scaling in the process control system (software) and to use two separate control signals (individually scaled from 0 – 100 %) in the field.

The control strategy in figure 5.4 is in fact identical to the control strategy in the illustrating example of the HEN in figure 5.1. Instead of implementing the control sceme using two controllers and then switch between them, it is simpler to use only one controller to control the bypasses u_{I} and u_{II} in a split-range configuration as in figure 5.4b. Note that if we in the problem in figure 5.4 want to minimize the (energy) flow from high pressure to low pressure steam, not only the control strategies are similar to each other, in fact, the two problems are completely analogous.

In other applications where split-range is used, the range of each control device may partly or fully overlap. One may question if “split-range” is the correct term when the ranges overlap completely, though.

Using split-range control, the controller parameters when the different valves are active, may be different from each other. Concerning the controller gain, this may be solved by selecting proper settings/scalings for the valves. As an example, assume that for “good” control of the HEN in figure 5.1 it has been found that the gain when using u_{I} is three times the gain when

using u_{II}. Then, if u_{II} is active in the range 0 – 75% and u_{I} is active from 75 to 100%, there will be no large discontinuities of the process gain when switching between the two bypass valves.

As it has been clear from this section, the method for optimal operation based on structural information often leads to a control strategy that may easily be implemented using split-range control. In fact, one may think of the method as a systematic way to find an optimal split-range control structure. In section 5.8, an example will demonstrate the method and the split-range implementation when a controller may utilize more than two bypasses. In that example, it is not trivial to find the strategy for optimal operation without using a systematic method.

5.7 How to handle multiple bypass controlled outputs

Until now, the method has only been applied to a simple example with only one bypass controlled target. If there are several bypass controlled targets, the following situation will typically occur during operation: Assume that a bypass saturates and thus a new has to be assigned for control of a given outlet temperature. What if the new bypass for this control purpose already is occupied controlling an other outlet temperature? It is clear that a new candidate bypass has to be selected since one bypass cannot control two outlet temperatures independently. However, it is not clear how to select a new bypass, or how the two outlet temperatures and the two bypasses should be paired.

To address this problem when there are several bypass controlled outputs, the following approaches may be considered:

1. All possible pairings may be listed in a prioritized order, and when one bypass is preferred for two different bypass controlled outputs, then find the second best bypass for both outputs (from the priority table), and choose the combination and pairing that gives highest total priority.
2. Minimize switching of pairings. That is, if the selected bypass for one output is occupied, do not change the existing pairing but switch to the next manipulations for the output that needs a new manipulation.
3. When a manipulation saturates, and a new needs to be assigned, the pairing problem is solved simultaneously to find the combination that maximizes the total priority.

Here, it will be focused on the third option – partly because it is expected to give the best results since all manipulations are considered simultaneously and partly because it is very similar to the method proposed in the next chapter. In section 5.5, the following rules were found:

Priority *i*:		$e_k^{\mathrm{BP}} \cdot g_{k,j}^{\mathrm{BP}} \cdot g_j^{\mathrm{U}} = [+]$
Priority *ii*:	With $g_{k,j}^{\mathrm{BP}} \neq [0]$,	$e_k^{\mathrm{BP}} \cdot g_{k,j}^{\mathrm{BP}} \cdot g_j^{\mathrm{U}} = [0]$ or $[\pm]$
Priority *iii*:		$e_k^{\mathrm{BP}} \cdot g_{k,j}^{\mathrm{BP}} \cdot g_j^{\mathrm{U}} = [-]$

Recall that k is index for bypass controlled outputs and j is index for the manipulations. All information from these expressions can be stored in a new sign *priority* matrix P given by

$$sign(P)_{i,j} = \begin{cases} e_k^{\mathrm{BP}} \cdot g_{k,j}^{\mathrm{BP}} \cdot g_j^{\mathrm{U}} & \text{if } g_{k,j}^{\mathrm{BP}} \neq 0 \\ [\times] & \text{if } g_{k,j}^{\mathrm{BP}} = 0 \end{cases} \tag{5.8}$$

