PART 1

PINCH AND MINIMUM UTILITY USAGE

WHAT IS THE PINCH?

- The pinch point is a temperature.
- Typically, it divides the temperature range into two regions.
- Heating utility can be used only above the pinch and cooling utility only below it.

WHAT IS A PINCH DESIGN

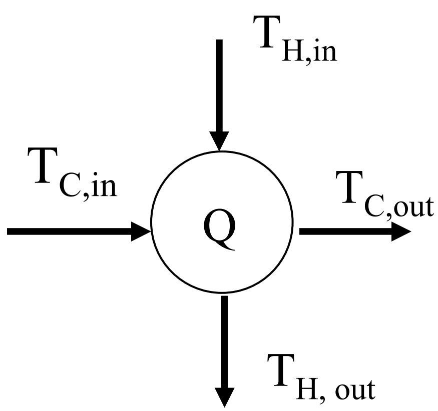
- A heat exchanger network obtained using the pinch design method is a network where no heat is transferred from a hot stream whose temperature is above the pinch to a cold stream whose temperature is below the pinch.

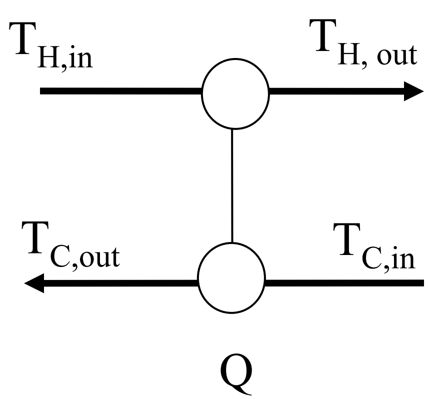
IS PINCH TECHNOLGY CURRENT?

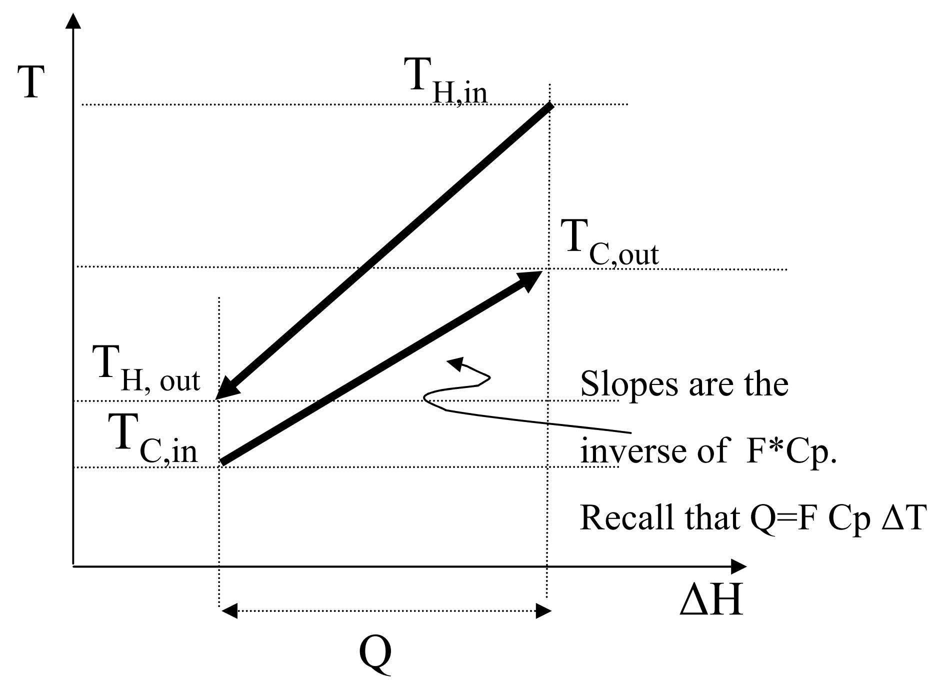
- YES and NO.
- It is a good first approach to most problems.
- Pinch technology is at the root of many other heat integration technologies. It is impossible to understand them without the basic concepts of pinch technology.

TEMPERATURE-ENTHALPY (T-H) DIAGRAMS

- Assume one heat exchanger. These are alternative representations

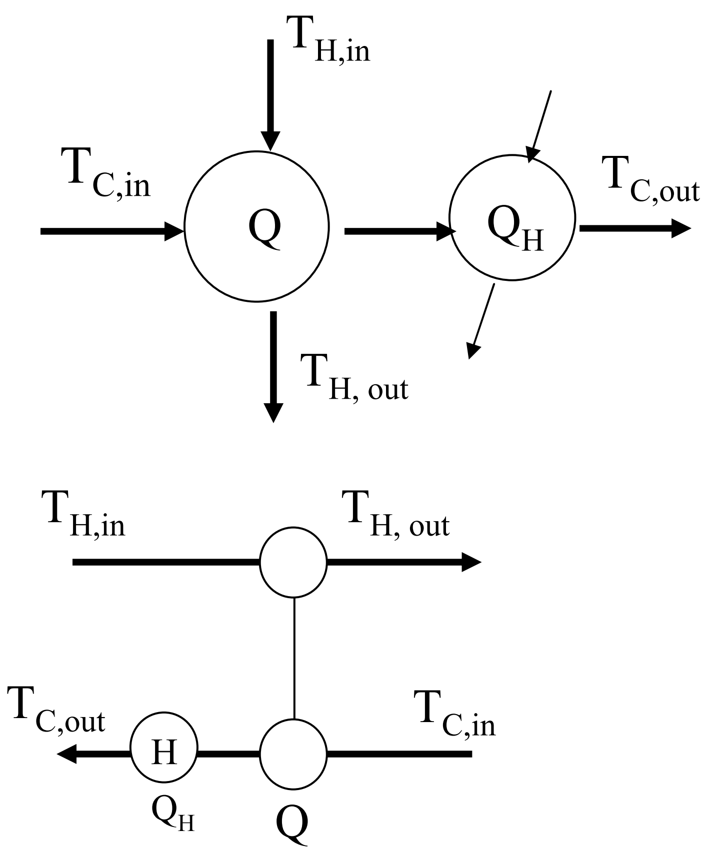


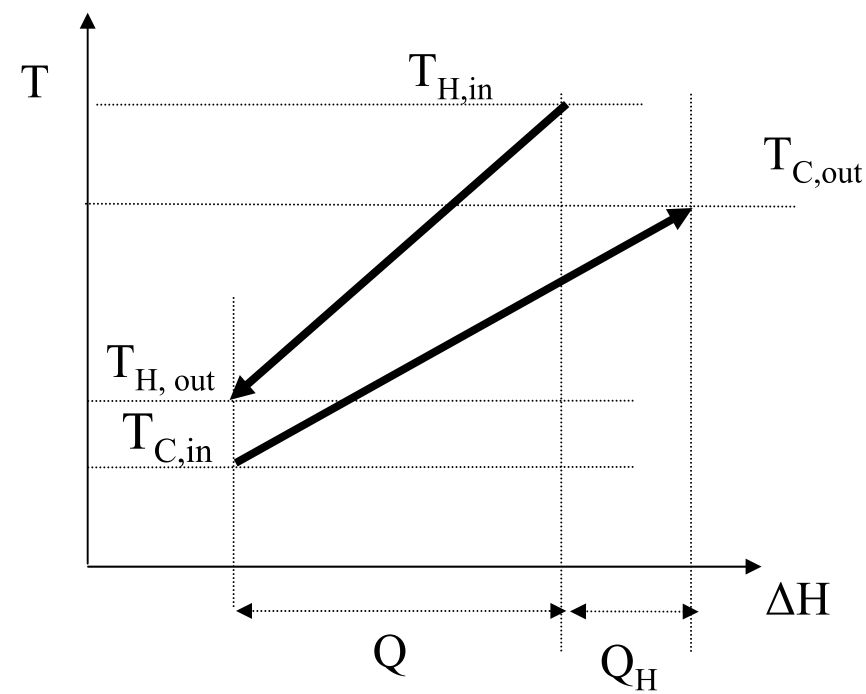




T-H DIAGRAMS

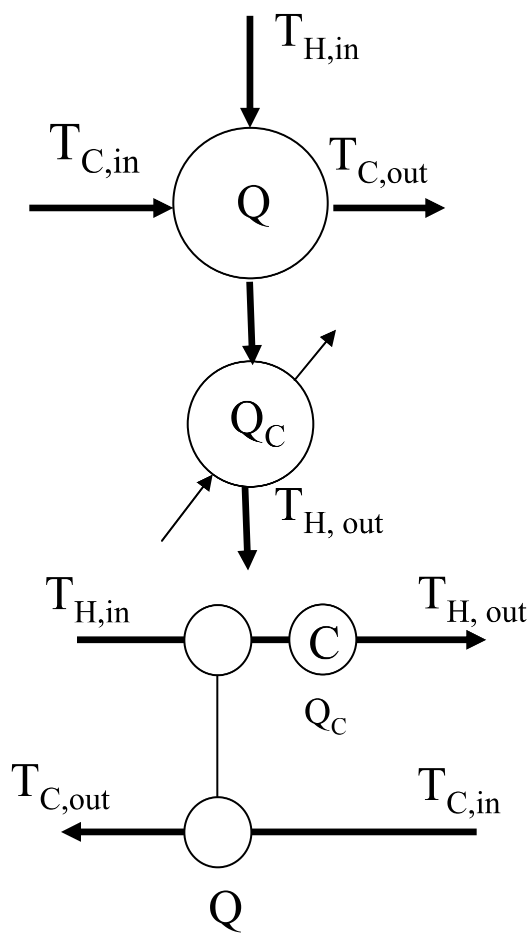
- Assume one heat exchanger and a heater

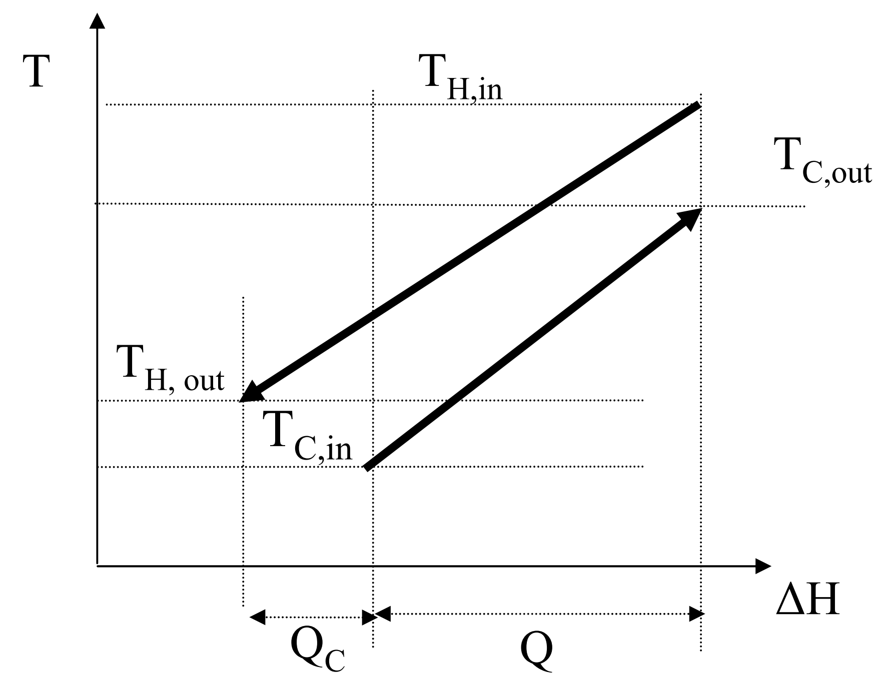




T-H DIAGRAMS

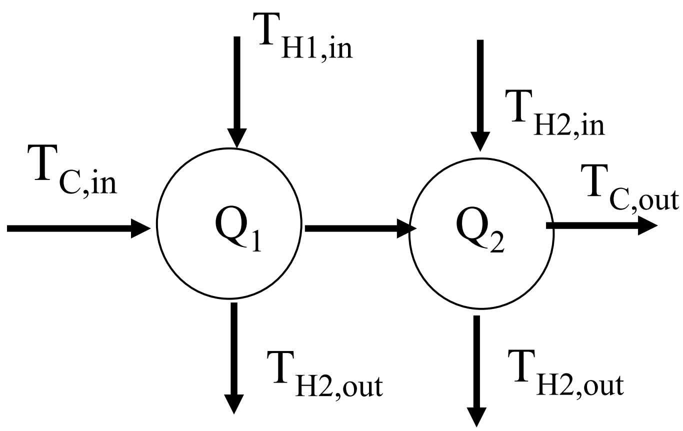
- Assume one heat exchanger and a cooler

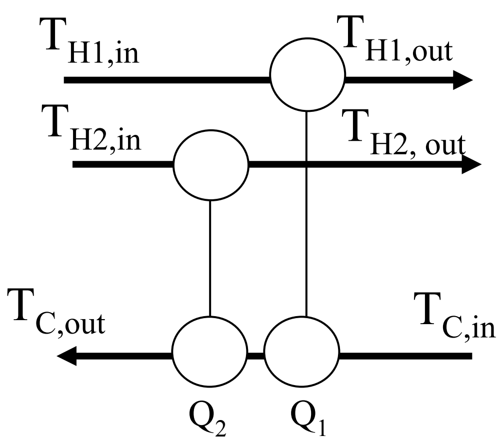


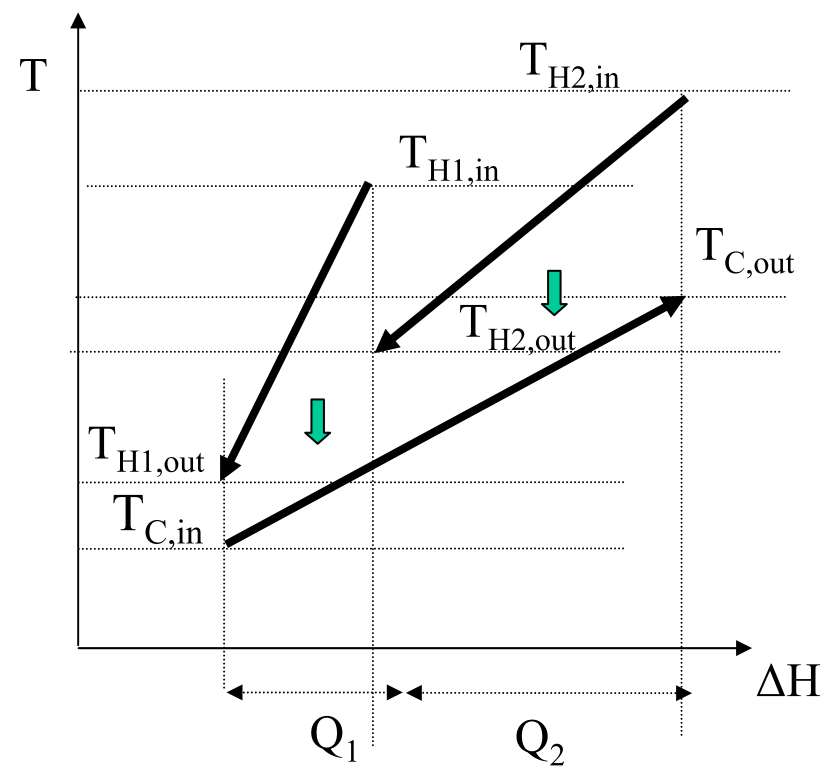


T-H DIAGRAMS

- Two hot-one cold stream





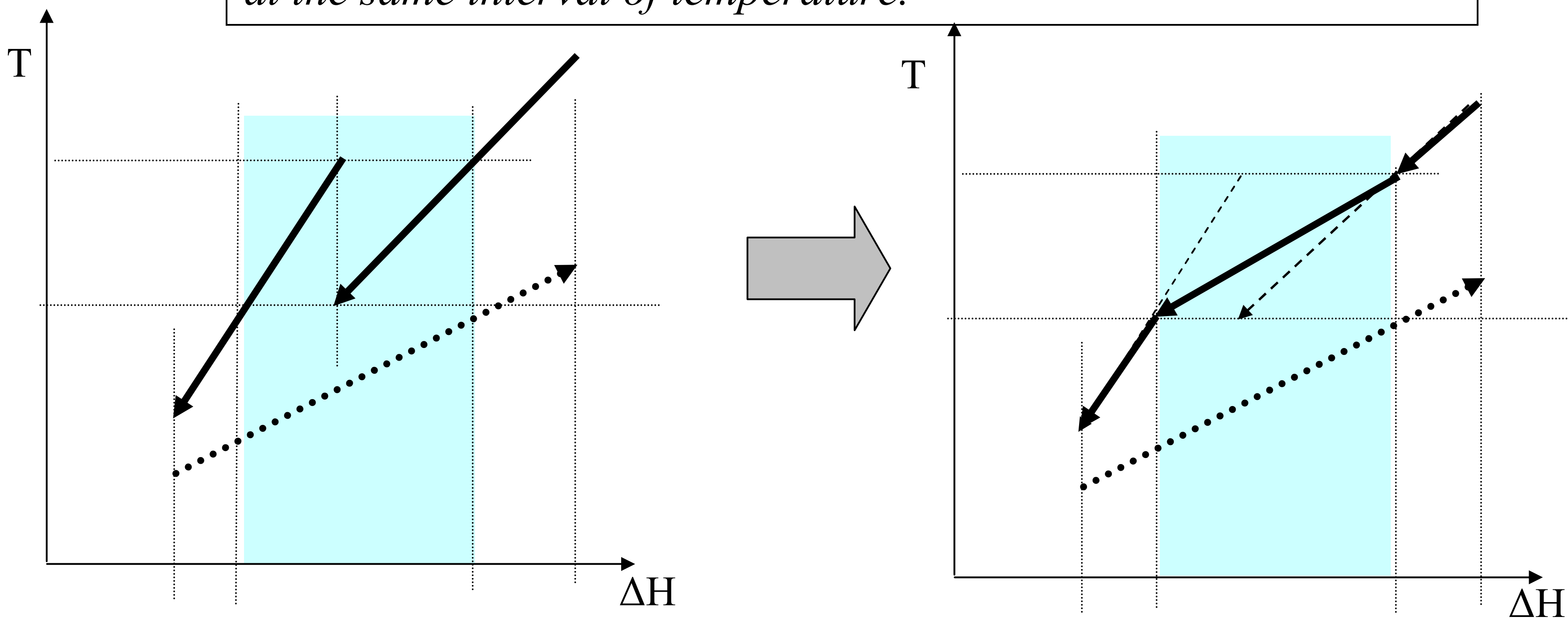


Notice the vertical arrangement of heat transfer

T-H DIAGRAMS

- Composite Curve

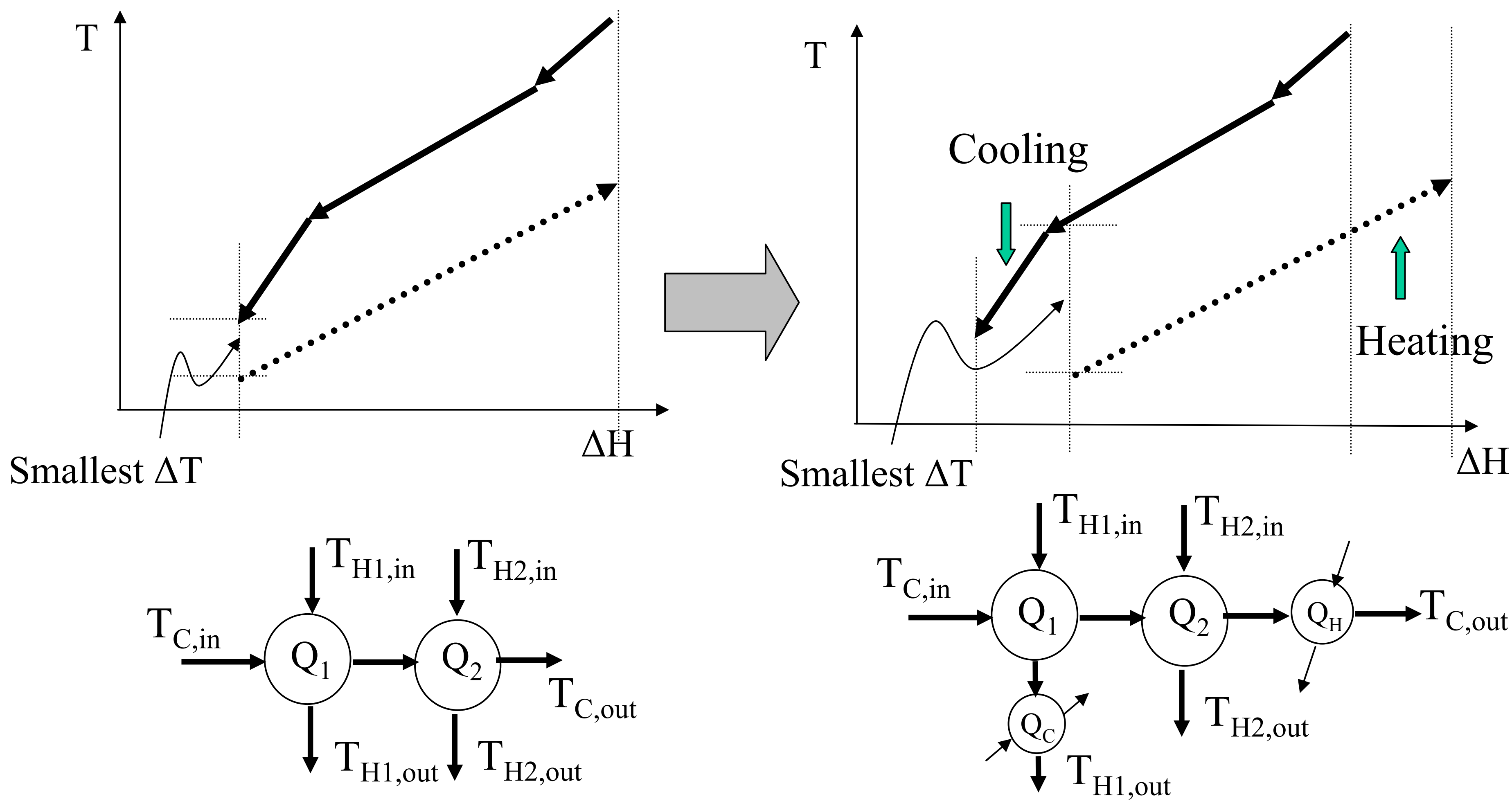
Obtained by lumping all the heat from different streams that are at the same interval of temperature.



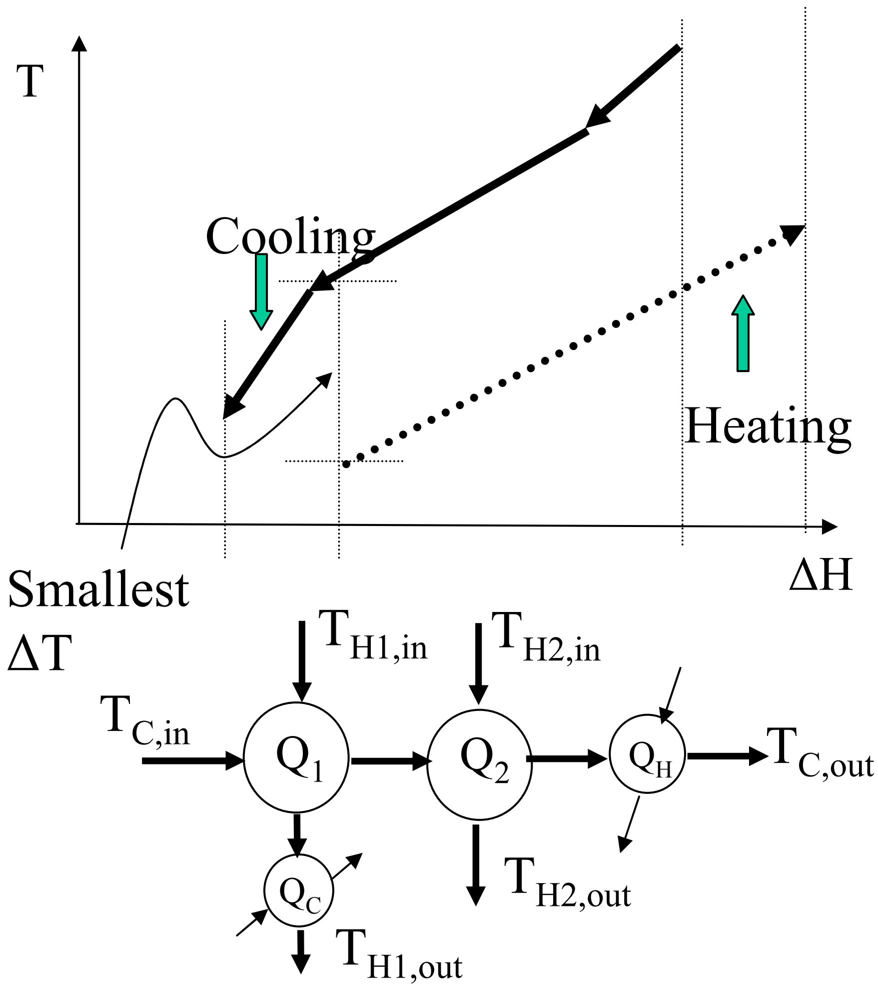
Remark: By constructing the composite curve we loose information on the vertical arrangement of heat transfer between streams

T-H DIAGRAMS

- Moving composite curves horizontally



T-H DIAGRAMS

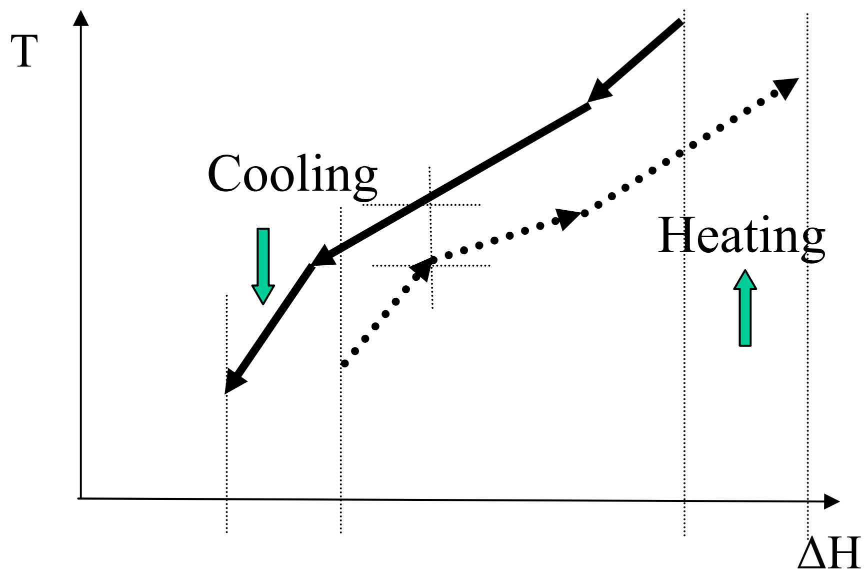


Moving the cold composite stream to the right

- Increases heating and cooling BY THE SAME AMOUNT
- Increases the smallest ΔT
- Decreases the area needed $A=Q/(U^* \Delta T)$

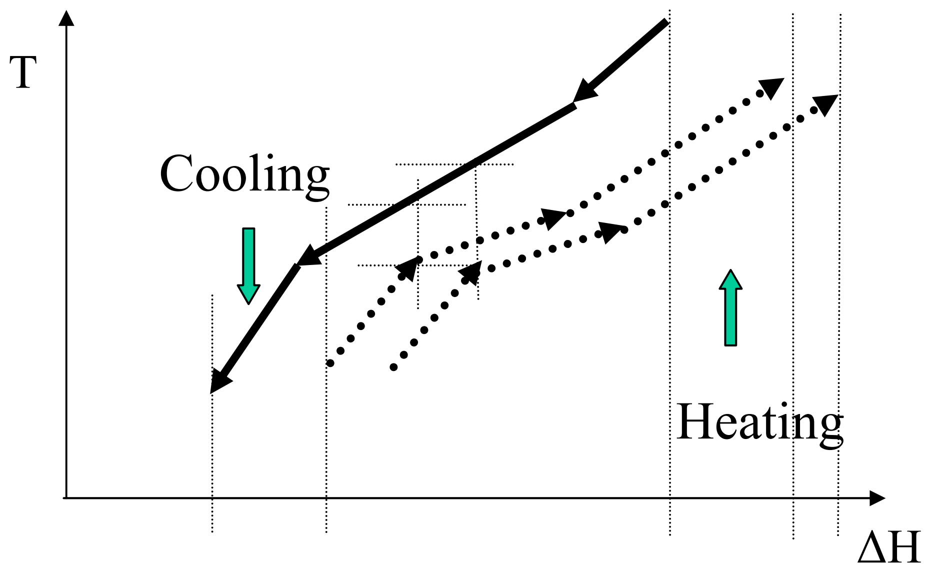
Notice that for this simple example the smallest ΔT takes place in the end of the cold stream

T-H DIAGRAMS



- ***In general, the smallest*** ΔT can take place anywhere.
- We call the temperature at which this takes place THE PINCH.

TEMPERATURE-ENTHALPY DIAGRAMS

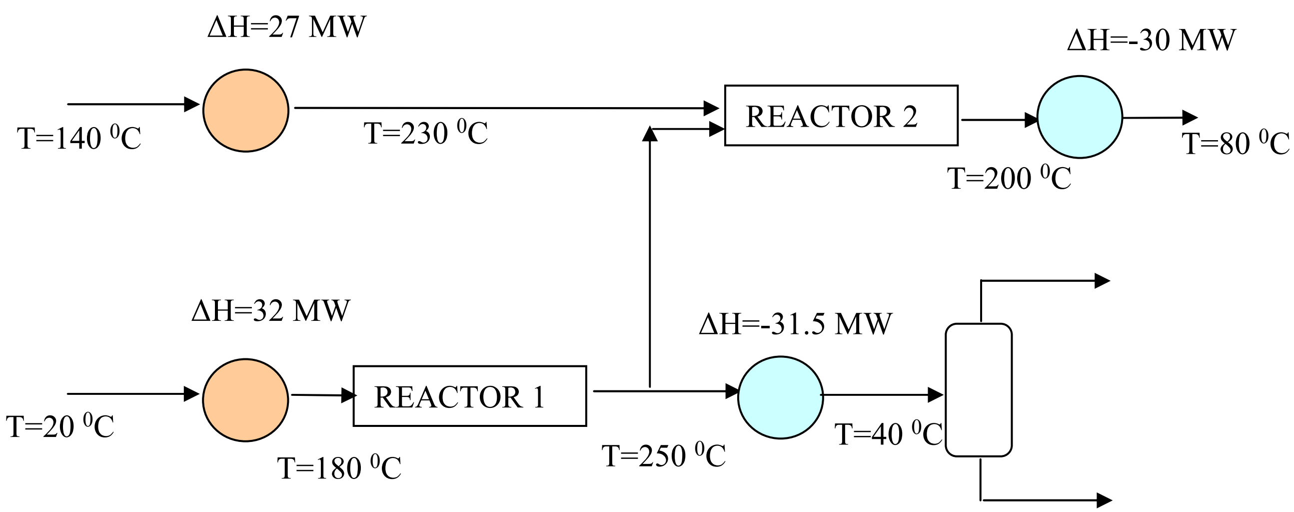


- ***From the energy point of view it is then convenient*** to move the cold stream to the left.
- However, the area may become too large.
- To limit the area, we introduce a minimum approach ΔT_{min}

GRAPHICAL PROCEDURE

- Fix ΔT_{min}
- Construct the hot and cold composite curve
- Draw the hot composite curve and leave it fixed
- Draw the cold composite curve in such a way that the smallest $\Delta T=\Delta T_{min}$
- The temperature at which $\Delta T=\Delta T_{min}$ is the PINCH
- The non-overlap on the right is the Minimum Heating Utility and the non-overlap on the left is the Minimum Cooling Utility

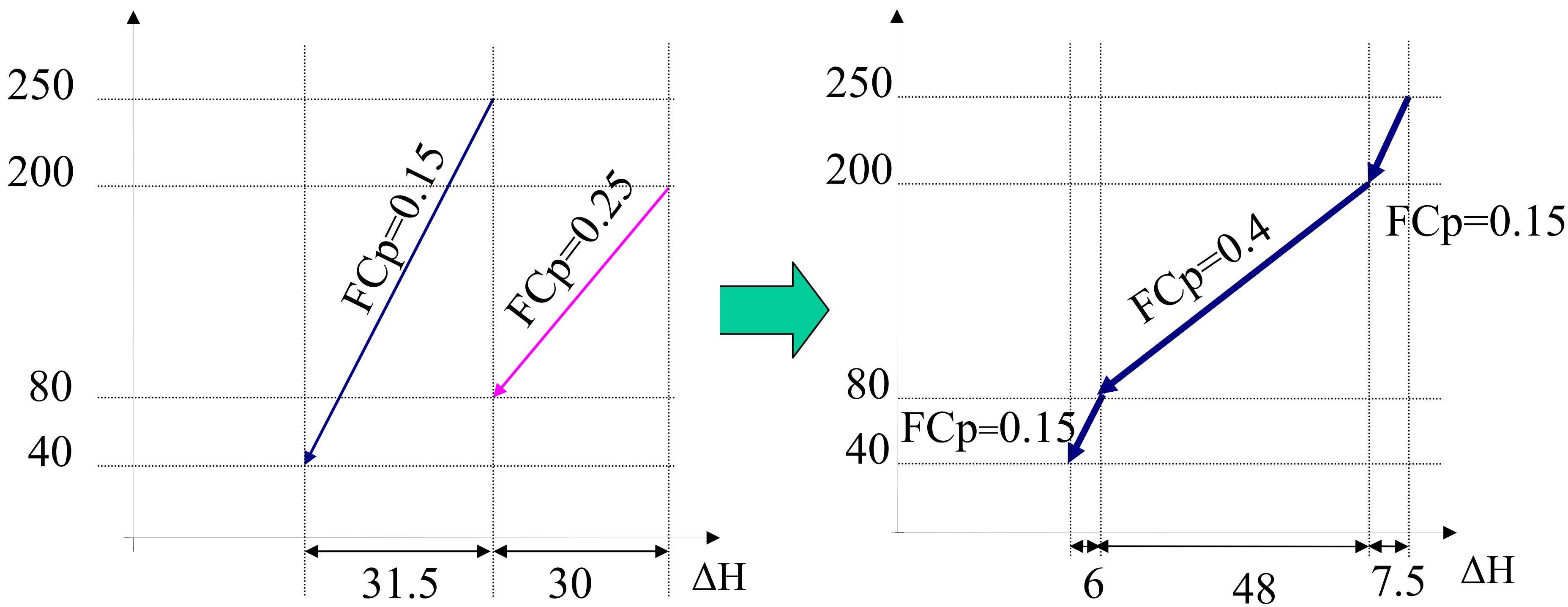
HANDS ON EXERCISE



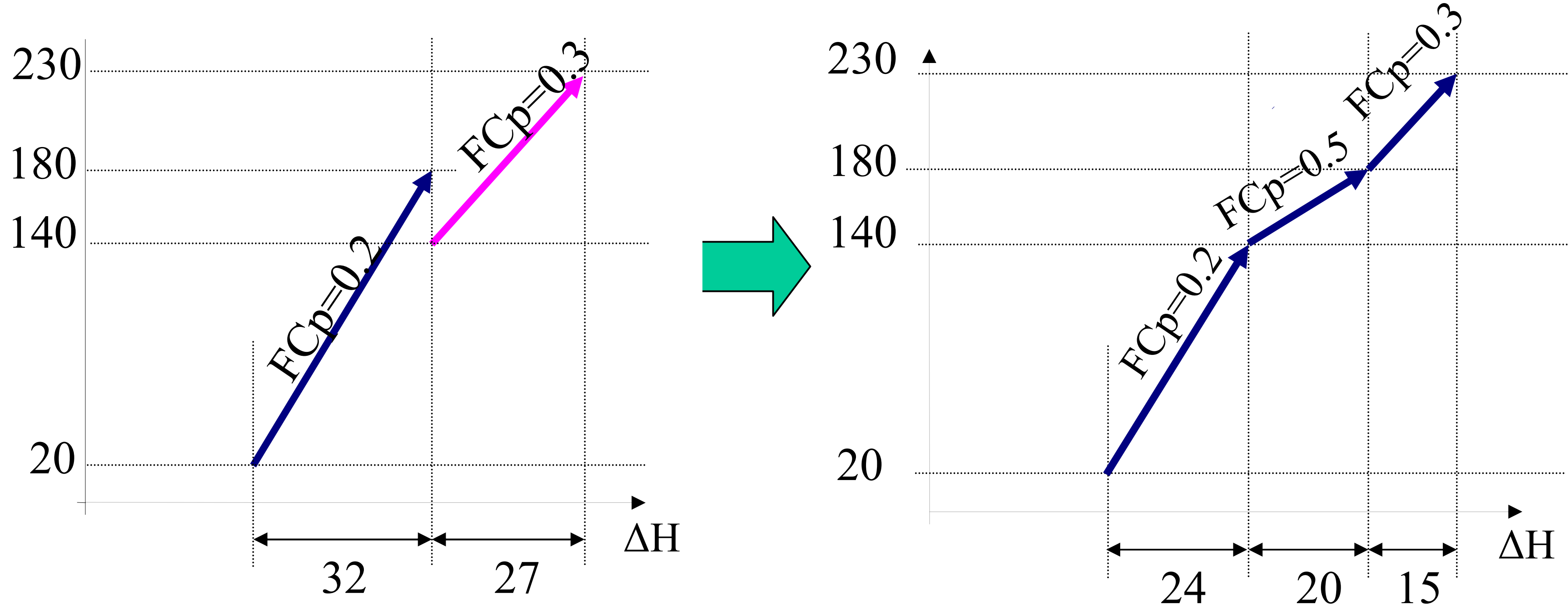
Stream	Type	Supply T (°C)	Target T (°C)	ΔH (MW)	F*Cp (MW °C^{-1})
Reactor 1 feed	Cold	20	180	32.0	0.2
Reactor 1 product	Hot	250	40	-31.5	0.15
Reactor 2 feed	Cold	140	230	27.0	0.3
Reactor 1 product	Hot	200	80	-30.0	0.25

ΔT_{min}=10 °C

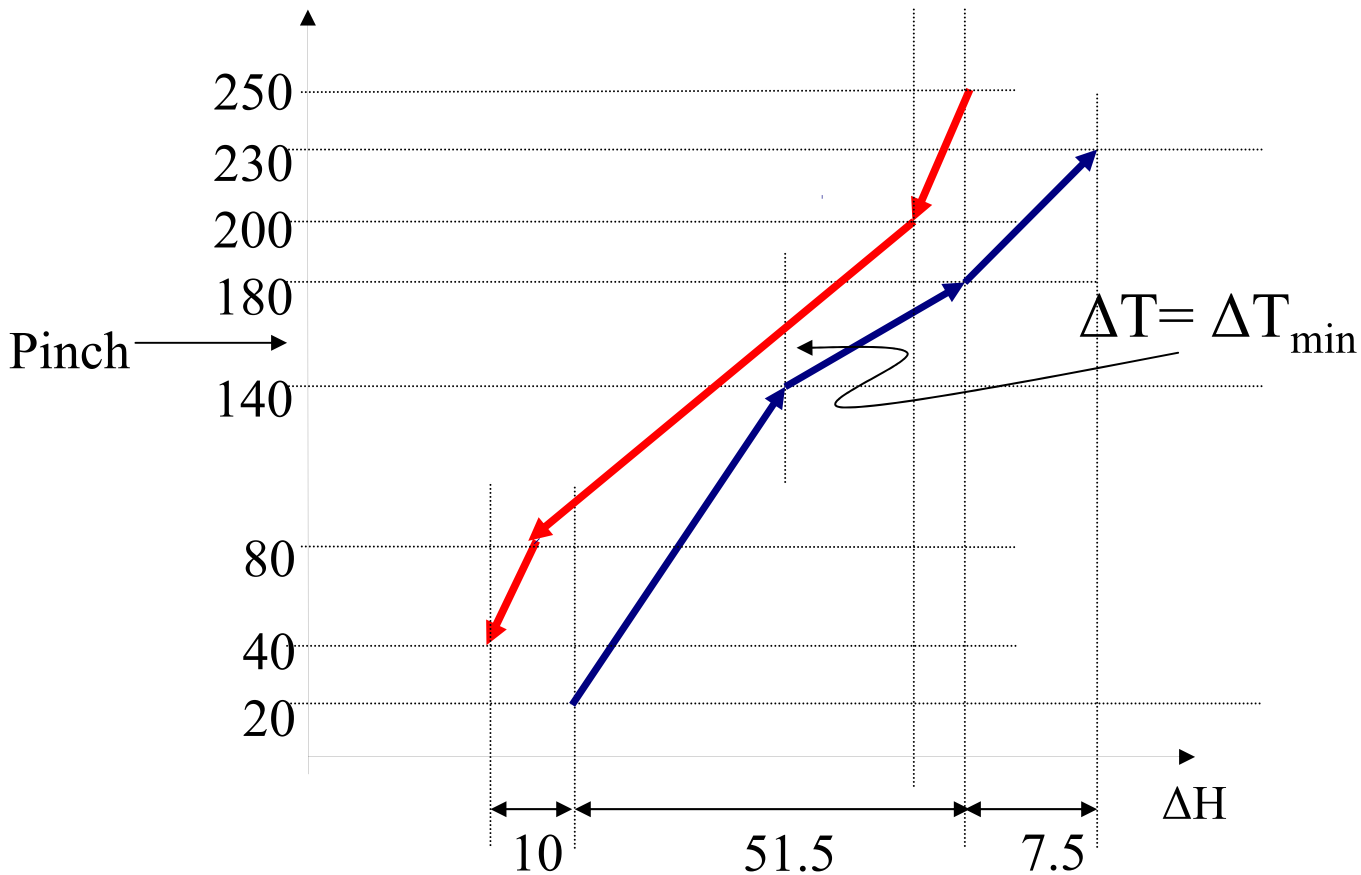
Answer: Hot Streams



Answer: Cold Streams



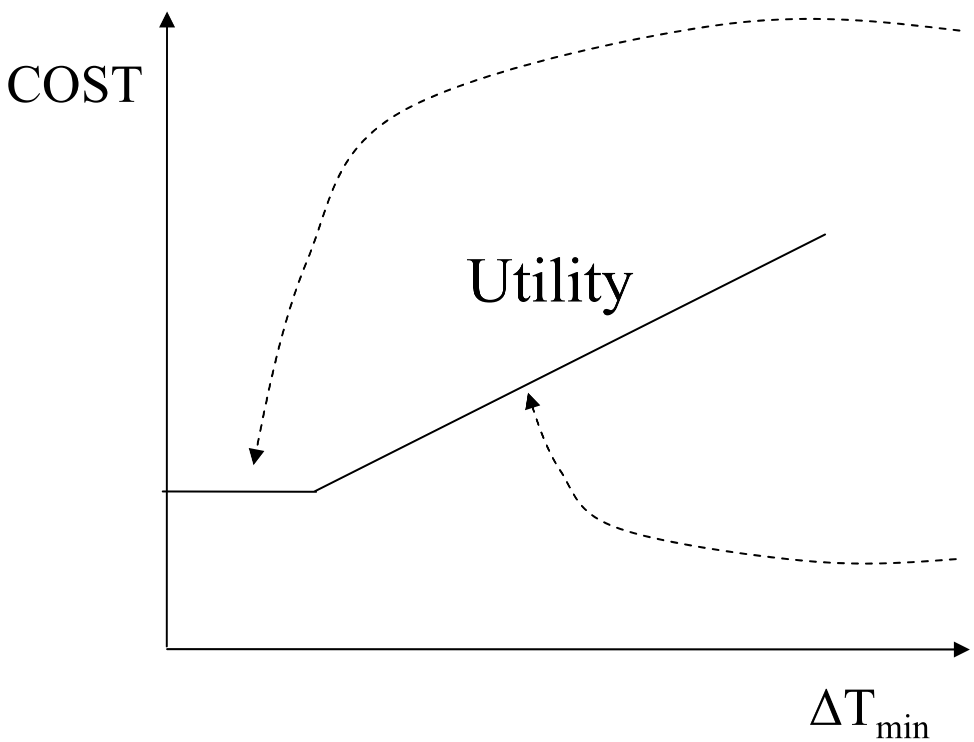
Answer: Both Curves Together.

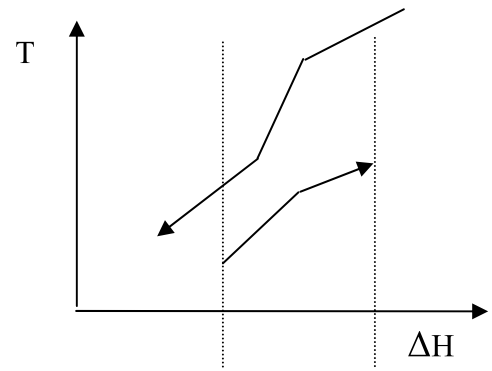


Important observation: The pinch is at the beginning of a cold stream or at the beginning of a hot stream.

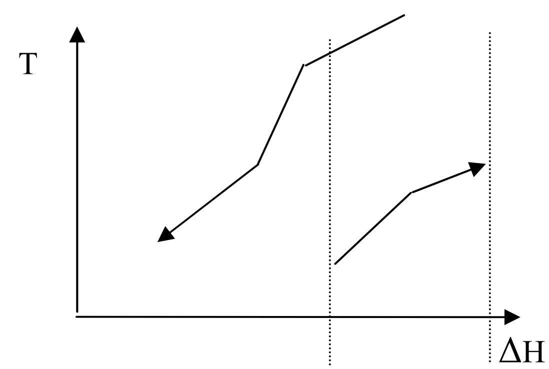
UTILITY COST vs. ΔT_{min}

- There is total overlap for some values of ΔT_{min}





TOTAL OVERLAP



PARTIAL OVERLAP

Note: There is a particular overlap that requires only cooling utility

PROBLEM TABLE

- Composite curves are inconvenient. Thus a method based on tables was developed.

- STEPS:
    1. Divide the temperature range into intervals and shift the cold temperature scale
    2. Make a heat balance in each interval
    3. Cascade the heat surplus/deficit through the intervals.
    4. Add heat so that no deficit is cascaded

PROBLEM TABLE

- We now explain each step in detail.