The new symbol [×] in this sign matrix denotes a forbidden pairing since the corresponding manipulation does not affect the specific bypass controlled output. While sign(G^{BP}) and sign(g^{U}) are constant, the sign of the control error sign(e^{BP}) changes during operation, hence the sign matrix sign(P) will change during operation. When a change in the sign of the control error is detected, sign(P) will change, and new control configurations should be evaluated. This is done automatically by first assigning numerical values to the priority matrix P according to the following rules:

$$\begin{array}{lll} p_{k,j} = -1 & \text{if } \mathrm{sign}(P)_{k,j} = [+] & (\text{priority } i) \\ p_{k,j} = \ \ 0 & \text{if } \mathrm{sign}(P)_{k,j} = [0] \text{ or } [\pm] & (\text{priority } ii) \\ p_{k,j} = \ \ 1 & \text{if } \mathrm{sign}(P)_{k,j} = [-] & (\text{priority } iii) \end{array} \tag{5.9}$$

Now, the task is to select pairings that minimizes the *total* utility consumption, i.e. the objective function to be minimized is $\sum p_{k,j}$ for the selected pairings. Pairings are chosen such that there is one manipulation for each bypass controlled output, and no manipulations control more than one output. In addition, constraints that prevent forbidden pairings and selection of manipulations that are saturated must be included. As an example consider a system with 2 bypass controlled outputs and 3 manipulations, and the priority matrix at one instant during operation is

$$P = \begin{bmatrix} (-1) & 0 & \times \\ -1 & (-1) & +1 \end{bmatrix}$$

Pairing input 3 with output 1 is forbidden. Assuming that none of the manipulations are saturated, it is preferred to pair input 1 with output 1 and input 2 with output 2, as indicated.

The presentation concerning how multiple bypass controlled outputs can be handled is made very brief in this section. The reason for this is that the method proposed in the next chapter handles multiple bypass controlled outputs in a similar way. In that chapter, the explanations are more thorough and the method may easily be applied to sign matrices as well. For this reason, multiple bypass controlled outputs are not considered any further in this chapter.

5.8 Example

Finally in this chapter, the procedure is applied to an example. The HEN in the example has one bypass controlled outlet temperature.

Consider the stream data in table 5.3 and the design in figure 5.5. From the stream data we see that there are two disturbances; ±20°C in $T_{\mathrm{s}}^{\mathrm{H2}}$, and ±7.5 kW/°C in CP^{C1}. The nominal design in figure 5.5 is based on a design (before retrofit) in Kotjabasakis and Linnhoff (1986),

but modified since T_o^{H2} here is a free outlet temperature. Also, note that the disturbances and the problem statement here are different from the problem discussed by Kotjabasakis and Linnhoff (1986). Assume that the nominal design for control purposes already has been modified by increasing the area of exchanger III and that bypass has been installed across this exchanger so that each of the two disturbances can be rejected completely (one at a time). Added area and bypass on the last heat exchanger is in accordance with common engineering practice, and we will refer to this as case A.

Stream	T_s [°C]	T_t [°C]	CP [kW/°C]
H1	300	80	30
H2	200±20	X	45
C1	40	180	40±7.5
C2	140	240	60

Table 5.3 Stream data for example.

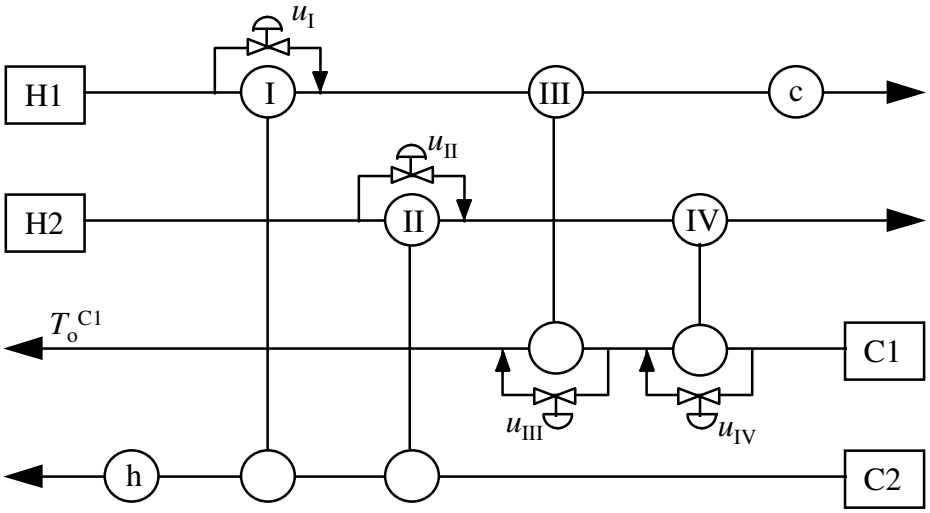


Figure 5.5 Network in example.