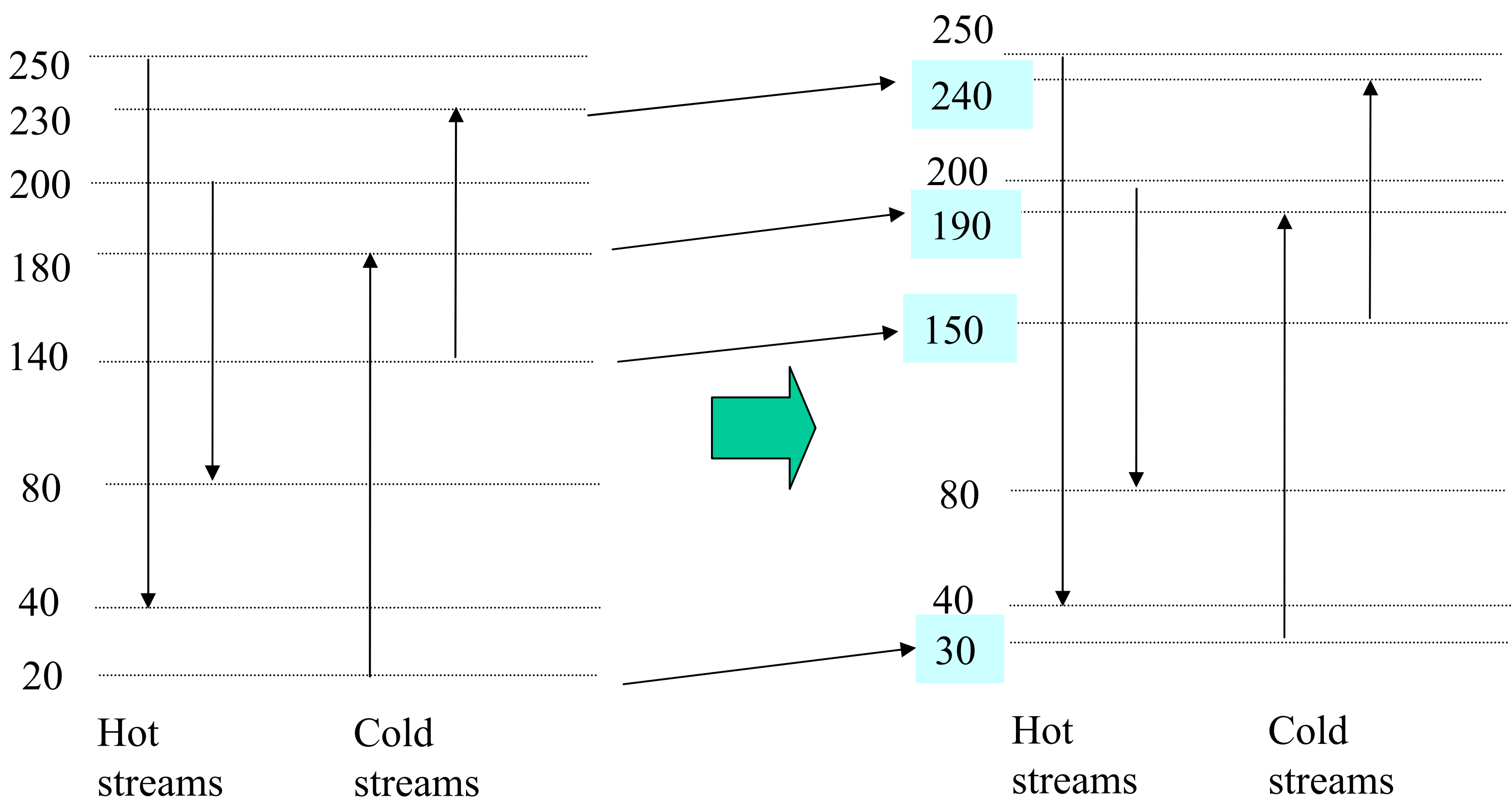
Consider the example 1.1

Stream	Type	Supply T (°C)	Target T (°C)	ΔH (MW)	F*Cp (MW °C^{-1})
Reactor 1 feed	Cold	20	180	32.0	0.2
Reactor 1 product	Hot	250	40	-31.5	0.15
Reactor 2 feed	Cold	140	230	27.0	0.3
Reactor 2 product	Hot	200	80	-30.0	0.25

ΔT_{min}=10 °C

PROBLEM TABLE

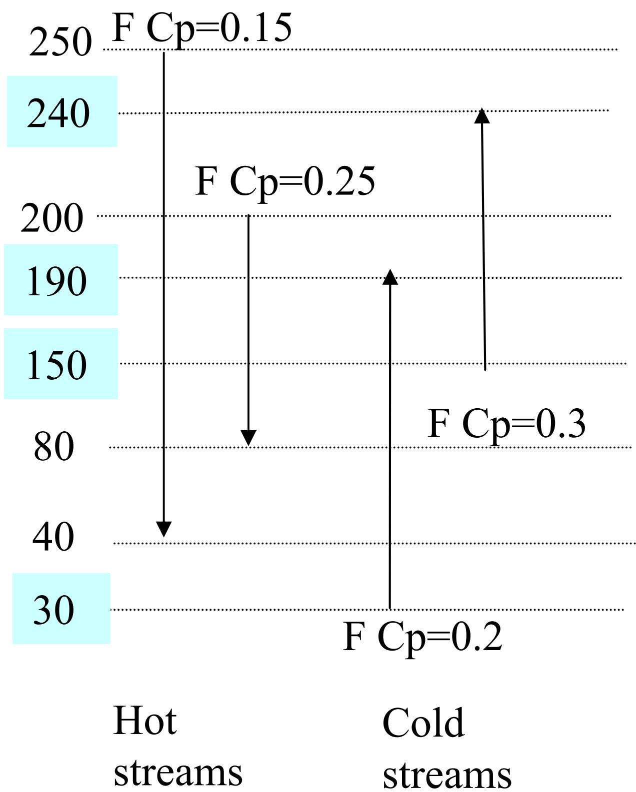
1. Divide the temperature range into intervals and shift the cold temperature scale



Now one can make heat balances in each interval. Heat transfer within each interval is feasible.

PROBLEM TABLE

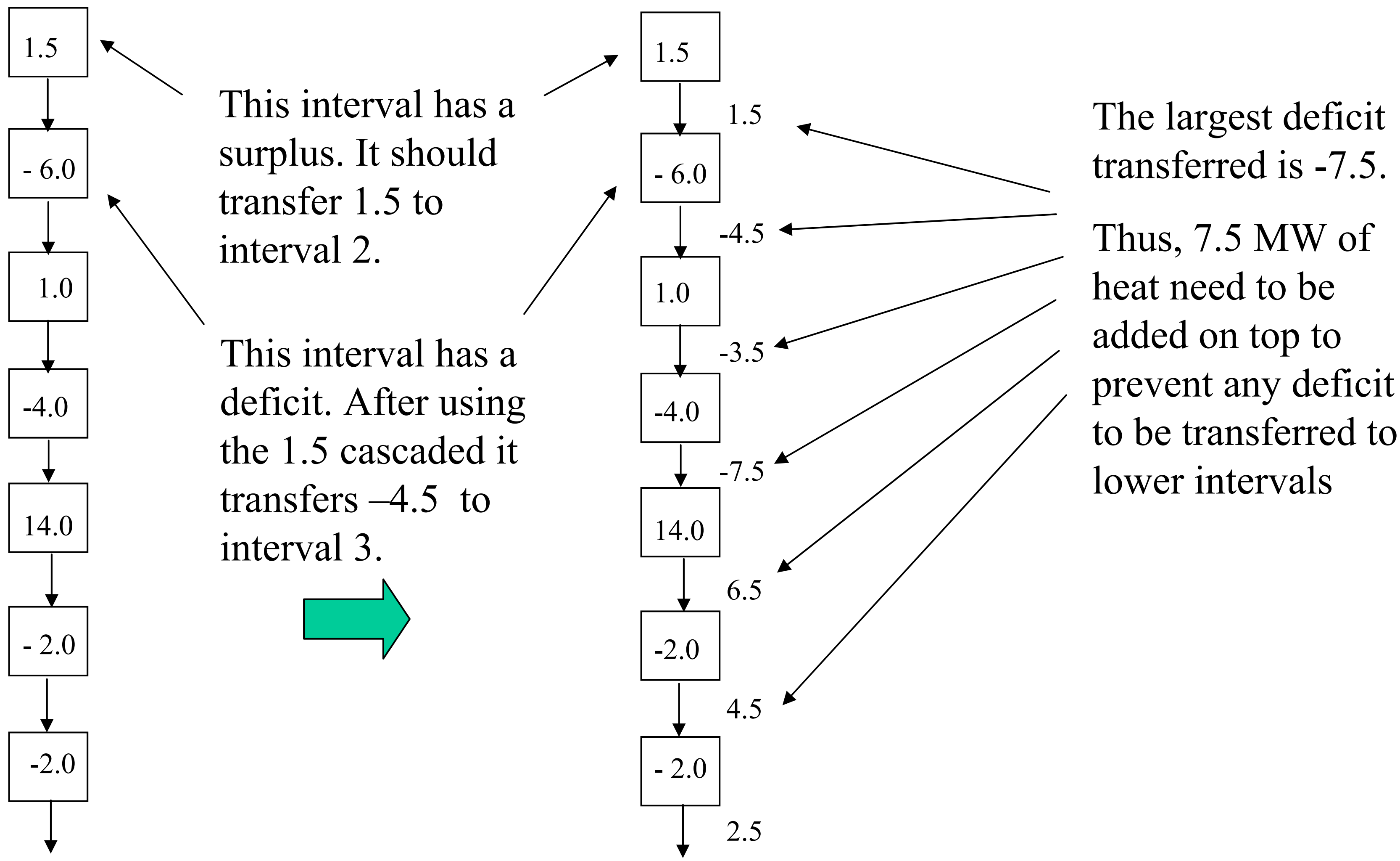
2. Make a heat balance in each interval. (We now turn into a table format distorting the scale)



$\Delta T_{interval}$	$\Delta H_{interval}$	**Surplus/Deficit?**
10	1.5	Surplus
40	- 6.0	Deficit
10	1.0	Surplus
40	-4.0	Deficit
70	14.0	Surplus
40	-2.0	Deficit
10	- 2.0	Deficit

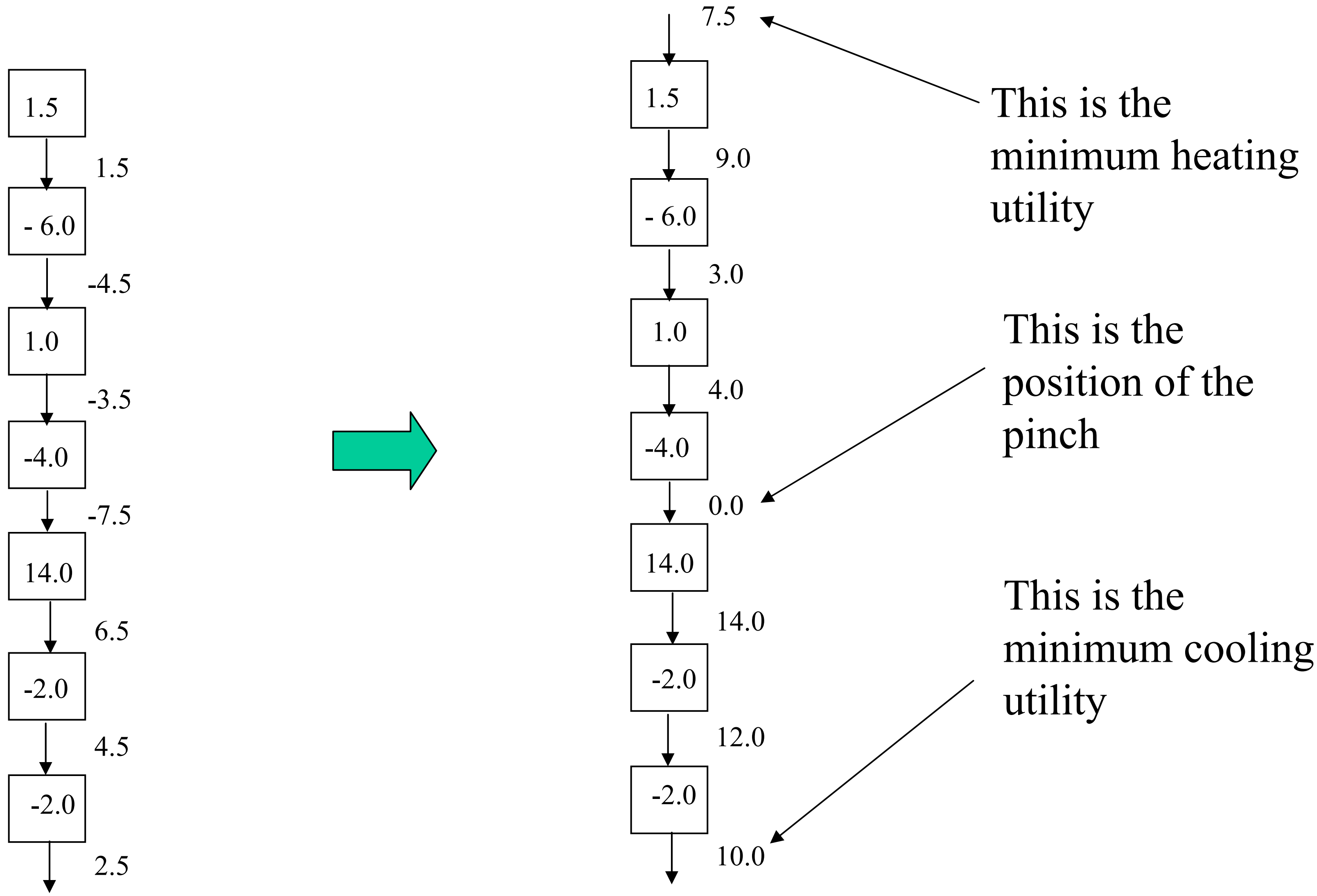
PROBLEM TABLE

3. Cascade the heat surplus through the intervals. That is, we transfer to the intervals below every surplus/deficit.



PROBLEM TABLE

4. Add heat so that no deficit is cascaded.

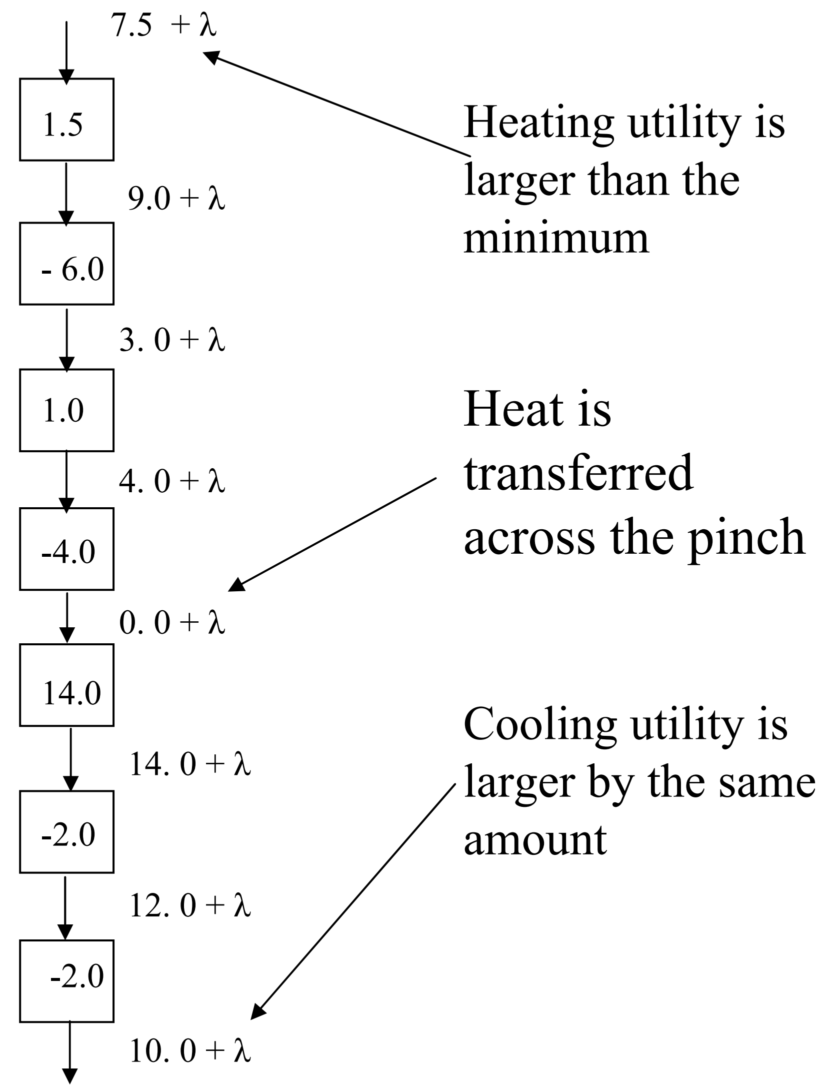


IMPORTANT CONCLUSION

DO NOT TRANSFER HEAT ACROSS THE PINCH

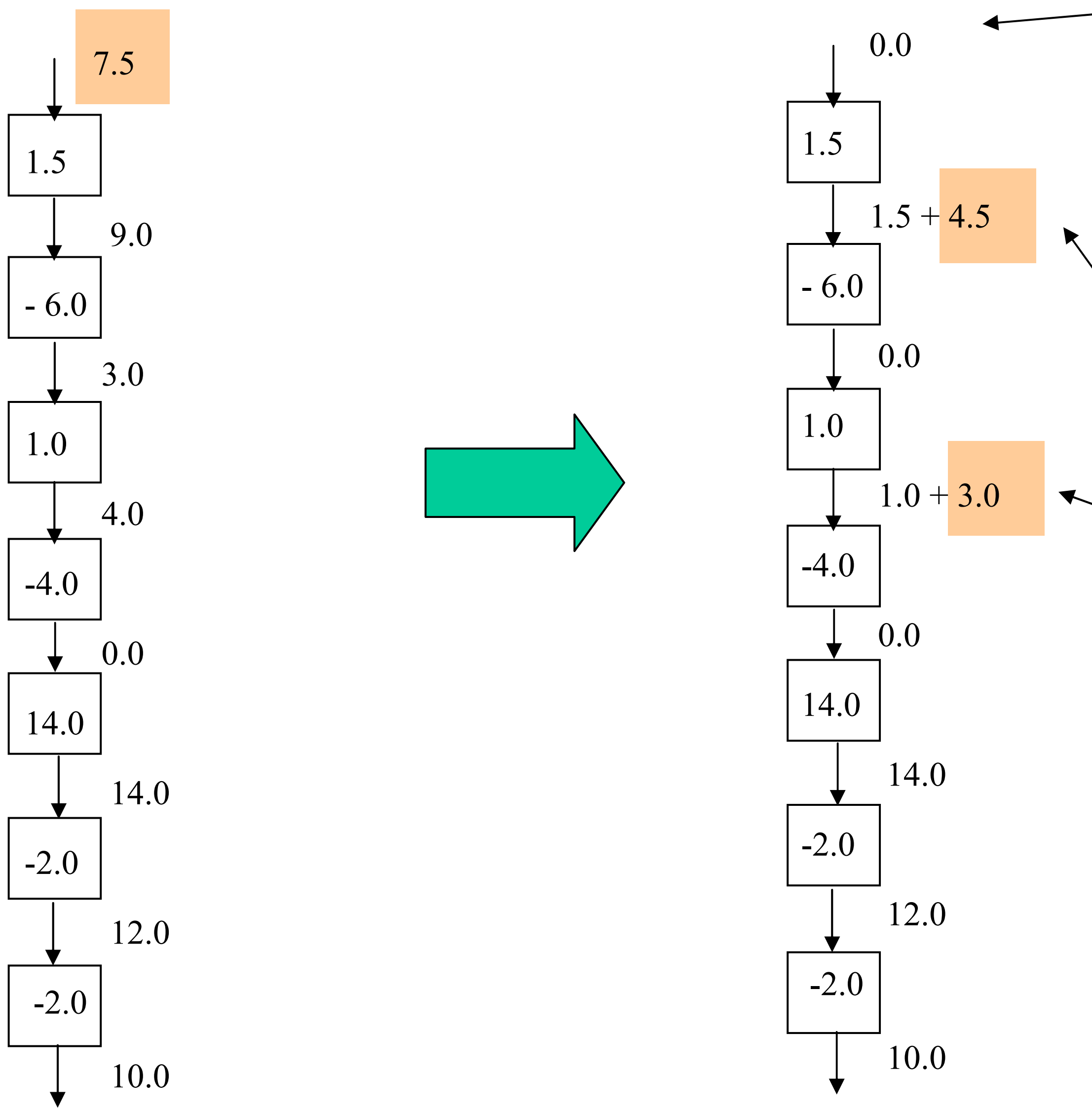
THIS IS A GOLDEN RULE OF PINCH TECHNOLOGY.

- ***WE WILL SEE LATER HOW THIS IS RELAXED FOR DIFFERENT PURPOSES***
- ***WHEN THIS HAPPENS IN BADLY INTEGRATED PLANTS THERE ARE HEAT EXCHANGERS WHERE SUCH TRANSFER ACROSS THE PINCH TAKES PLACE***



PROBLEM TABLE

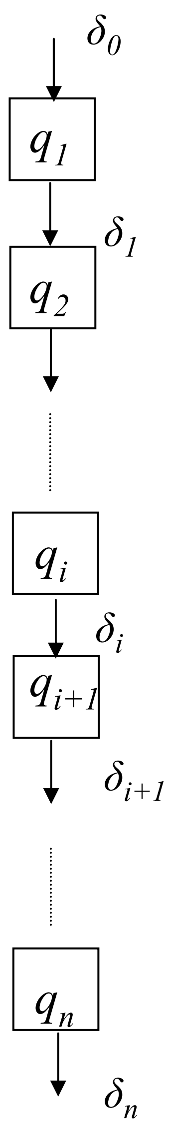
Heating utility of smaller temperature.



Heating utility at the largest temperature is now zero.

These are the minimum values of heating utility needed at each temperature level.

MATHEMATICAL MODEL



Let q_i be the surplus or demand of heat in interval i . It is given by:

$$q_i = \sum_{k \in \Gamma_i^H} F_k^H cp_k^H (T_{i-1} - T_i) - \sum_{s \in \Gamma_i^C} F_s^C cp_s^C (T_{i-1} - T_i)$$

The minimum heating utility is obtained by solving the following linear programming (LP) problem

$$S_{\min} = Min\ \delta_0$$

$$s.t$$

$$\delta_i = \delta_{i-1} + q_i \quad \forall i = 1, \ldots m_I$$

$$\delta_i \geq 0$$

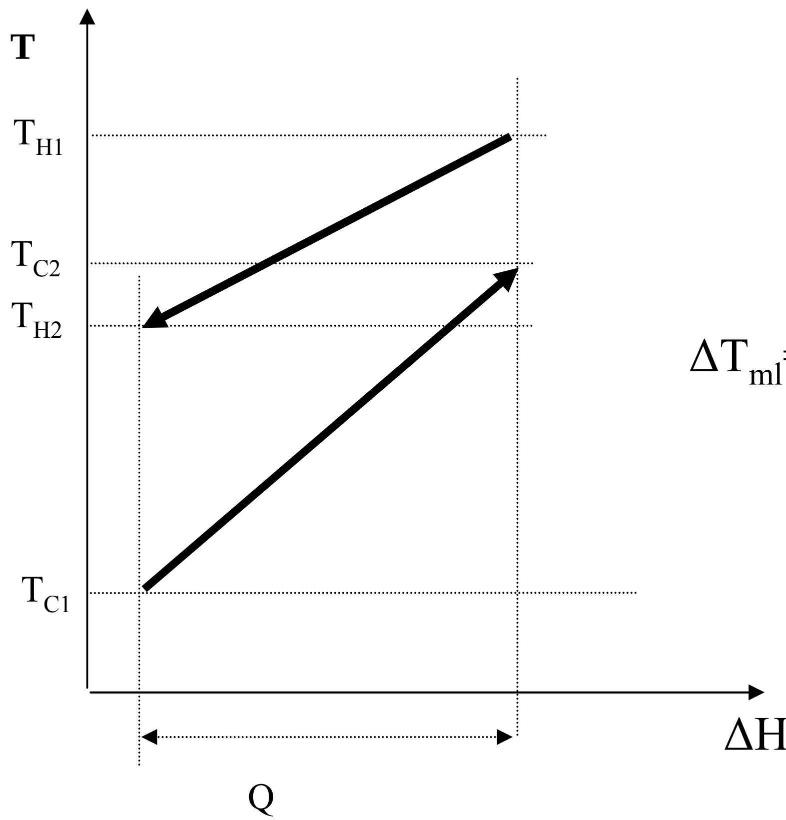
PART 2

TOTAL AREA TARGETING

TOTAL AREA TARGETING

In this part we will explore ways to predict the total area of a network without the need to explore specific designs.

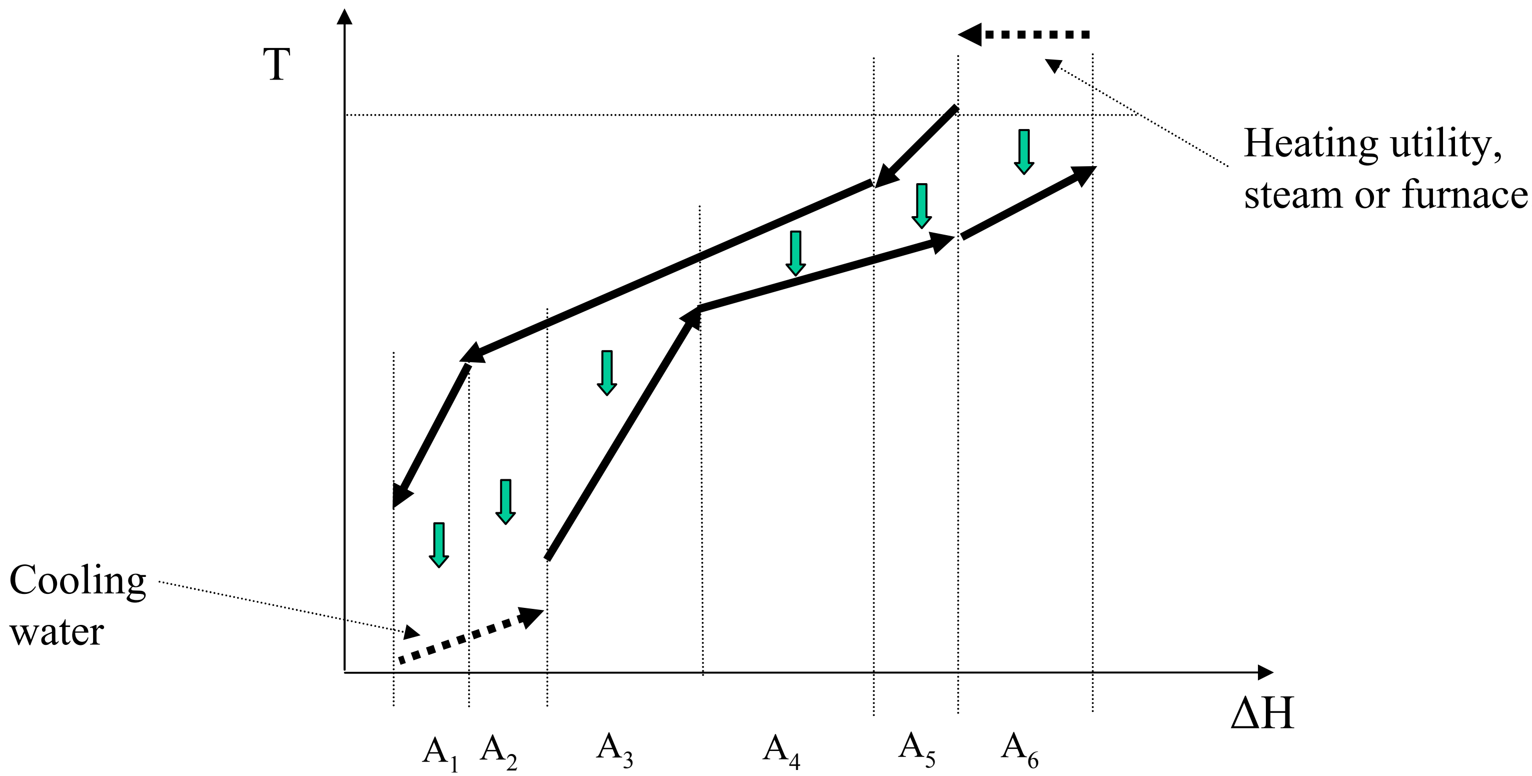
Because $A = Q/(U * \Delta T_{ml})$, one can calculate the area easily in the following situation.



$$\Delta T_{ml} = \frac{(T_{H1}-T_{C2})-(T_{H2}-T_{C1})}{\ln \dfrac{(T_{H1}-T_{C2})}{(T_{H2}-T_{C1})}}$$

TOTAL AREA TARGETING

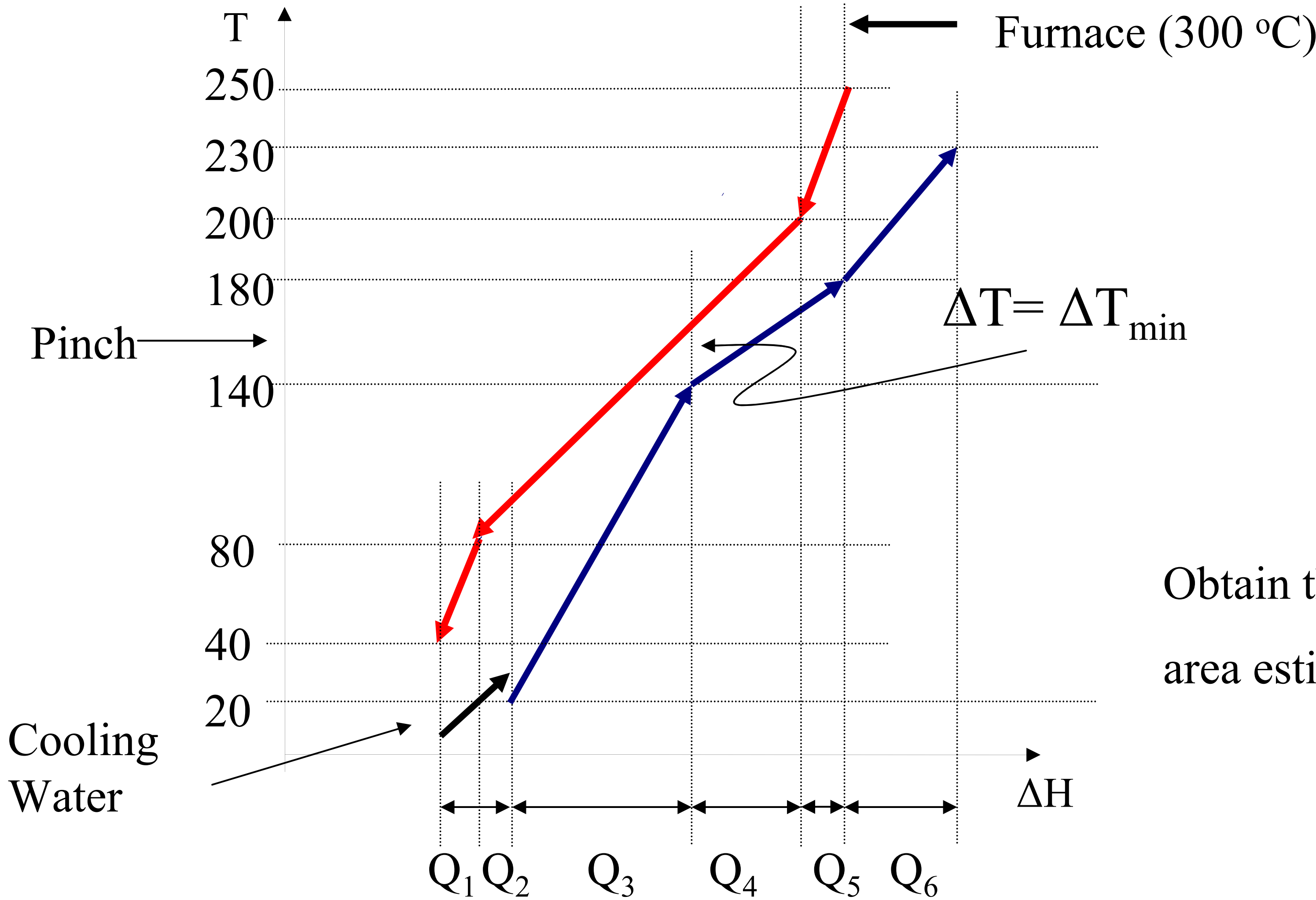
Since area=Q/(U ΔT_{ml}), the composite curve diagram provides one way of estimating the total area involved. Isolate all regions with a pair of straight line sections and calculate the area for each.



The above scheme of heat transfer is called VERTICAL HEAT TRANSFER

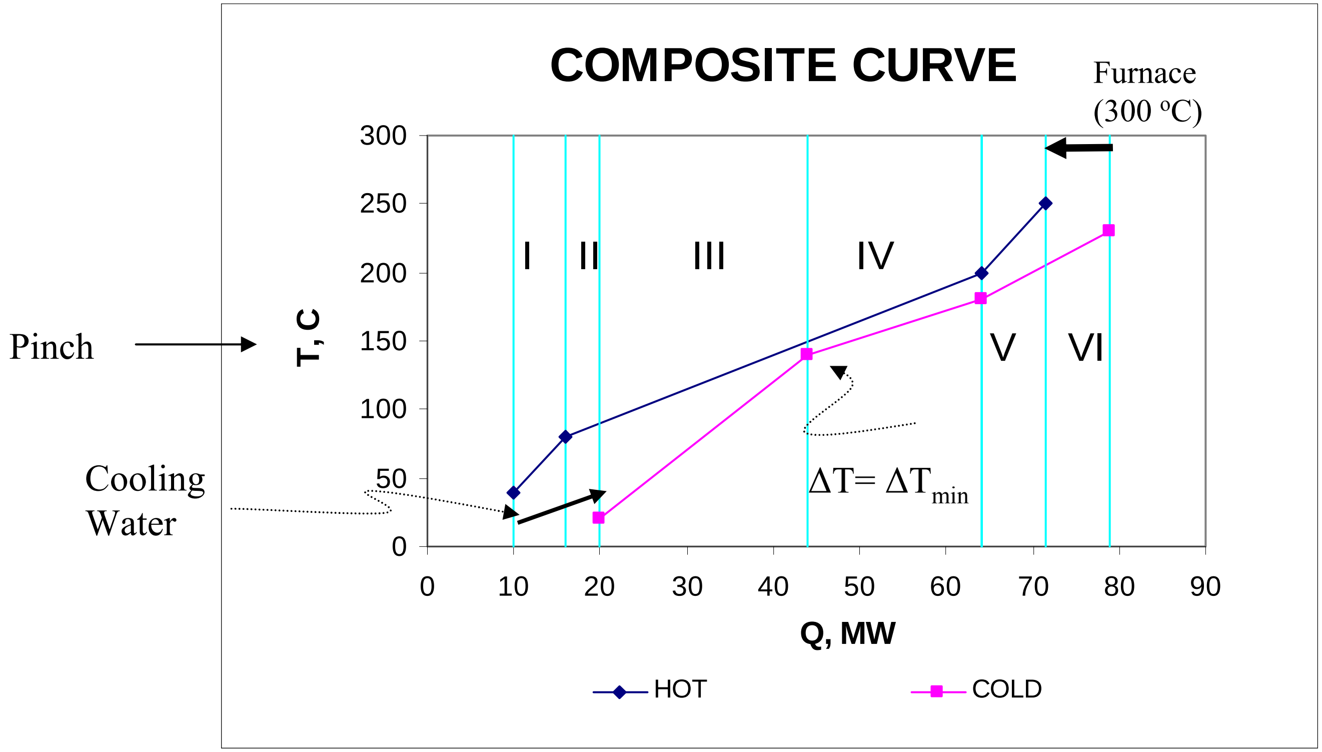
EXERCISE

Calculate the values of Q in each interval and estimate the corresponding area. Use U= 0.001 MW m^{-2} ^{o}C



Obtain the total area estimate

EXERCISE



Units:

Q= MW

T= °C

A= m²

Interval	*Q*	T_{H1}	T_{H2}	T_{C1}	T_{C2}
I	6	80	40	15	20
II	4	90	80	20	30
III	24	150	90	20	140
IV	20	200	150	140	180
V	7.5	250	200	180	205
VI	7.5	300	250	205	230

EXERCISE

Interval	Q	T_{H1}	T_{H2}	T_{C1}	T_{C2}	ΔT_{ml}	A
I	6	80	40	15	20	40.0	150.1
II	4	90	80	20	30	60.0	66.7
III	24	150	90	20	140	30.8	778.4
IV	20	200	150	140	180	14.4	1386.3
V	7.5	250	200	180	205	30.8	243.3
VI	7.5	300	250	205	230	81.9	91.6
					Total Area		2716.3

Units: Q = MW T = °C , A = m^2

U = 0.001 MW m^{-2} °C

TOTAL AREA TARGETING

<u>Drawbacks</u>

- ***Fixed costs associated with the number of units are not considered.***

We will see later how the number of units can be calculated

QUESTIONS FOR DISCUSSION

- ***Is the total area predicted this way, realistic? That is, is it close enough to a value that one would obtain in a final design?***

- ***Is the estimate, realistic or not, conservative? That is, is it larger than the one expected from a final design?***

- ***How complex is a design built using the vertical transfer?***

ANSWERS

- ***Is the total area predicted this way, realistic? That is, is it close enough to a value that one would obtain from a final design?***

YES, Within 10-15%

ANSWERS

- ***Is the estimate, realistic or not, conservative? That is, is it larger than the one expected from a final design?***

The area obtained is actually the minimum area needed to perform the heat transfer.

ANSWERS

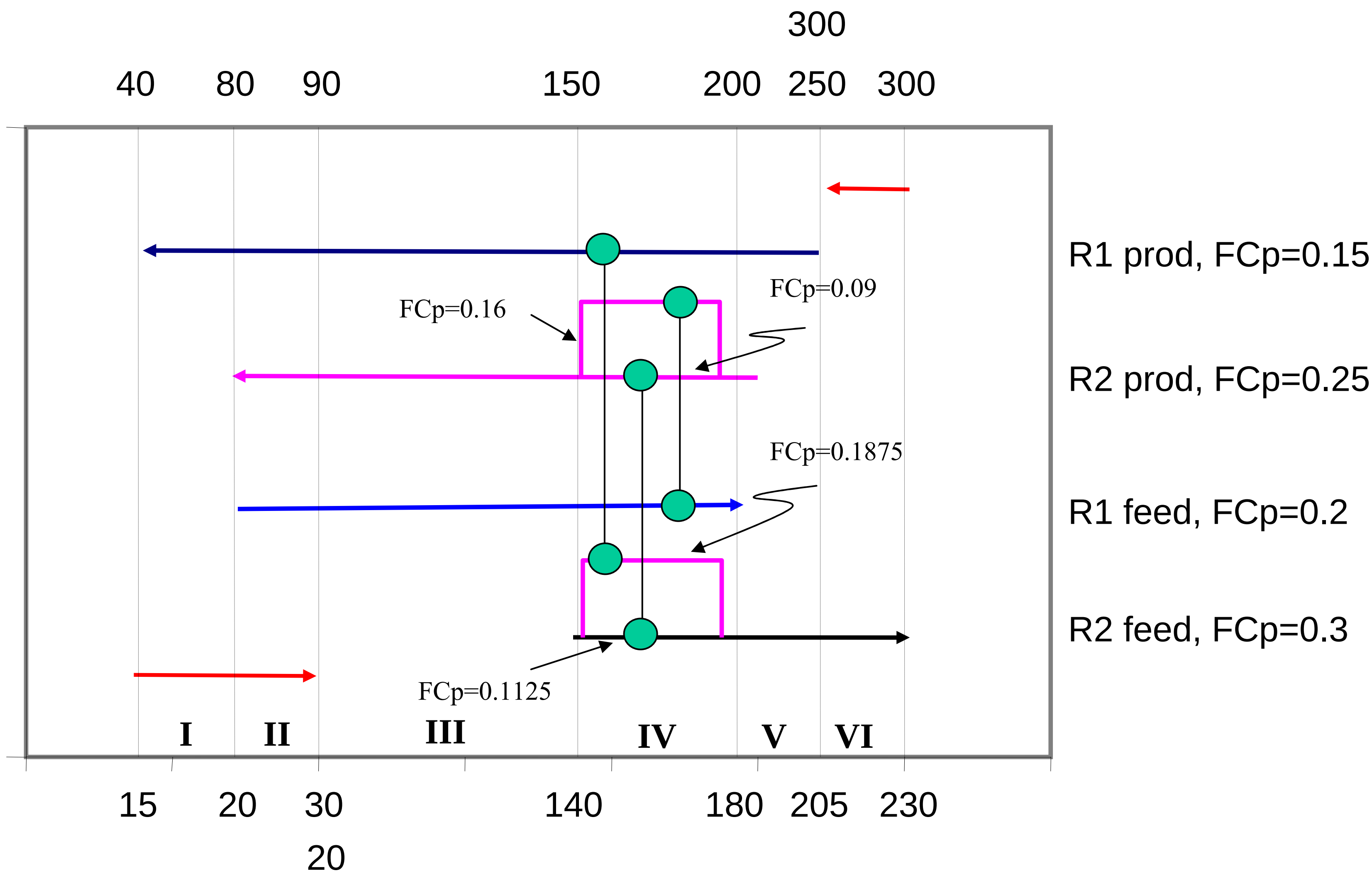
- ***How complex is a design built using the vertical transfer?***

Very Complex. Take for example interval 4. There are four streams in this interval.

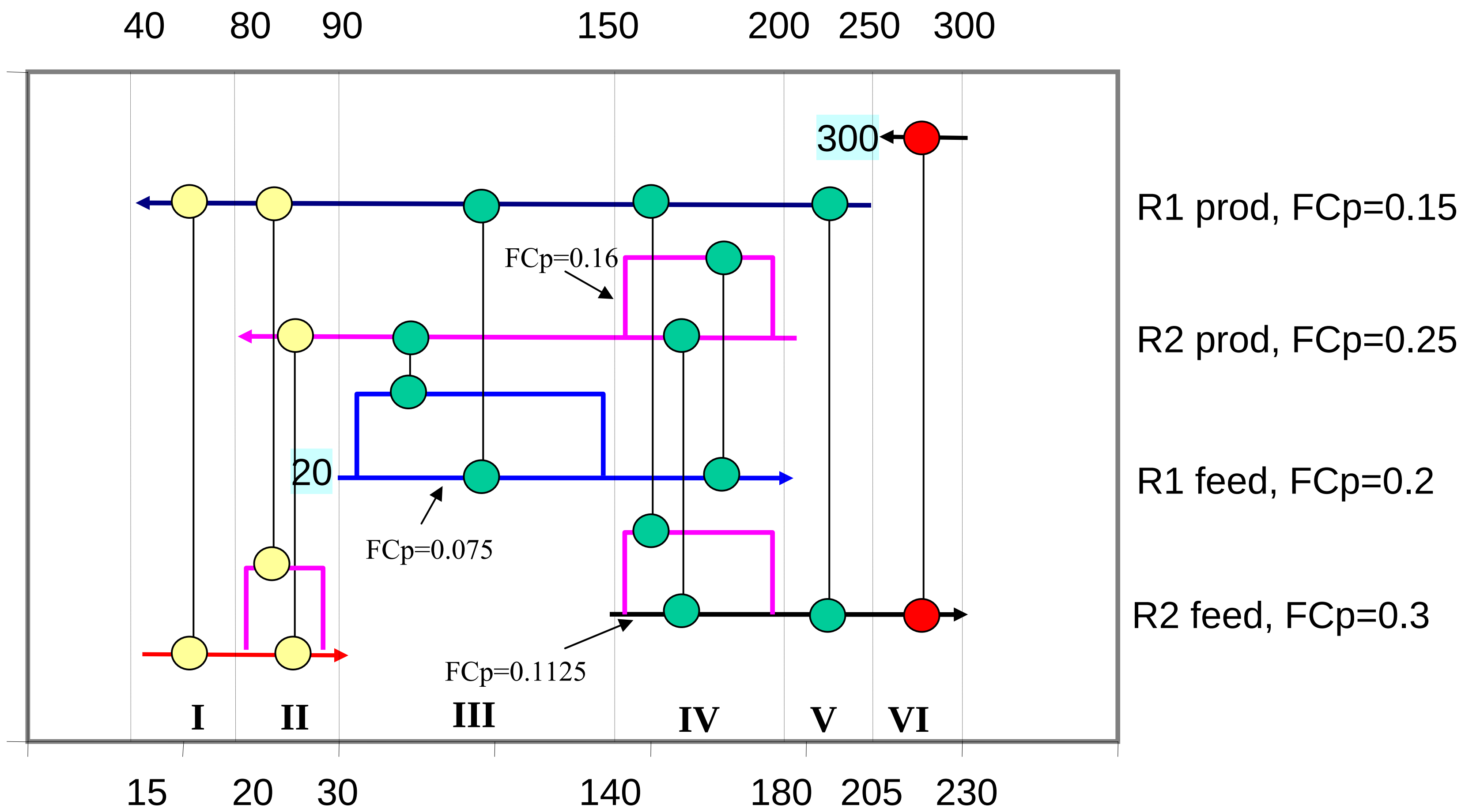
Stream	Type	Supply T (^oC)	Target T (^oC)	ΔH (MW)	F*Cp (MW $^oC^{-1}$)
Reactor 1 feed	Cold	140	180	8.0	0.2
Reactor 1 product	Hot	200	150	-7.5	0.15
Reactor 2 feed	Cold	140	180	12.0	0.3
Reactor 1 product	Hot	200	150	-12.5	0.25

This implies at least three heat exchangers, just in this interval.

HEAT EXCHANGER NETWORK



HEAT EXCHANGER NETWORK



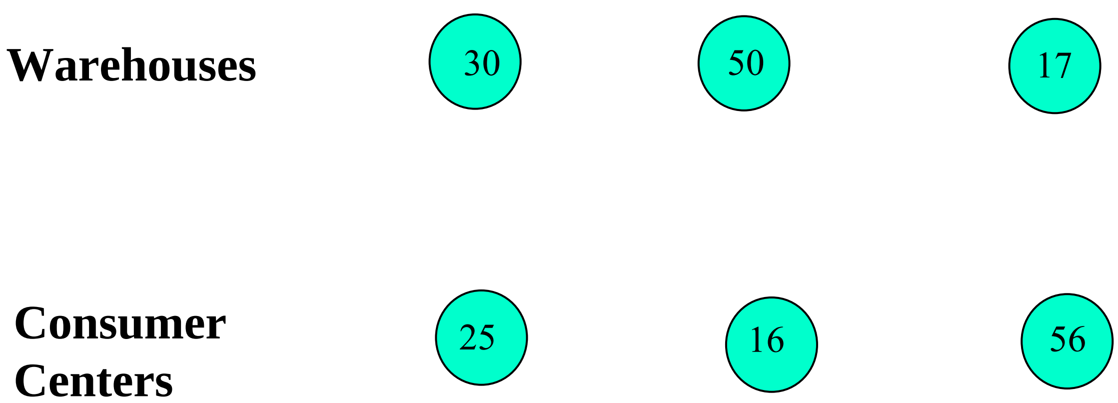
TOTAL= 10 Exchangers

Called "Spaghetti" design

PREDICTING THE NUMBER OF UNITS

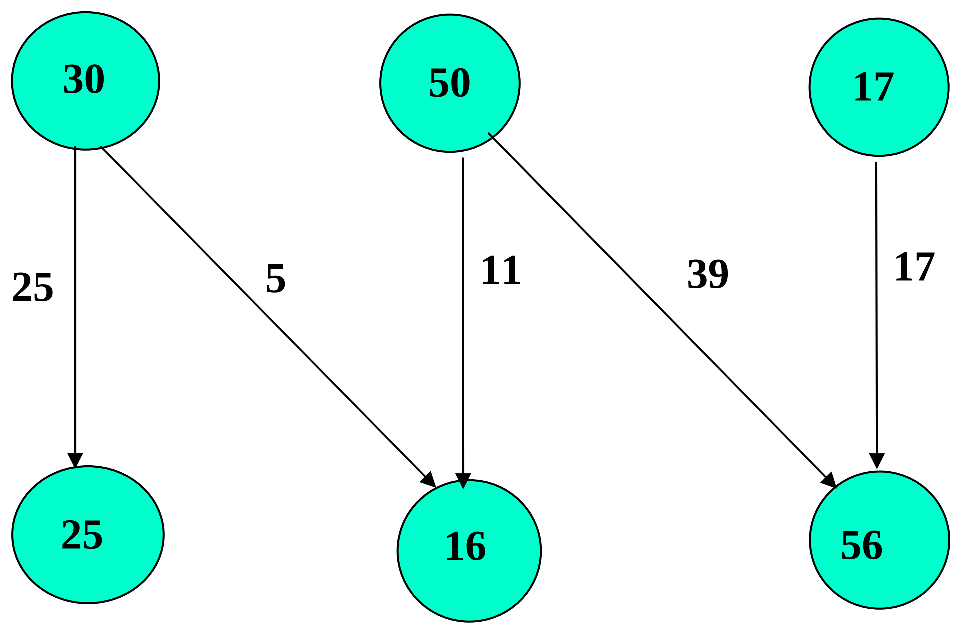
We can anticipate very simply how many exchangers we should have!!!

Consider the following warehouses, each containing some merchandise that needs to be delivered to the row of consumer centers. What is the minimum number of trucks needed?



ANSWER

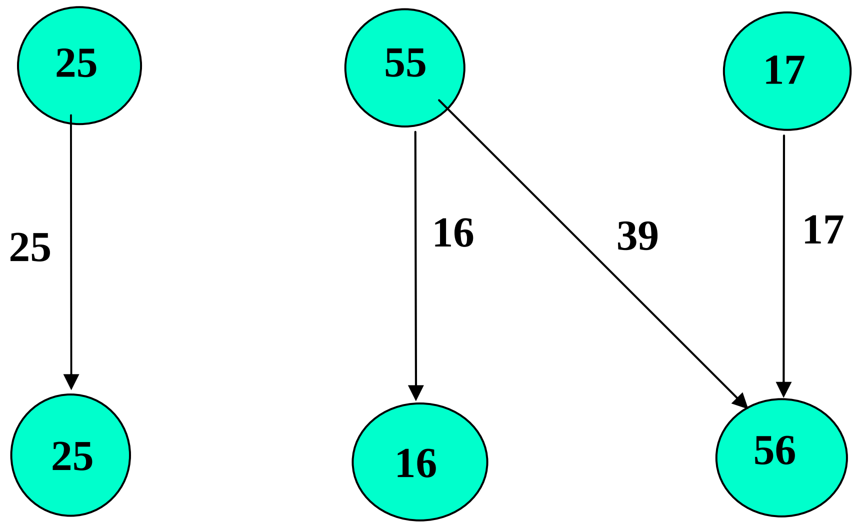
You need five trucks, possibly less in some other cases. Here is how you solve the problem specifically.



The general answer is $N=S-1$. ***When does one need less?***

ANSWER

When there is an exact balance between two streams or a subset of streams.



The general answer is $\boxed{N=S-P}$***. P is the number of independent subsystems. (Two in this case)***

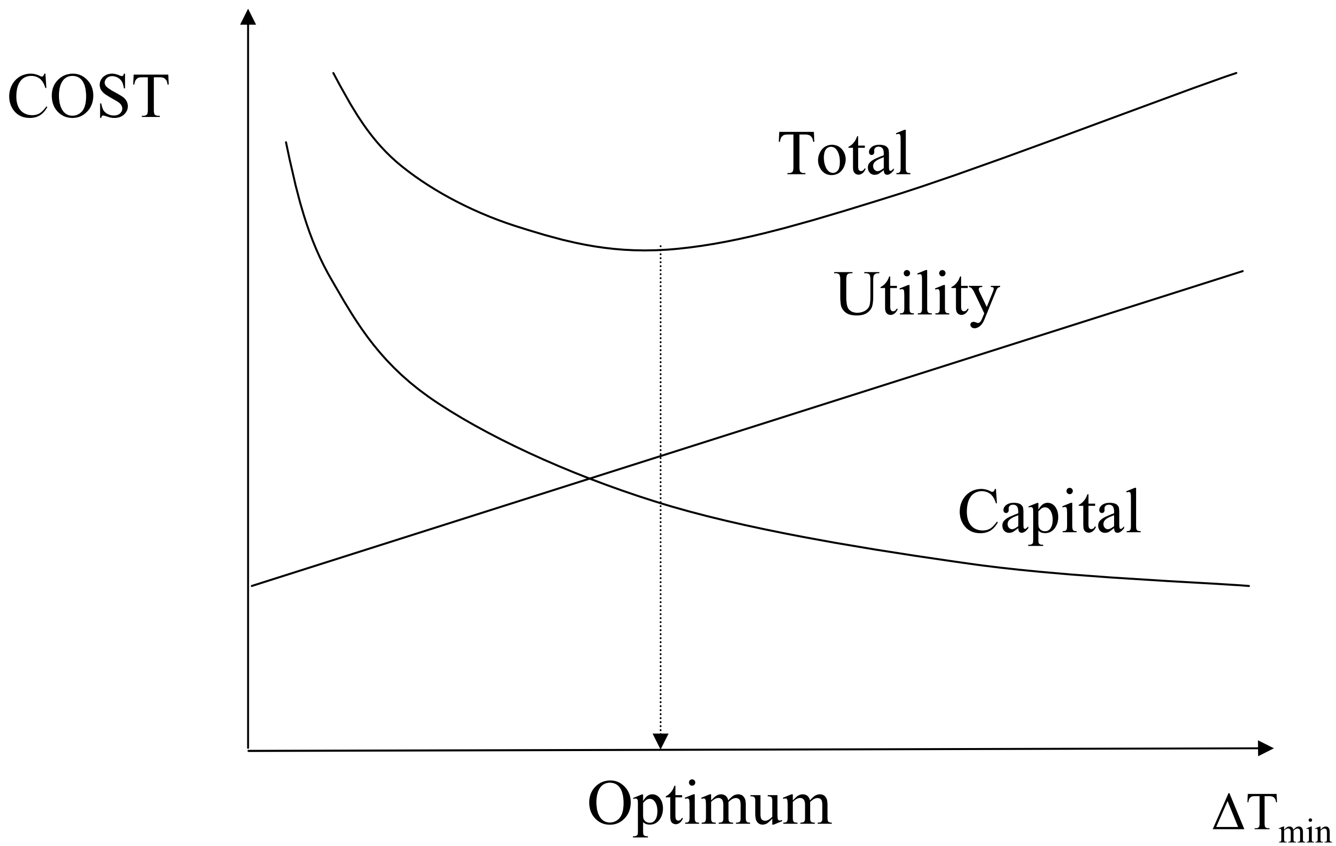
GENERAL FORMULA FOR UNIT TARGETING

$$\mathbf{N_{min}} = \mathbf{(S\text{-}P)}_{\text{above pinch}} + \mathbf{(S\text{-}P)}_{\text{below pinch}}$$

If we do not consider two separate problems, above and below the pinch we can get misleading results.

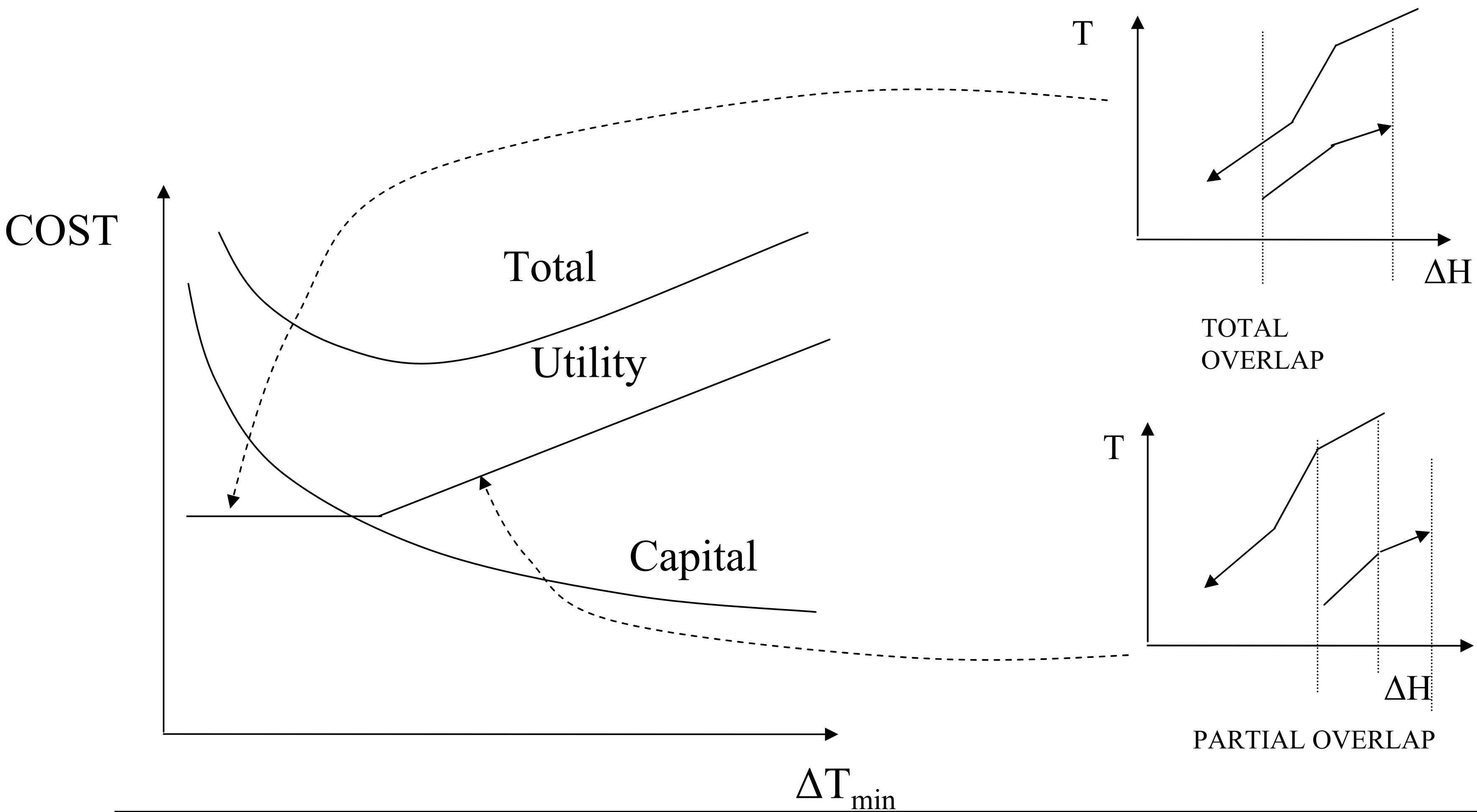
SUPERTARGETING

- Economy of the system is dependent on ΔT_{min}



SPECIAL CASES

- There is total overlap for some values of ΔT_{min}



Note: There is a particular overlap that requires only cooling utility

PART 3

DESIGN OF MAXIMUM ENERGY RECOVERY NETWORKS

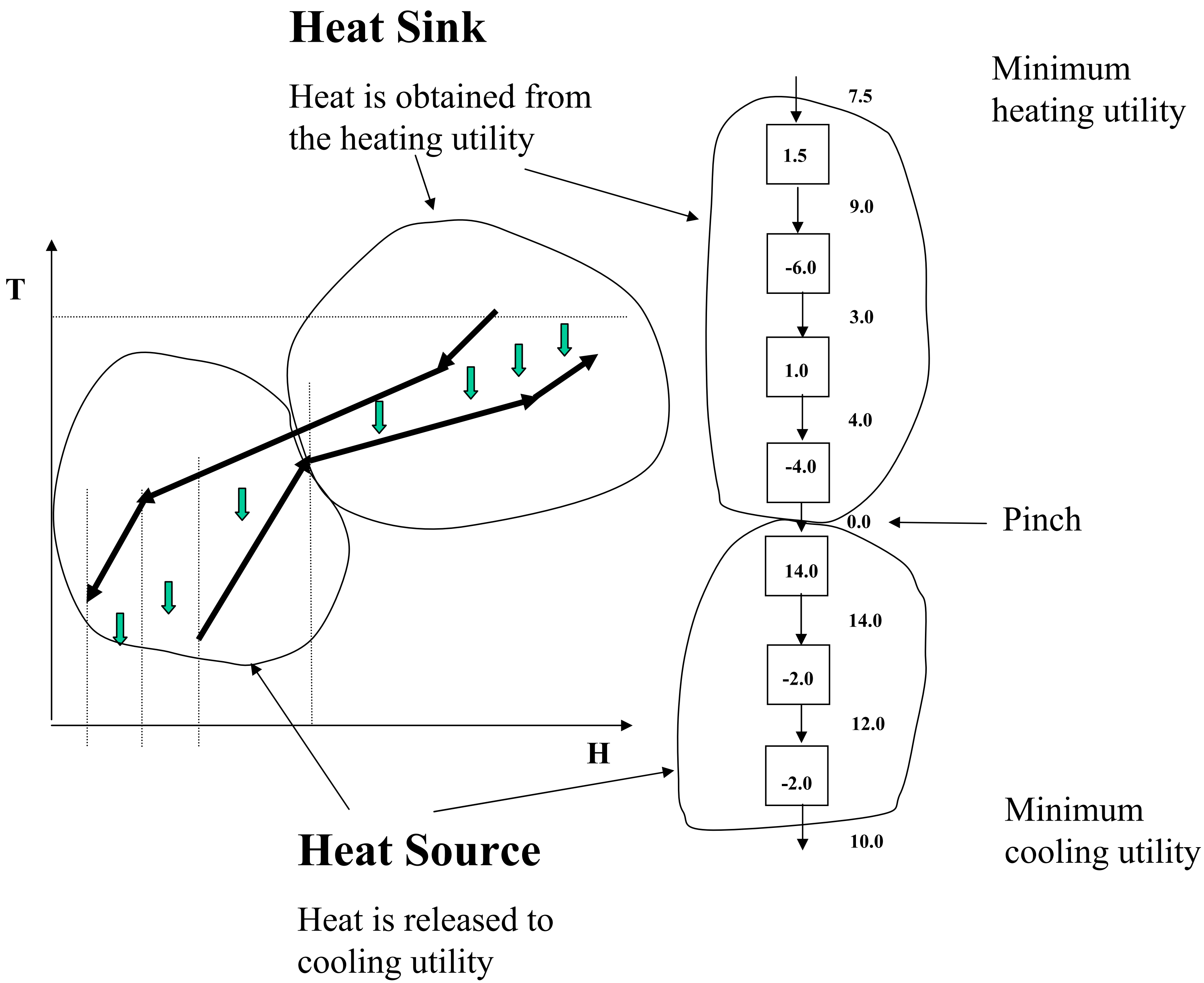
MER NETWORKS

- Networks featuring minimum utility usage are called MAXIMUM ENERGY RECOVERY (MER) Networks.

PINCH DESIGN METHOD

RECALL THAT

- No heat is transferred through the pinch.
- This makes the region above the pinch a HEAT SINK region and the region below the pinch a HEAT SOURCE region.


Heat Sink
Heat is obtained from the heating utility
T
H
Heat Source
Heat is released to cooling utility
7.5
1.5
9.0
-6.0
3.0
1.0
4.0
-4.0
0.0
14.0
14.0
-2.0
12.0
-2.0
10.0
Minimum heating utility
Pinch
Minimum cooling utility

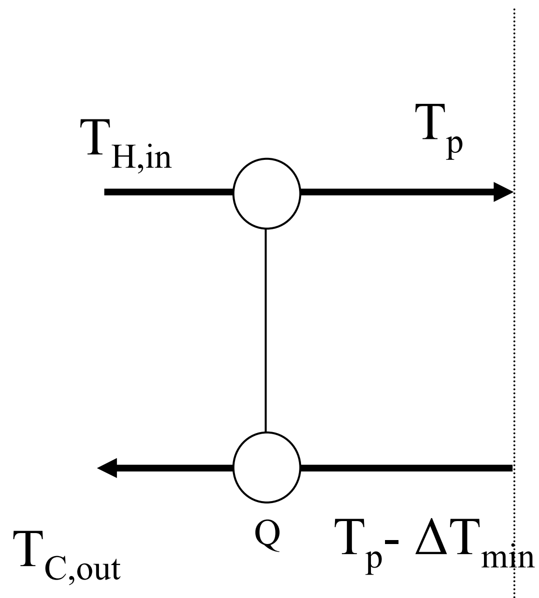
CONCLUSION

- One can analyze the two systems separately, that is,

- Heat exchangers will not contain heat transfer across the pinch.

PINCH MATCHES

- Consider two streams above the pinch



$T_{C,out} = T_p - \Delta T_{min} + Q/FCp_C$

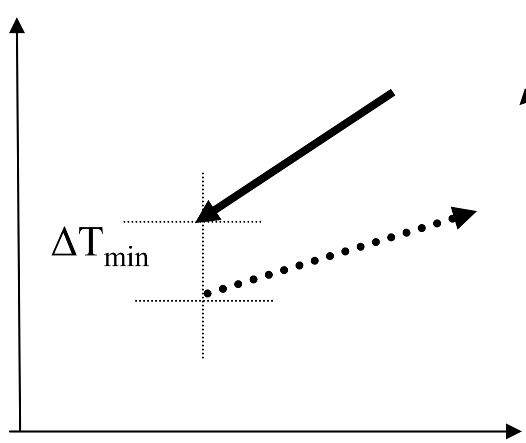
$T_{H,in} = T_p + Q/FCp_H$

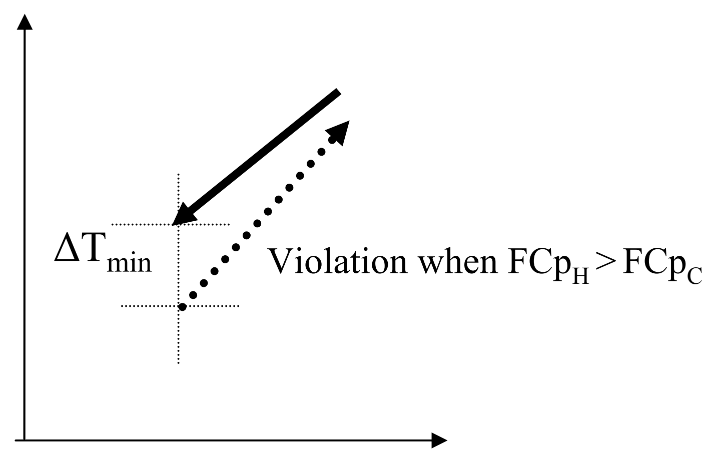
But $T_{H,in} > T_{C,out} + \Delta T_{min}$.

Thus replacing one obtains $Q/FCp_H > Q/FCp_C$

$FCp_H < FCp_C$

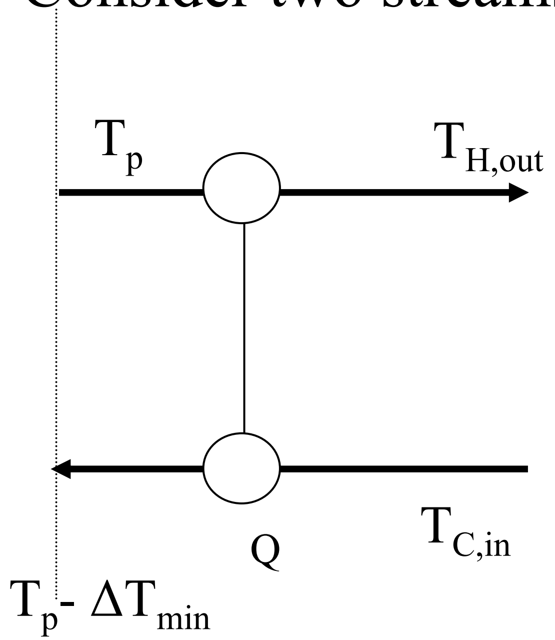
Golden rule for pinch matches above the pinch.





PINCH MATCHES

- Consider two streams below the pinch



$T_{C,in}$= T_p- ΔT_{min} - Q/FCp_C

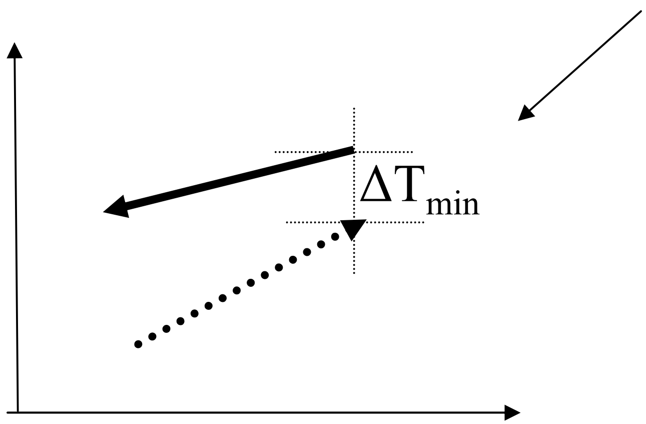
$T_{H,out}$= T_p-Q/FCp_H

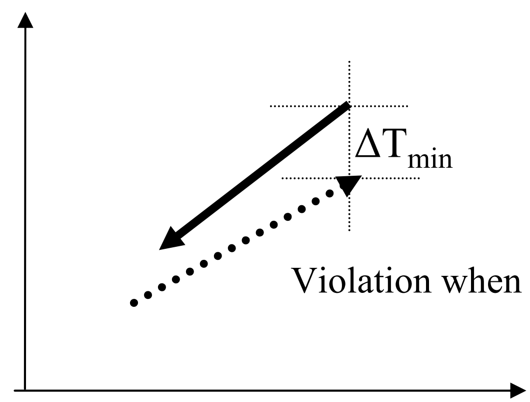
But $T_{H,out}$> $T_{C,in}$ + $\Delta T_{min.}$

Thus replacing one obtains

$$FCp_C < FCp_H$$

Golden rule for pinch matches below the pinch.





CONCLUSION

- Since matches at the pinch need to satisfy these rules, one should start locating these matches first. Thus, our first design rule:

START BY MAKING PINCH MATCHES

QUESTION

- Once a match has been selected how much heat should be exchanged?

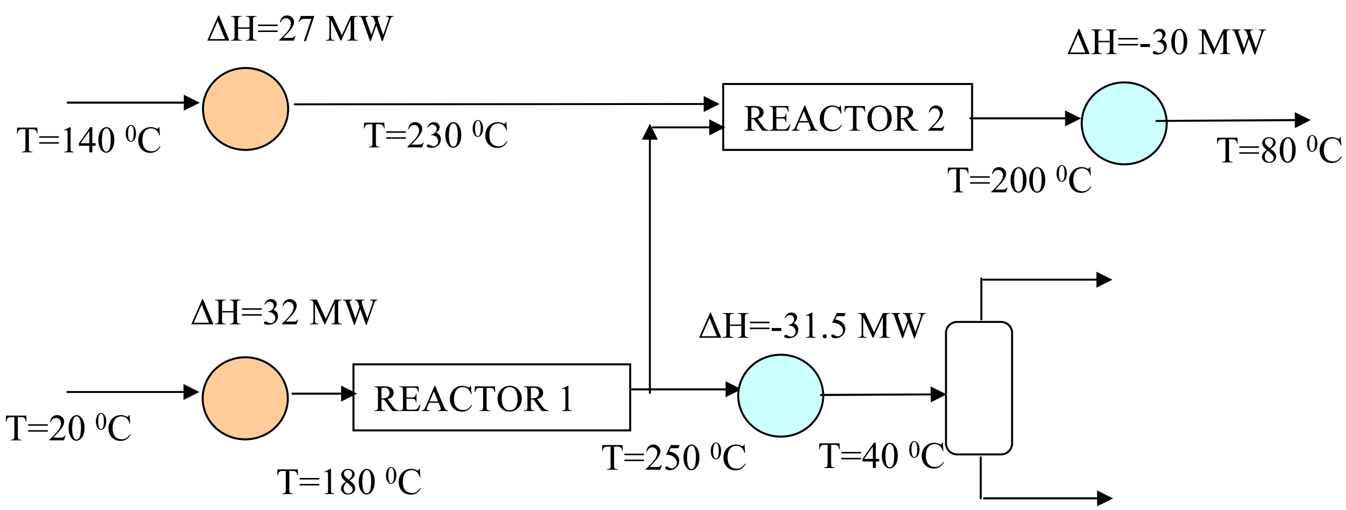
ANSWER

- As much as possible!
- This means that one of the streams has its duty satisfied!!

THIS IS CALLLED THE

TICK-OFF RULE

HANDS ON EXERCISE

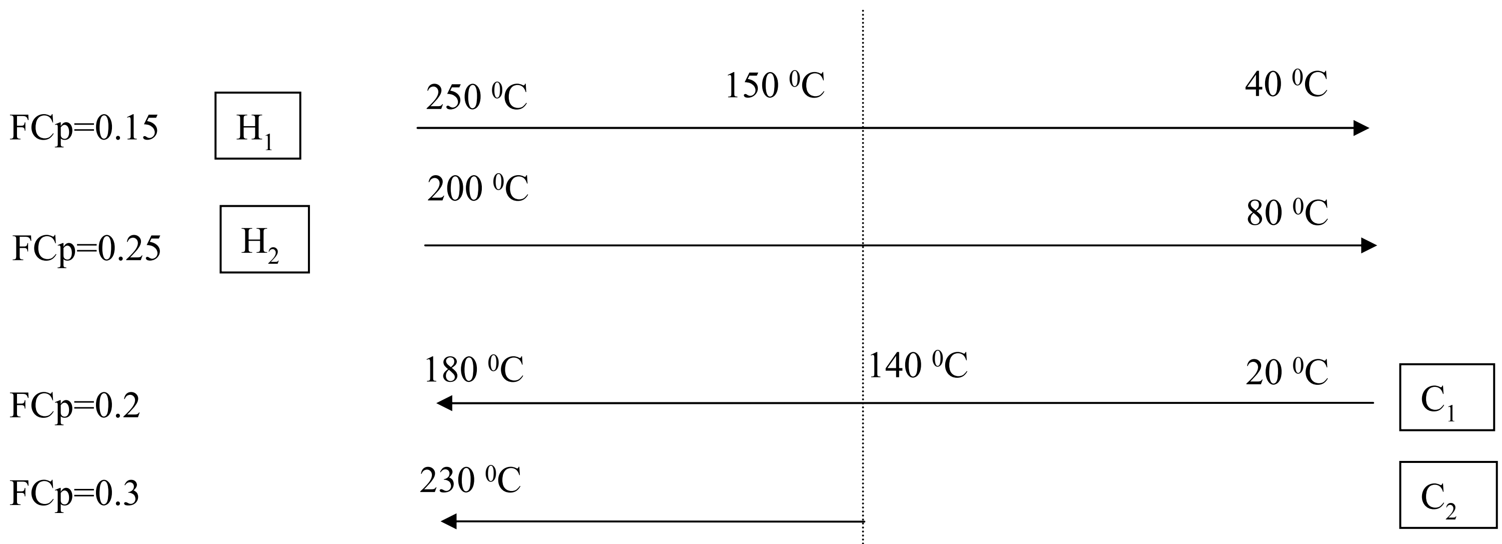


Stream	Type	Supply T (°C)	Target T (°C)	ΔH (MW)	F*Cp (MW °C^{-1})
Reactor 1 feed	Cold	20	180	32.0	0.2
Reactor 1 product	Hot	250	40	-31.5	0.15
Reactor 2 feed	Cold	140	230	27.0	0.3
Reactor 1 product	Hot	200	80	-30.0	0.25

ΔT_{min}=10 °C

PINCH=150 °C

HANDS ON EXERCISE

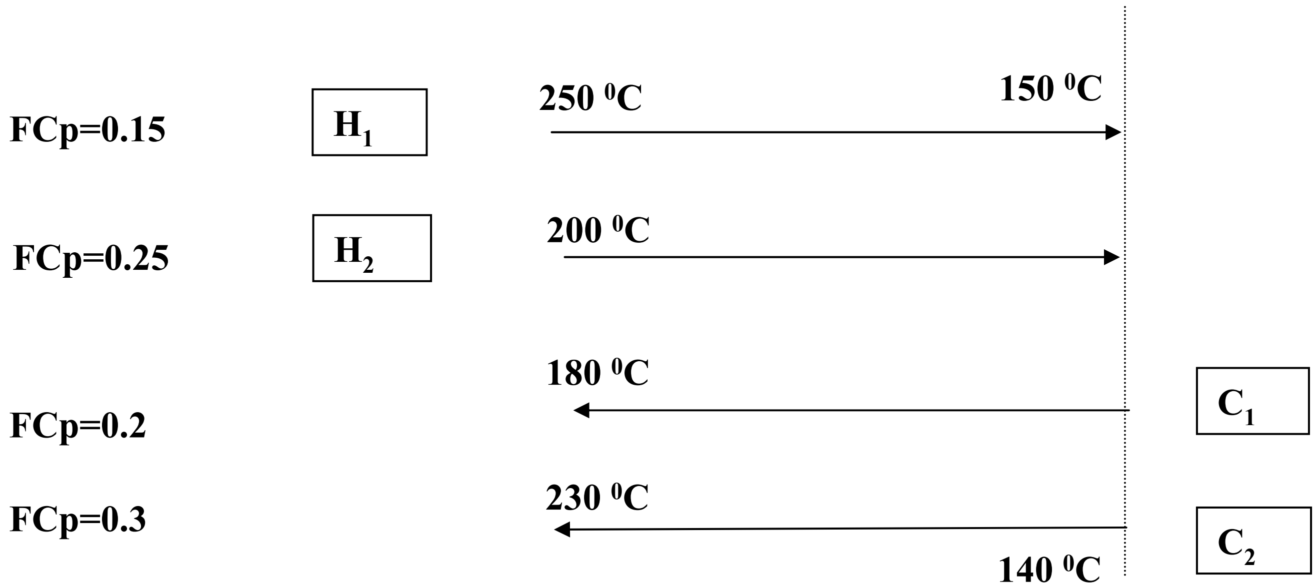


Stream	Type	Supply T (°C)	Target T (°C)	ΔH (MW)	F*Cp (MW °C^{-1})
Reactor 1 feed	Cold	20	180	32.0	0.2
Reactor 1 product	Hot	250	40	-31.5	0.15
Reactor 2 feed	Cold	140	230	27.0	0.3
Reactor 1 product	Hot	200	80	-30.0	0.25

ΔT_{min}=10 °C

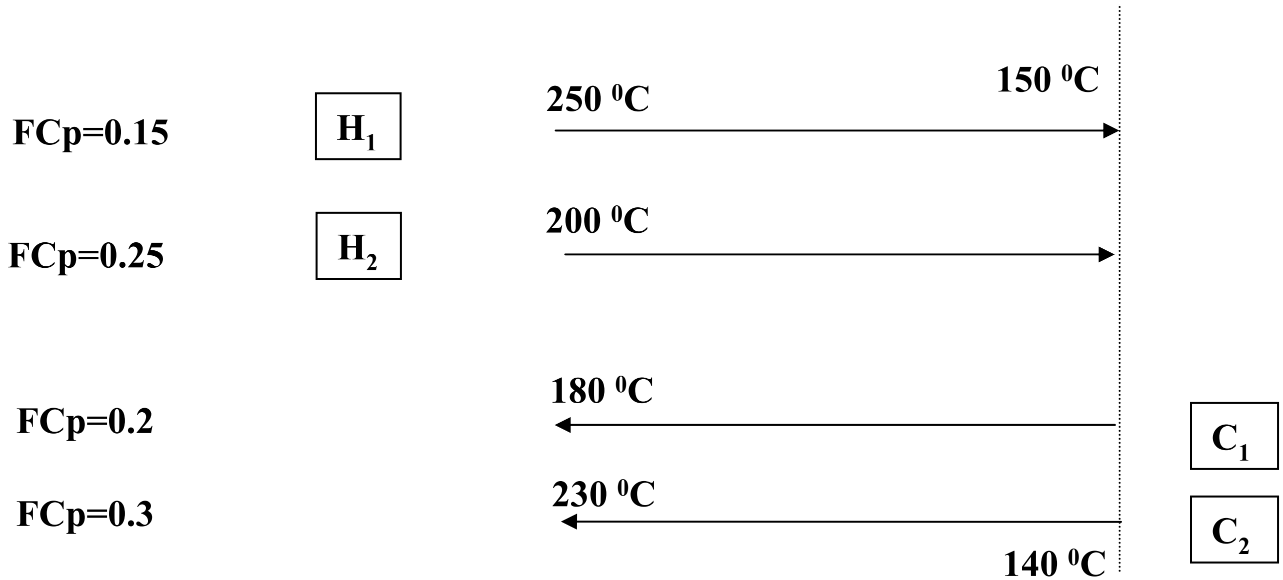
PINCH=150 °C

ABOVE THE PINCH



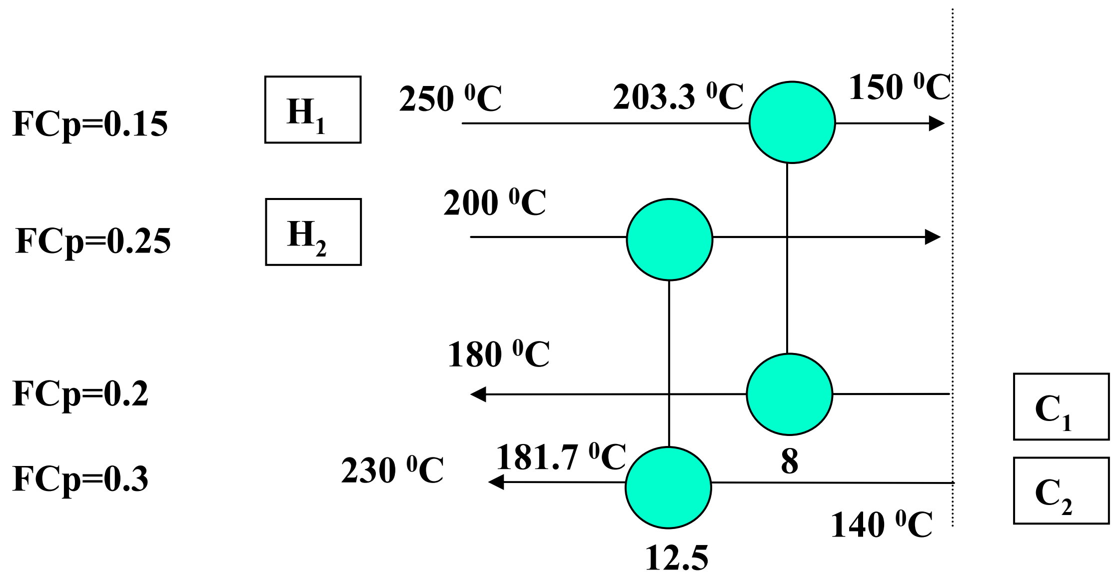
- Which matches are possible?

ANSWER (above the pinch)



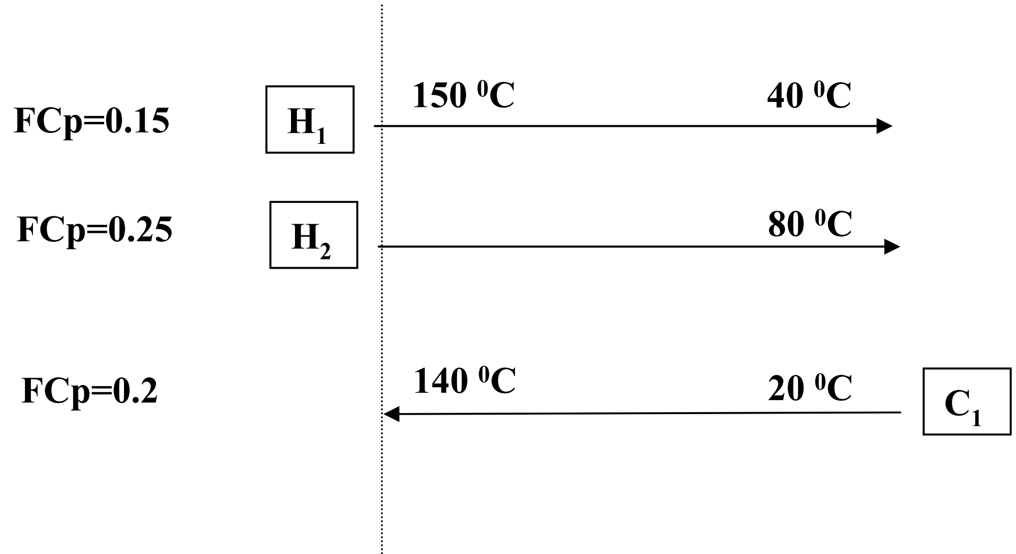
- The rule is that $FCp_H < FCp_C$. We therefore can only make the match H1-C1 and H2-C2.

ANSWER (above the pinch)



- The tick-off rule says that a maximum of 8 MW is exchanged in the match H1-C1 and as a result stream C1 reaches its target temperature.
- Similarly 12.5 MW are exchanged in the other match and the stream H2 reaches the pinch temperature.

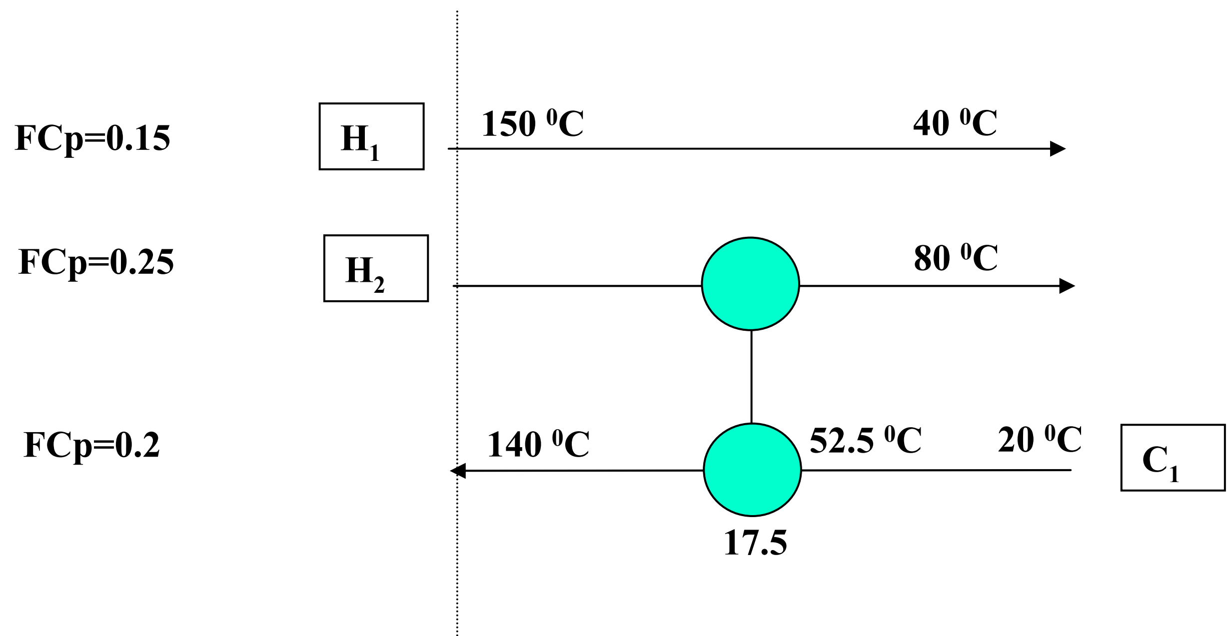
BELOW THE PINCH



- Which matches are possible?

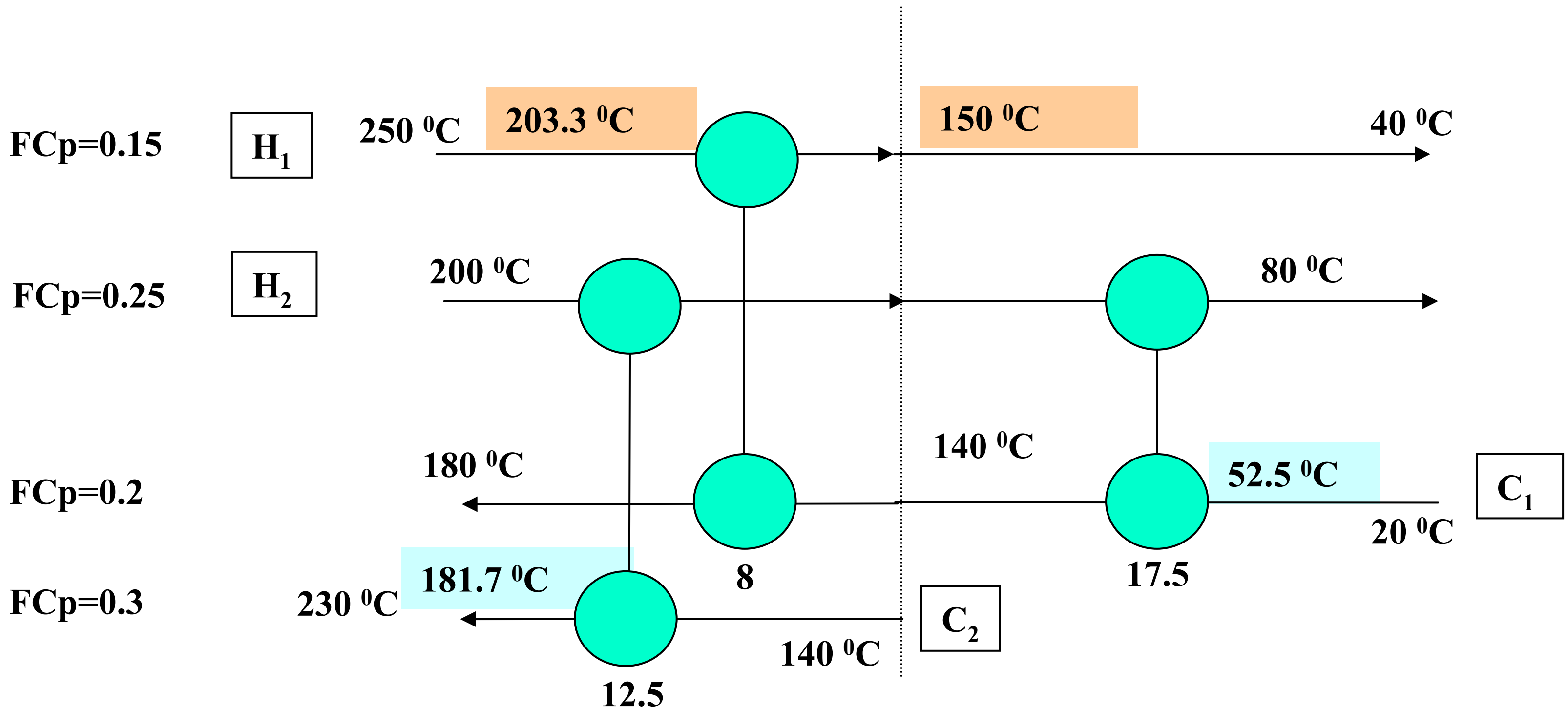
The rule is that $FCp_C < FCp_H$. Thus, we can only make the match H2-C1

ANSWER (below the pinch)



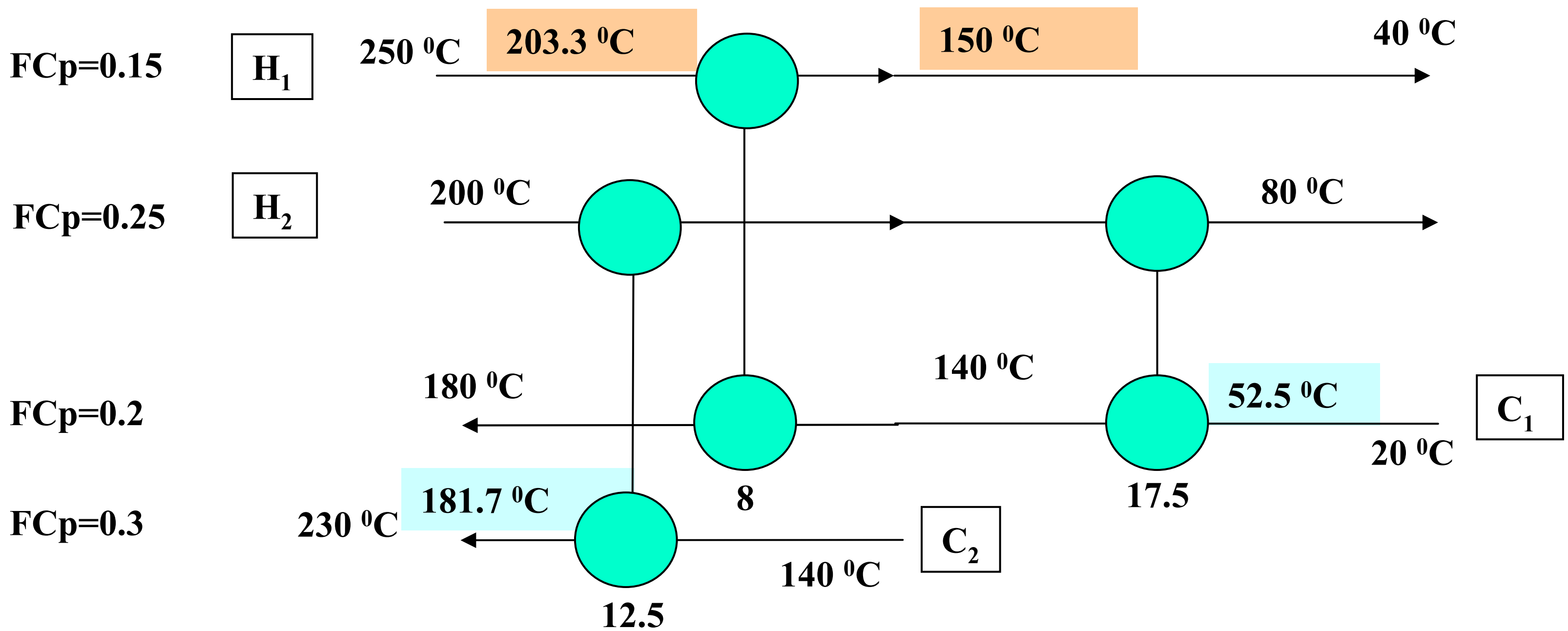
- The tick-off rule says that a maximum of 17.5 MW is exchanged in the match H2-C1 and as a result stream H2 reaches its target temperature.

COMPLETE NETWORK AFTER PINCH MATCHES



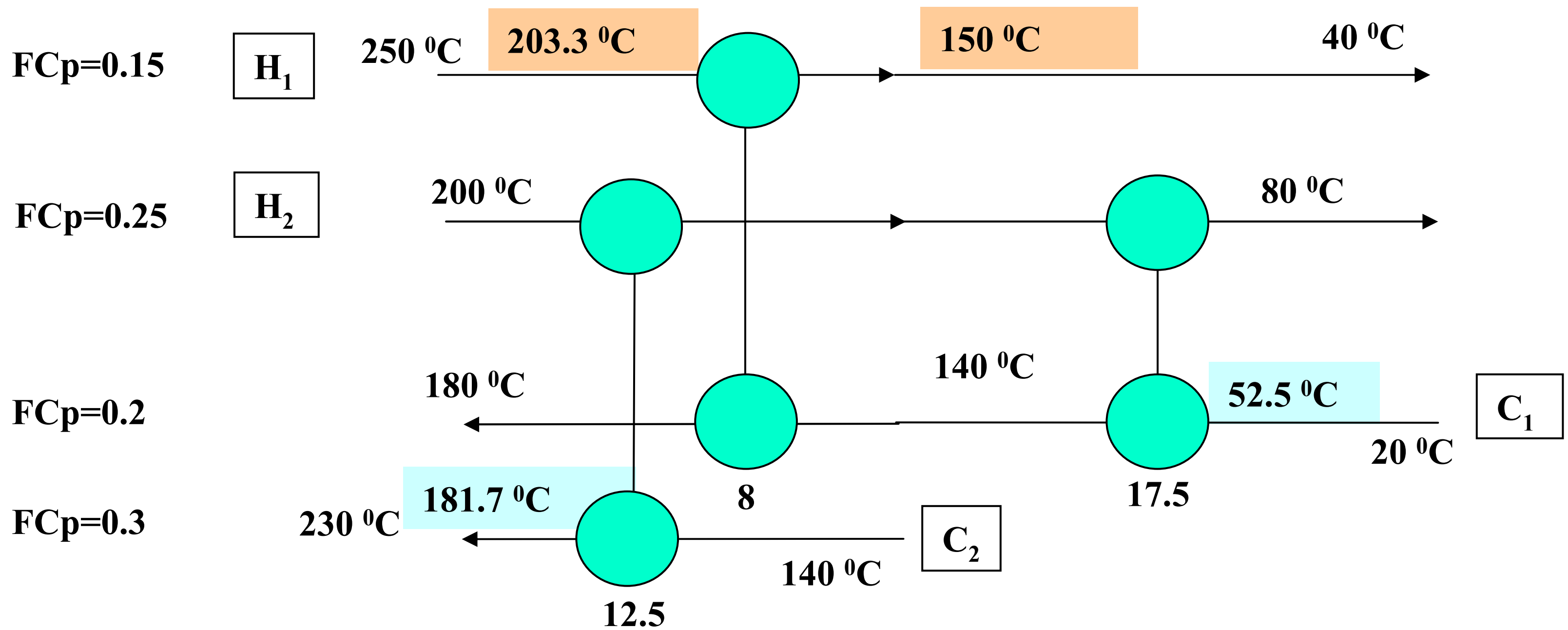
- Streams with unfulfilled targets are colored.

WHAT TO DO NEXT?