We will apply the procedure to this network (including the extra area already installed on exchanger 3) and show that the utility consumption is reduced. This case is denoted B. Remember that bypasses now can be placed across all four process/process heat exchangers. Each bypass is placed on that side of the heat exchanger which is closest to the bypass controlled output. This is to improve controllability, and it will not influence the steady state performance. Defining $u = [u_I\ u_{II}\ u_{III}\ u_{IV}]^T$, $y^{BP} = T_o^{C1}$, $y^U = [Q_c\ \ Q_h]^T$ and $e = T_o^{C1} - T_t^{C1}$ gives the sign matrices:

$$sign(G^{BP}) = \begin{bmatrix} + & \pm & - & - \end{bmatrix} \quad \text{and} \quad sign(G^U) = \begin{bmatrix} + & \pm & + & - \\ + & + & 0 & 0 \end{bmatrix}$$

From $sign(G^U)$, we obtain $sign(g^U) = [+ \pm + -]$, and the procedure yields:

Step 1. From $sign(G^U)$ it is clear that $u_I = u_{III} = 0$ during initialization. Inspecting the network, we assume that the plus in column 2 will dominate the possible negative effect from the $[\pm]$ element so we also set $u_{II} = 0$. u_{IV} reduces the utility consumption and is therefore initialized to one.

Step 2. $e > 0$ gives priority *i* to u_I and u_{IV}, and priority *iii* to u_{III}. $e < 0$ gives priority *i* to u_{III} and priority *iii* to u_I and u_{IV}. Priority ii) is given to u_{II}.

Step 3. To distinguish between u_I and u_{IV}, both have to travel through one exchanger to reach T_o^{C1} but we prefer u_{IV} since it bypasses a larger heat exchanger and therefore probably has larger influence on T_o^{C1}.

Step 4. Not applicable.

When constructing the priority table from the results in step 2 and step 3, the following considerations are made:

- Bypass u_{II} has a mixed influence on T_o^{C1}. Thus, it can not be concluded (from structural information) whether we shall decrease or increase this bypass to counteract a control error. Inspecting the network structure, it is reasonable to assume that u_{II} have little influence on T_o^{C1} since both hot and cold outlet from heat exchanger II traverses two heat exchanger before affecting T_o^{C1}. For simplicity, we totally disregard bypass u_{II} in the control structure.
- With the bypass fractions initialized according to step 1, it is reasonable to assume that T_o^{C1} is too small. The preferred choice for control is to reduce bypass u_{IV}. If u_{IV} should saturate at zero, u_I has to be opened. However, when T_o^{C1} is too high and u_I is opened, we prefer to reset u_I to zero before u_{IV} is used.

The priority table with these considerations is shown in the table below. Note that the "primary", "secondary" and "third" manipulation is not the same as priorities *i*, *ii* and *iii*. Also, preferring u_I before u_{IV} when *e* is positive is not a violation of the priorities given in step 3, but it ensures that u_I returns to zero after it has been opened.

	Primary manipulation	Secondary manipulation	Third manipulation
$e > 0$	$u_I \downarrow$	$u_{IV} \uparrow$	$u_{III} \uparrow$
$e < 0$	$u_{III} \downarrow$	$u_{IV} \downarrow$	$u_I \uparrow$

Table 5.3 Priority table for example.

Figure 5.6 shows the results when simple PI-controllers are used for both case A (traditional engineering approach) and case B ("sign"-method). From figure 5.6c, it is clear that the sign-method results in considerably reduced utility consumption (thick line), compared to the traditional engineering approach (thin line). For nominal disturbances, (4 to 6 hours on the time axis) the utility reduction is close to 0.9 MW at steady state.

Using the sign-method (case B), the controlled HEN has become more flexible (*effective* flexibility has improved) since it is able to compensate for both disturbances occurring at the same time in their worst case combination (8 to 10 hours). In this period, case A has the lowest utility consumption but target temperatures are not met, see figure 5.6b. Thus, the primary goal of optimal operation is not satisfied.

Note that case B does not utilize u_{III} for any of the disturbances in this example. From figure 5.6b, it is clear that the sign-method may result in deteriorated dynamic behavior.