- **Away from the pinch, there is more flexibility to make matches, so the inequalities do not have to hold.**
- **The pinch design method leaves you now on your own!!!!!**
- **Therefore, <u>use your judgment</u> as of what matches to select!!**

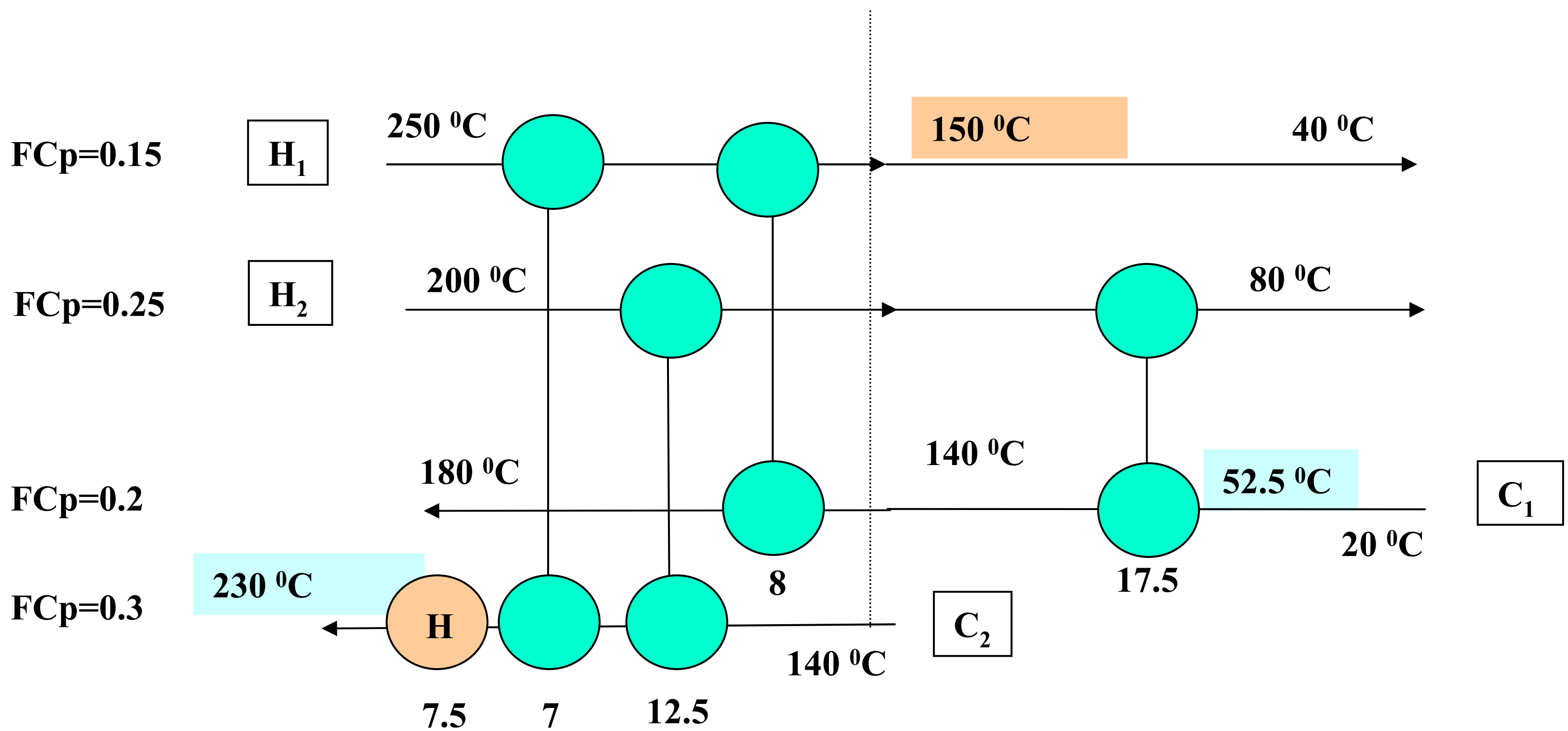
ANSWER



- **We first note that we will use heating above the pinch. Thus all hot streams need to reach their inlet temperature. We are then forced to look for a match for H1. Please locate it.**

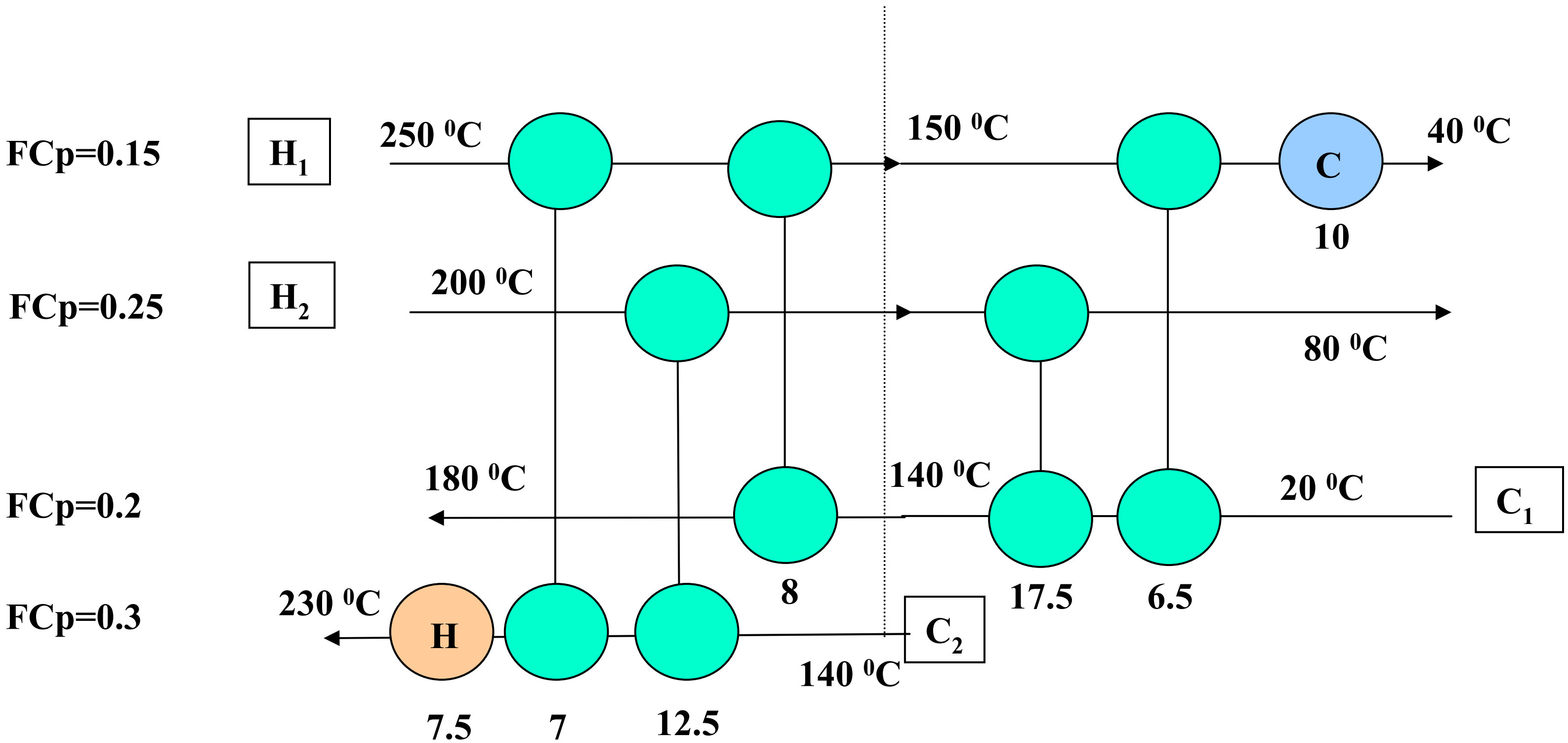
ANSWER

- The match is H1-C1. We finally put a heater on the cold stream

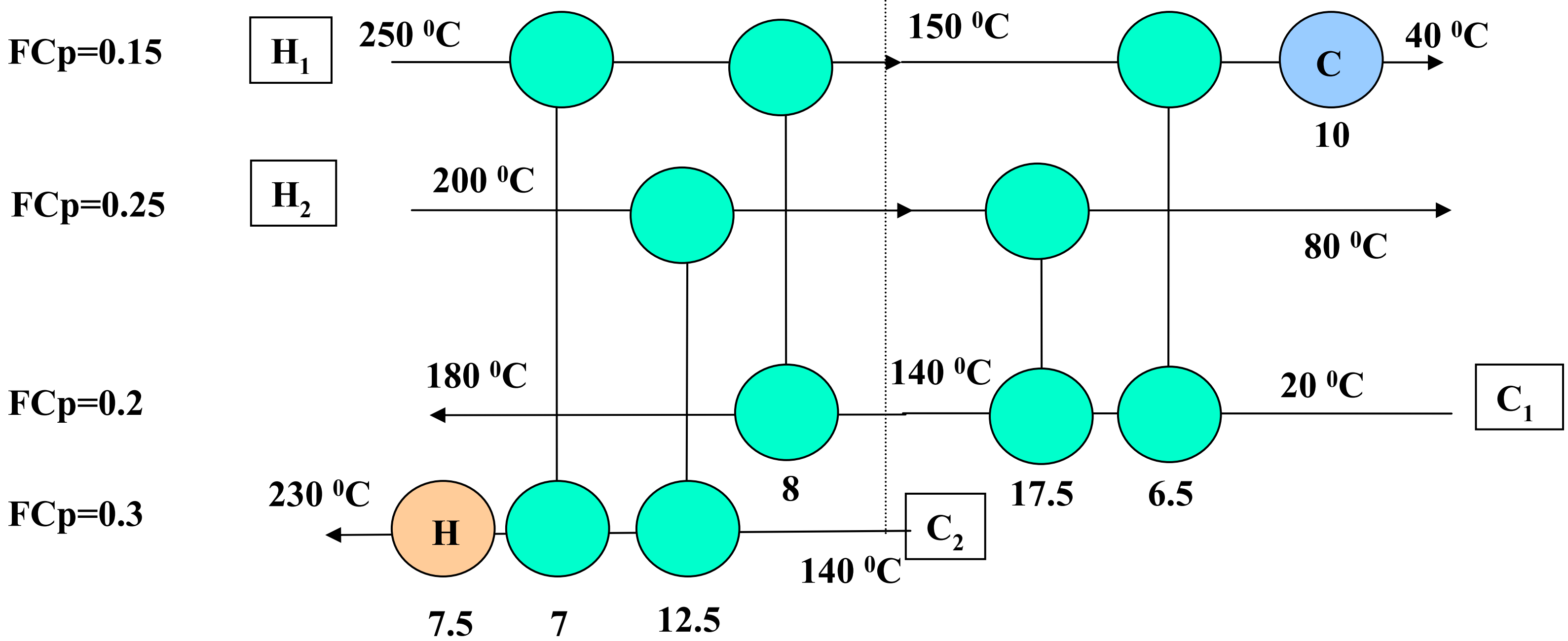


ANSWER

- **Below the pinch we try to have the cold streams start at their inlet temperatures and we later locate coolers (one in this case).**



EXAMPLE



N_{min}= (S-P)$_{above\ pinch}$+ (S-P)$_{below\ pinch}$ =

=(5-1) + (4-1) = 7

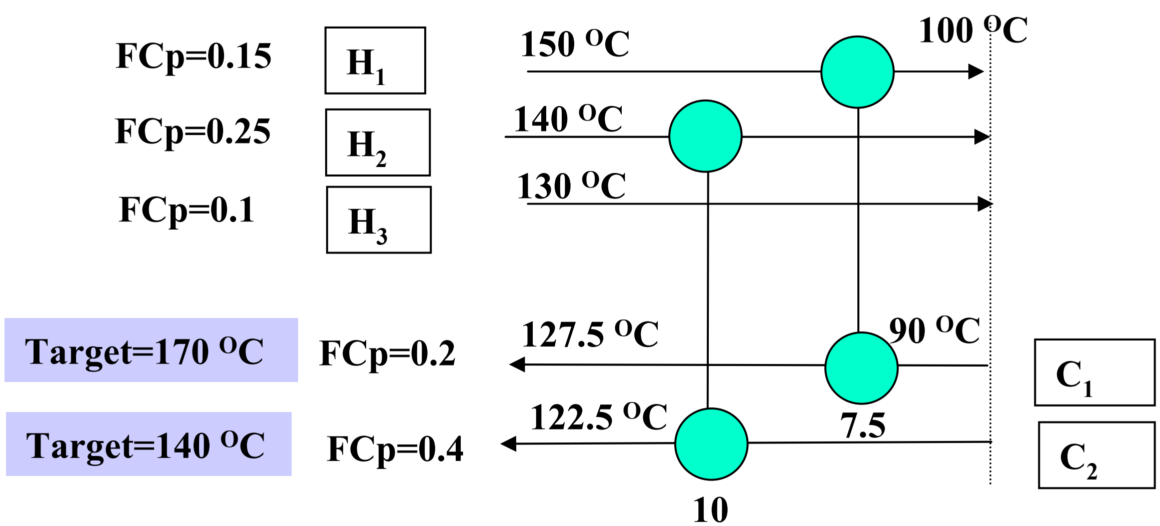
If we do not consider two separate problems

Nmin= (6-1)= 5, which is wrong

Note: A heat exchanger network with 5 exchangers exists, but it is impractical and costly. This is beyond the scope of this course.

UNEQUAL NUMBER OF STREAMS AT THE PINCH

Indeed, if the number of hot streams is larger than the number of cold streams, then no pinch matches are possible.

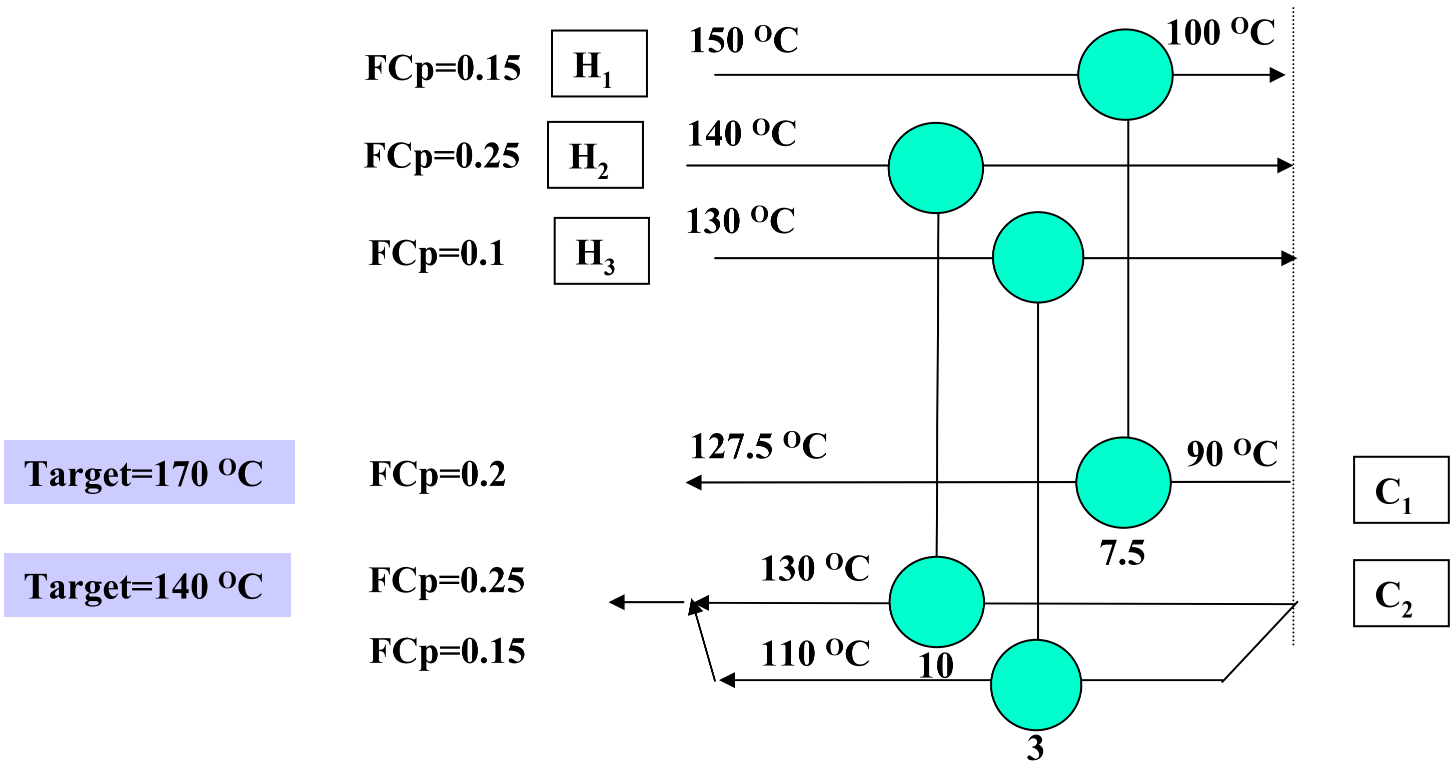


Assume the matches H_1-C_1 and the matches H_2-C_2 have been selected. Since H_3 needs to go to the pinch temperature, there is no cold stream left to match, even if there is portions of C_1 or C_2 that are left for matching. Such matching would be infeasible.

What is then, the solution?

ANSWER

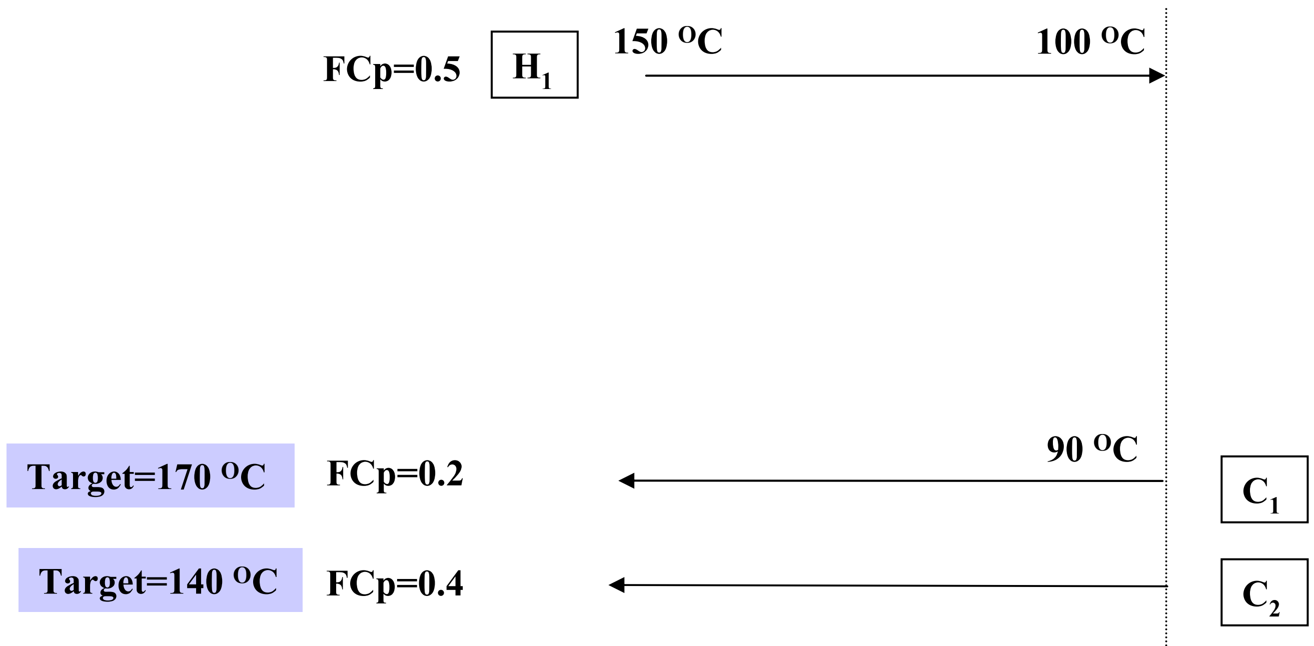
Split cold stream until the inequality is satisfied.



Notice that different combinations of flowrates in the split satisfy the inequality.

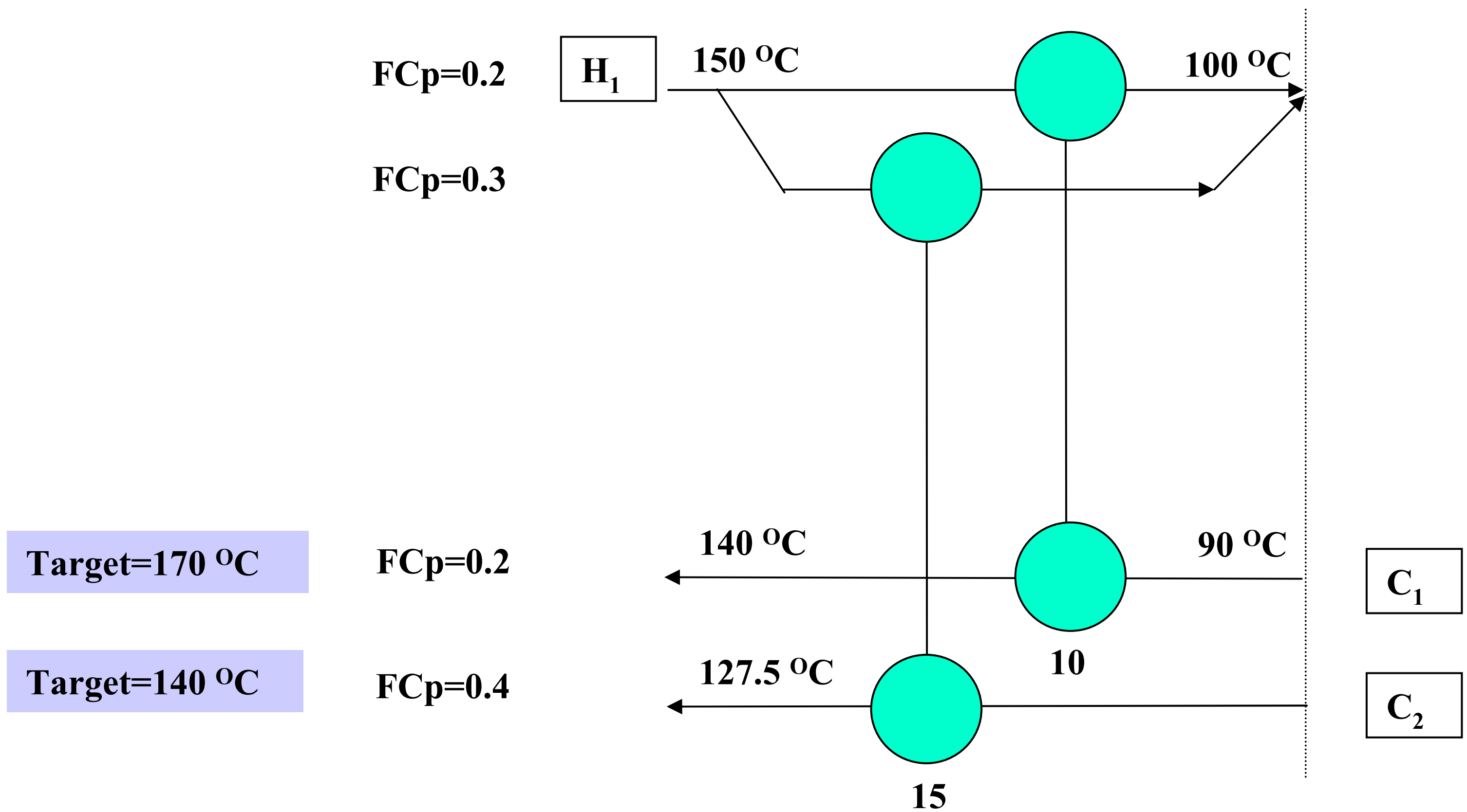
INEQUALITY NOT SATISFIED

Consider the following case:



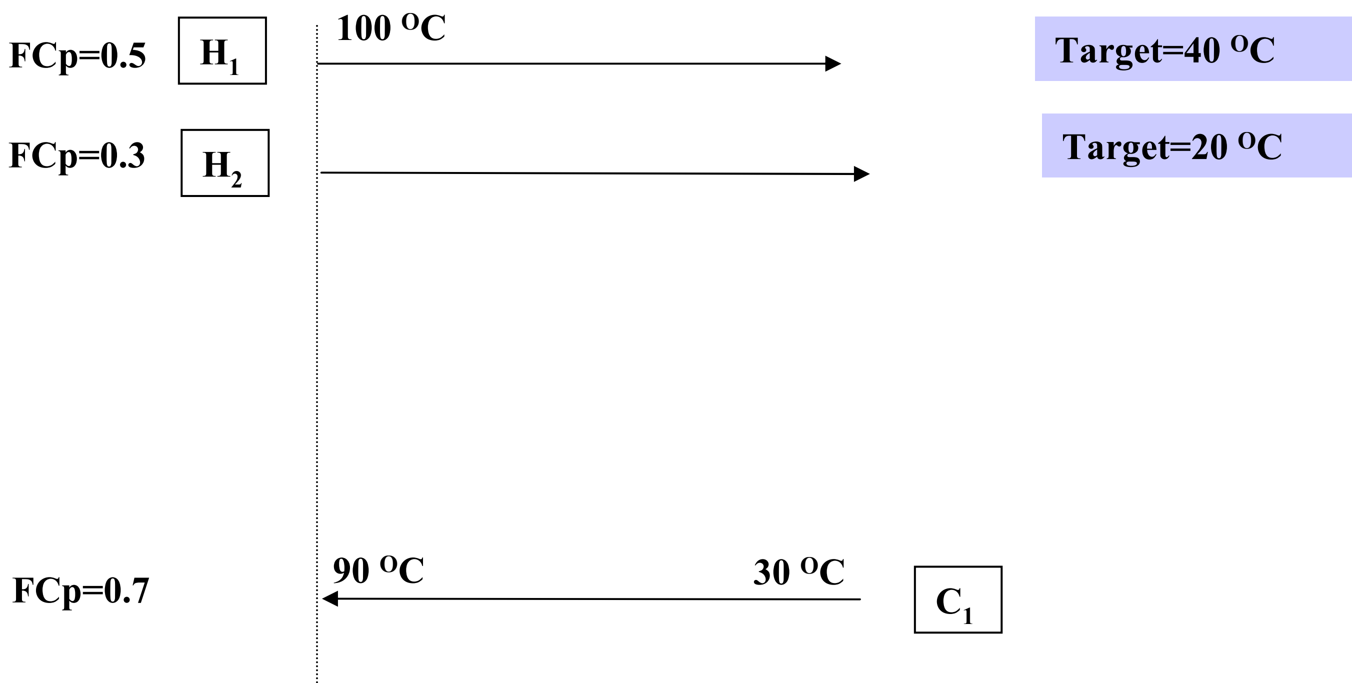
ANSWER

Split the hot stream



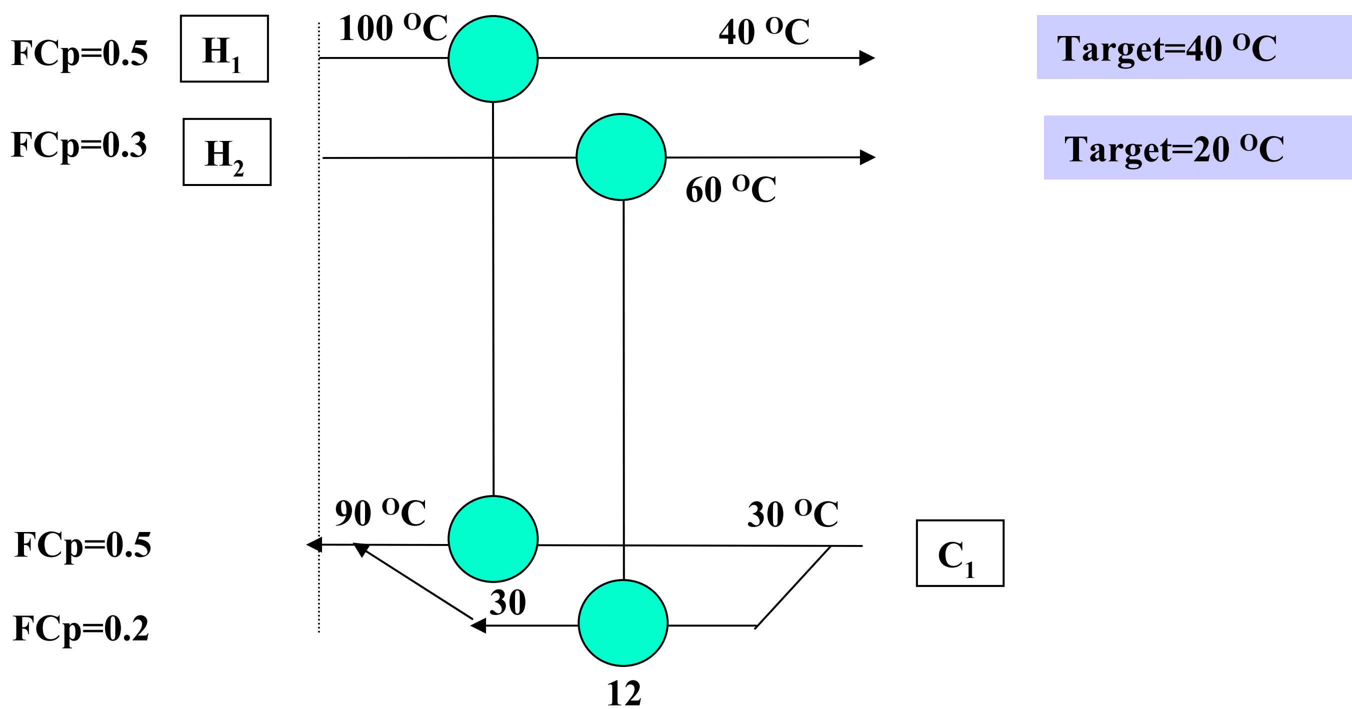
SOLVE THE FOLLOWING PROBLEM

Below the Pinch :



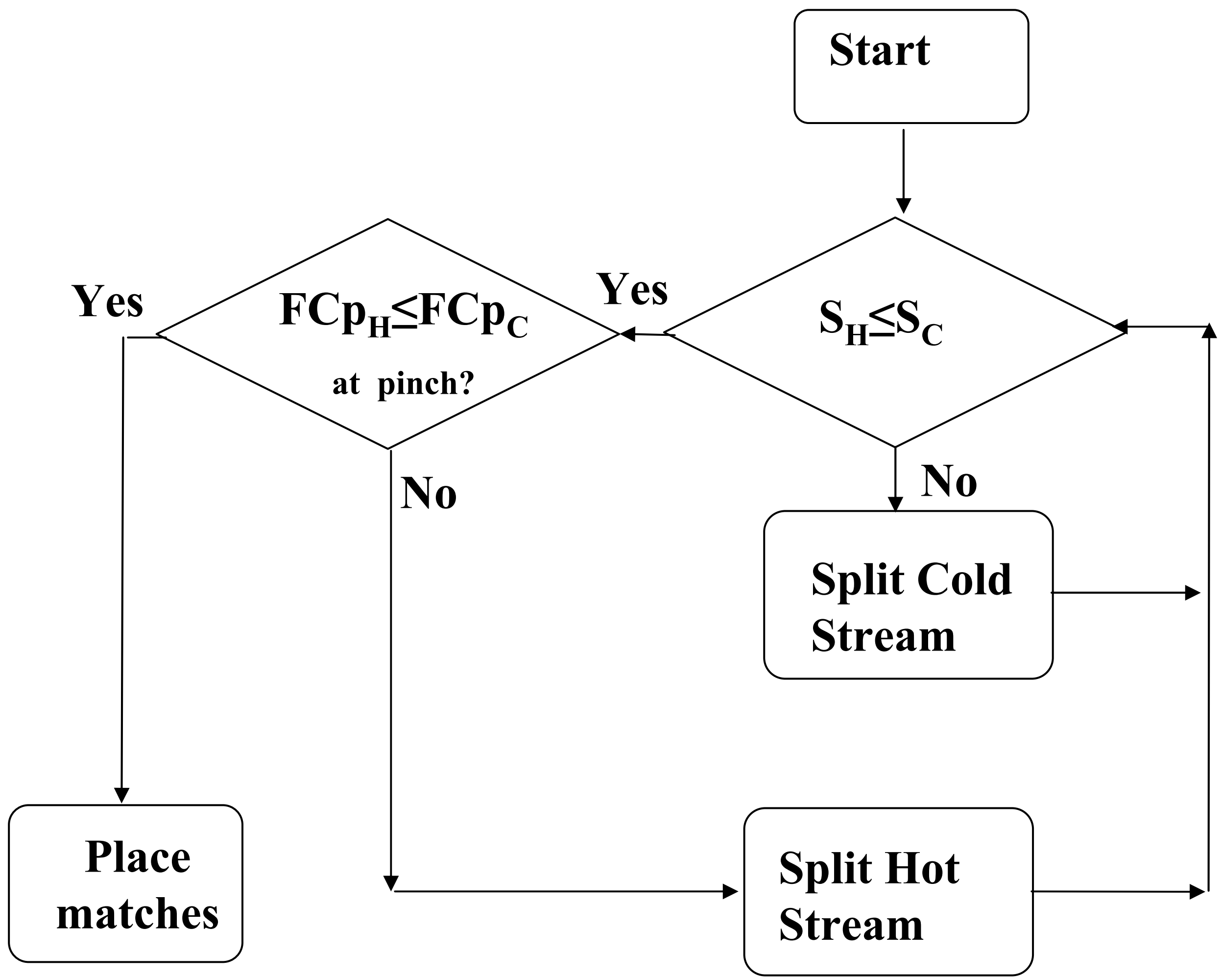
ANSWER

Below the Pinch :



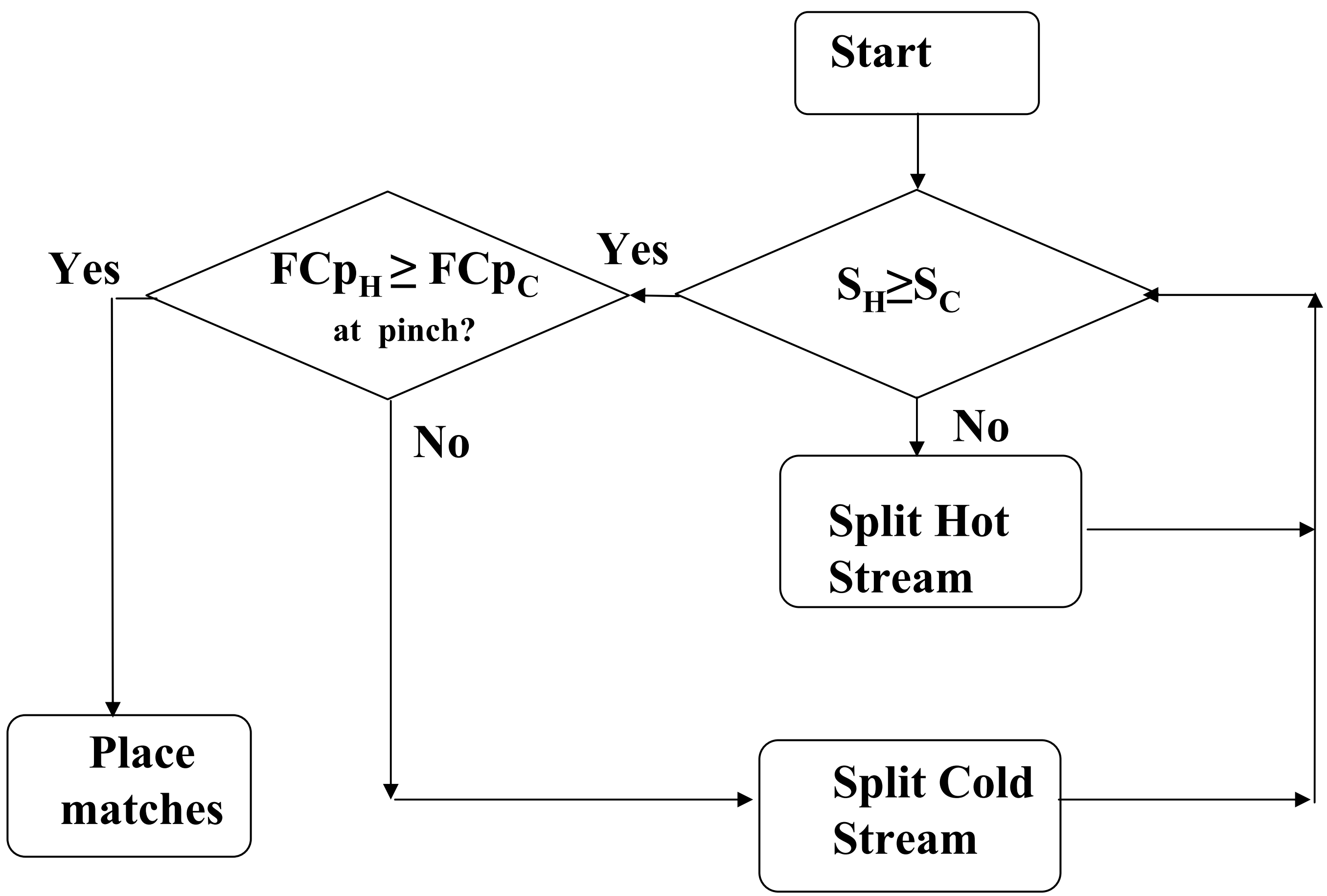
COMPLETE PROCEDURE

ABOVE THE PINCH



COMPLETE PROCEDURE

BELOW THE PINCH



HANDS ON EXERCISE

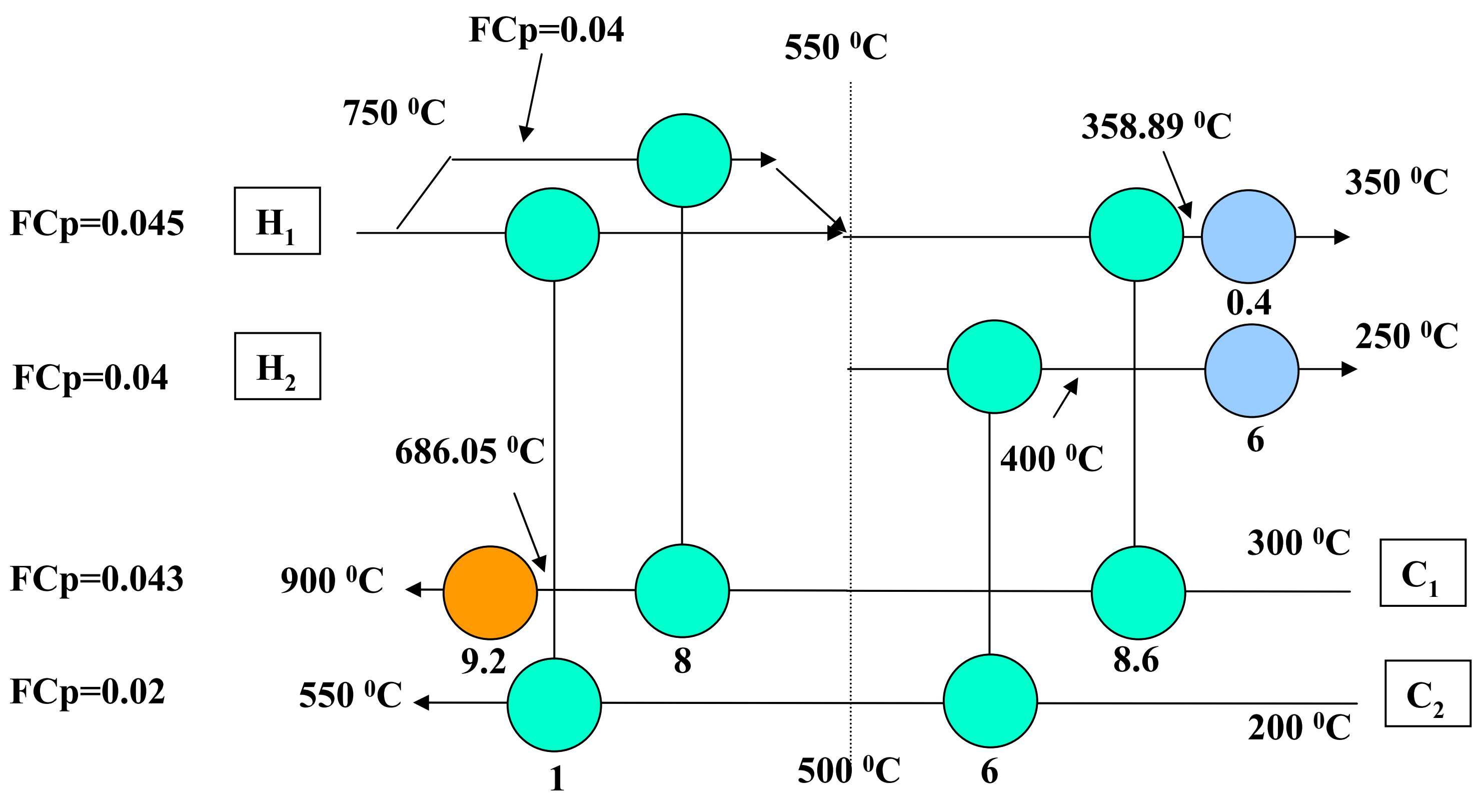
Type	Supply T (^oC)	Target T (^oC)	F*Cp ($MW\ ^oC^{-1}$)
Hot	750	350	0.045
Hot	550	250	0.04
Cold	300	900	0.043
Cold	200	550	0.02

ΔT_{min}=50 ^oC

Minimum Heating Utility= 9.2 MW

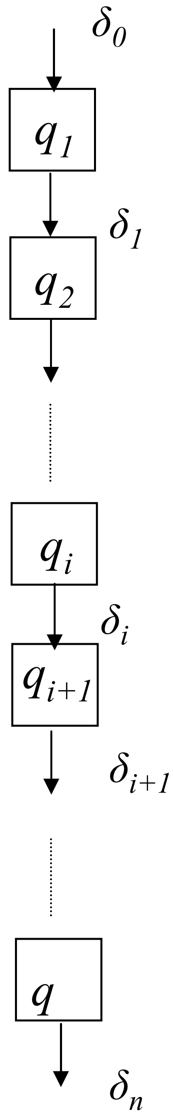
Minimum Cooling Utility= 6.4 MW

ANSWER



FCp=0.04
550 ⁰C
750 ⁰C
358.89 ⁰C
350 ⁰C
FCp=0.045
H1
0.4
250 ⁰C
FCp=0.04
H2
6
686.05 ⁰C
400 ⁰C
300 ⁰C
FCp=0.043
900 ⁰C
C1
9.2
8
8.6
FCp=0.02
550 ⁰C
C2
200 ⁰C
1
500 ⁰C
6

TRANSSHIPMENT MODEL (Papoulias and Grossmann, 1983)



We will now expand the mathematical model we presented to calculate the minimum utility.

$$S_{\min} = Min\, \delta_0$$

$$s.t$$

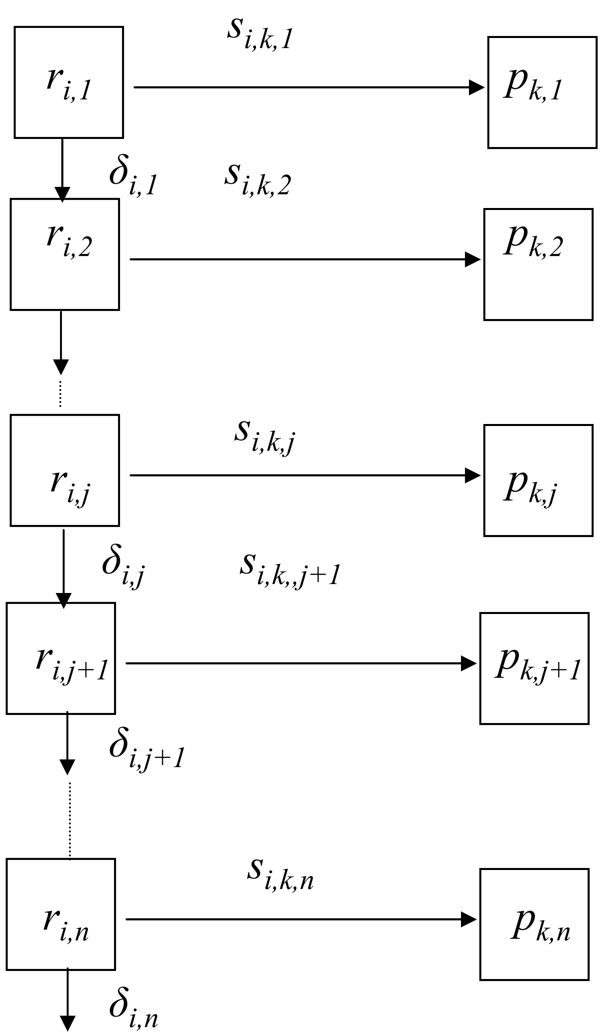
$$\delta_i = \delta_{i-1} + q_i \quad \forall i = 1,\ldots m_I$$

$$\delta_i \geq 0$$

Where

$$q_i = \sum_{k \in \Gamma_i^H} F_k^H cp_k^H (T_{i-1} - T_i) - \sum_{s \in \Gamma_i^C} F_s^C cp_s^C (T_{i-1} - T_i)$$

TRANSSHIPMENT MODEL



Assume now that we do the same cascade for each hot stream, while we do not cascade the cold streams at all. In addition we consider heat transfer from hot to cold streams in each interval.

The material balances for hot streams are:

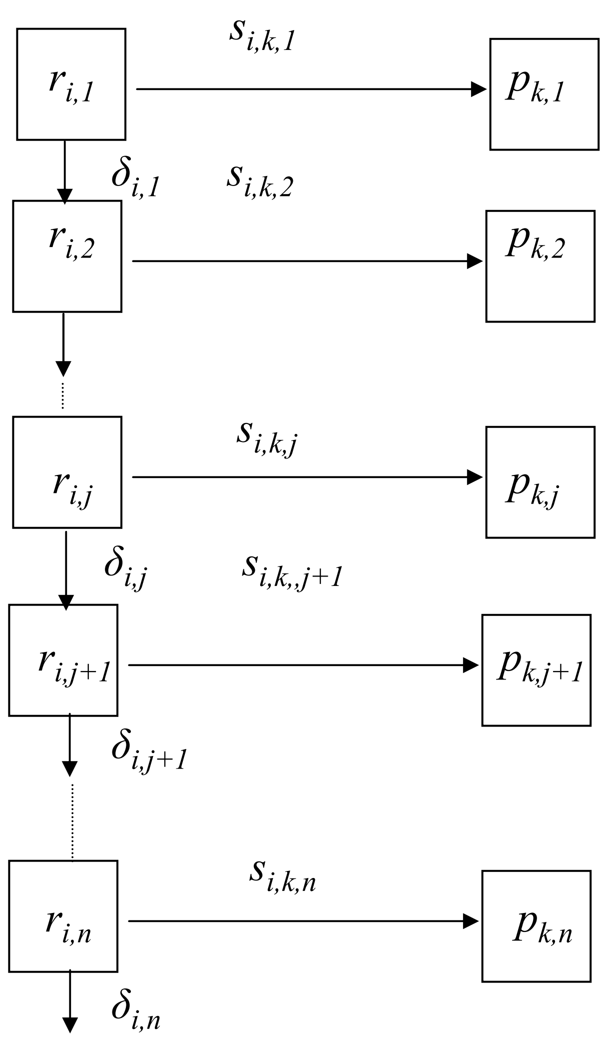
$$\begin{cases} \delta_{i,0} = 0 \\ \delta_{i,j} = \delta_{i,j-1} + r_{i,j} - \sum_k s_{i,k,j} \quad \forall j = 1,\dots m_I \end{cases}$$

The material balances for cold streams are:

$$p_{k,j} = \sum_i s_{i,k,j} \quad \forall j = 1,\dots m_I$$

Where $r_{i,j}$ and $p_{k,j}$ are the heat content of hot stream I and cold stream k in interval j.

TRANSSHIPMENT MODEL



Although we have a simpler model to solve it, in this new framework, the minimum utility problem becomes:

$$Min \quad \delta_{U,0}$$

$$s.t$$

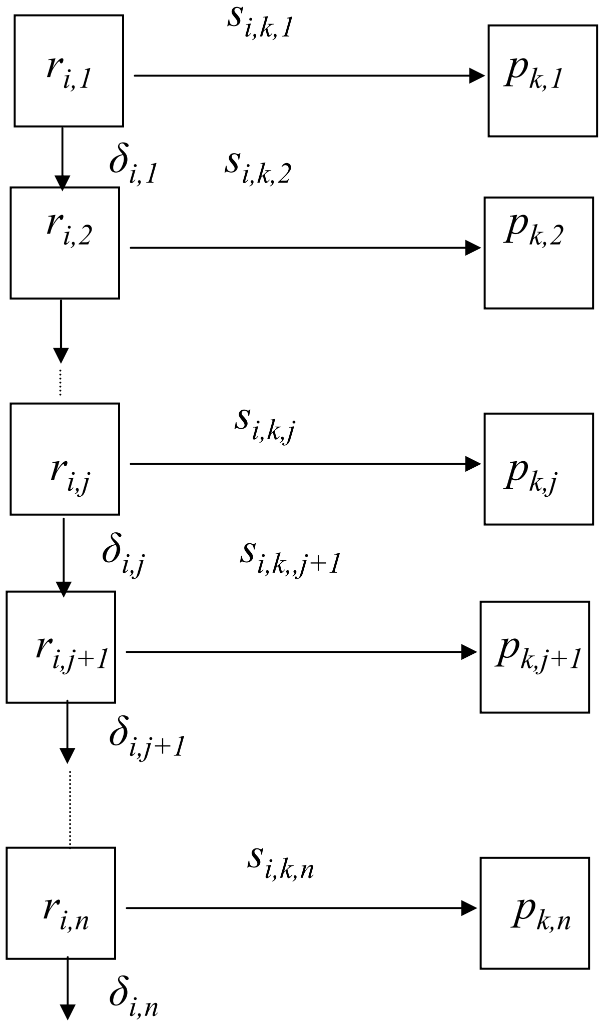
$$\delta_{i,0} = 0 \qquad \forall i, \forall j = 1,\ldots m_I$$

$$\delta_{i,j} = \delta_{i,j-1} + r_{i,j} - \sum_k s_{i,k,j} \qquad \forall i, \forall j = 1,\ldots m_I$$

$$p_{k,j} = \sum_i s_{i,k,j} \qquad \forall k, \forall j = 1,\ldots m_I$$

Note that the set of hot streams now includes process streams and the utility *U*. Cold streams include cooling water.

TRANSSHIPMENT MODEL



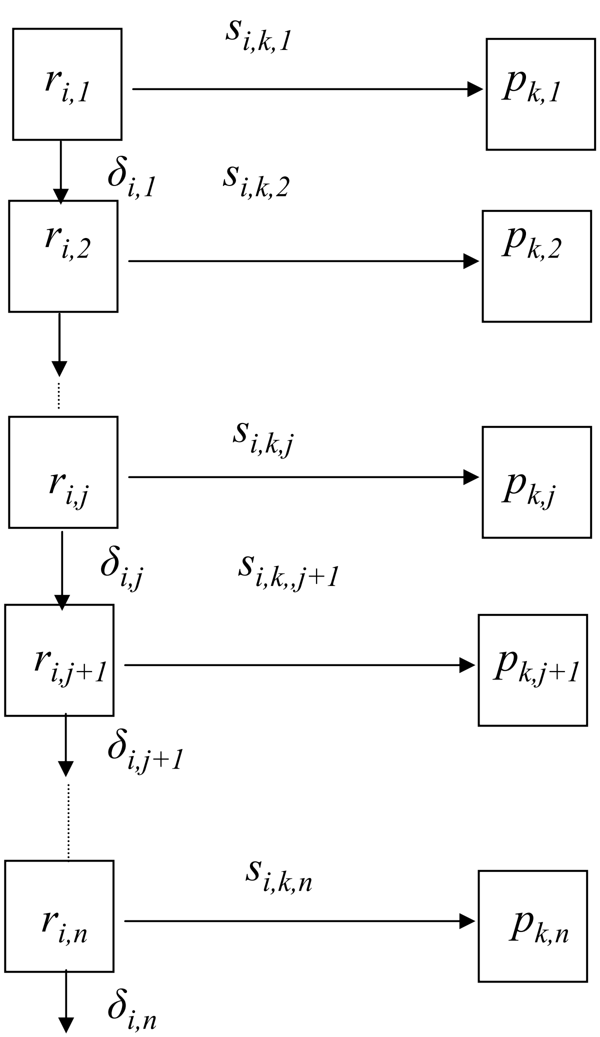
We would like to have a model that would tell us the $s_{i,k,j}$ such that the number of units is minimum. We now introduce a way of counting matches between streams. Let $Y_{i,k}$ be a binary variable (can only take the value 0 or 1).

Then we can force $Y_{i,k}$ to be one using the following inequality

$$\sum_{j} s_{i,k,j} - \Gamma Y_{i,k} \leq 0$$

indicating therefore that heat has been transferred from stream *i* to stream *k* in at least one interval.

TRANSSHIPMENT MODEL



The complete model would be:

$$Min \quad \sum_i \sum_k Y_{i,k}$$

$$s.t$$

$$\delta_{U,0} = \delta^*_{U,0}$$

$$\delta_{i,0} = 0 \qquad \forall i, \forall j = 1,\dots m_I$$

$$\delta_{i,j} = \delta_{i,j-1} + r_{i,j} - \sum_k s_{i,k,j} \qquad \forall i, \forall j = 1,\dots m_I$$

$$p_{k,j} = \sum_i s_{i,k,j} \qquad \forall k, \forall j = 1,\dots m_I$$

$$\sum_j s_{i,k,j} - \Gamma Y_{i,k} \le 0 \qquad \forall i, \forall k$$

The model can only be solved above and below the pinch separately. Why???

TRANSSHIPMENT MODEL

We are minimizing the number of matches. Different answers can be obtained if separate regions are not considered. These answers are not guaranteed to be realistic.

GAMS MODEL

$$Min \sum_i \sum_k Y_{i,k}$$

$s.t$

$$\delta_{U,0} = \delta^*_{U,0}$$

$$\delta_{i,0} = 0 \qquad \forall i, \forall j = 1,...m_I$$

$$\delta_{i,j} = \delta_{i,j-1} + r_{i,j} - \sum_k s_{i,k,j} \qquad \forall i, \forall j = 1,...m_I$$

$$p_{k,j} = \sum_i s_{i,k,j} \qquad \forall k, \forall j = 1,...m_I$$

$$\sum_j s_{i,k,j} - \Gamma Y_{i,k} \le 0 \qquad \forall i, \forall k$$

GAMS MODEL

```
SETS
    I   hot streams above pinch   / S, H1 /
    K   cold streams above pinch  / C1,C2,W/
    J   temperature intervals / J0*J3 / ;

 SCALAR GAMMA /10000/;

 TABLE R(I,J)  load of hot stream I1 in interval K
          J0    J1     J2       J3
    S     9.2    0      0        0
    H1     0     0     6.75     2.25;

TABLE P(K,J)  load of cold stream K1 in interval J
           J0    J1    J2      J3
    C1      0    8.6   6.45    2.15
    C2      0    0      0        1
    W       0    0      0       6.4   ;

VARIABLES
     S(I,K,J)  heat exchanged hot and cold streams
     D(I,J)  heat of hot streams flowing between intervals
     Y(I,K)  existence of match
     Z       total number of matches  ;

 POSITIVE VARIABLE S
 POSITIVE VARIABLE D
 BINARY VARIABLE Y   ;

 EQUATIONS
     MINMATCH        objective function-number of matches
     HSBAL(I,J)      heat balances of hot stream I in INTERVAL J
     CSBAL(K,J)      heat balances of cold stream J1 in K
     HTINEQ1(I,K)    heat transferred inequalities;

 MINMATCH .. Z =E= SUM((I,K), Y(I,K));
 HSBAL(I,J)$(ORD(J) NE  0)  .. D(I,J)-D(I,J-1)+ SUM(K,S(I,K,J)) =E= R(I,J);
 CSBAL(K,J)$(ORD(J) NE  0) ..   SUM(I, S(I,K,J)) =E= P(K,J) ;
 HTINEQ1(I,K) ..   SUM(J, S(I,K,J))-GAMMA*Y(I,K)  =L= 0  ;

 MODEL TSHIP /ALL/ ;
 SOLVE TSHIP USING MIP MINIMIZING Z;
 DISPLAY S.L, D.L, Y.L;
```

GAMS MODEL

SOLUTION

---- VARIABLE S.L

	J1	J2	J3
S .C1	8.600	0.600	
H1.C1		5.850	2.150
H1.C2			1.000

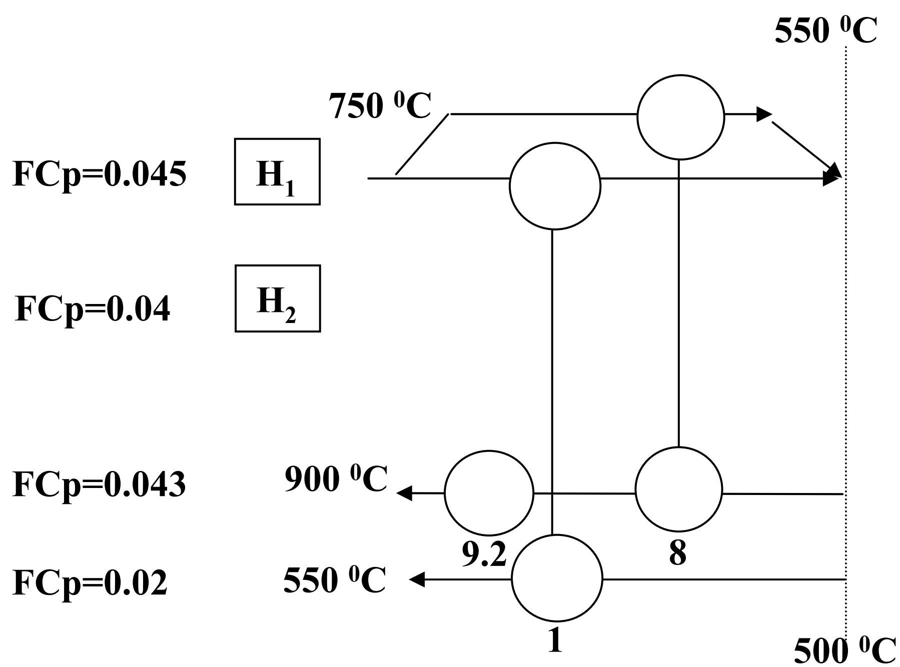
---- VARIABLE D.L

	J0	J1	J2
S	9.200	0.600	
H1			0.900

---- VARIABLE Y.L

	C1	C2
S	1.000	
H1	1.000	1.000

EXECUTION TIME = 0.090 SECONDS

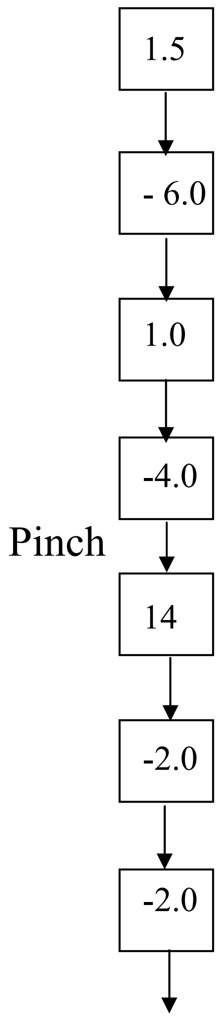


PART 4

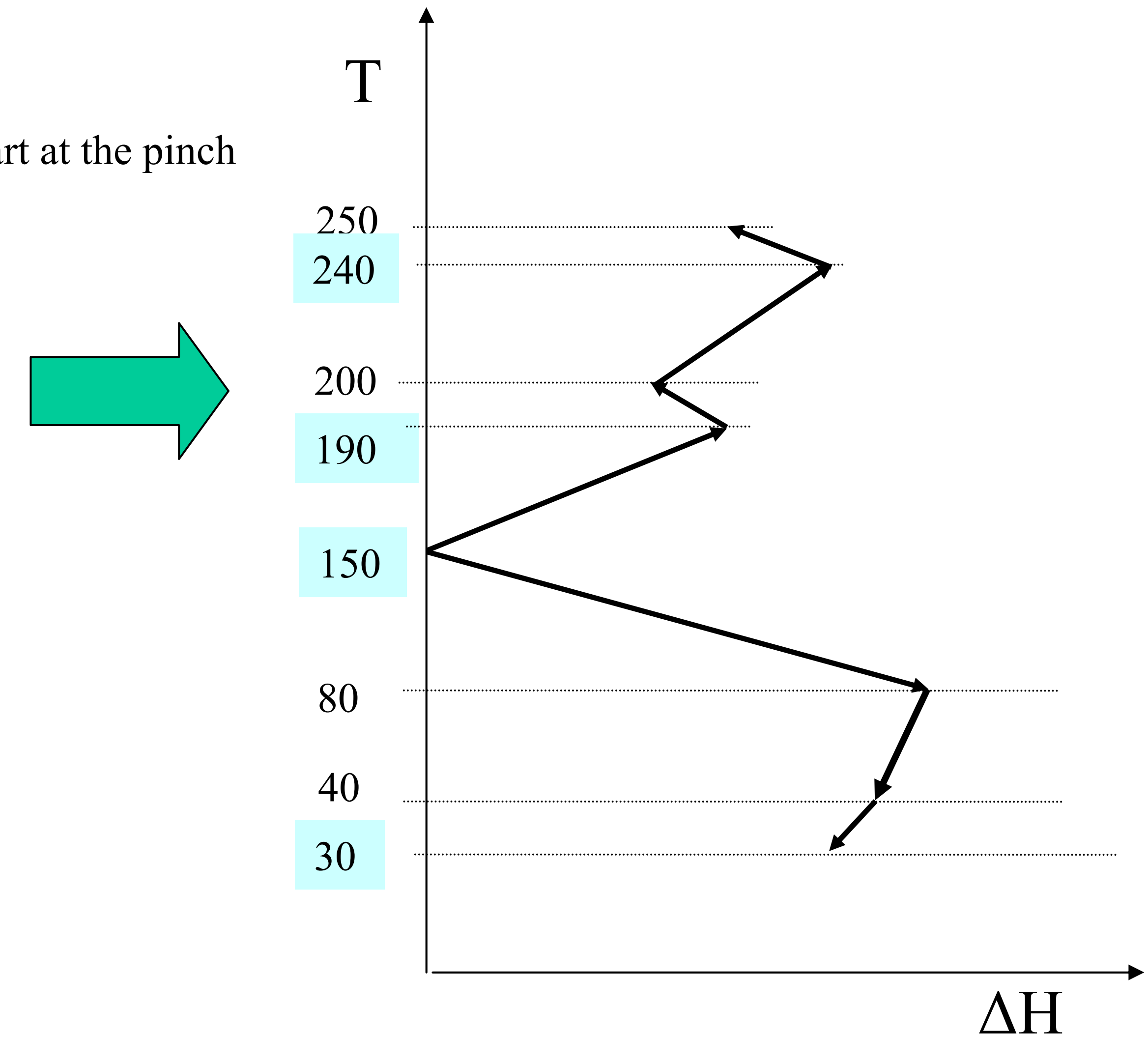
UTILITY PLACEMENT HEAT AND POWER INTEGRATION

UTILITY PLACEMENT

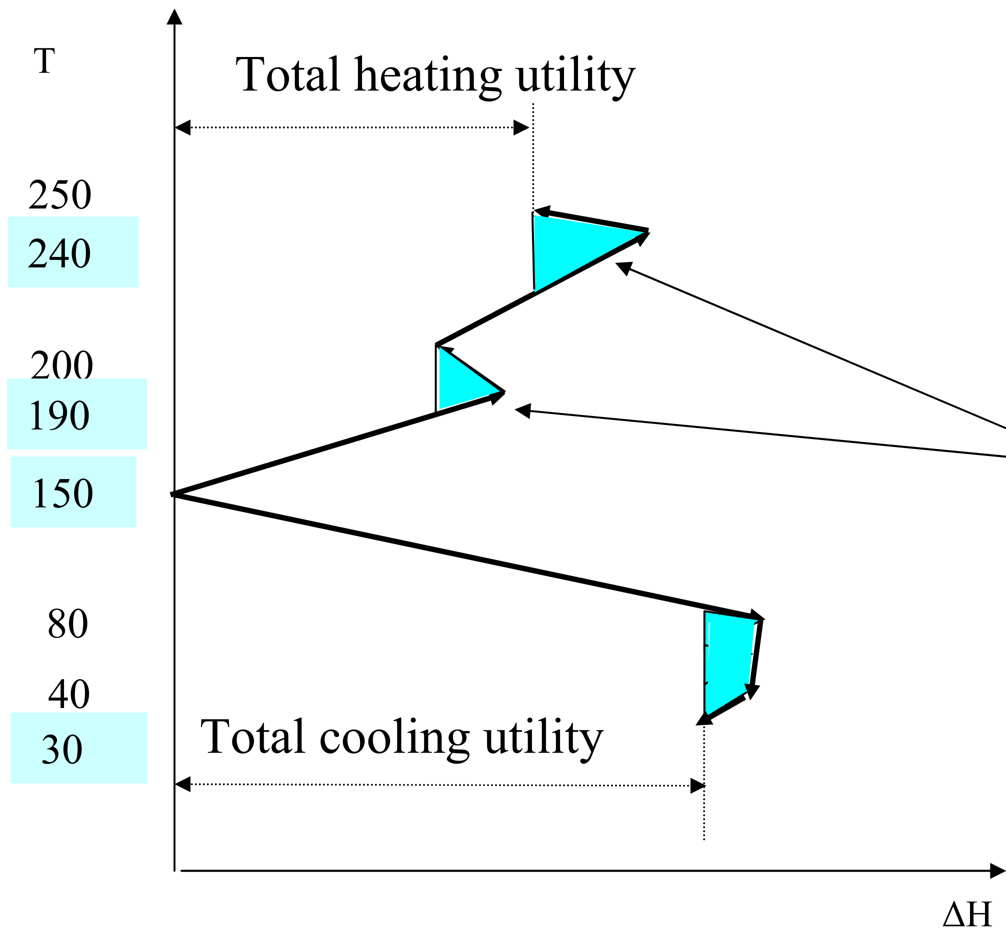
We now introduce the GRAND COMPOSITE CURVE, which will be useful to analyze the placement of utilities.



Start at the pinch



GRAND COMPOSITE CURVE

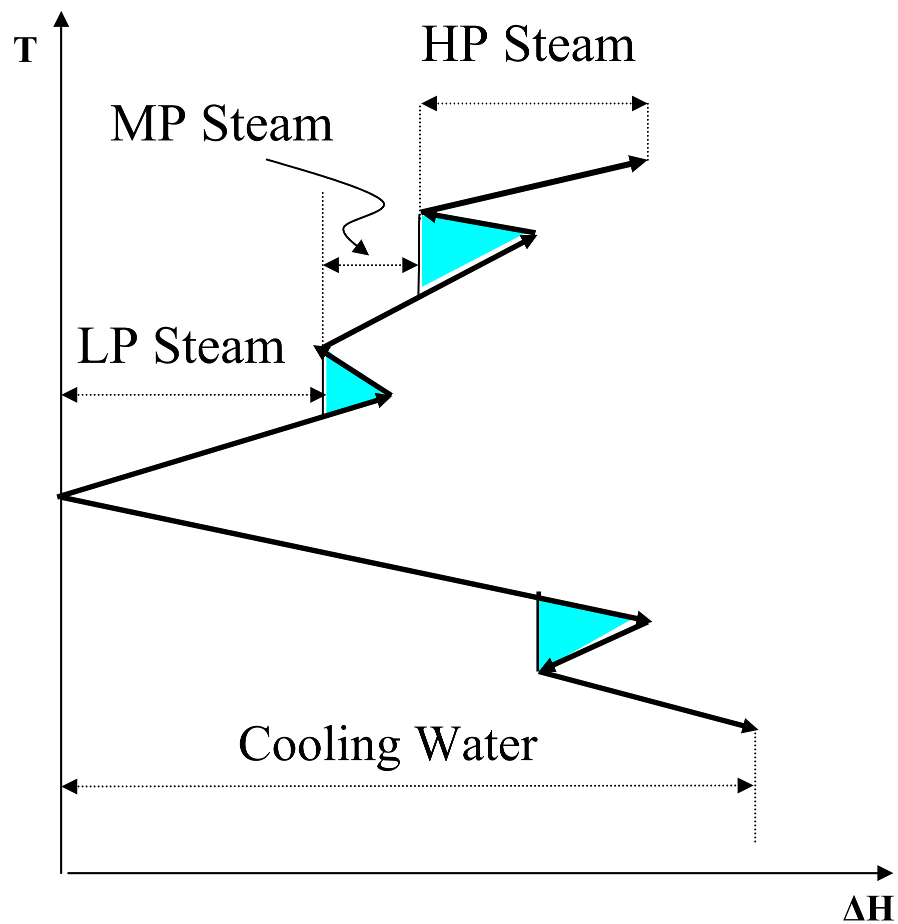


These are called "pockets"

Process-to Process integration takes place here

UTILITY PLACEMENT

We now resort to a generic grand composite curve to show how utilities are placed.



Transshipment model for multiple utilities

$$Min \quad \sum_{m \in S} c_m Q_m^S + \sum_{n \in W} c_n Q_n^W$$

$s.t$

$$\delta_{i,0} = 0 \qquad \forall i, \forall j = 1,\ldots m_I$$

$$\delta_{i,j} = \delta_{i,j-1} + r_{i,j} - \sum_k s_{i,k,j} - \sum_{m \in S} Q_{i,n,j} \qquad \forall i, \forall j = 1,\ldots m_I$$

$$\delta_{m,j} = \delta_{m,j-1} - \sum_{m \in S} Q_{i,n,j} + Q_m^S \qquad \forall i, \forall j = 1,\ldots m_I$$

$$p_{k,j} = \sum_i s_{i,k,j} + \sum_{m \in S} Q_{m,k,j} \qquad \forall k, \forall j = 1,\ldots m_I$$

$$\sum_{m \in S} Q_{m,k,j} = Q_n^W \qquad \forall k, \forall j = 1,\ldots m_I$$

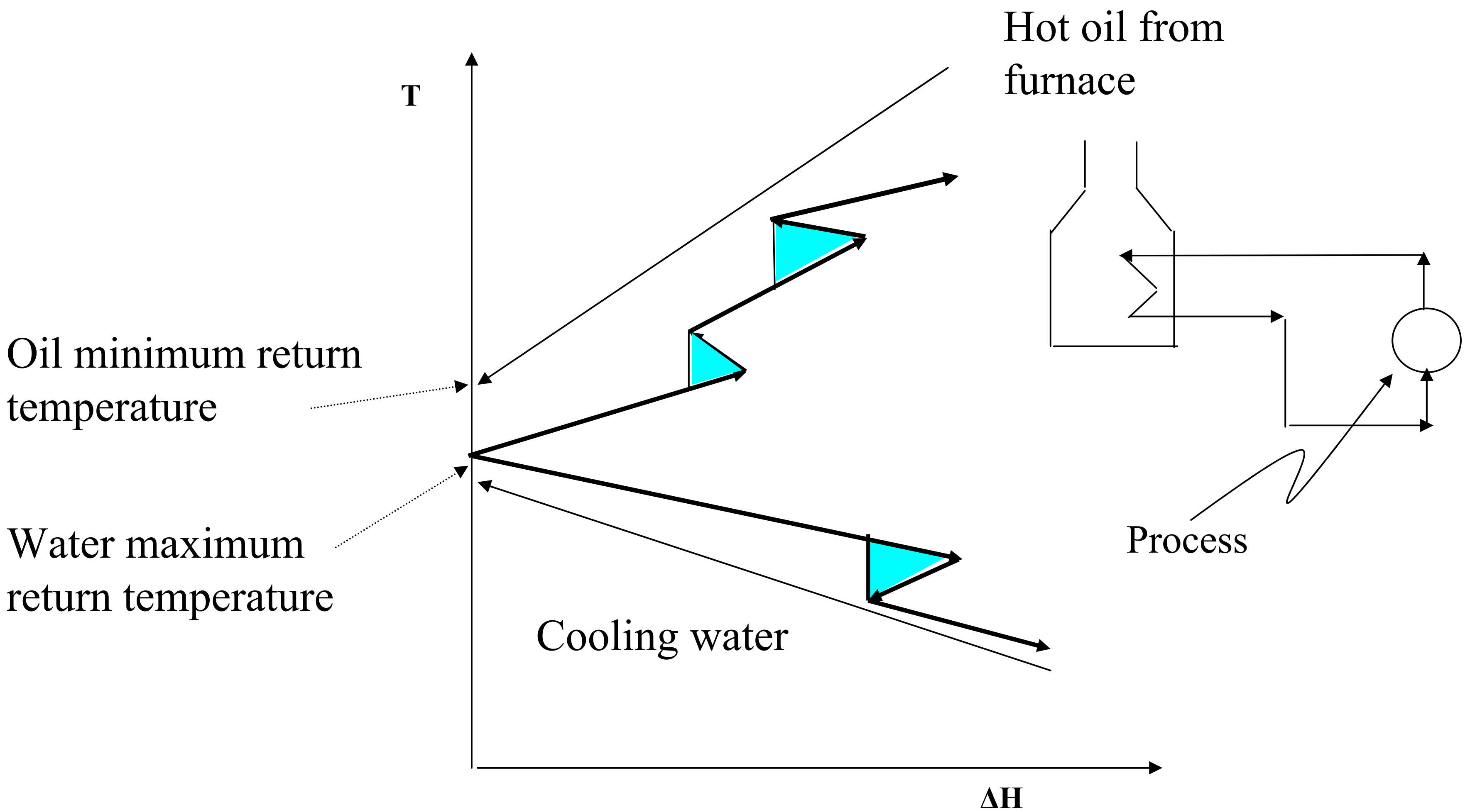
Results

HOT UTILITY 1 = HP STEAM **HOT UTILITY 2 = MP STEAM**

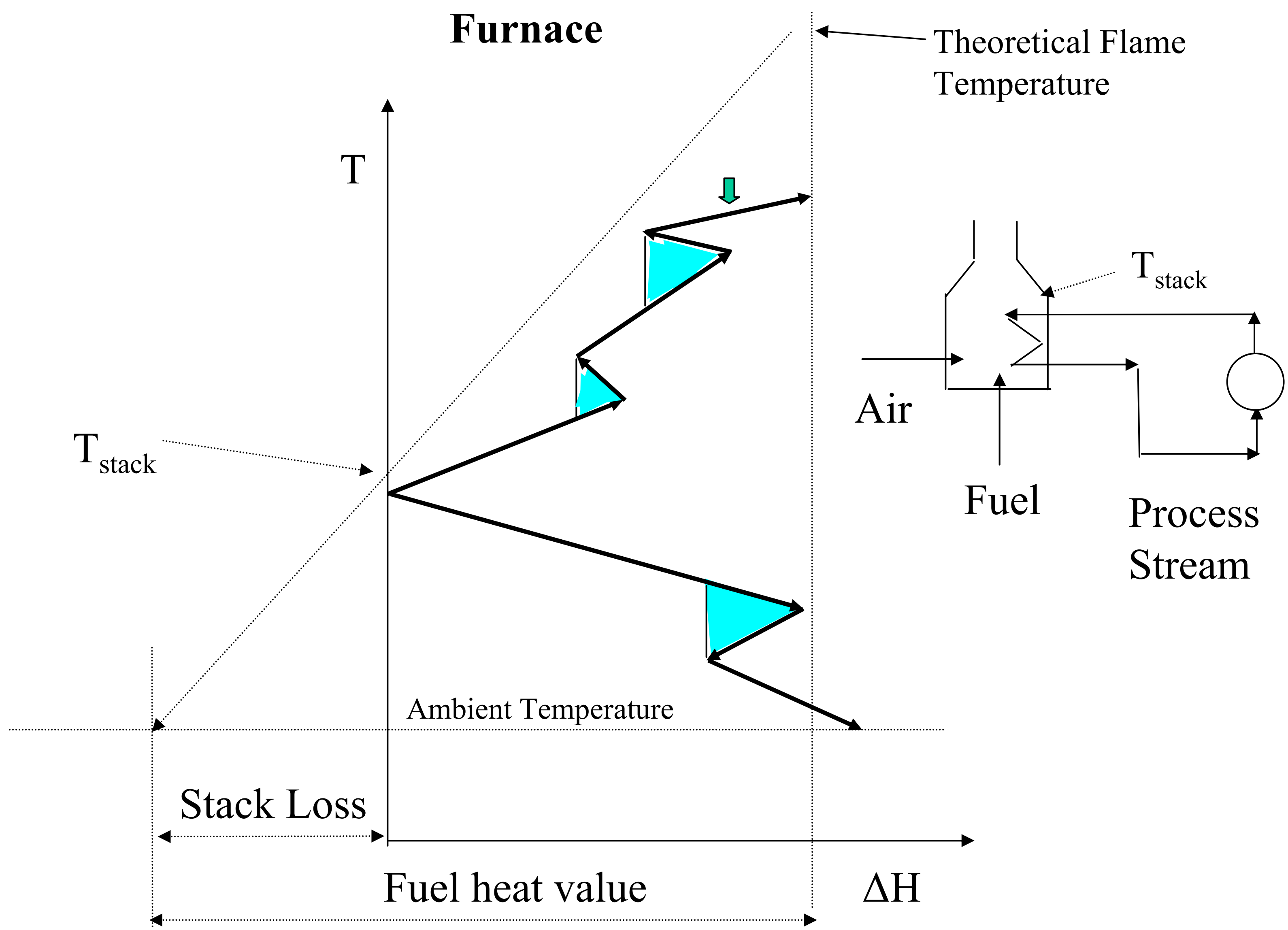
Interval	T(i)	Q(i)	δ(i)	HU_1(i)	HU_2(i)	CU_1(i)	
I0	250						
I1	200	-4.5	0	**4.5**			**HOT UTILITY 1**
I2	150	-3	0		**3**		**HOT UTILITY 2**
I3	30	10	0			**10**	**COLD UTILITY**

UTILITY PLACEMENT

Hot Oil placement and extreme return temperatures

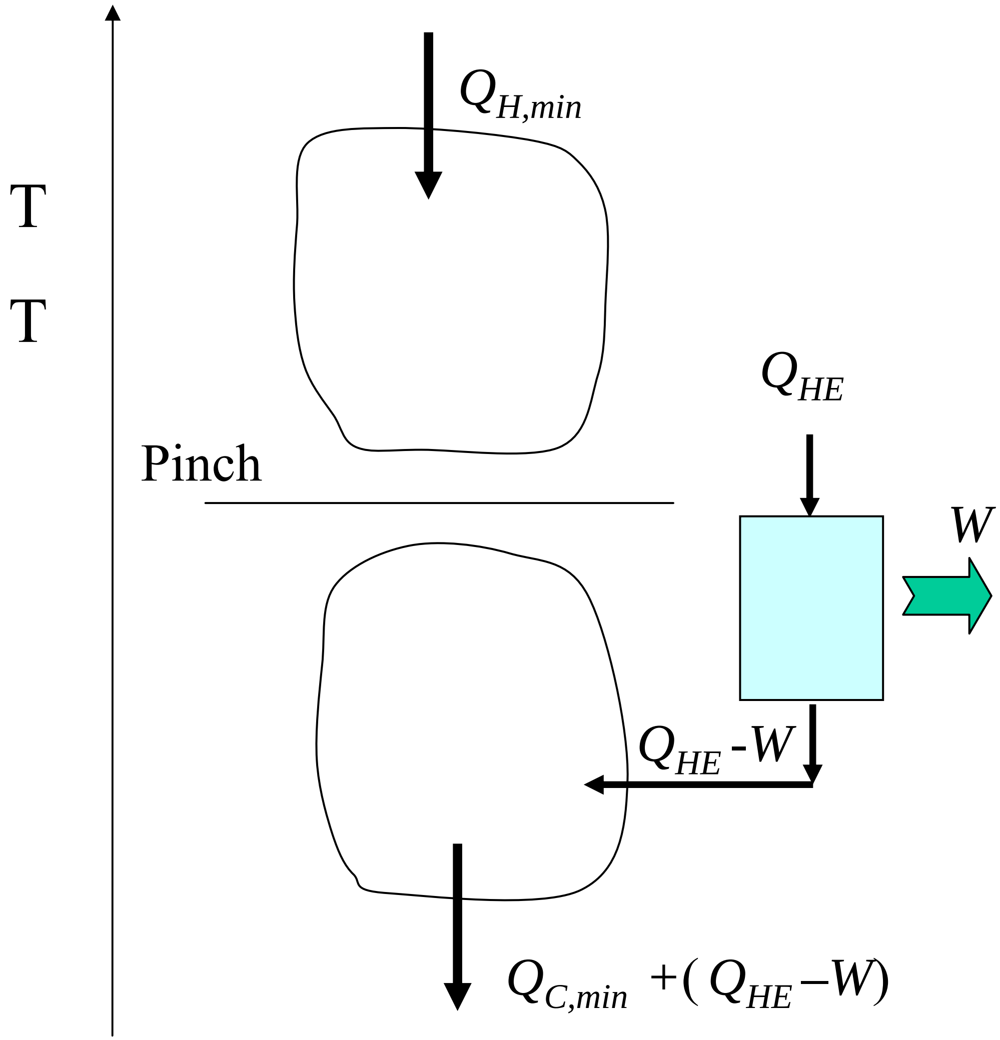


UTILITY PLACEMENT



COMBINED HEAT AND POWER

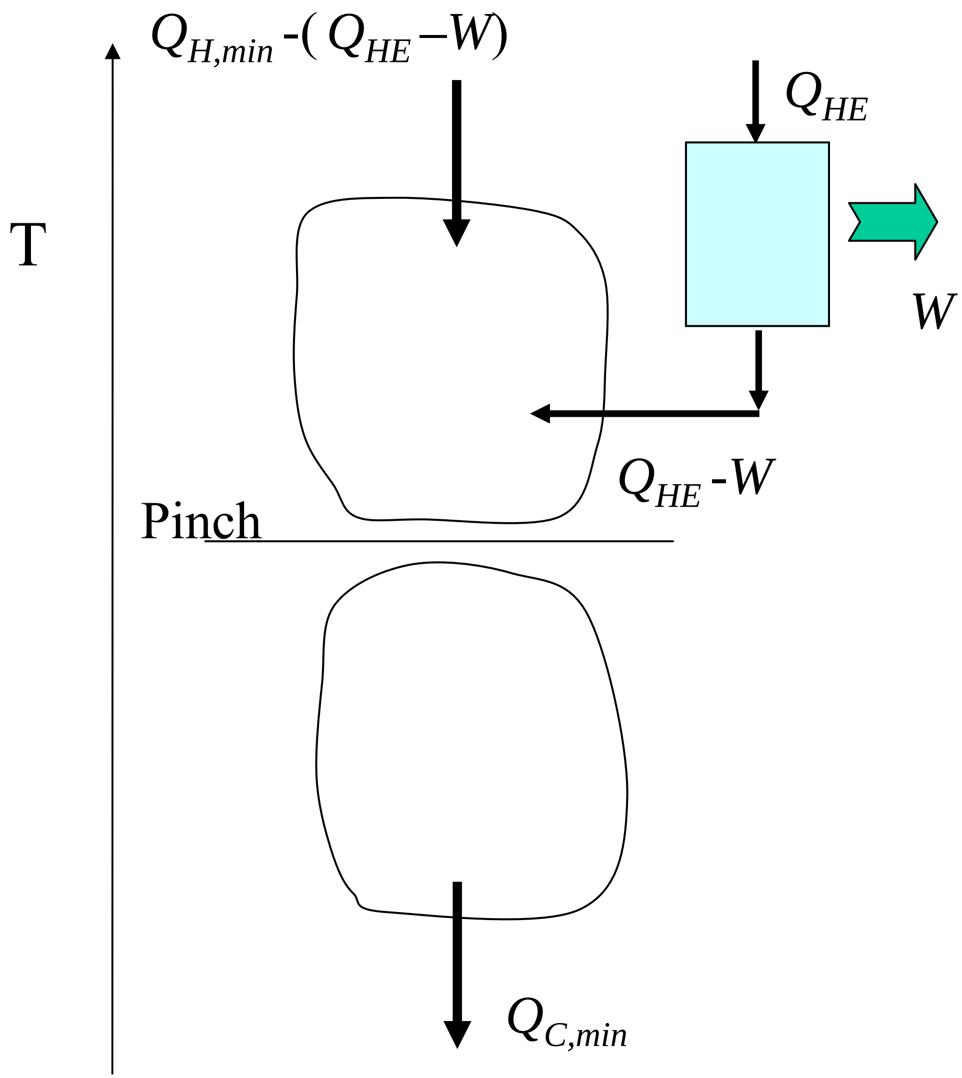
Integration of a Heat Engine below the Pinch.



Note that in this case there is no gain. The heat engine can be arranged separately and the utility usage will not change.

COMBINED HEAT AND POWER

Integration of a Heat Engine Across the Pinch.



TOTAL HEN ENERGY INTAKE

$Q_{H,min}$ -(Q_{HE} – W)

(Smaller)

SYSTEM TOTAL ENERGY INTAKE

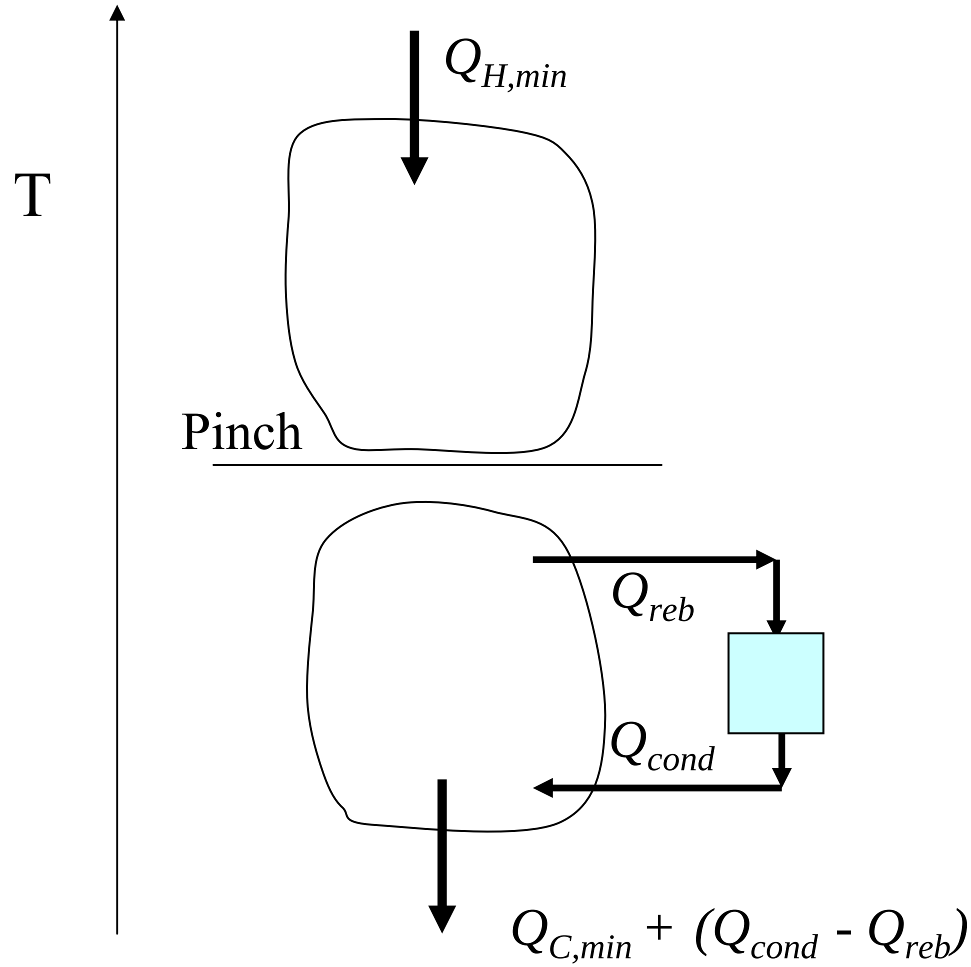
$Q_{H,min} + W$

vs. $Q_{H,min} + Q_{HE}$

(separate)

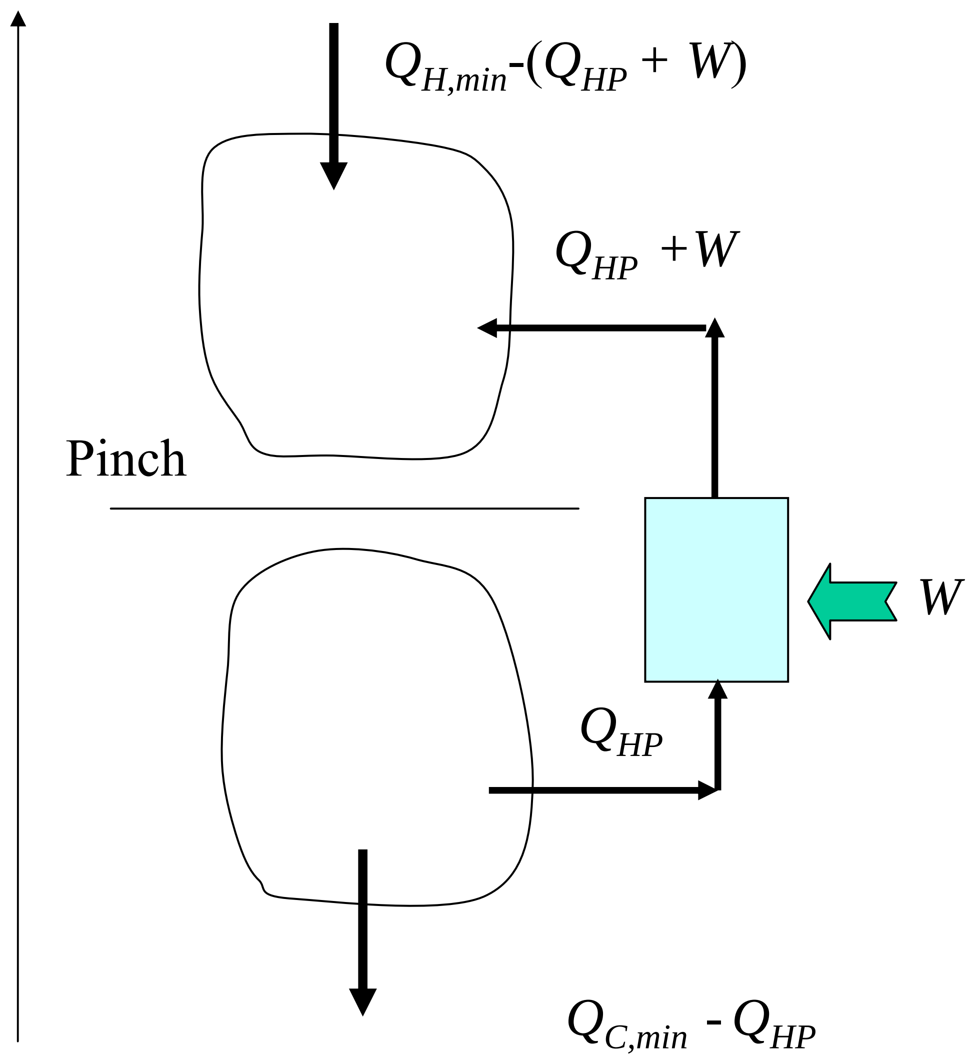
INTEGRATION WITH DISTILLATION

Placement below the pinch.



In this case there is a gain of $(Q_{cond} - Q_{reb})$ ***in the cooling utility.***

HEAT PUMPS/REFRIGERATION CYCLES



TOTAL HEN INTAKE

$Q_{H,,min} - (Q_{HP}+W)$

(smaller)

TOTAL SYSTEM INTAKE

$Q_{H,,min}$ -Q_{HP}

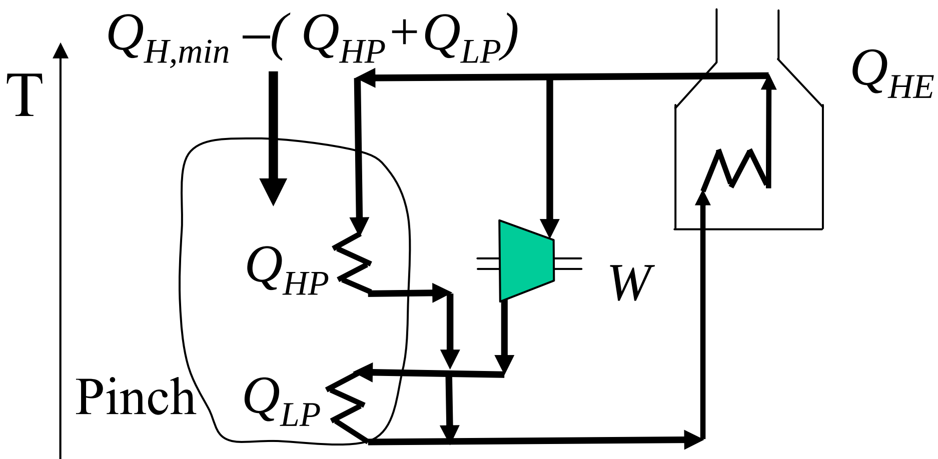
vs. $Q_{H,,min}$ +W *(separate)*

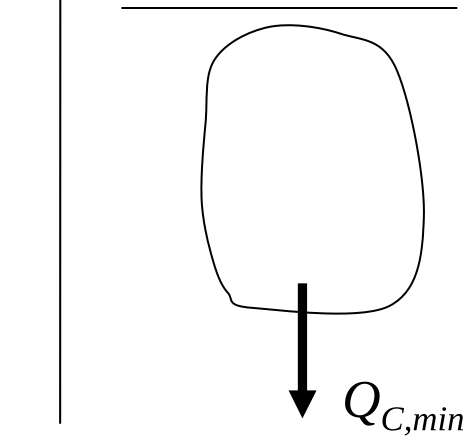
Savings in cooling utility

Q_{HP}

COMBINED HEAT AND POWER

Utility Placement





TOTAL HEN INTAKE

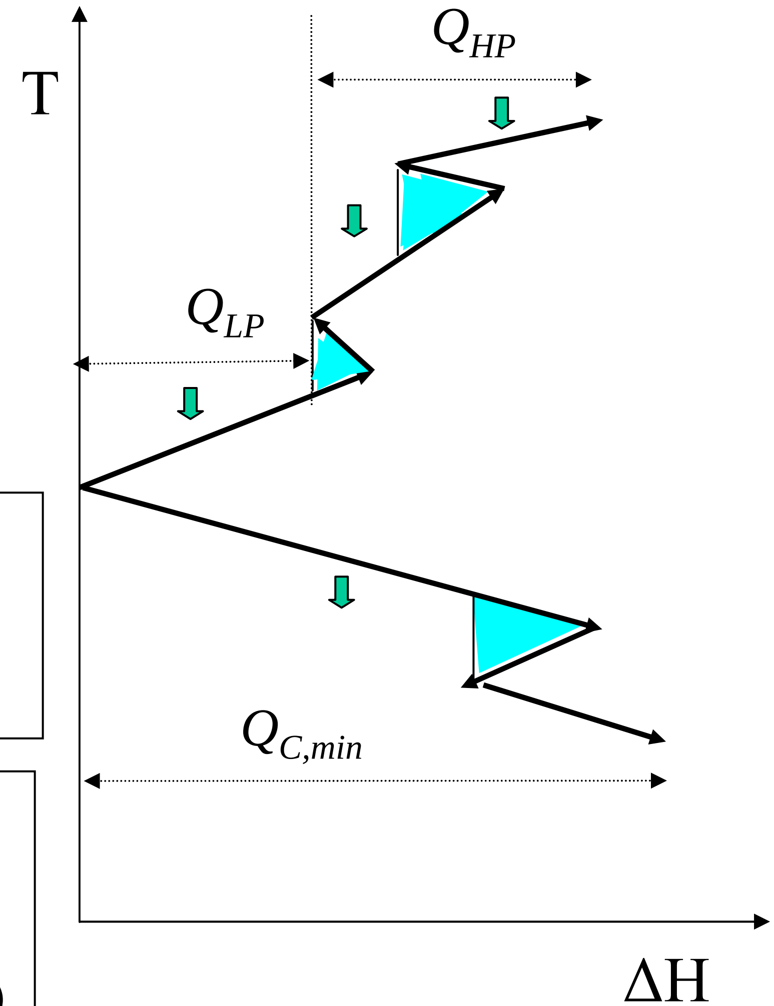
$$Q_{H,min} - (Q_{HP} + Q_{LP})$$

(smaller)

TOTAL SYSTEM INTAKE

$$Q_{H,min} + W$$

vs. $Q_{H,min} + W + (Q_{HP} + Q_{LP})$
(separate)