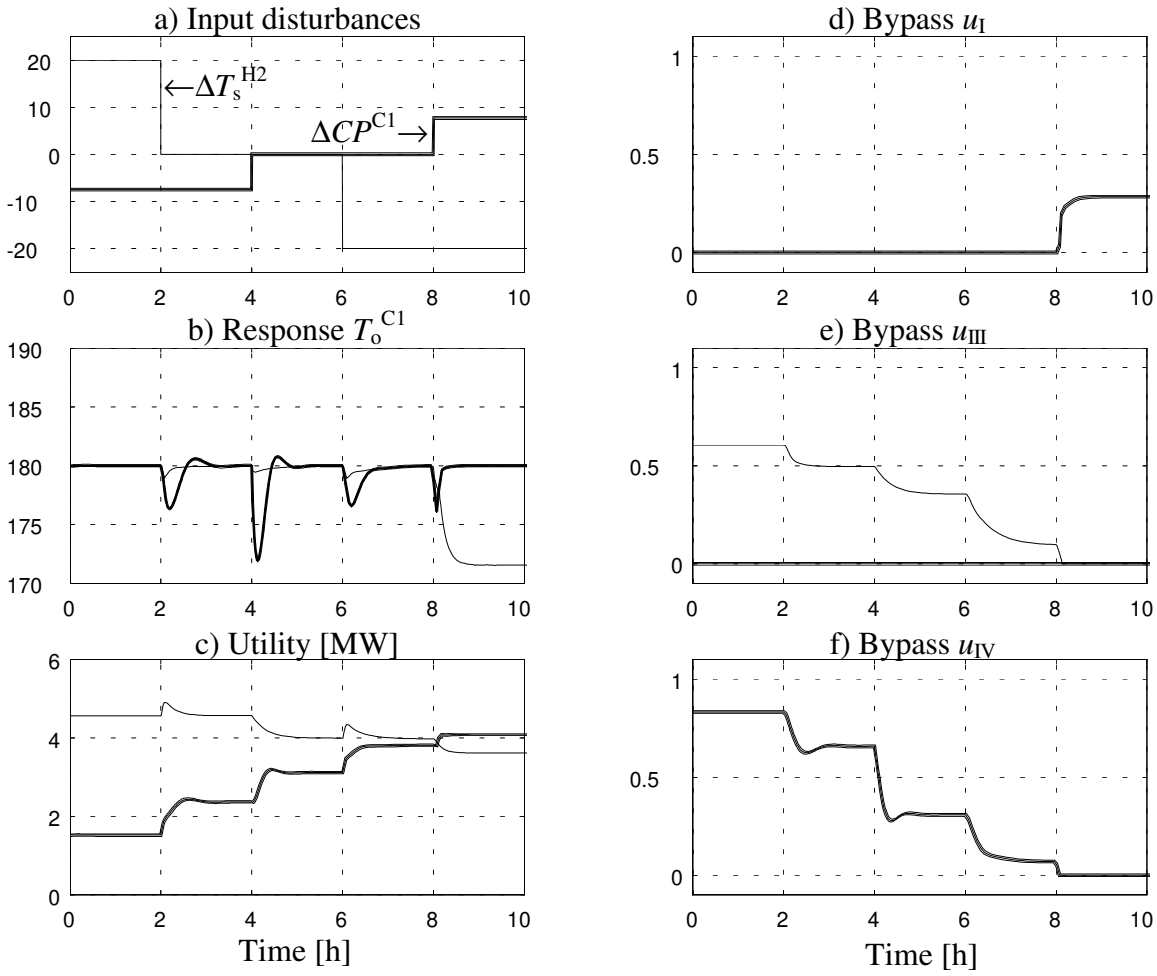


Figure 5.6 Closed loop simulation results. (a) Deviation from nominal disturbance inputs, T_s^{H2} (thin line) and CP^{C1} (thick line). (b) Response in T_o^{C1}, case A (thin) and case B (thick). (c) Utility consumption, case A (thin) and case B (thick). (d), (e) and (f) Bypasses u_I, u_{III} and u_{IV}, case A (thin, (e) only) and cases B (thick).

Finally in this example section, the split-range implementation for this example is discussed. Figure 5.7a shows graphically how the three bypasses open and close in a similar way as in figure 5.4, however, split points are not located correctly.