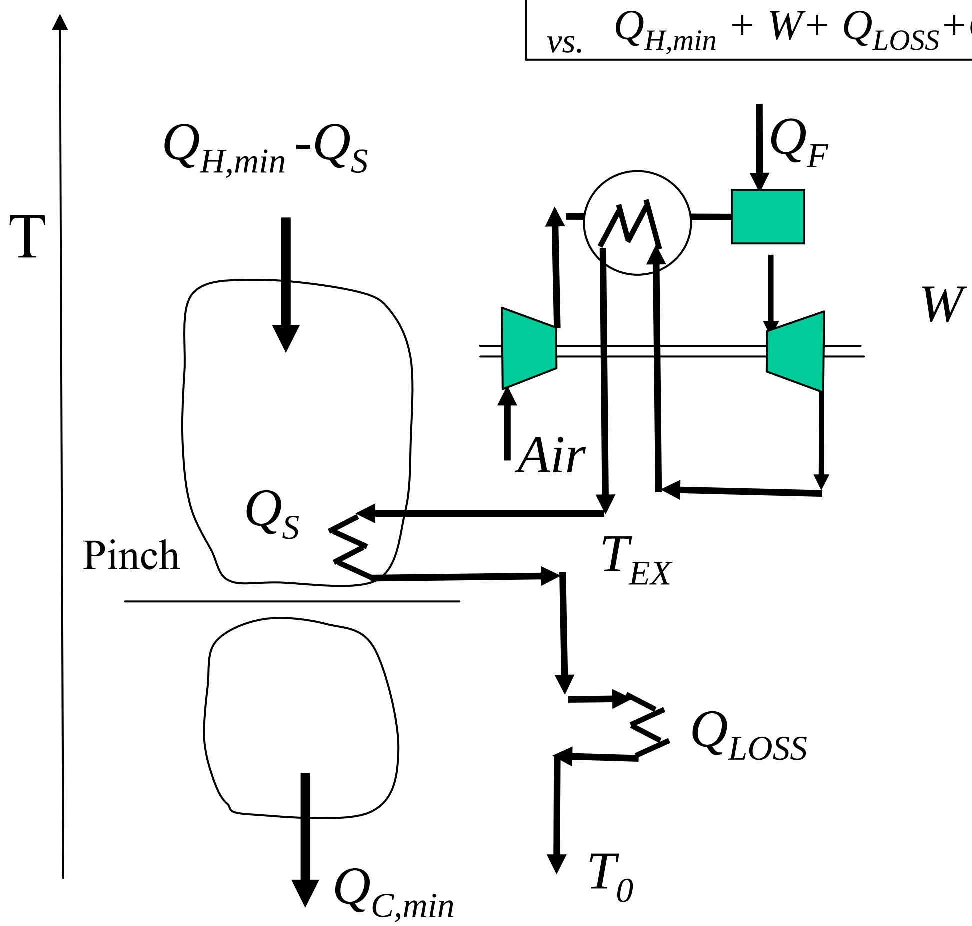
COMBINED HEAT AND POWER

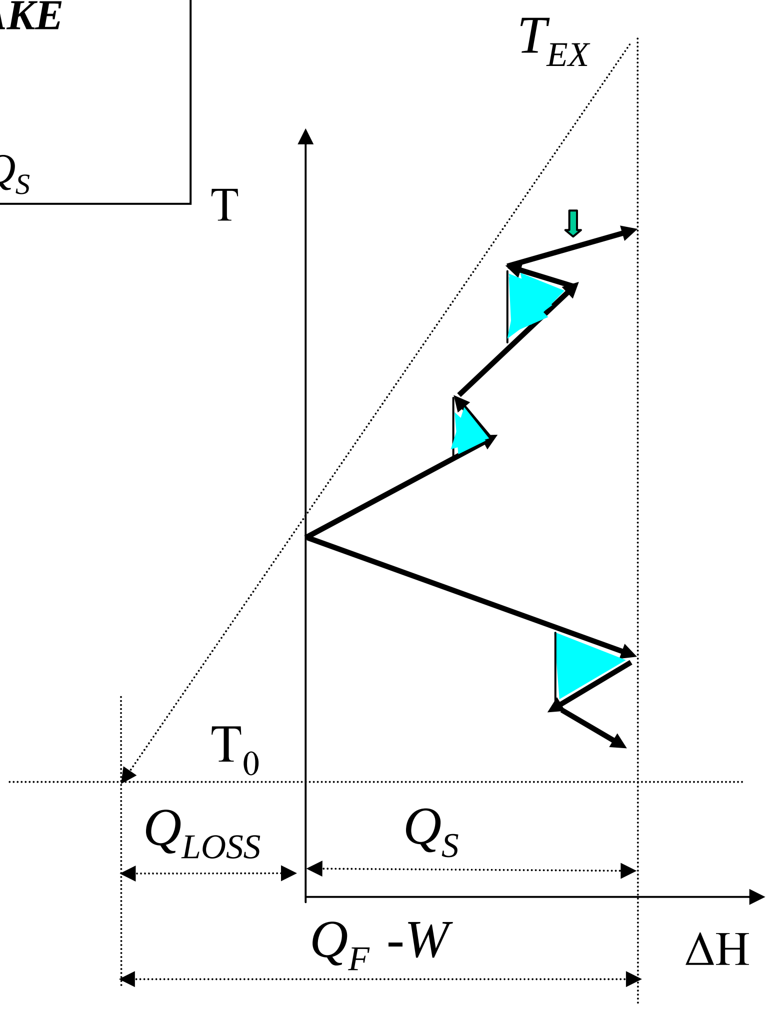
Gas Turbine Placement

TOTAL ENERGY INTAKE

$Q_{H,min} + W + Q_{LOSS}$

vs. $Q_{H,min} + W + Q_{LOSS} + Q_S$



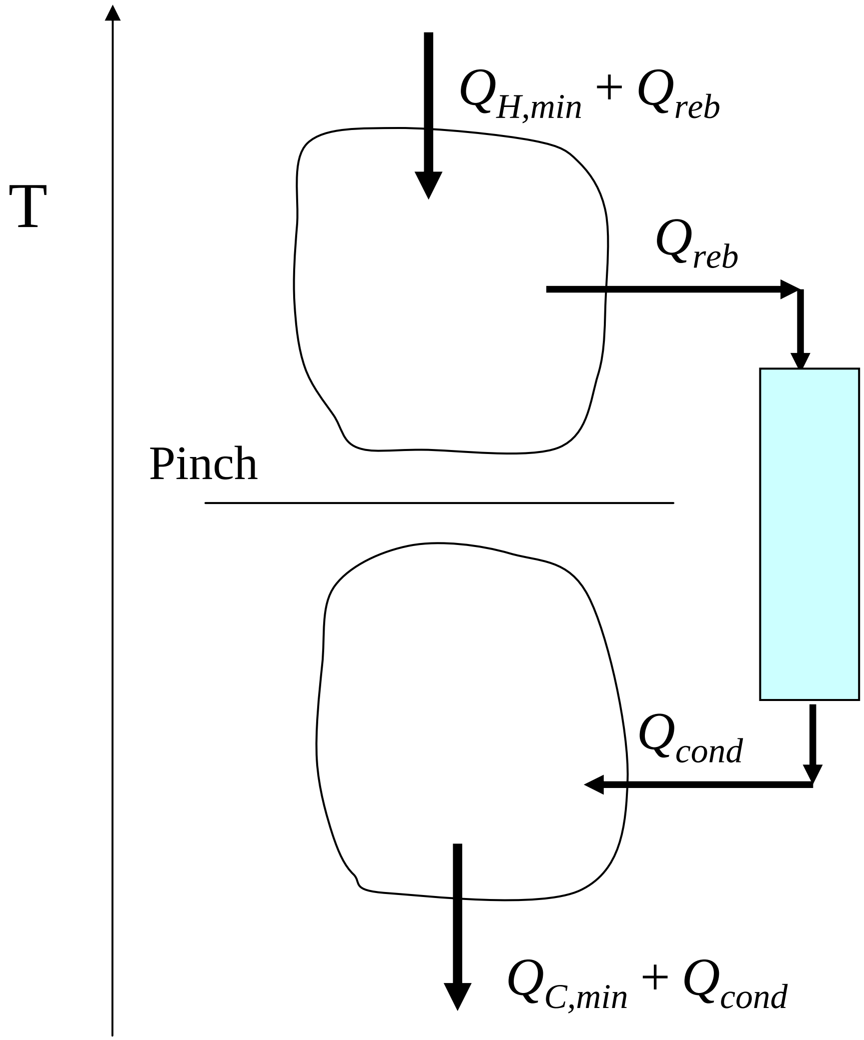


PART 5

DISTILLATION PLACEMENT

PLACEMENT OF DISTILLATION

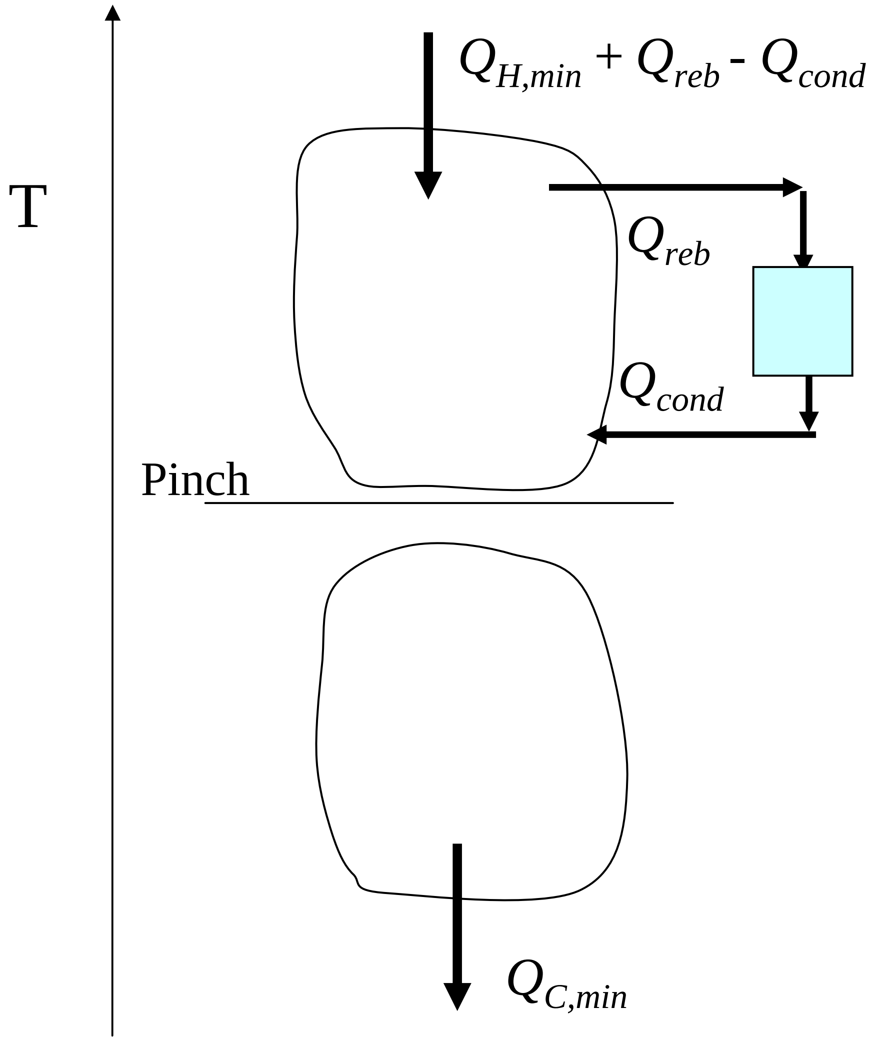
Placement across the pinch.



Note that in this case there is no gain. The distillation column can be arranged separately and the utility usage will not change.

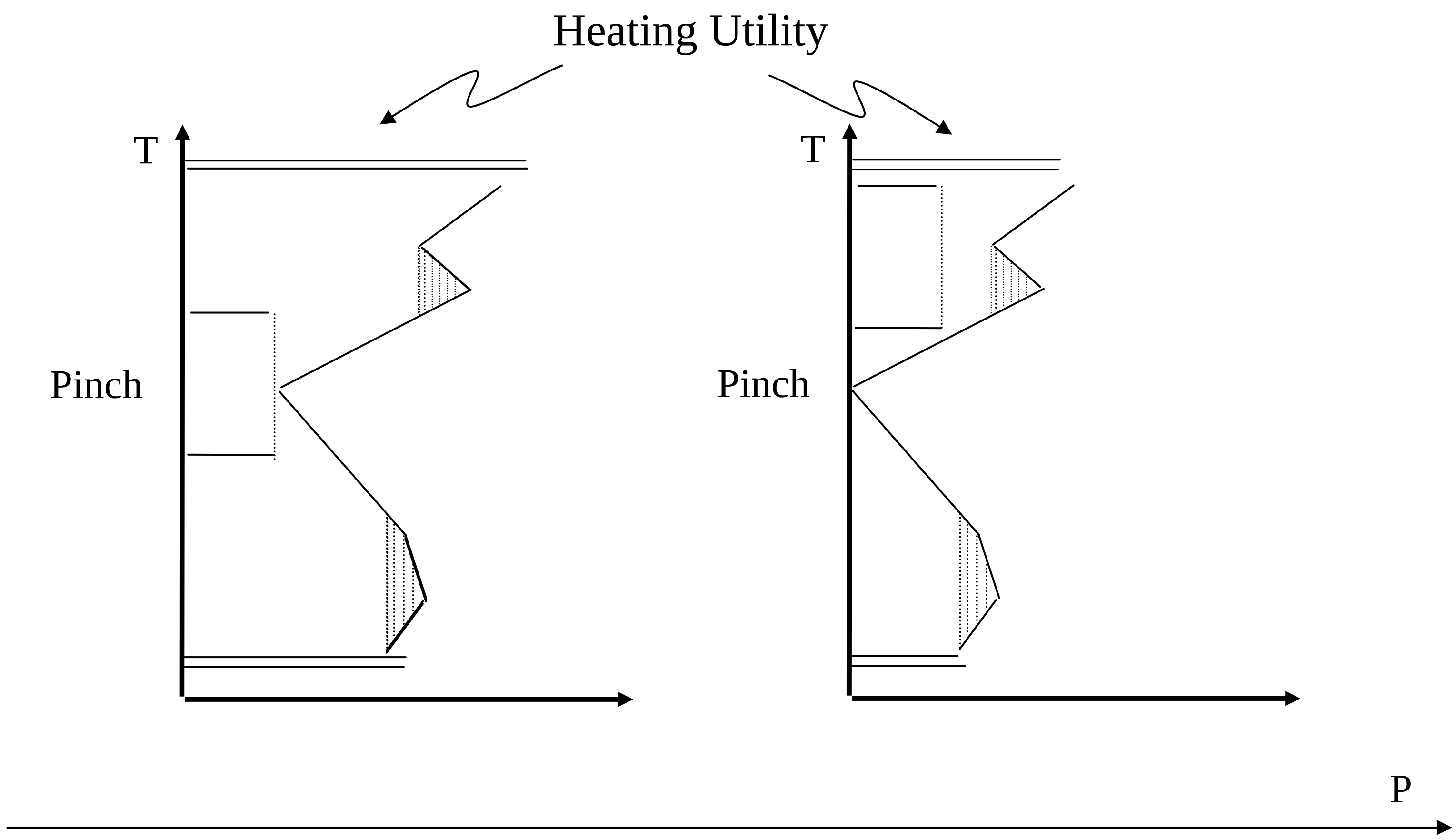
PLACEMENT OF DISTILLATION

Placement above the pinch.



Note that in this case there is a possible gain in the heating utility.

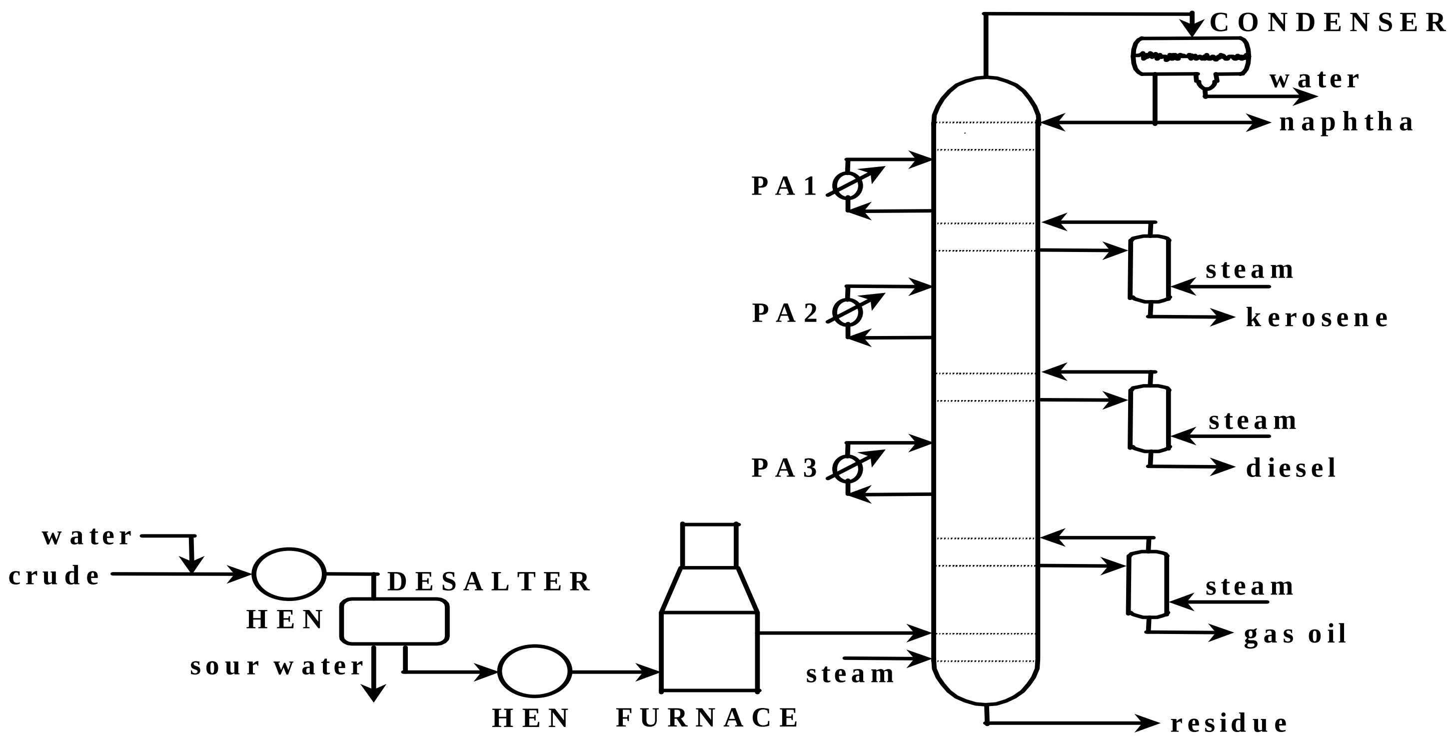
ADJUSTING PRESSURE FOR PROPER PLACEMENT



As pressure increases utility usage decreases.

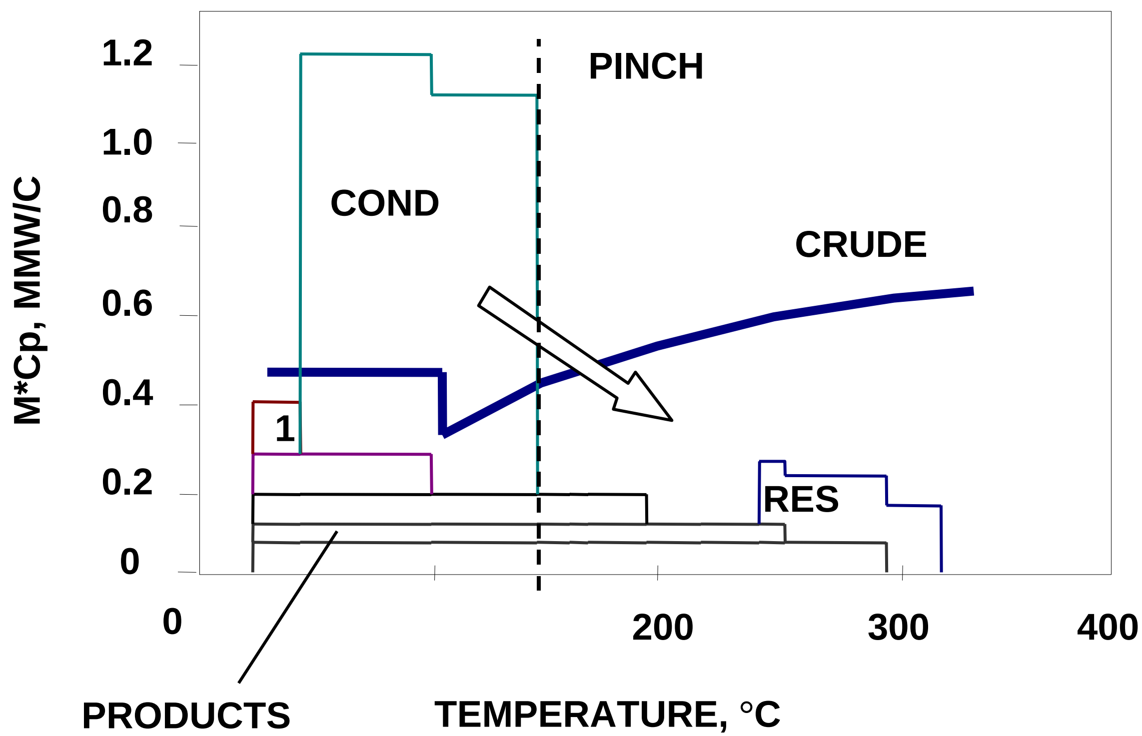
CRUDE FRACTIONATION EXAMPLE

- **We now show a complete analysis of an atmospheric crude fractionation unit. We start with the supply demand diagram**



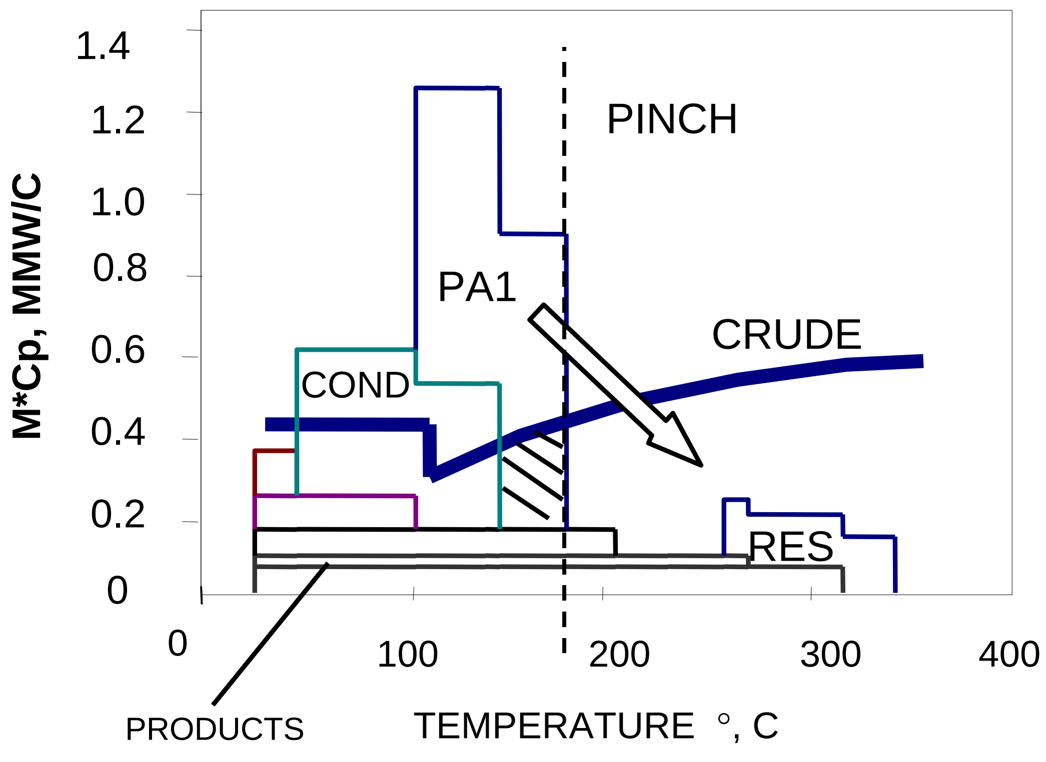
CRUDE FRACTIONATION EXAMPLE

- We now show how to determine the heat load of pumparounds.
- We start with a column with no pumparound (results from are from a rigorous simulation)



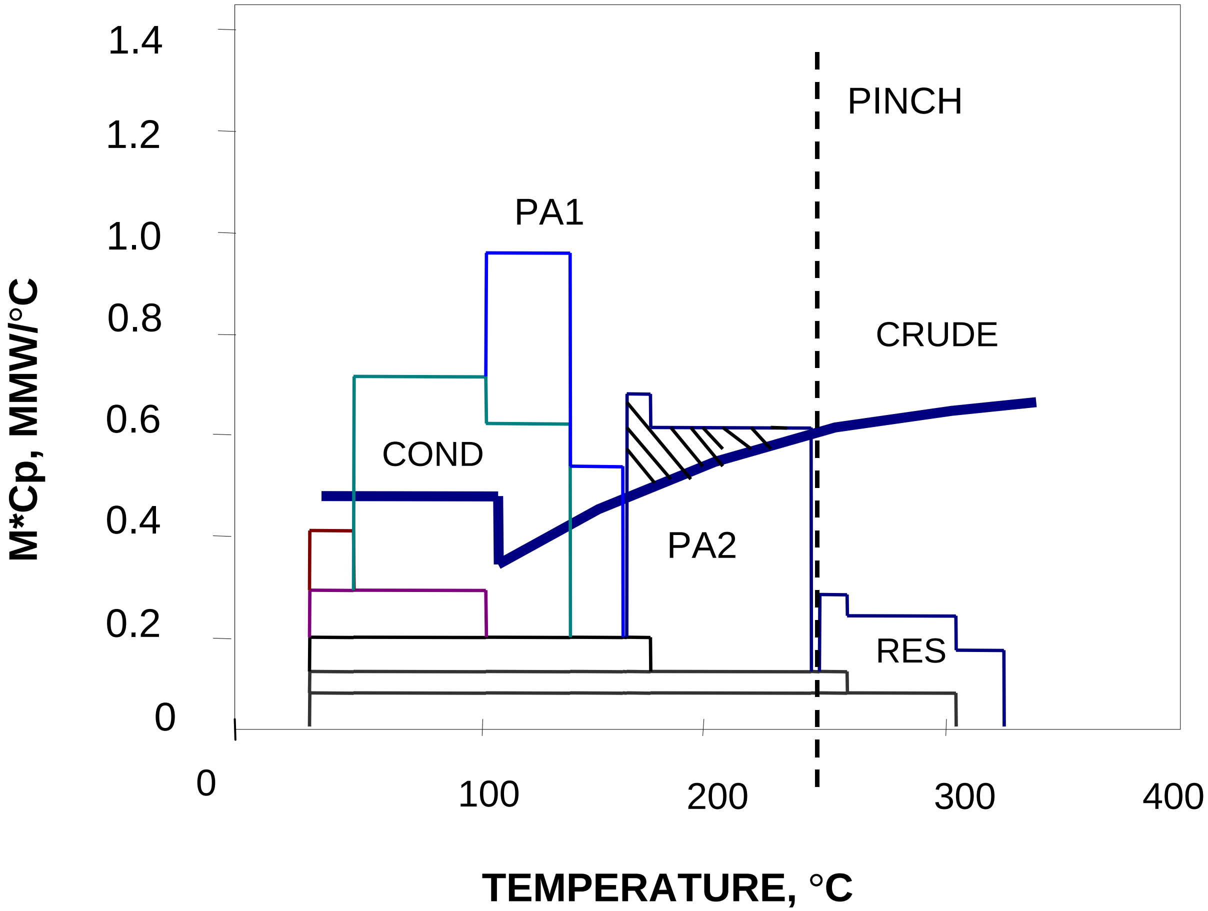
CRUDE FRACTIONATION EXAMPLE

- We move as much heat from the condenser to the first pumparound as possible. The limit to this will be when a plate dries up. If the gap worsens to much, steam is added.



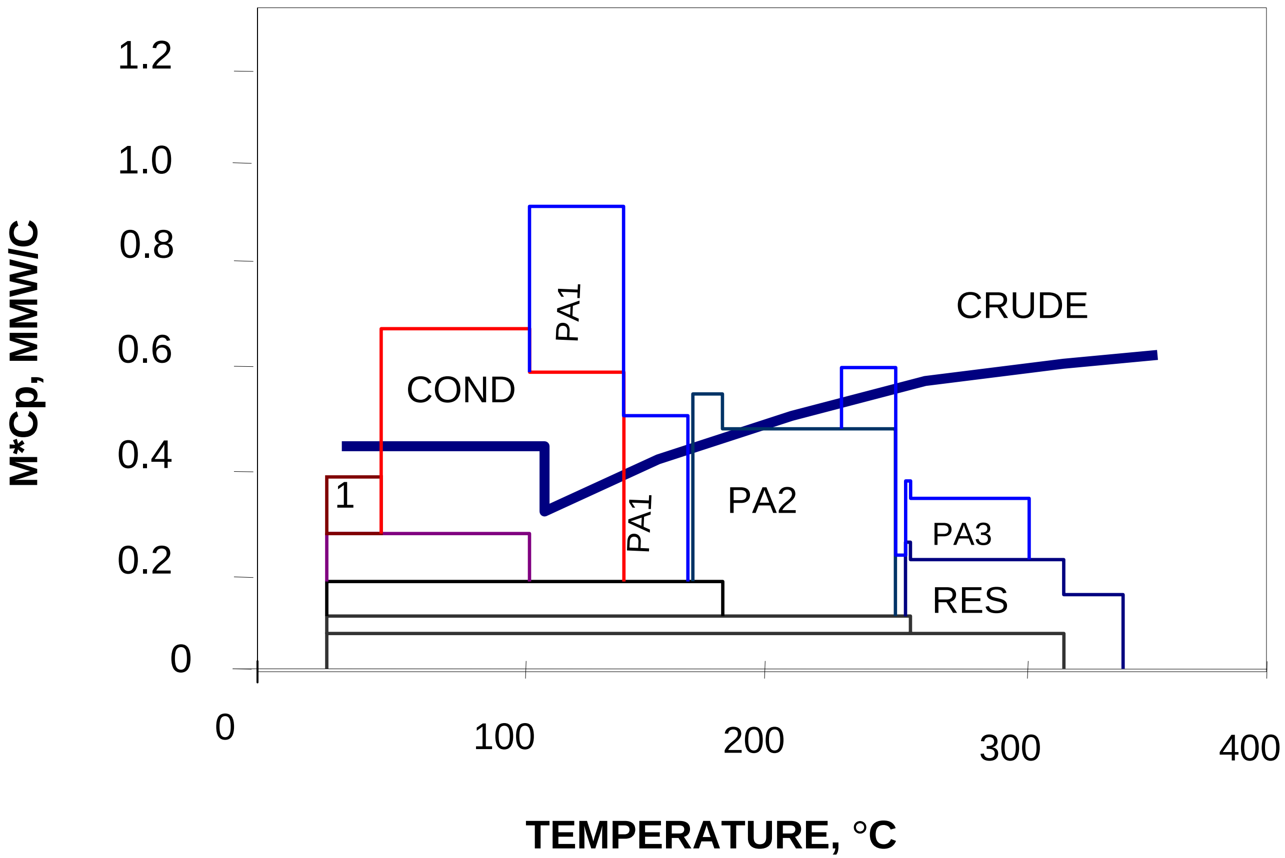
CRUDE FRACTIONATION EXAMPLE

- We continue in this fashion until the total utility reaches a minimum. .



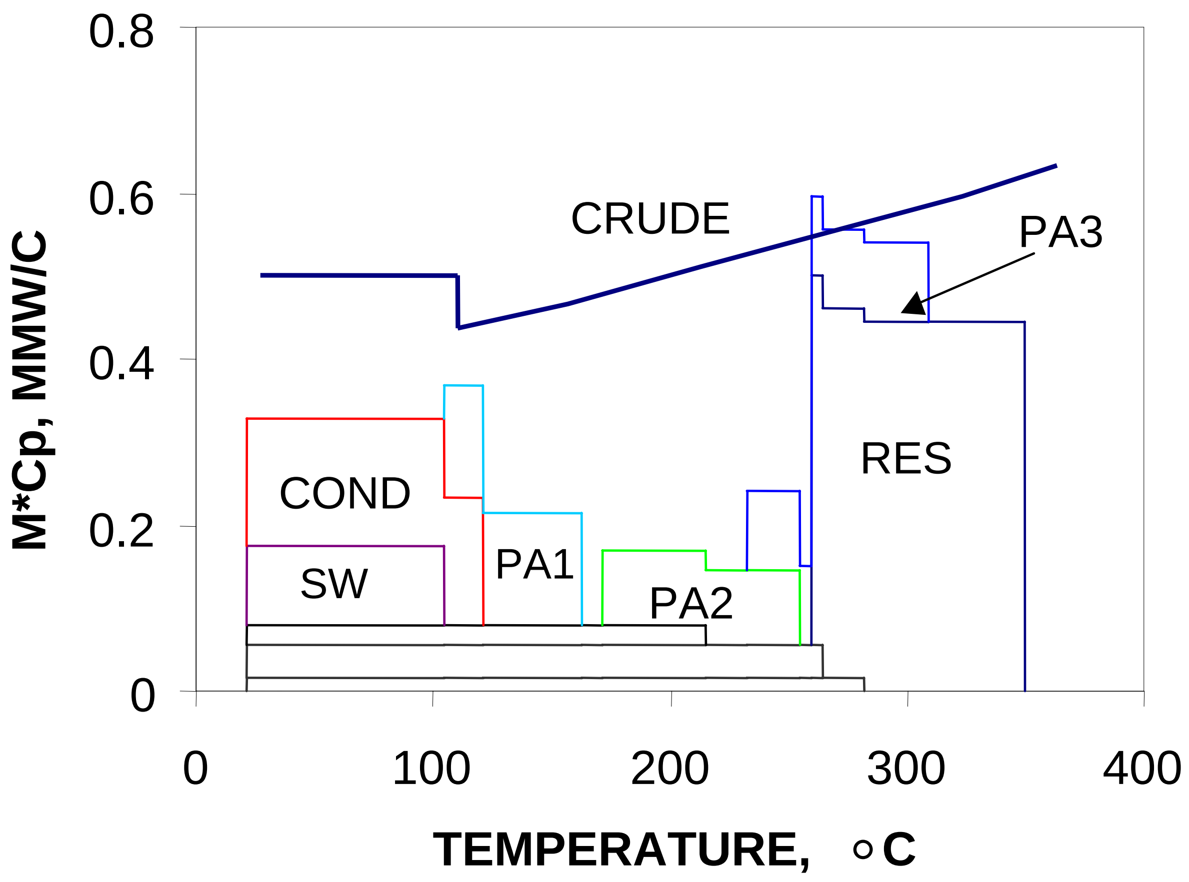
CRUDE FRACTIONATION EXAMPLE

- Especially when moving heat from PA2 to PA3, steam usage increases so that the flash point of products is correct and the gap is within limits.



CRUDE FRACTIONATION EXAMPLE

- Situation for a heavy crude



PART 6

ENERGY RELAXED NETWORKS

ENERGY RELAXATION

Energy relaxation is a name coined for the procedure of allowing the energy usage to increase in exchange for at least one of the following effects :

a) a reduction in area
b) a reduction in the number of heat exchangers
c) a reduction in complexity (typically less splitting)

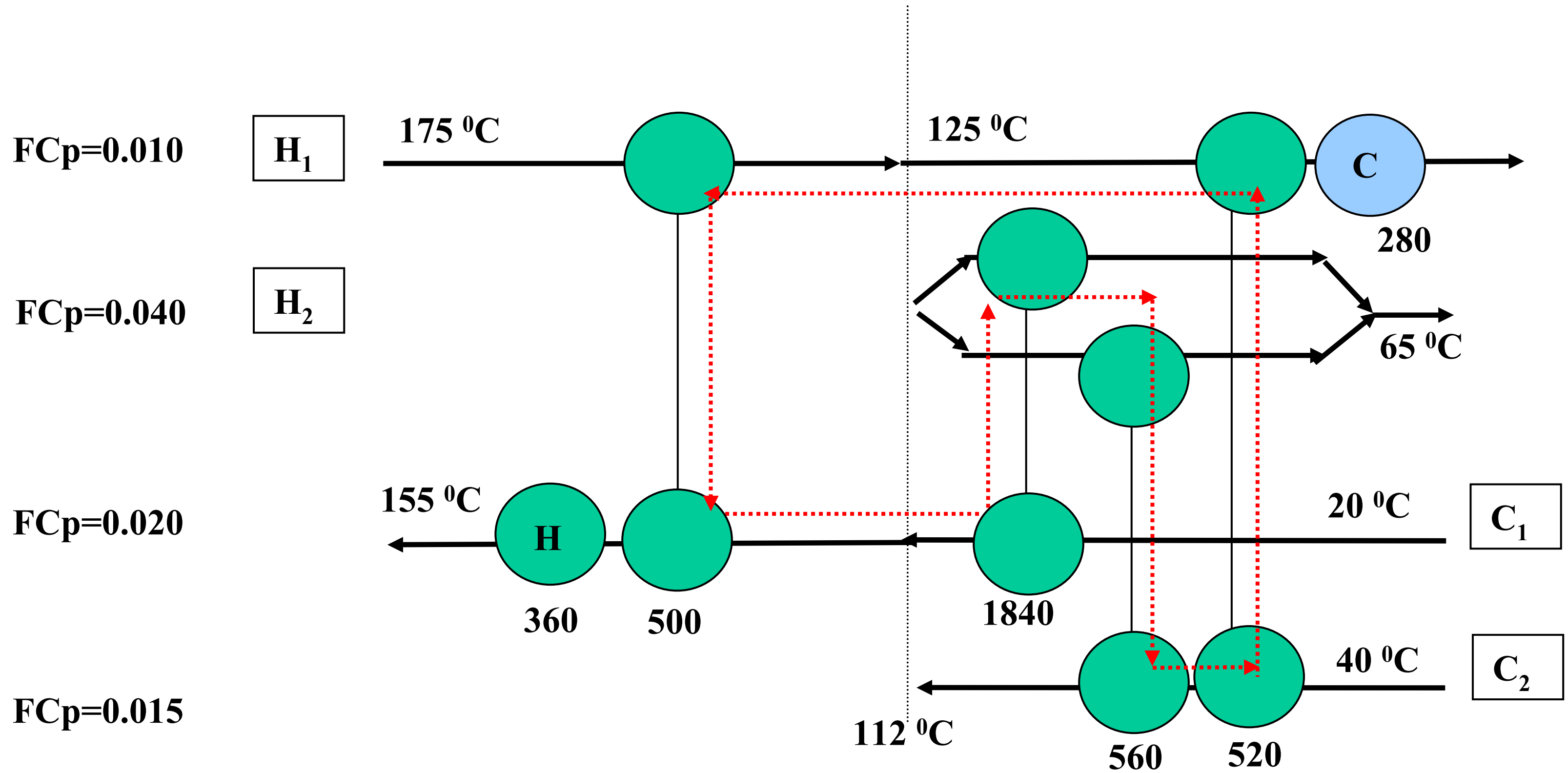
ENERGY RELAXATION IN THE PINCH DESIGN METHOD

- LOOP: A loop is a circuit through the network that starts at one exchanger and ends in the same exchanger

- PATH: A path is a circuit through the network that starts at a heater and ends at a cooler

ENERGY RELAXATION

- Illustration of a Loop

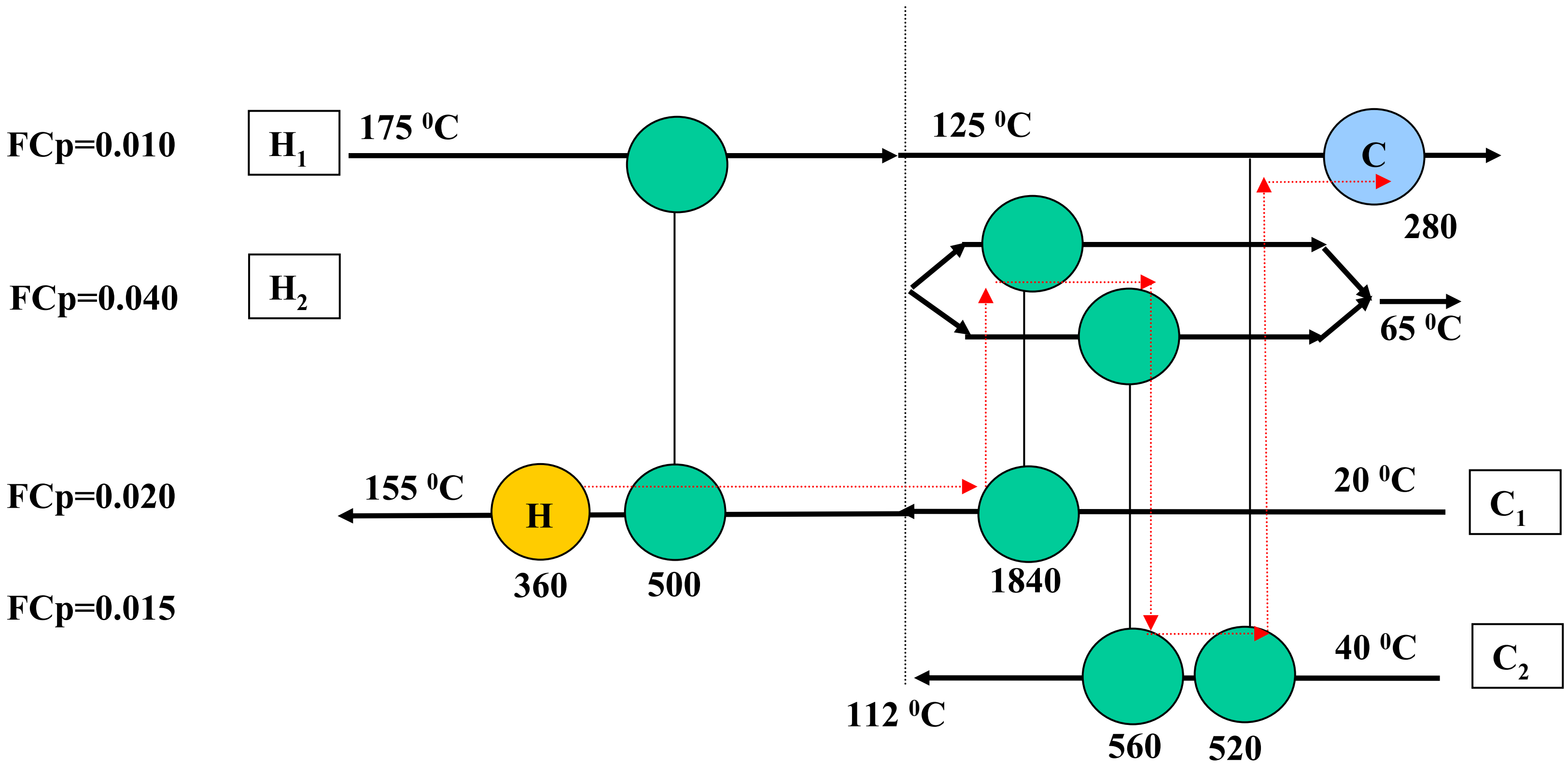


(*) Heat exchanger loads are in kW

ΔTmin=13 °C

ENERGY RELAXATION

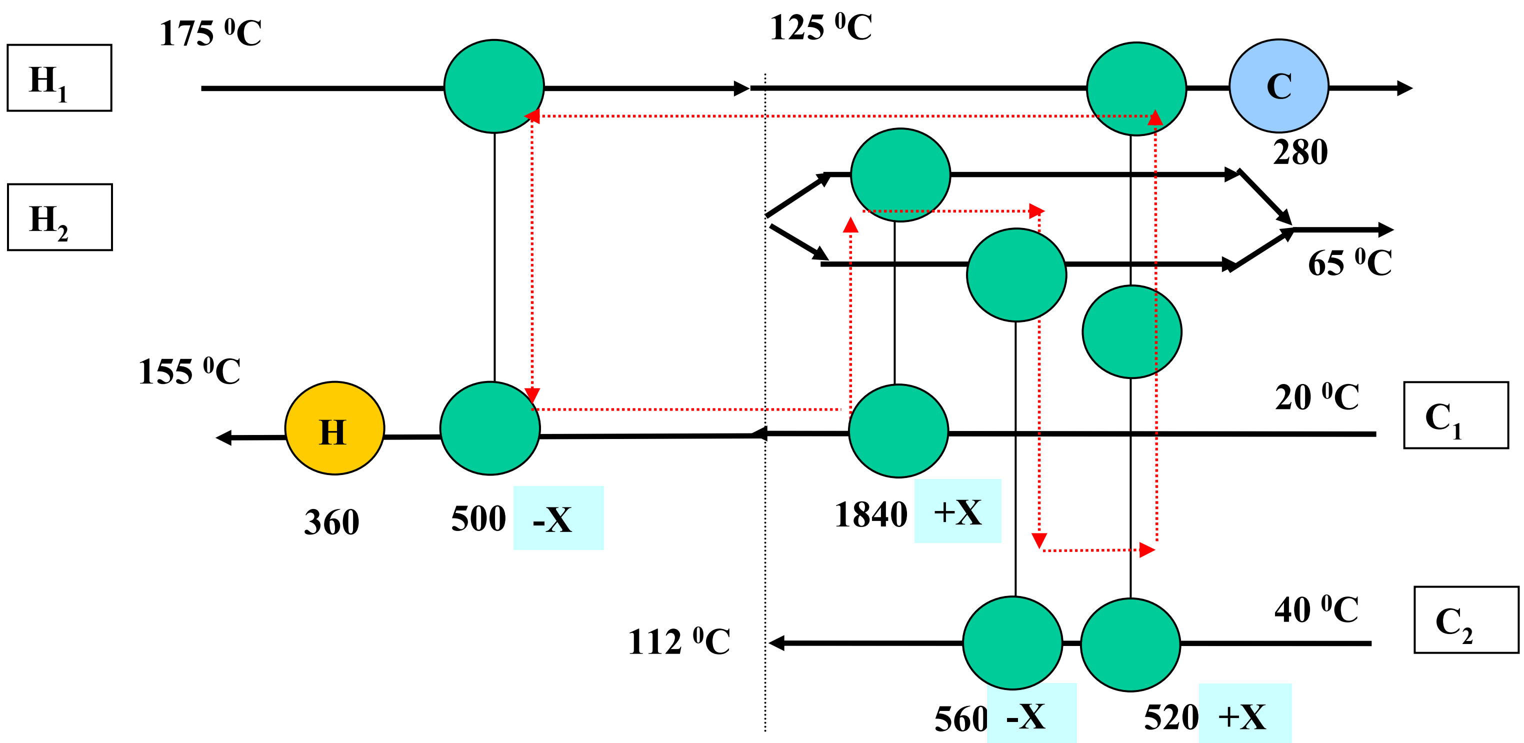
- Illustration of a Path



(*) Heat exchanger loads are in kW

ENERGY RELAXATION

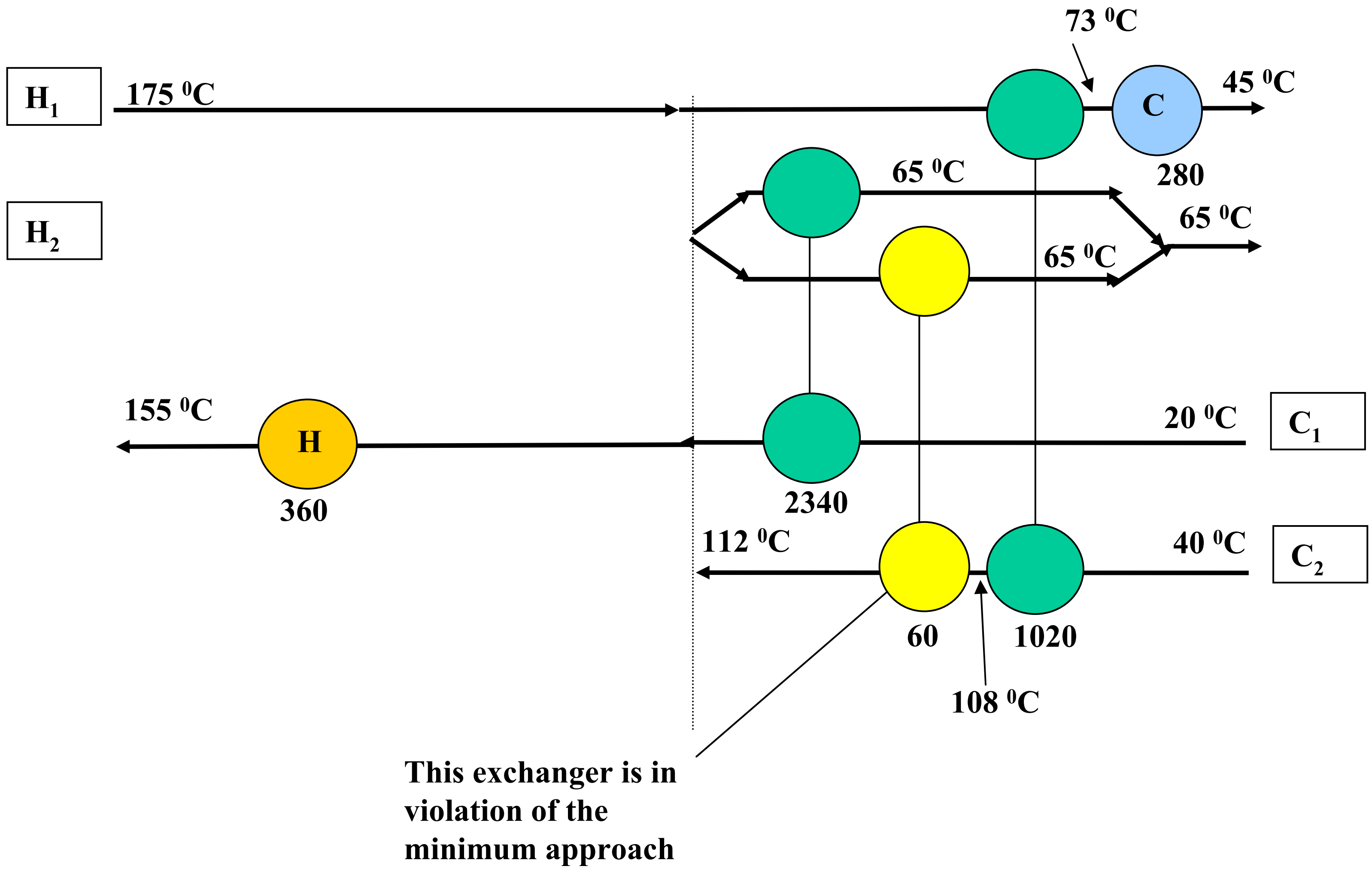
- Procedure : Find a loop and move around heat from exchanger to exchanger until one exchanger is eliminated.



- If one wants to eliminate one exchanger: X=500. Note that X could have been negative, but we chose the smallest possible in absolute value.

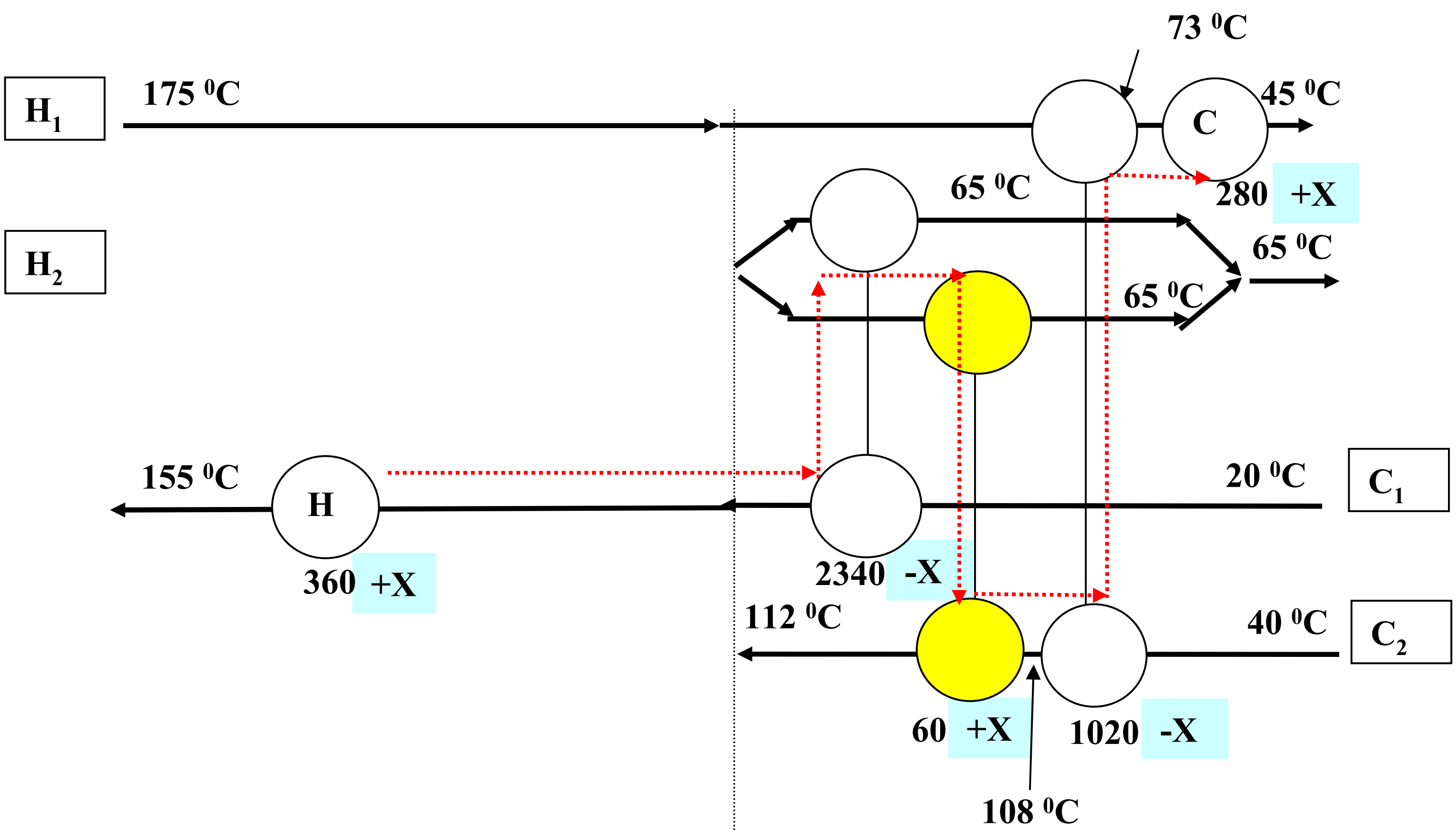
ENERGY RELAXATION

- Result: Notice that the result is infeasible!!!



ENERGY RELAXATION

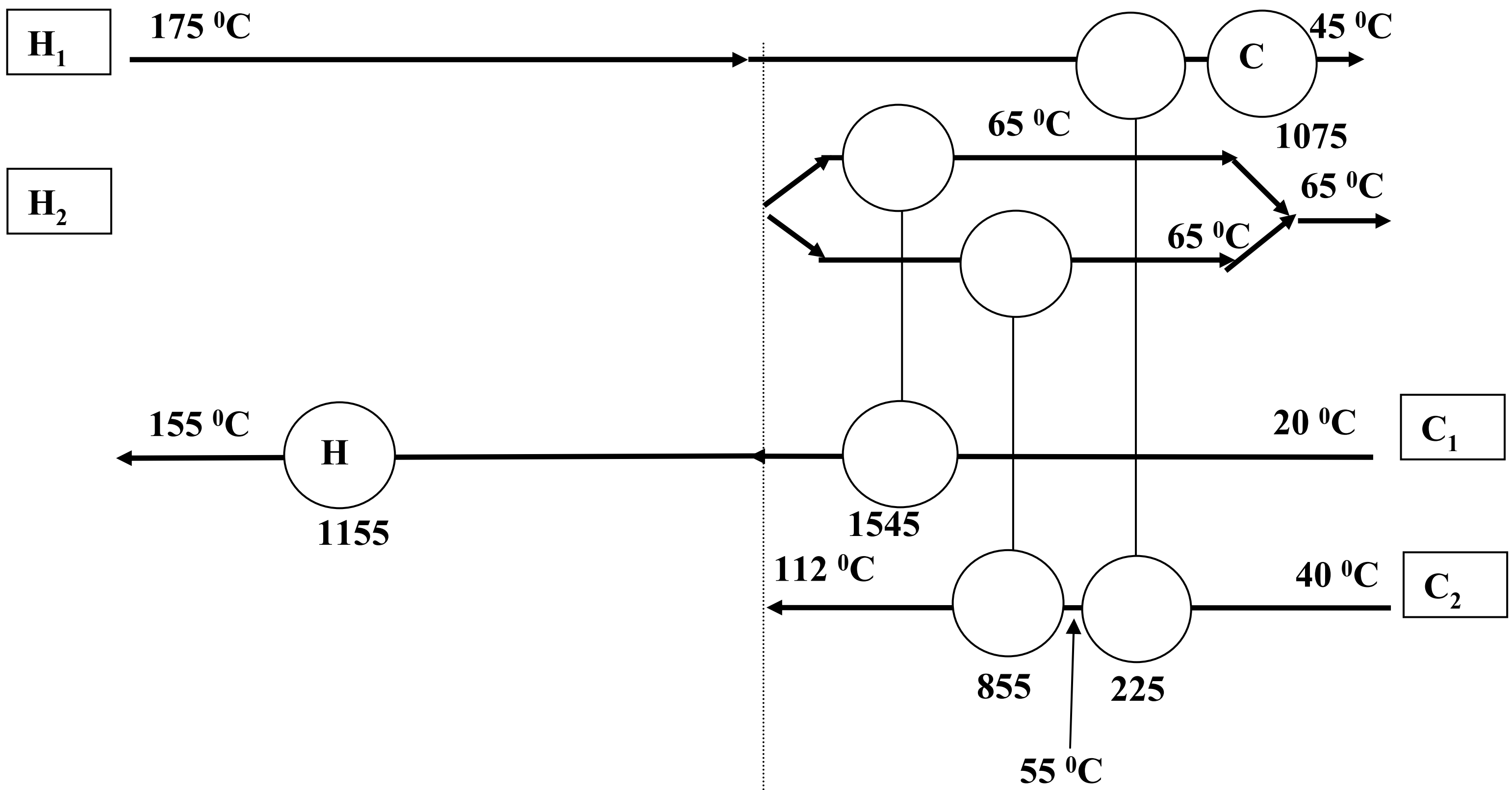
- We use a path to move heat around to restore feasibility



The value of X needed to restore feasibility is X=795

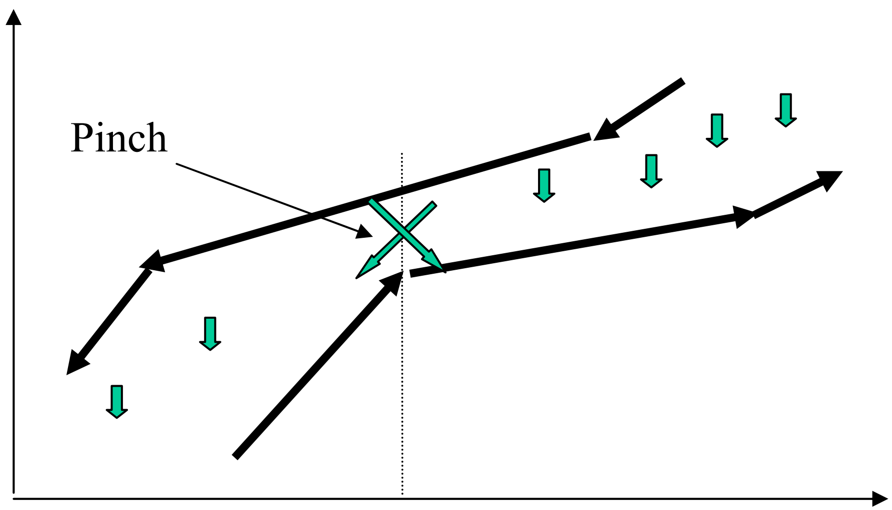
ENERGY RELAXATION

- Final Network



TEMPERATURE APPROACH (ΔT) RELAXATION

- We recall stating "NO HEAT ACROSS THE PINCH".
- Being more specific, we should say, "NO ***NET*** HEAT ACROSS THE PINCH". Thus we allow the following situations.



as long as the ***NET*** heat transferred across the pinch is zero.

However this implies allowing the temperature difference to be lower than ΔT_{min}

ΔT RELAXATION

- We thus define two types of Minimum Temperature Approach.

- HRAT: (Heat Recovery Approach Temperature): This is the ΔT_{min} we use to calculate minimum utility.

- EMAT: (Exchanger Minimum Approach Temperature): This is the minimum approach we will allow in heat exchangers.

When EMAT< HRAT networks can have

1. less splitting
2. less number of units
3. No significant increase in the total area.

ΔT RELAXATION

Consider the following problem

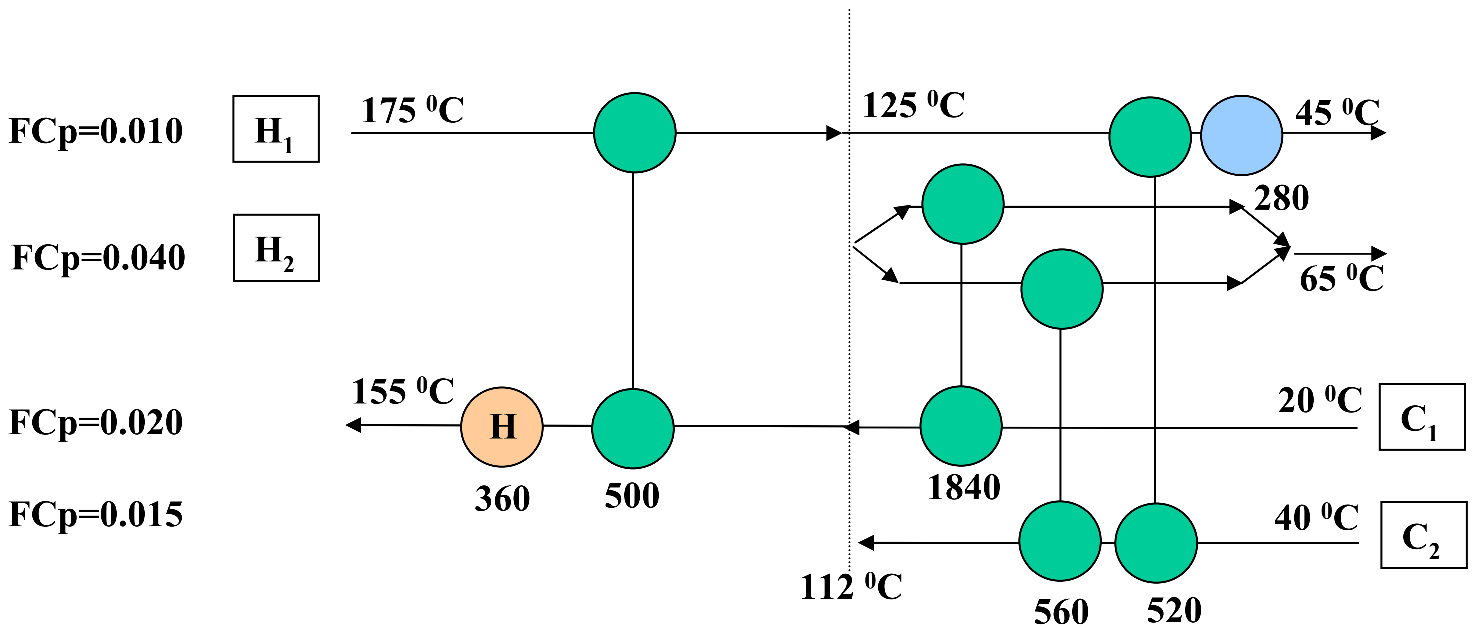
Stream	Type	Supply T (^oC)	Target T (^oC)	F*Cp ($MW\ ^oC^{-1}$)
H1	Hot	175	45	0.010
H2	Hot	125	65	0.040
C1	Cold	20	155	0.020
C2	Cold	40	112	0.015

We now consider HRAT=20 ^oC and EMAT= 13 ^oC. The corresponding minimum utility are:

ΔT_{min}	***Hot Utility***	***Cold Utility***	***Pinch***
20 (HRAT)	0.605 MW	0.525 MW	132 ^OC
13 (EMAT)	0.360 MW	0.280 MW	112 ^OC

PSEUDO-PINCH METHOD

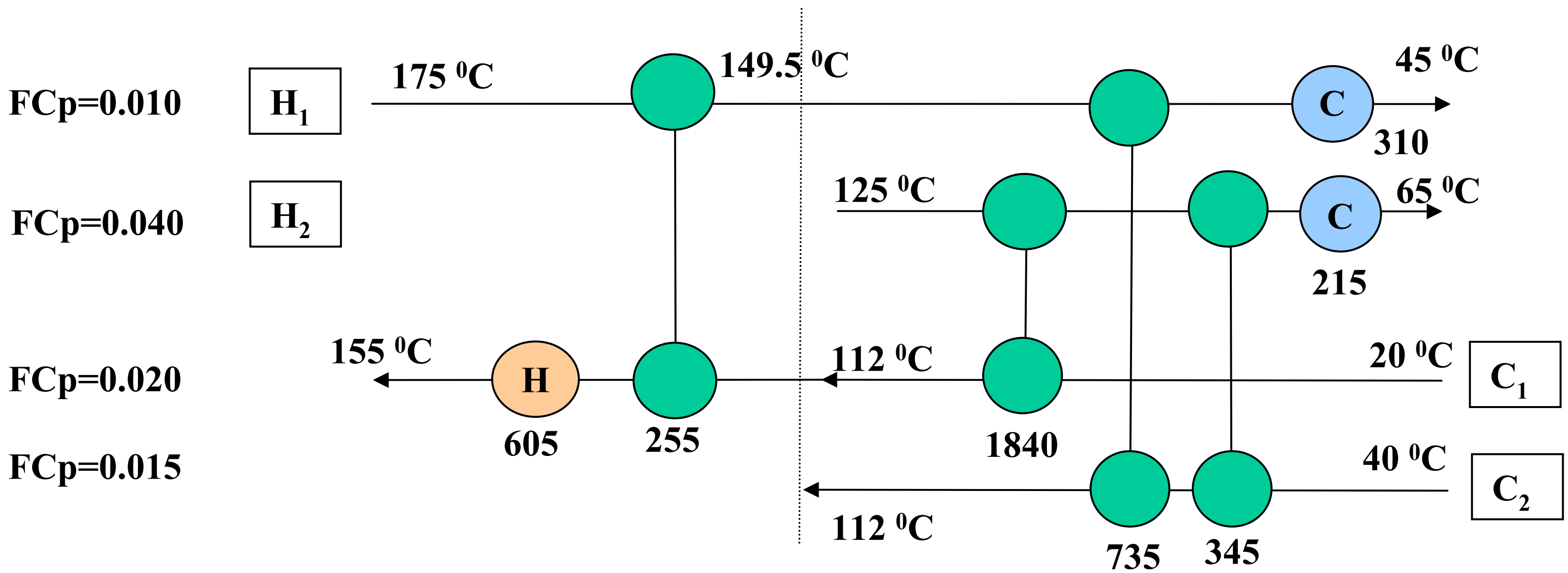
We now consider that the difference (245 kW= 605 kW-360 kW) needs to go across the pinch of a design made using EMAT. Thus we first look at the solution of the pinch design method (PDM) for ΔT_{min} =13 °C



(*) Heat exchanger loads are in kW

PSEUDO-PINCH METHOD

To relax this network by 245 kW we extend the only heat exchanger above the pinch by this amount. We then proceed below the pinch as usual.

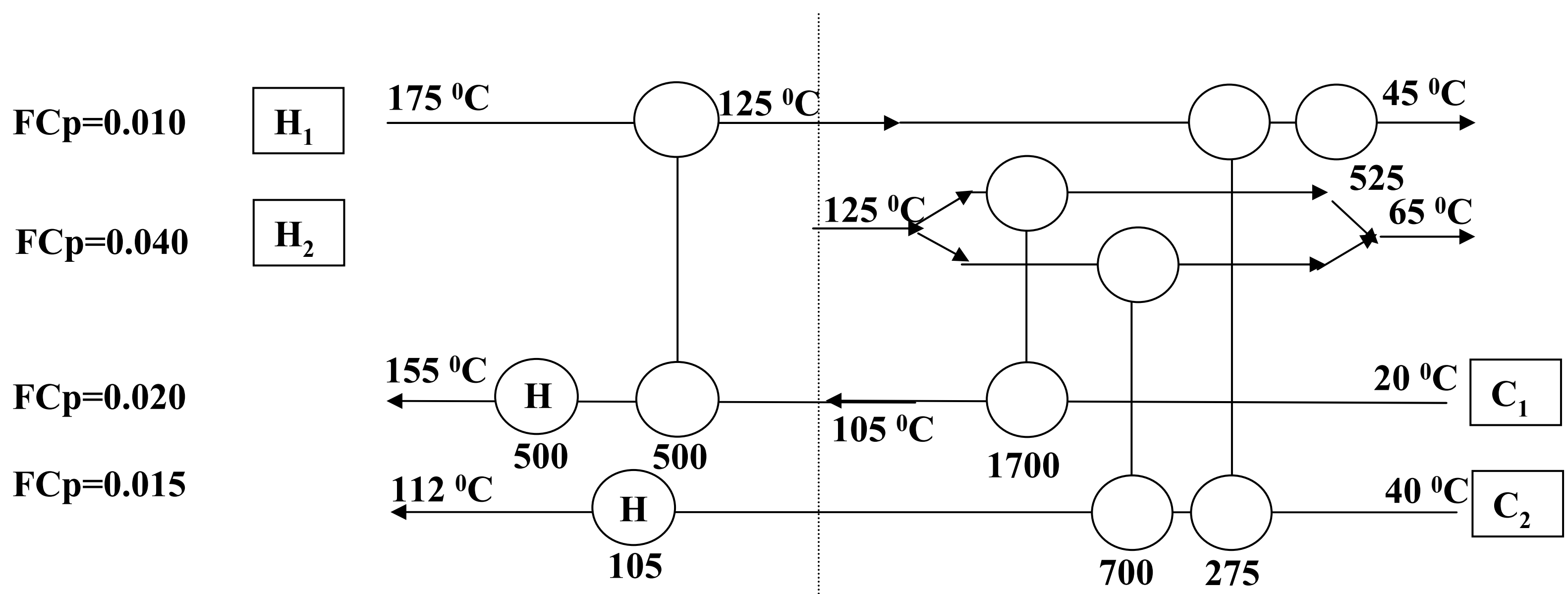


(*) Heat exchanger loads are in kW

Note that the matching rules (FCp inequalities) can be somewhat relaxed.

PSEUDO-PINCH METHOD

We know the solution of the pinch design method (PDM) for $\mathbf{\Delta T_{min}}$ =20 °C



(*) Heat exchanger loads are in kW

The PDM produces one additional split, and two heaters, while the PPDM features two coolers

DIFFICULTIES IN THE PPDM METHOD

- No clear indication what to do when there is many hot streams above the pinch. How to distribute the difference in heat?
- Even if the above is clarified it is not practical for more than a few streams.

ΔT RELAXATION USING AUTOMATIC METHODS

- One can use the Transshipment model fixing the level of hot utility and creating the intervals using EMAT instead of HRAT.
- More sophisticated methods add area estimation to the model (This has been called the Vertical model)
- The number of units can also be controlled and sophisticated techniques have been used to explore all the flowsheets with the same number of matches.
- Finally, once a flowsheet is obtained a regular optimization can be conducted.
- This will be explored in the next Part.

PART 7

MATHEMATICAL PROGRAMMING APPROACHES

RECENT REVIEW PAPER
(until 2000)

- Furman and Sahinidis. *A critical review and annotated bibliography for Heat Exchanger Network Synthesis in the 20th Century*. Ind. Eng. Chem. Res., 41 pp. 2335-2370, (2002).

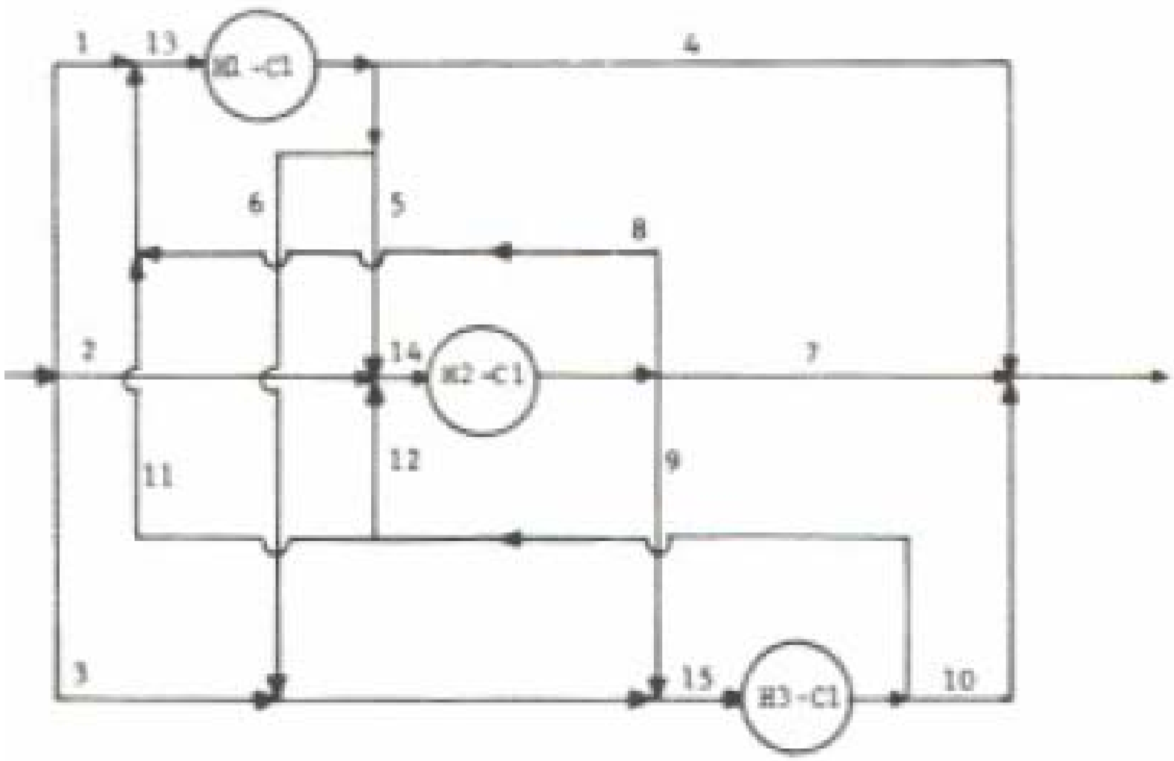
PINCH DESIGN METHOD

- It is a DECOMPOSITION approach (3 steps)
  - Perform Supertargeting and obtain the right HRAT, the pinch (or pinches) and the minimum utility usage
  - Pick matches away from the pinch using the tick-off rule
  - Evolve into higher energy consumption solutions by loop breaking and adjusting loads on paths.

SUPERSTRUCTURE APPROACH

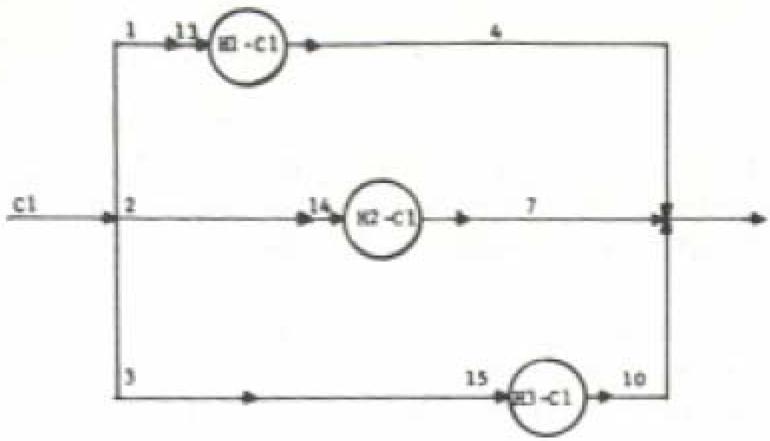
- CONCEPT: A single optimization model, if solved globally, provides all the answers simultaneously.

Superstructure of matches.

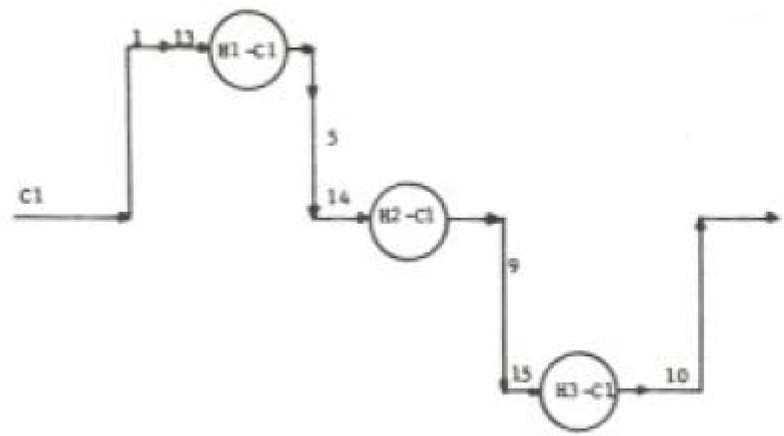


SUPERSTRUCTURE APPROACH

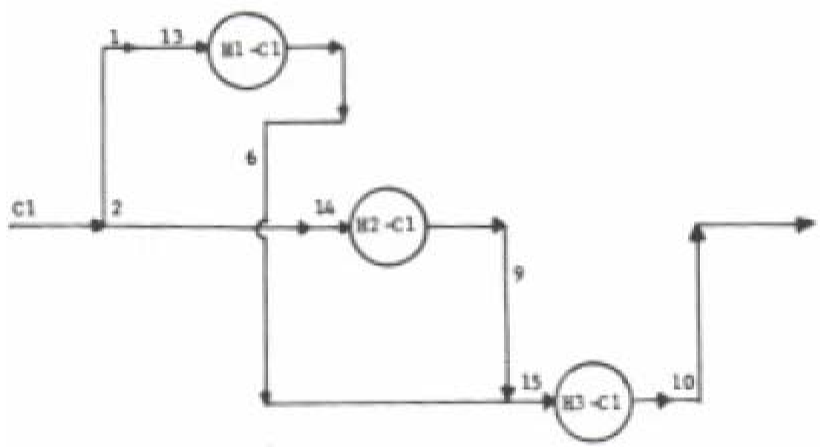
Possible flow sheets embedded **(recycles/by-passes excluded)**



(a) Sequence in parallel



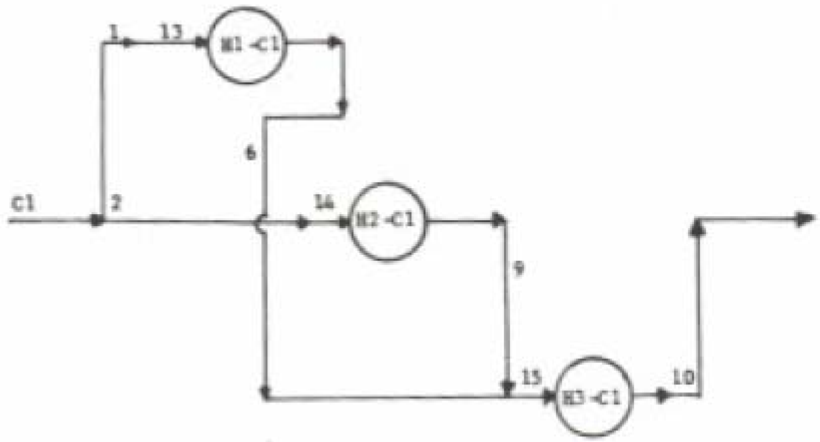
(b) Sequence in series



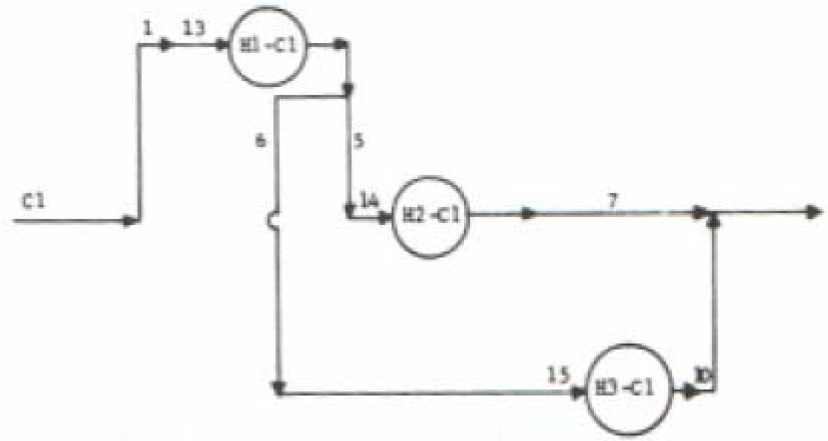
(c) Sequence in parallel-series

SUPERSTRUCTURE APPROACH

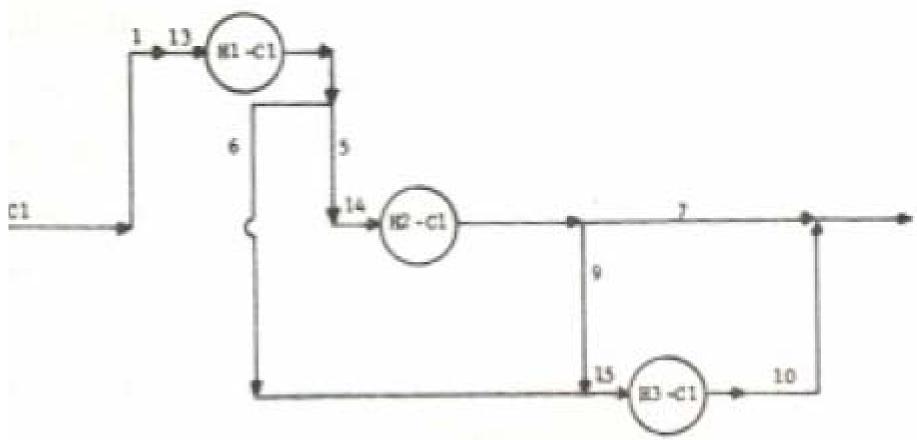
Possible flow sheets embedded (continued)



(c) Sequence in parallel-series



(d) Sequence in series-parallel



(e) Sequence in series-parallel with by-pass

SUPERSTRUCTURE APPROACH

Model Constraints

Mass Balances for Splitters

$$\sum_{\ell \in S_k^{IN}(s)} f_\ell^k - \sum_{\ell \in S_k^{OUT}(s)} f_\ell^k = 0 \quad s \in S_k \quad k \in HCT \tag{5}$$

Mass Balances for Mixers

$$\sum_{\ell \in M_k^{IN}(m)} f_\ell^k - \sum_{\ell \in M_k^{OUT}(m)} f_\ell^k = 0 \quad m \in M_k \quad k \in HCT \tag{6}$$

Heat Balances for Mixers

$$\sum_{\ell \in M_k^{IN}(m)} f_\ell^k t_\ell^k - \sum_{\ell \in M_k^{OUT}(m)} f_\ell^k t_\ell^k = 0 \quad m \in M_k \quad k \in HCT \tag{7}$$

Heat Balances for Exchangers

$$\left.\begin{array}{llll}
Q_{ij} - f_\ell^i (t_n^i - t_p^i) = 0 & & & \\
 & n \in E_{ij}^{HIN} & p \in E_{ij}^{HOUT} & i \notin HU' \\
Q_{ij} - f_\ell^i \Delta H_i^H = 0 & & & \\
 & n \in E_{ij}^{HIN} & p \in E_{ij}^{HOUT} & i \in HU' \\
Q_{ij} - f_\ell^j (t_q^j - t_r^j) = 0 & & & \\
 & q \in E_{ij}^{COUT} & r \in E_{ij}^{CIN} & j \notin CU' \\
Q_{ij} - f_\ell^j \Delta H_j^C = 0 & & & \\
 & q \in E_{ij}^{COUT} & r \in E_{ij}^{CIN} & j \in CU'
\end{array}\right\} (i,j) \in MA \tag{8}$$

Minimum Temperature Approach Constraints

$$\left.\begin{array}{lll}
t_n^i - t_q^j \geq \Delta T_{min} & n \in E_{ij}^{HIN} & q \in E_{ij}^{COUT} \\
t_p^i - t_r^j \geq \Delta T_{min} & p \in E_{ij}^{HOUT} & r \in E_{ij}^{CIN}
\end{array}\right\} (i,j) \in MA \tag{9}$$

Specifications for Inlet Heat Capacity Flow Rates

$$f_\ell^k = F_k \quad \ell \in S_k^{IN}(s^*) \quad k \in (H) \cup (C) \tag{10}$$

where

$$F_k = \{F_i, i \in H, F_j, j \in C\}$$

Specifications for Inlet and Outlet Temperatures

$$\left.\begin{array}{ll}
t_\ell^k = T_k^{IN} & \ell \in S_k^{IN}(s^*) \\
t_\ell^k = T_k^{OUT} & \ell \in M_k^{OUT}(m^*)
\end{array}\right\} k \in HCT \tag{11}$$

where

$$T_k^{IN} = \{T_i^{IN}, i \in H, T_j^{IN}, j \in C, \\ T_i^{HIN}, i \in HU', T_j^{CIN}, j \in CU'\}$$

$$T_k^{OUT} = \{T_i^{OUT}, i \in H, T_j^{OUT}, j \in C, \\ T_i^{HOUT}, i \in HU', T_j^{COUT}, j \in CU'\}$$

Equality of Temperatures for Inlets and Outlets of Splits

$$t_\ell^k = t_p^k \quad \ell \in S_k^{IN}(s), \quad p \in S_k^{OUT}(s) \quad s \in S_k \quad k \in HCT \tag{12}$$

Nonnegativity Constraints

$$f_\ell^k \geq 0 \quad \ell \in N_k \quad k \in HCT \tag{13}$$

Finally, the areas of each exchanger can be expressed in terms of the given heat loads Q_{ij} and the temperatures of the streams, that is

$$A_{ij} = Q_{ij} U_{ij}^{-1} (LMTD)_{ij}^{-1} \tag{14}$$

where U_{ij} is the overall heat transfer coefficient for the match $(i,j) \in MA$ and $(LMTD)_{ij}$ is the log mean temperature difference for the match (i,j).

Objective **(no fixed costs)** →

$$\min \sum_{(i,j) \in MA} c_{ij} A_{ij}^{b_{ij}} \tag{15}$$

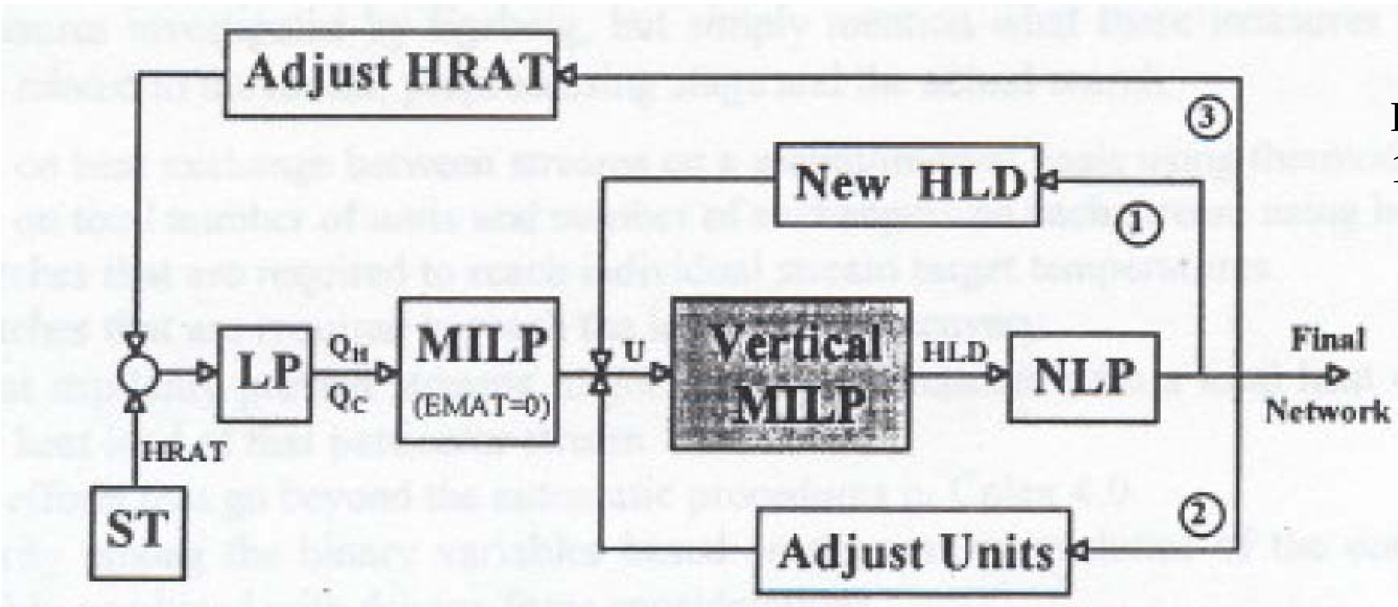
SUPERSTRUCTURE APPROACH

– This is an MINLP formulation with which several researches have struggled. (MINLP methods could not be easily solved globally until recently (?).
– Therefore it needs some initial points.

ALTOUGH A ONE-STEP CONCEPT IT BECAME IN REALITY AN ITERATIVE PROCESS

SUPERSTRUCTURE APPROACH

- Some Strategies to overcome the “curse of non-convexity”

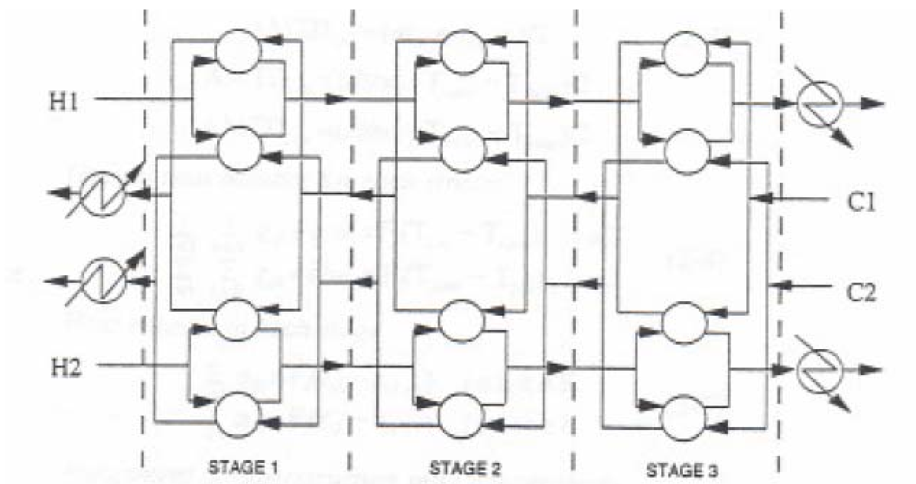


Hasemy-Ahmady et al., 1999.

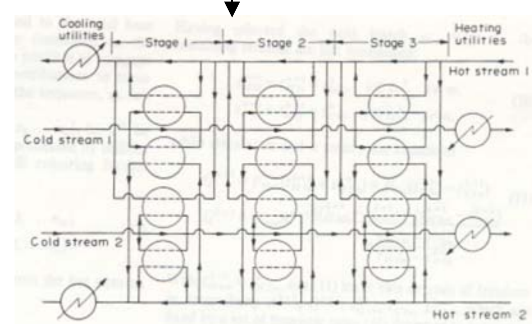
Many other methodologies attempted this goal (provide good initial points) like evolutionary algorithms, simulated annealing, etc.

STAGE SUPERSTRUCTURE APPROACH

- With isothermal mixing. Yee and Grossmann (1990, 1998)



Note on the side: This is a remarkable coming back to origins.