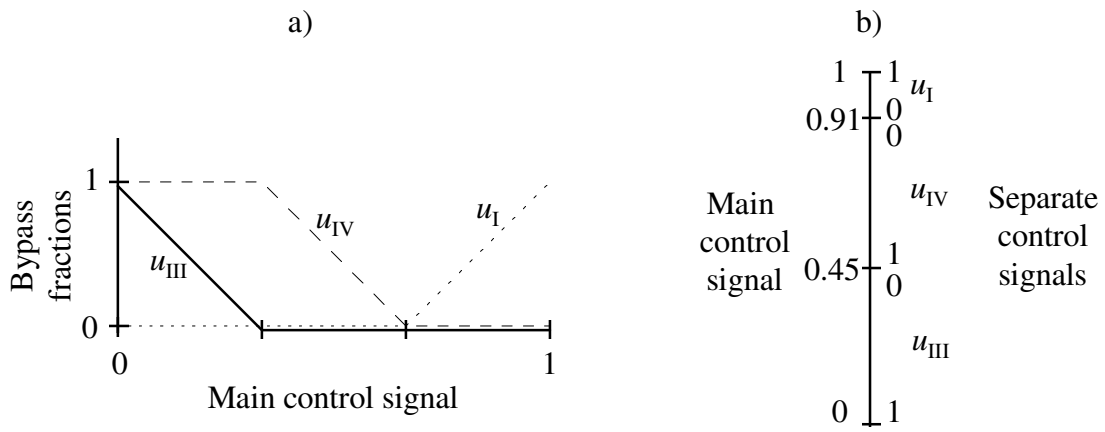


Figure 5.7 Two representations of the split-range implementation.

Figure 5.7b (to the right) shows the same, with the main control signal to the left of the vertical line and the control signal to the separate manipulations to the right. In this figure, the split points (0.45 and 0.91) are shown approximately at their correct positions. The split points were found as follows: First, the parameters of the three separate controllers were found separately such that satisfying results were obtained. Then, the gain of the three controllers were used to compute the split points together with the total gain, such that when using only one controller, the gain is the same as when switching between the separate controllers. The integral time constants were interpolated between the values found for the separate controllers. This interpolation was performed in a range close to each split point, and only on the side with the shortest integral time for the separate controller. The simulations are carried out using only one control algorithm and by splitting the output signal according to figure 5.7b. See also figure 3.6 where the controller (denoted “escreg4d”) is shown in the upper left part.

5.9 Conclusions

In this chapter, a method for optimal operation based on structural information has been discussed. The method has been derived for operation of HENs, but may be applied to other parts of the process as well. Applying the procedure, feasible manipulations for control are given one of three possible priorities:

i. Manipulations that decrease utility consumption while decreasing the control error.

ii. Manipulations with zero or mixed effect on utility consumption.

iii. Manipulations that increase utility consumption while decreasing the control error.

From these three categories, a priority table for the manipulations is constructed and this table dictates the control structure. The control structure may change during operation, however, in many cases it simply corresponds to split-range control.

While it is clear that manipulations with priority *i* is better than manipulations with priority *iii*, no clear conclusions can be drawn for those manipulations priority *ii* with mixed effects [±]. Manipulations with mixed effects may reduce utility consumption more than some manipulations with priority *i*, or they may increase utility consumption more than some

manipulations with priority *ii*. Hence the procedure will not always guarantee that the utility consumption is minimized at steady state. Heuristic rules based on controllability considerations are used to choose among manipulations with the same priority. While these rules may result in selecting a manipulation which is not optimal from a steady state utility consumption point of view, they will usually result in the control structure with best dynamic performance among manipulations of equal priority.

Using structural information only, there may be cases where the available information is not sufficient to distinguish quantitatively between different effects. However, even in cases where the method does not guarantee optimal solution in all situations, it may still result in optimal or near optimal operation. Despite the disadvantage of not guaranteeing globally optimal operation in all cases, the method also has some of nice features:

- The method requires very little information about the process to be operated. In fact, the procedure is easily carried out by hand, and no quantitative information is needed.
- The method results in a decentralized control structure with variable pairing. As it has been shown, the control configuration can usually be implemented as split-range control. The control strategy can be included in today's control systems.
- Optimal operation can often be achieved without any quantitative process model or any numerical optimizations.

Since the method only guarantees optimal operation in a few cases, and since it may result in poor dynamic performance, it is advisable to combine it with dynamic simulations and verify several possible options. Alternatively, the methods proposed in the two next chapters may be evaluated.

Notation

e Control error.
g Element in transfer matrix.
G Transfer matrix.
CP Heat capacity flowrate.
P Priority matrix.
Q Heat load (duty) of heat exchanger.
T Temperature
u Manipulated input (bypass fraction).

Superscripts:
BP Bypass.
U Utility.

Subscripts:
i Index for utility controlled outputs.
j Index for manipulated inputs.
k Index for bypass controlled outputs.
o Actual output or outlet (temperature).
s Supply (temperature).
t Target or reference (temperature).

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