From Grossmann and Sargent (1978)

In the 90's the mathematical programming/ superstructure approach emerged as the dominant methodology

SUPERSTRUCTURE APPROACH

Model (P)

Indices:
i = hot process stream
j = cold process stream
k = index for stage, and temperature location
cu = cold utility
hu = hot utility
in = inlet
out = outlet

Sets
I = {i: i is a hot process stream}
J = {j: j is a cold process stream}
K = {k: k is a stage in the superstructure, $|K| = NOK$}

Parameters
$T_{i,in}$, $T_{i,out}$, $T_{j,in}$, $T_{j,out}$ = inlet and outlet temperatures
ΔT_{mapp} = minimum approach temperature differen (EMAT)
F_i, F_j = heat capacity flowrates
h_i, h_j, h_{cu}, h_{hu} = film heat transfer coefficients
$U_{i,j}$, $U_{i,cu}$, $U_{j,hu}$ = overall heat transfer coefficients
CCU = per unit cost of cold utility
CHU = per unit cost of hot utility
CF_{ij}, $CF_{i,cu}$, $CF_{j,hu}$ = fixed charges for exchangers
C_{ij}, $C_{i,cu}$, $C_{j,hu}$ = area cost coefficient

NOK = total number of stages
Ω = an upper bound for heat exchange
Γ = an upper bound for temperature difference

Positive, continuous variables
$t_{i,k}$ = temperature of hot stream i at hot end of stage k
$t_{j,k}$ = temperature of cold stream j at hot end of stage k
dt_{ijk} = temperature approach for match (i,j) at temperature location k
$dtcu_i$ = temperature approach for the match of hot stream i and cold utility
$dthu_j$ = temperature approach for the match of cold stream j and hot utility
q_{ijk} = heat exchanged between hot process stream i and cold process stream j in stage k
qcu_i = heat exchanged between hot stream i and cold utility
qhu_j = heat exchanged between cold stream j and hot utility
$AMTD_{i,j,k}$, $AMTD_{i,cu}$, $AMTD_{j,hu}$ = heat transfer driving forces

Binary variables
z_{ijk} = existence of unit for match (i,j) in stage k
zcu_i = existence of unit for match (i,cu)
zhu_j = existence of unit for match (j,hu)

Objective function

minimize

$$\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} CF_{ij}\, z_{ijk} + \sum_{i\in I} CF_{i,cu}\, zcu_i + \sum_{j\in J} CF_{j,hu}\, zhu_j + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} C_{ij}[q_{ijk}/(U_{i,j}\, AMTD_{i,j,k})] + \sum_{i\in I} C_{i,cu}[qcu_i/(U_{i,cu}\, AMTD_{i,cu})] + \sum_{j\in J} C_{j,hu}[qhu_j/(U_{j,hu}\, AMTD_{j,hu})] + \sum_{i\in I} CCU qcu_i + \sum_{j\in J} CHU qhu_j \qquad (2\text{-}1)$$

where

$$U_{i,j} = [1/h_i + 1/h_j]^{-1} \qquad (2\text{-}2)$$
$$U_{i,cu} = [1/h_i + 1/h_{cu}]^{-1}$$
$$U_{j,hu} = [1/h_j + 1/h_{hu}]^{-1}$$

From Grosmann and Sargent (1978)

SUPERSTRUCTURE APPROACH

$$AMTD_{i,j,k}=(dt_{ijk}+dt_{ijk+1})/2 \qquad (2\text{-}3)$$

$$AMTD_{i,cu}=(dtcu_i+T_{i,out}-T_{cu,in})/2$$

$$AMTD_{j,hu}=(dthu_j+T_{hu,in}-T_{j,out})/2$$

Overall heat balance for each stream

$$\begin{aligned} &\sum_{j\in J}\sum_{k\in K} q_{ijk}+qcu_i=F_i(T_{i,in}-T_{i,out}) && i\in I \\ &\sum_{i\in I}\sum_{k\in K} q_{ijk}+qhu_j=F_j(T_{j,out}-T_{j,in}) && j\in J \end{aligned} \qquad (2\text{-}4)$$

Heat balance at each stage

$$\begin{aligned} &\sum_{j\in J} q_{ijk}=F_i(t_{i,k}-t_{i,k+1}) && i\in I,\ k\in K \\ &\sum_{i\in I} q_{ijk}=F_j(t_{j,k}-t_{j,k+1}) && j\in J,\ k\in K \end{aligned} \qquad (2\text{-}5)$$

Assignment of superstructure inlet temperatures

$$t_{i,1}=T_{i,in} \qquad i\in I \qquad (2\text{-}6)$$

Monotonic decrease in temperatures

$$\begin{aligned} &t_{i,k}\geq t_{i,k+1} && i\in I,\ k\in K \\ &t_{i,NOK+1}\geq T_{i,out} && i\in I \\ &t_{j,k}\geq t_{j,k+1} && j\in J,\ k\in K \\ &T_{j,out}\geq t_{j,1} && j\in J \end{aligned} \qquad (2\text{-}7)$$

Hot and cold utilities load

$$\begin{aligned} &qcu_i=F_i(t_{i,NOK+1}-T_{i,out}) && i\in I \\ &qhu_j=F_j(T_{j,out}-t_{j,1}) && j\in J \end{aligned} \qquad (2\text{-}8)$$

Minimum approach temperature constraints

$$\begin{aligned} &dt_{ijk}\geq \Delta T_{mapp} && i\in I,\ j\in J,\ k\in K\cup\{NOK+1\} \\ &dtcu_i\geq \Delta T_{mapp} && i\in I, \\ &dthu_j\geq \Delta T_{mapp} && j\in J \end{aligned} \qquad (2\text{-}9)$$

Logical constraints

$$\begin{aligned} &q_{ijk}\leq \Omega z_{ijk} && i\in I,\ j\in J,\ k\in K \\ &qcu_i\leq \Omega zcu_i && i\in I \\ &qhu_j\leq \Omega zhu_j && j\in J \\ &dt_{ijk}\leq t_{i,k}-t_{j,k}+\Gamma(1-z_{ijk}) && i\in I, j\in J, k\in K \\ &dt_{ijk+1}\leq t_{i,k+1}-t_{j,k+1}+\Gamma(1-z_{ijk}) && i\in I, j\in J, k\in K \\ &dtcu_i\leq t_{i,NOK+1}-T_{cu,out}+\Gamma(1-zcu_i) && i\in I \\ &dthu_j\leq T_{hu,out}-t_{j,1}+\Gamma(1-zhu_j) && j\in J \end{aligned} \qquad (2\text{-}10)$$

No stream splitting constraints

$$\begin{aligned} &\sum_{j\in J} z_{ijk}\leq 1 && i\in I,\ k\in K \\ &\sum_{i\in I} z_{ijk}\leq 1 && j\in J,\ k\in K \end{aligned} \qquad (2\text{-}11)$$

Integrality conditions

$$z_{ijk},\ zcu_i,\ zhu_j=0,1 \qquad i\in I,\ j\in J,\ k\in K \qquad (2\text{-}12)$$

Bounds

$$\begin{aligned} &T_{i,out}\leq t_{i,k}\leq T_{i,in} && i\in I \\ &T_{j,in}\leq t_{j,k}\leq T_{j,out} && j\in J \\ &q_{ijk}, qcu_i, qhu_j\geq 0 && i\in I,\ j\in J,\ k\in K \\ &AMTD_{i,j,k},\ AMTD_{i,cu},\ AMTD_{j,hu}\geq \Delta T_{mapp} && i\in I,\ j\in J,\ k\in K \end{aligned} \qquad (2\text{-}13)$$

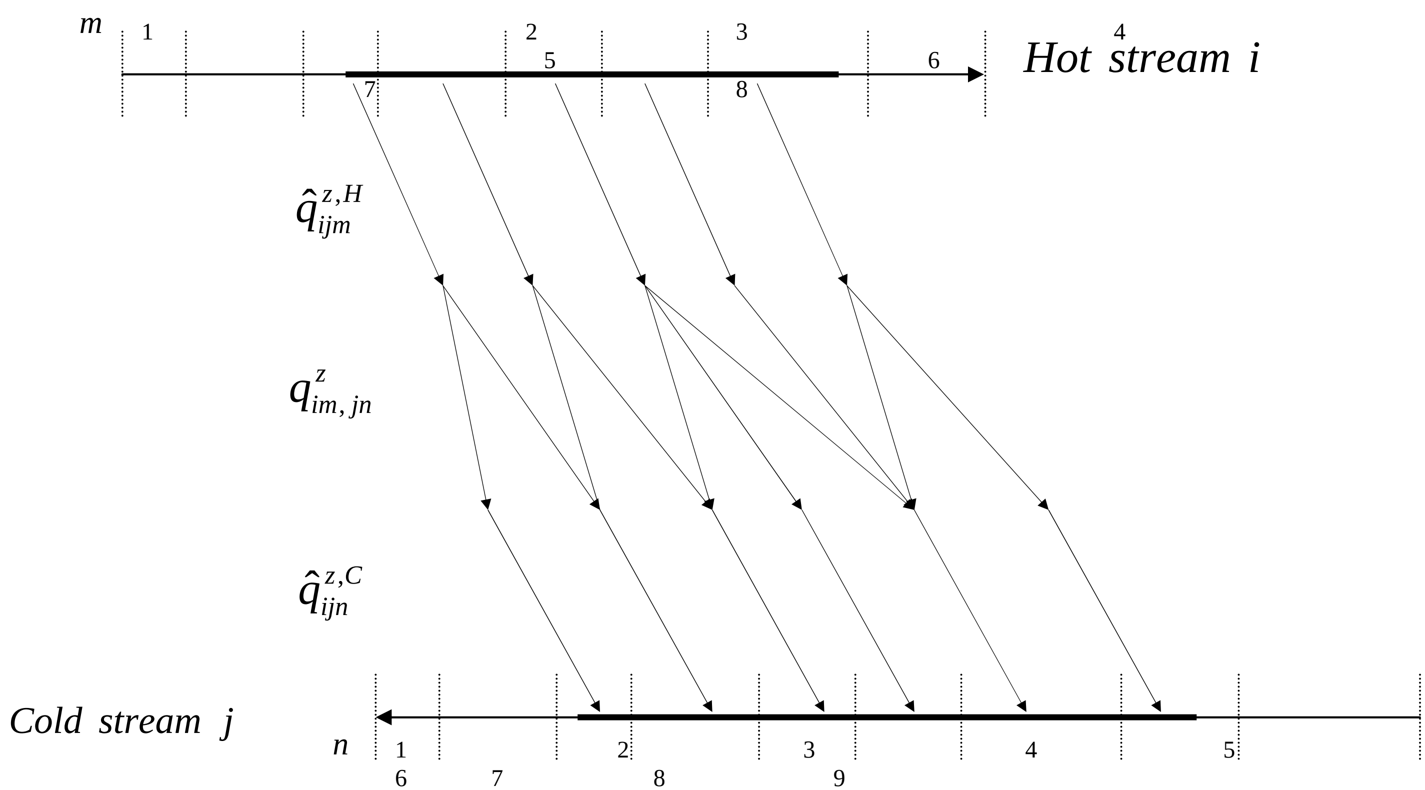
LATEST MILP APPROACH

(Barbaro and Bagajewicz, 2005)

- ❑ Counts heat exchangers units and shells
- ❑ Approximates the area required for each exchanger unit or shell
- ❑ Controls the total number of units
- ❑ Implicitly determines flow rates in splits
- ❑ Handles non-isothermal mixing
- ❑ Identifies bypasses in split situations when convenient
- ❑ Controls the temperature approximation (HRAT/EMAT or $\Delta Tmin$) when desired
- ❑ Allows multiple matches between two streams

LATEST MILP APPROACH

(Barbaro and Bagajewicz, 2005)



Transportation Model Approach

LATEST MILP APPROACH

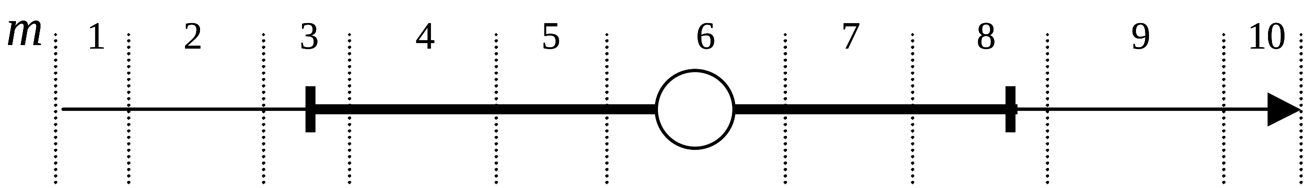
(Barbaro and Bagajewicz, 2005)

Heat Exchanger counting

$$\hat{K}_{ijm}^{z,H} \geq Y_{ijm}^{z,H}$$ First interval

$$\left.\begin{aligned} &\hat{K}_{ijm}^{z,H} \leq 2 - Y_{ijm}^{z,H} - Y_{ijm+1}^{z,H} \\ &\hat{K}_{ijm}^{z,H} \leq Y_{ijm}^{z,H} \\ &\hat{K}_{ijm}^{z,H} \geq Y_{ijm}^{z,H} - Y_{ijm+1}^{z,H} \\ &\hat{K}_{ijm}^{z,H} \geq 0 \end{aligned}\right\}$$ Rest of intervals

m	$Y_{ijm}^{z,H}$	$K_{ijm}^{z,H}$	$\hat{K}_{ijm}^{z,H}$
1	0	0	0
2	0	0	0
3	**1**	**1**	0
4	**1**	0	0
5	**1**	0	0
6	**1**	0	0
7	**1**	0	0
8	**1**	0	**1**
9	0	0	0
10	0	0	0

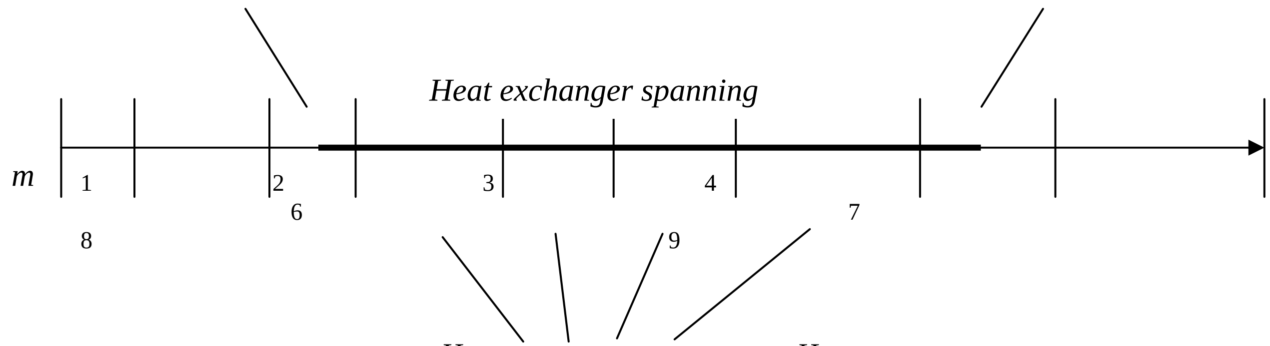


LATEST MILP APPROACH

(Barbaro and Bagajewicz, 2005)

Flowrate Consistency

$$\frac{\hat{q}_{ijm}^{z,H}}{Cp_{im}(T_m^U - T_m^L)} \geq \frac{\hat{q}_{ijm-1}^{z,H}}{Cp_{im-1}(T_{m-1}^U - T_{m-1}^L)} \qquad \frac{\hat{q}_{ijm}^{z,H}}{Cp_{im}(T_m^U - T_m^L)} \leq \frac{\hat{q}_{ijm-1}^{z,H}}{Cp_{im-1}(T_{m-1}^U - T_{m-1}^L)}$$



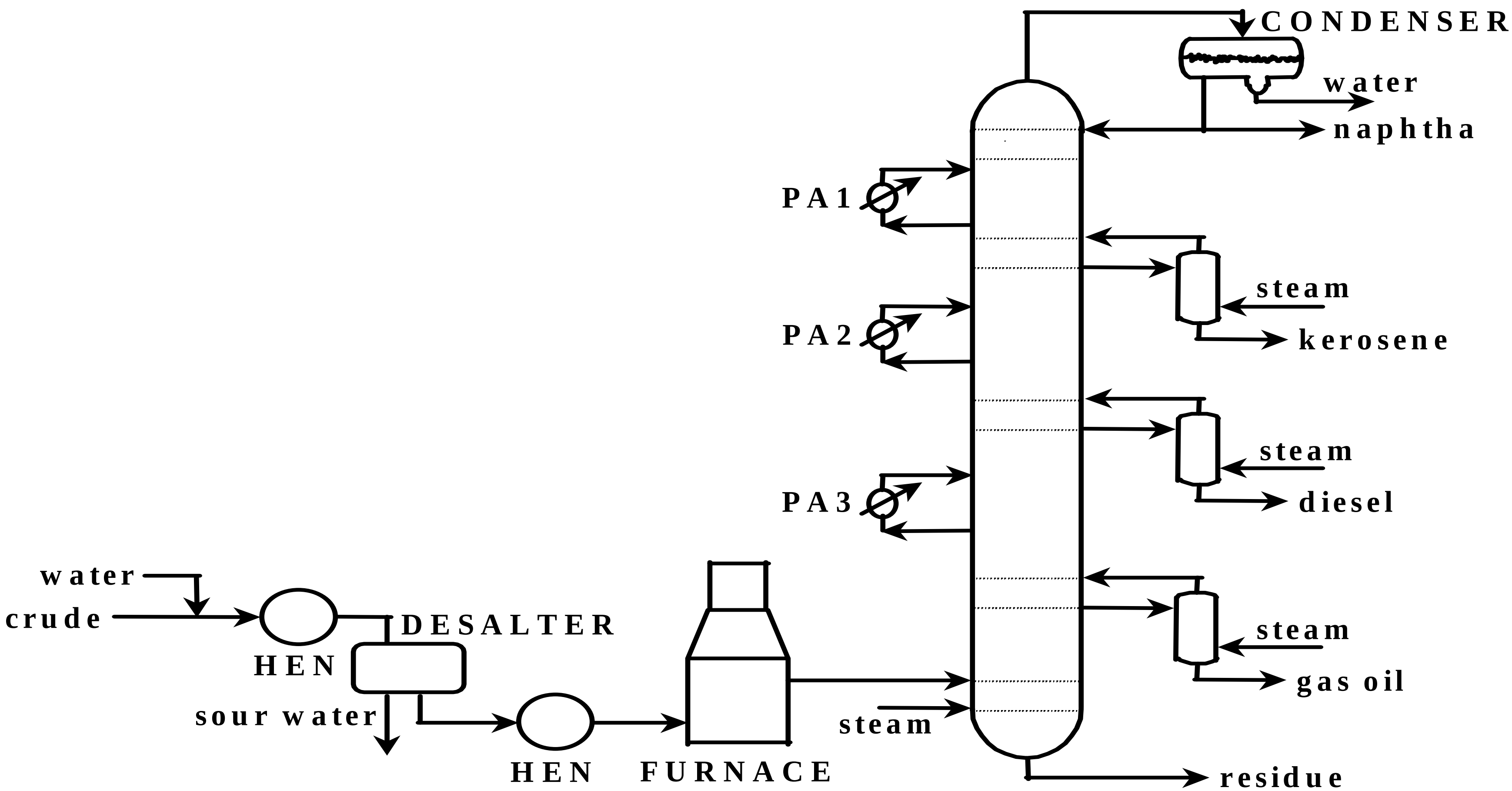
$$\frac{\hat{q}_{ijm}^{z,H}}{Cp_{im}(T_m^U - T_m^L)} = \frac{\hat{q}_{ijm-1}^{z,H}}{Cp_{im-1}(T_{m-1}^U - T_{m-1}^L)}$$

PART 8

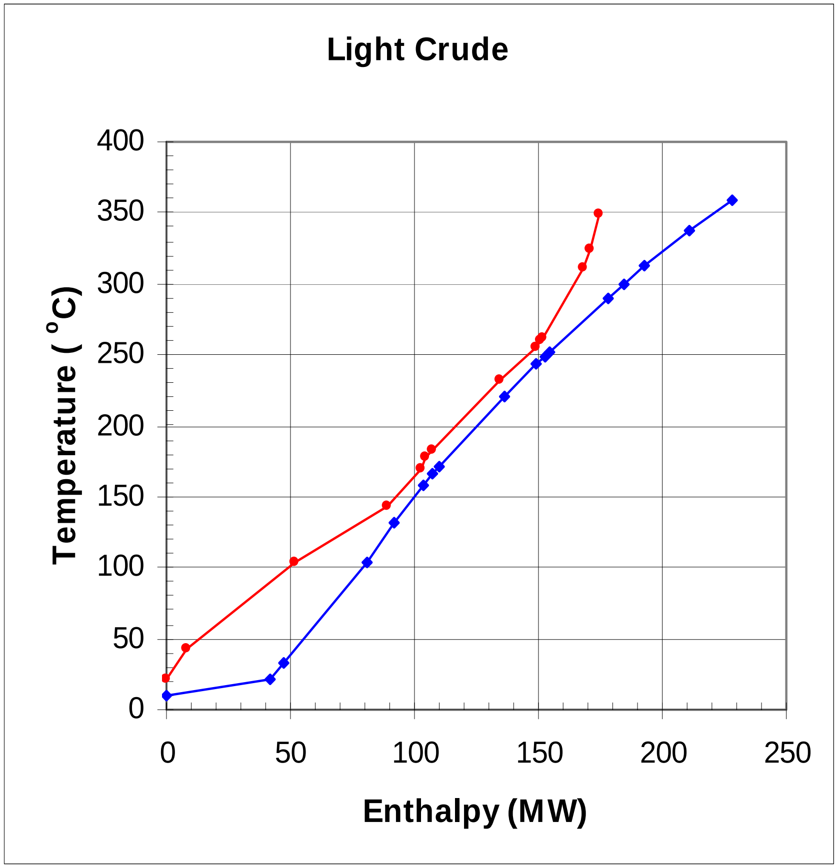
INDUSTRIAL IMPORTANCE OF USING THE RIGHT MODEL

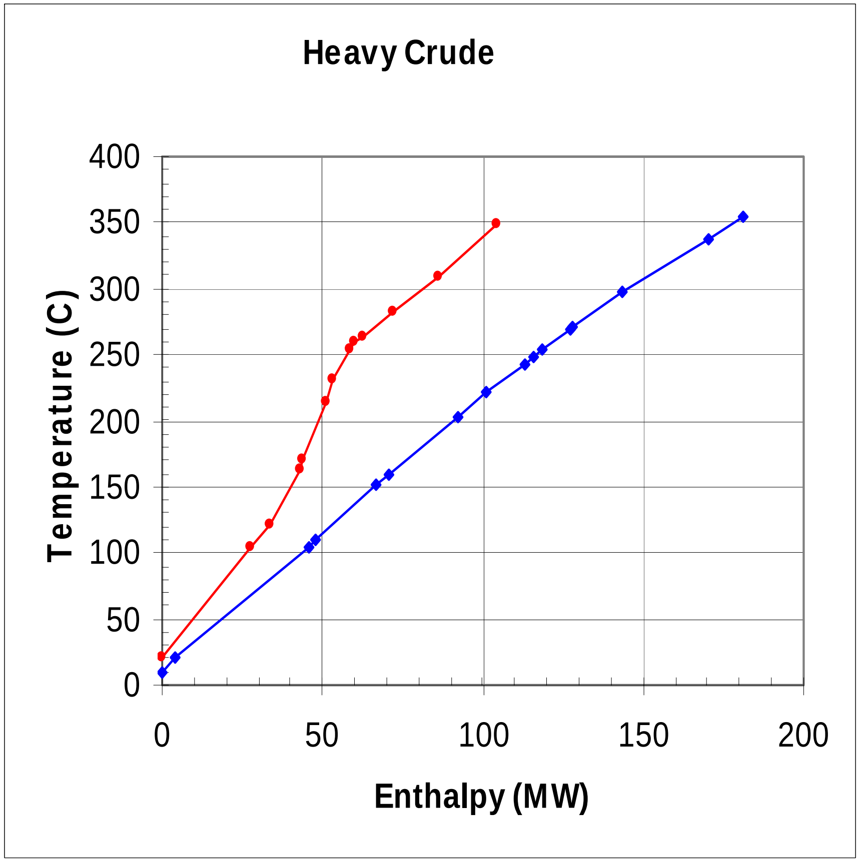
Crude fractionation case study

CRUDE FRACTIONATION EXAMPLE



CRUDE FRACTIONATION EXAMPLE

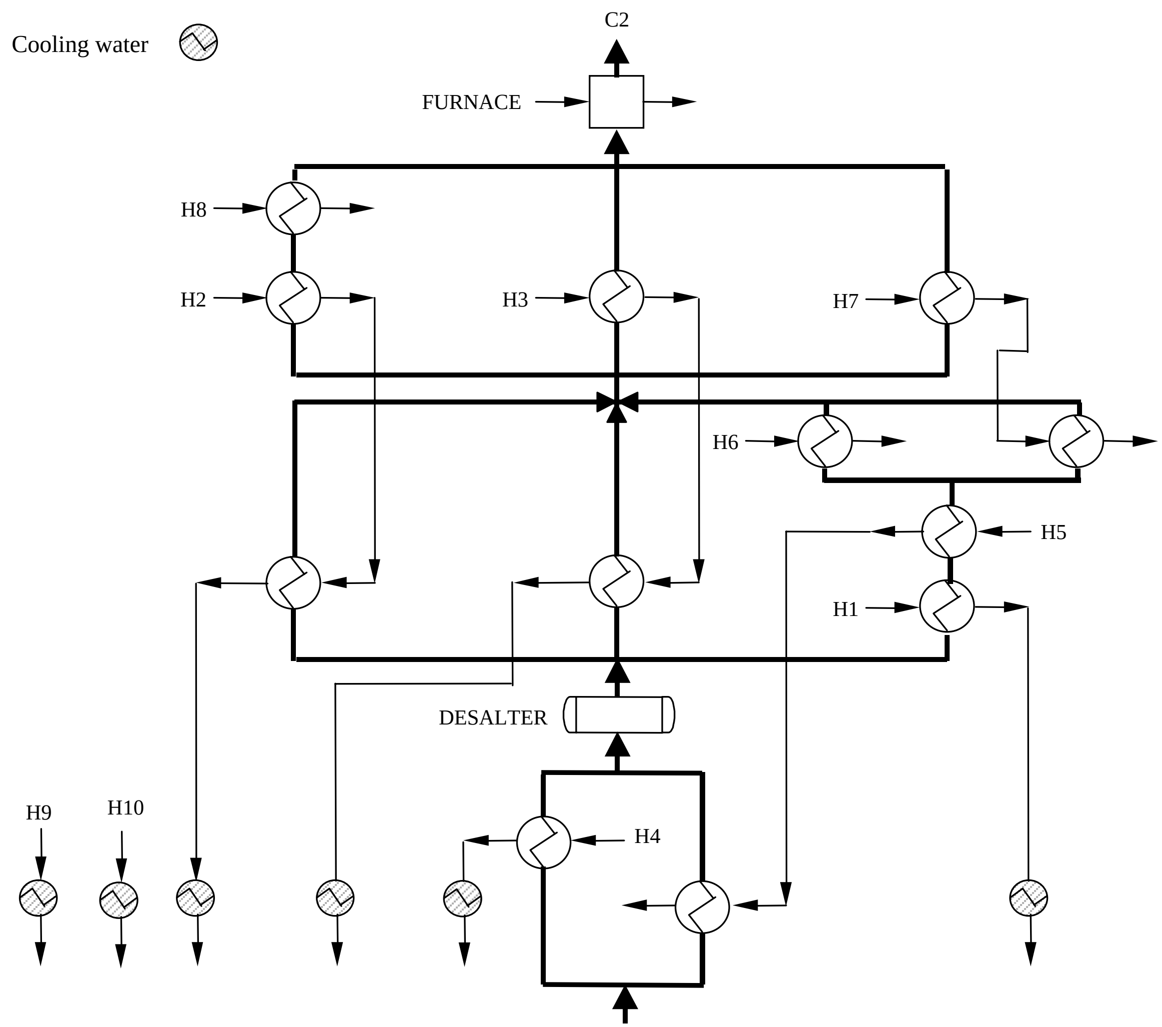




Cooling water is already included in the graphs.

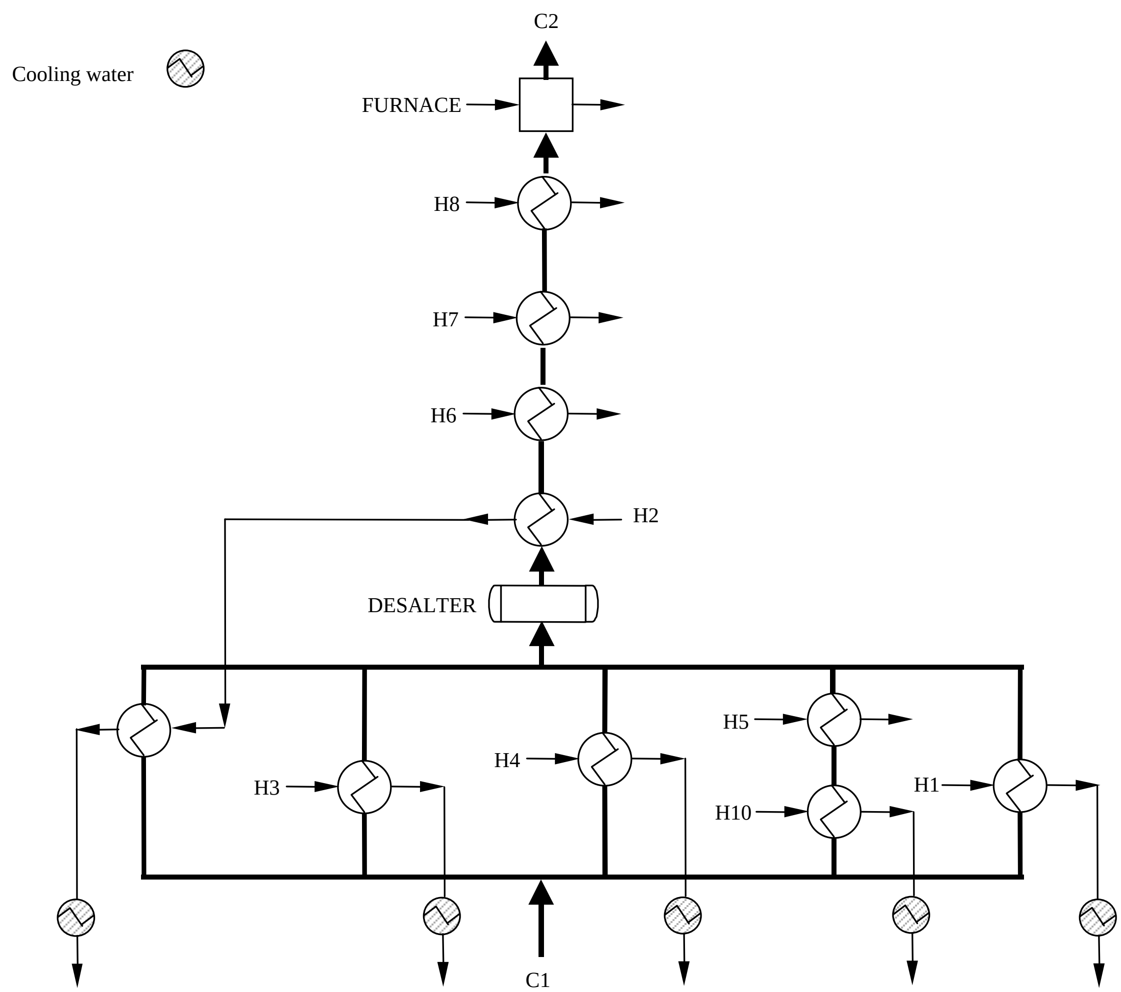
- **The light crude exhibits what is called a continuous pinch.**
- **The heavy crude is unpinched.**

CRUDE FRACTIONATION



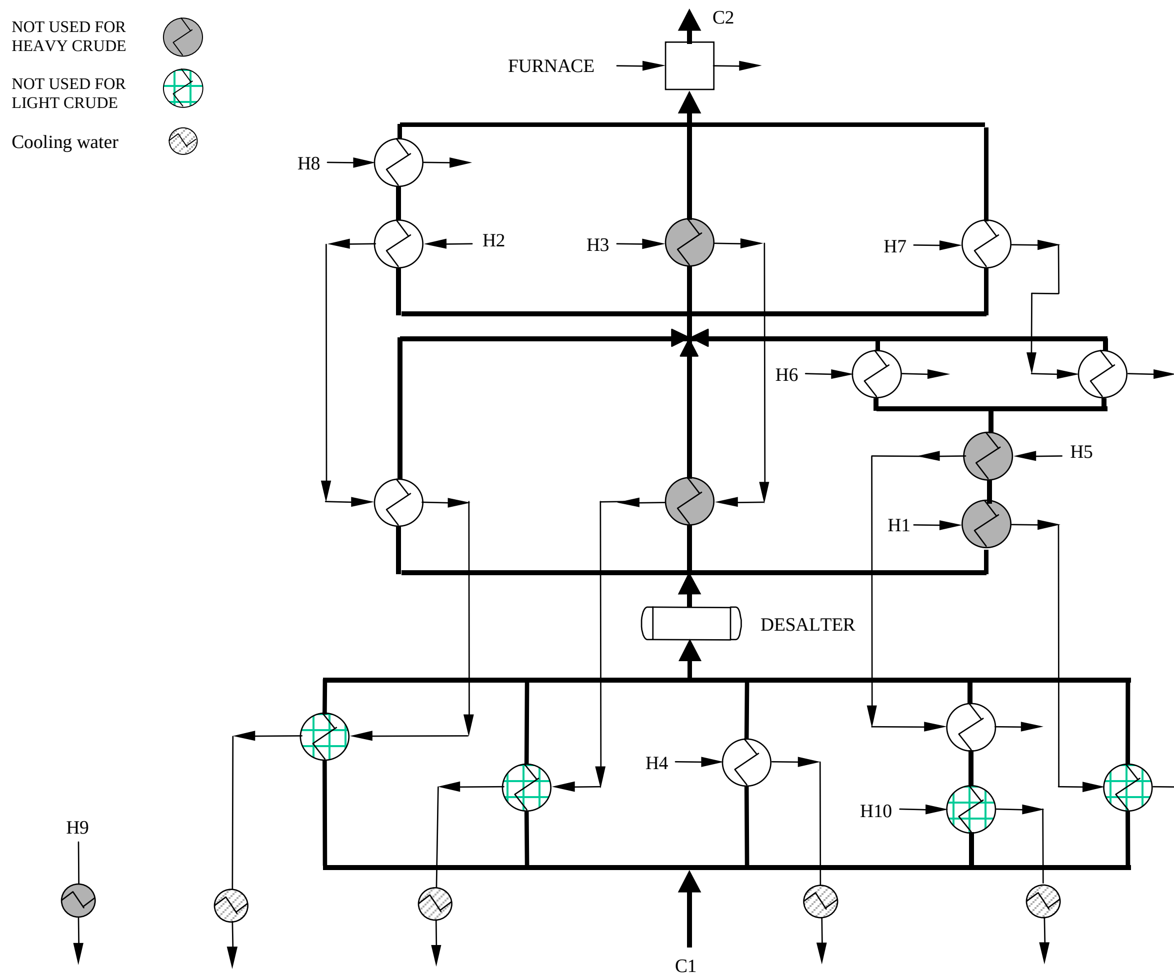
MER network for the light crude.

CRUDE FRACTIONATION



MER network for the heavy crude.

CRUDE FRACTIONATION



MER network efficient for both crudes.

CRUDE FRACTIONATION

It is clear from the previous results that efficient MER networks addressing multiple crudes can be rather complex and impractical.

Alternatives to the Pinch Design Method (PDM) are clearly needed.

This does not mean that the PDM fails all the time. It is still capable of producing good results in many other cases.

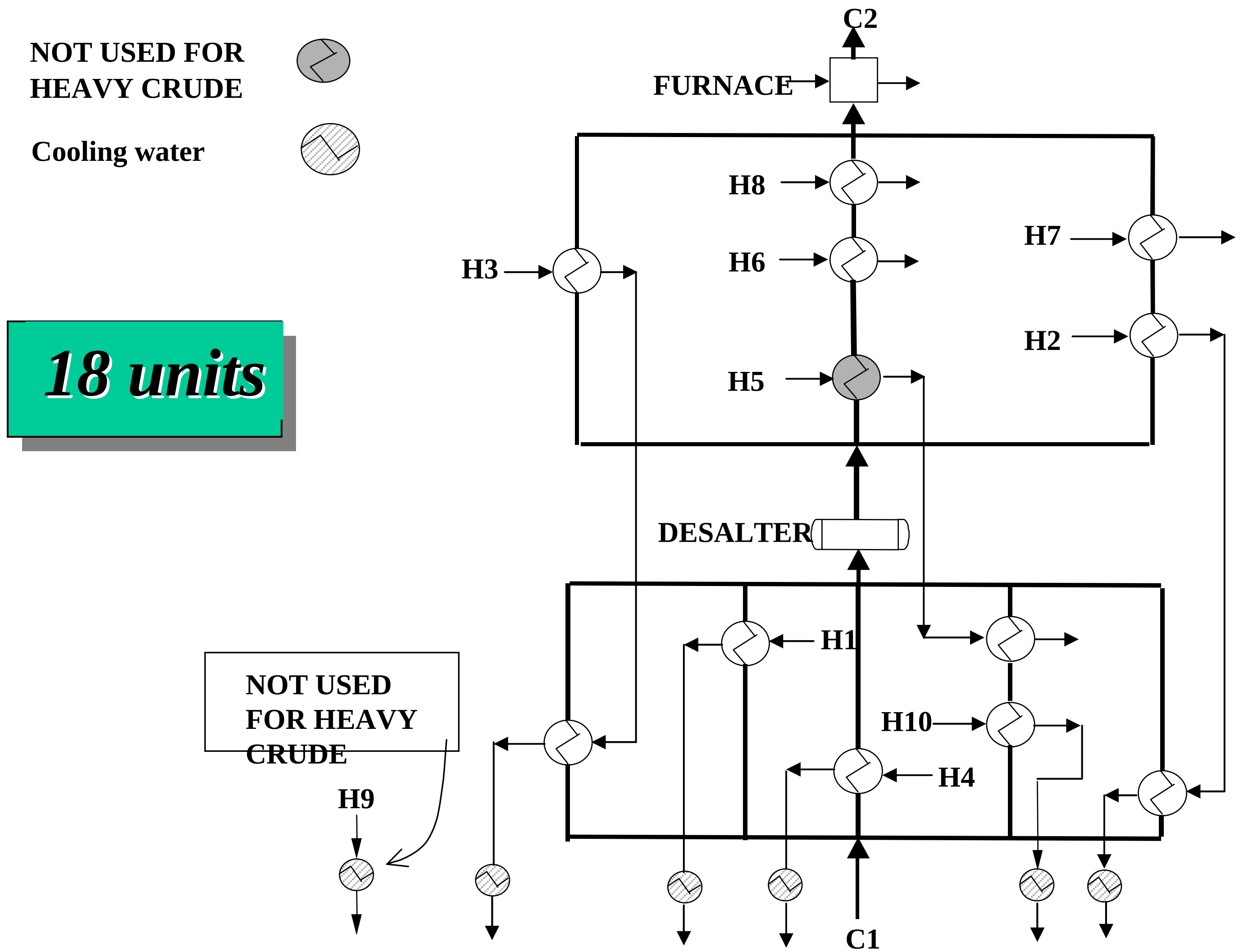
CRUDE FRACTIONATION EXAMPLE

We now illustrate the use of HRAT/EMAT procedures for the case of crude fractionation units.

We return to our example of two crudes. The problem was solved using mathematical programming. The networks have maximum efficiency for both crudes.

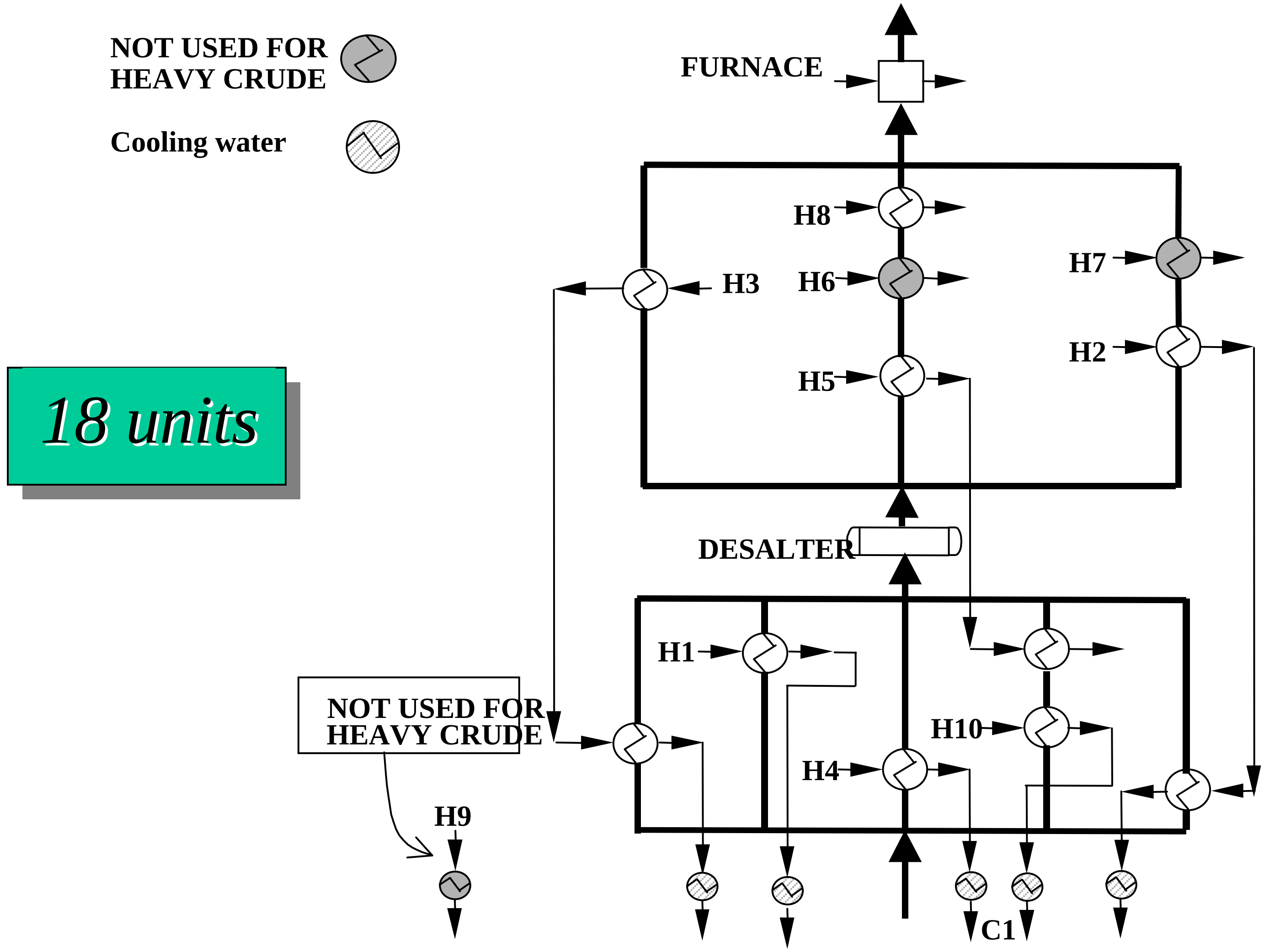
Only the vertical model and the control on the number of units was used. No variation in the matches was done (not really necessary in this case) and no further optimization was performed.

CRUDE FRACTIONATION



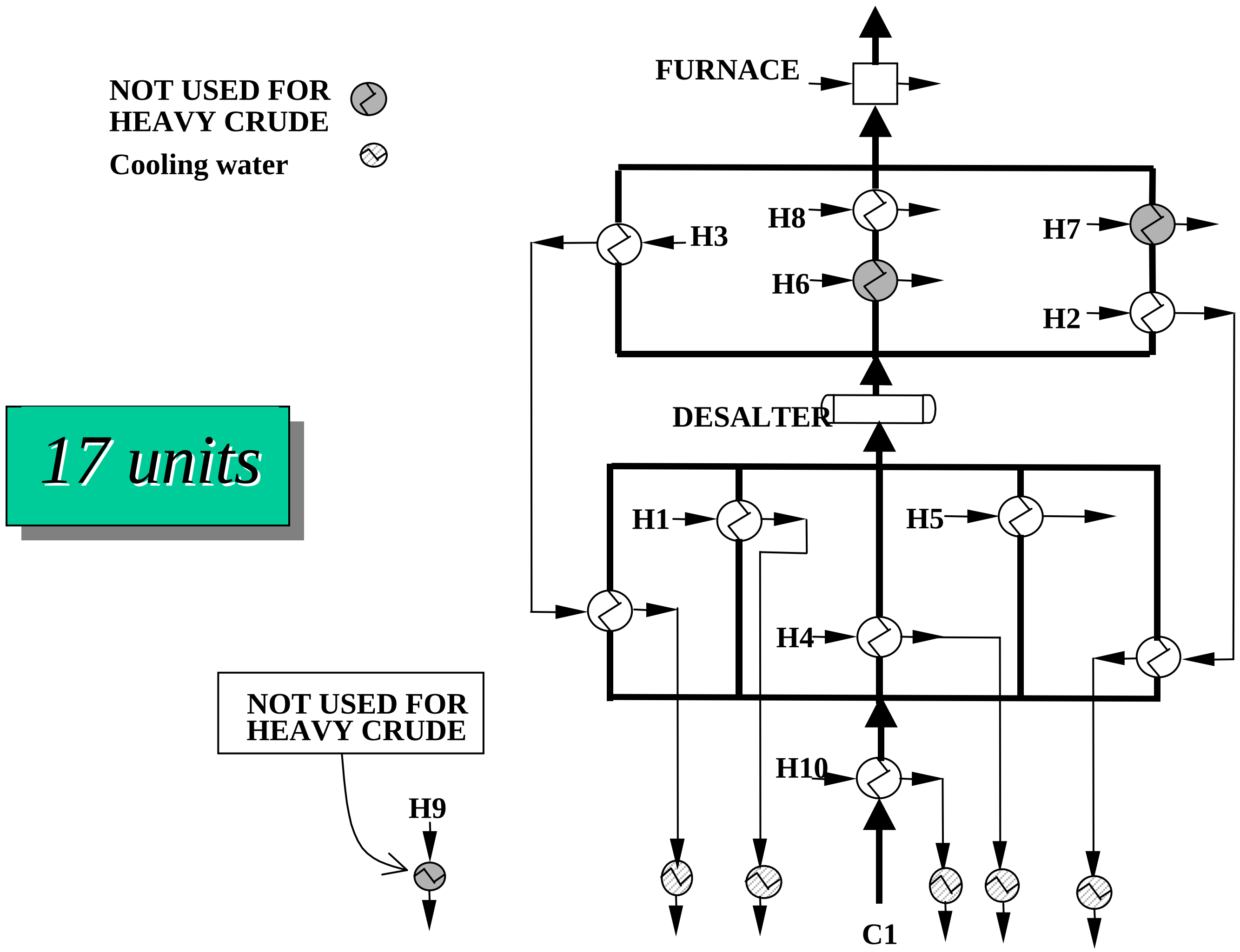
Solution for HRAT/EMAT = 20/10 ºF

CRUDE FRACTIONATION



Solution for HRAT/EMAT = 40/30 ºF

CRUDE FRACTIONATION



Solution for HRAT/EMAT = 80/60 ºF

CRUDE FRACTIONATION

Cost, MM$/yr

	Combined Network	Multiperiod Model	Multiperiod+ Desalt.Temp.	**Multip+Des.Temp** +Higher HRAT
HRAT/EMAT	20/20	20/10	20/10	40/30
Operational	3.96	3.96	3.96	4.94
Fixed	3.14	3.63	3.32	1.37
Total	7.10	7.59	7.28	6.32

CRUDE FRACTIONATION EXAMPLE

We now illustrate the use of more sophisticated models that allow the control of splitting. These are essentially transshipment models that are able to control the level of splitting (something that regular transshipment models cannot do).

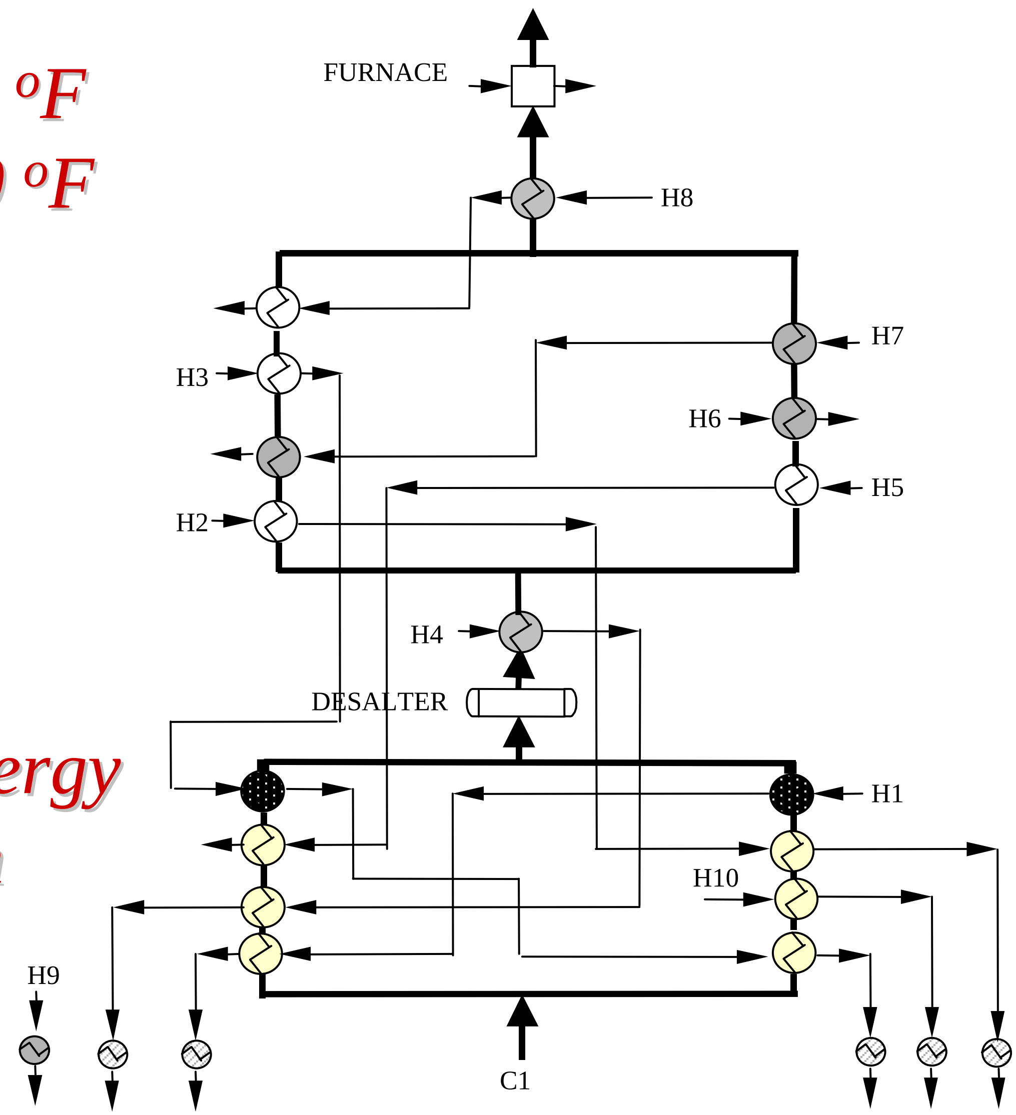
CRUDE FRACTIONATION
Two branches unrestricted

HRAT = 40 ^oF

EMAT = 30 ^oF

23 units

5% More Energy Consumption



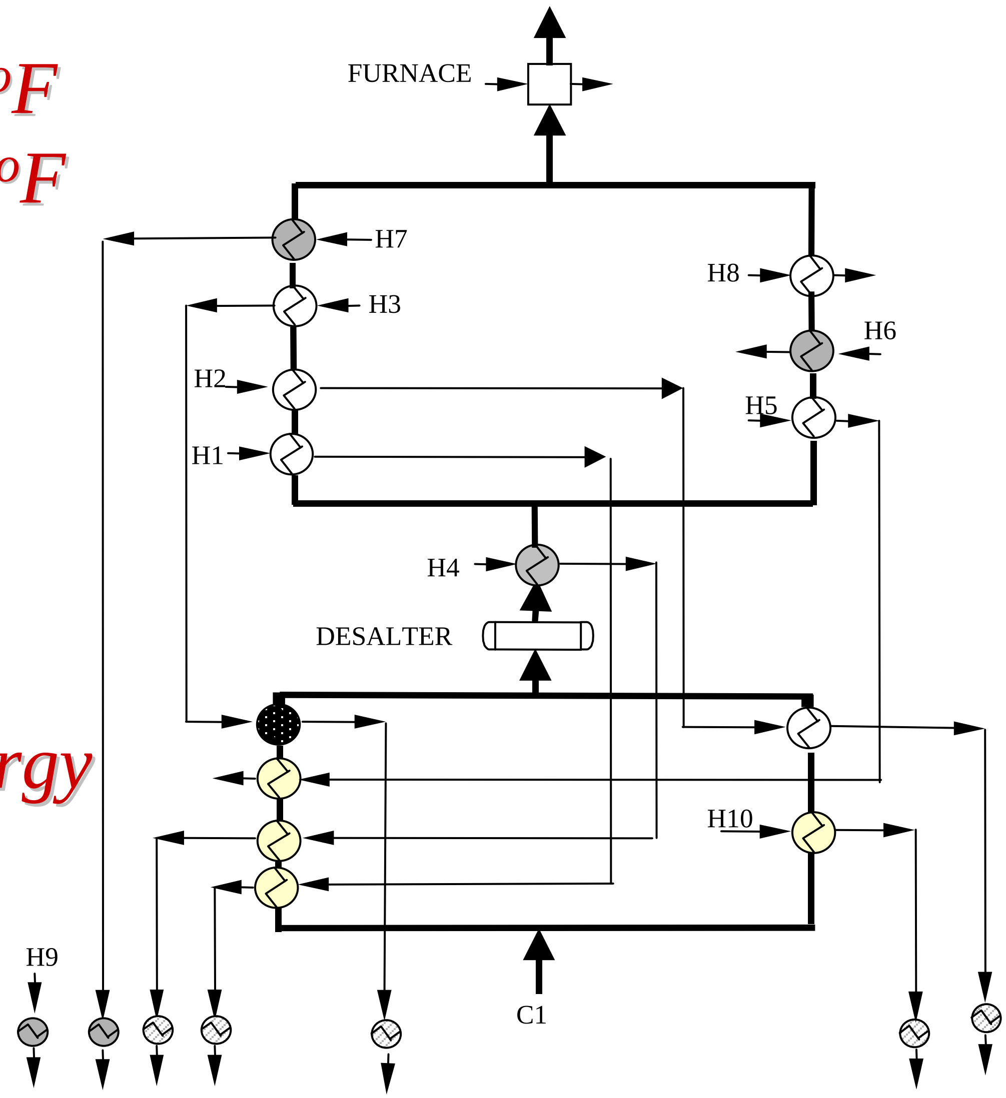
CRUDE FRACTIONATION restricted

HRAT = 40 °F

EMAT = 30 °F

21 units

5% More Energy Consumption



CRUDE FRACTIONATION

Cost, MM$/yr

	Multiperiod Model	Two-branch Unrestricted	Two-branch Restricted
Operational	4.32	4.52	4.53
Fixed	2.07	1.90	2.01
Total	6.39	6.42	6.54

CRUDE FRACTIONATION

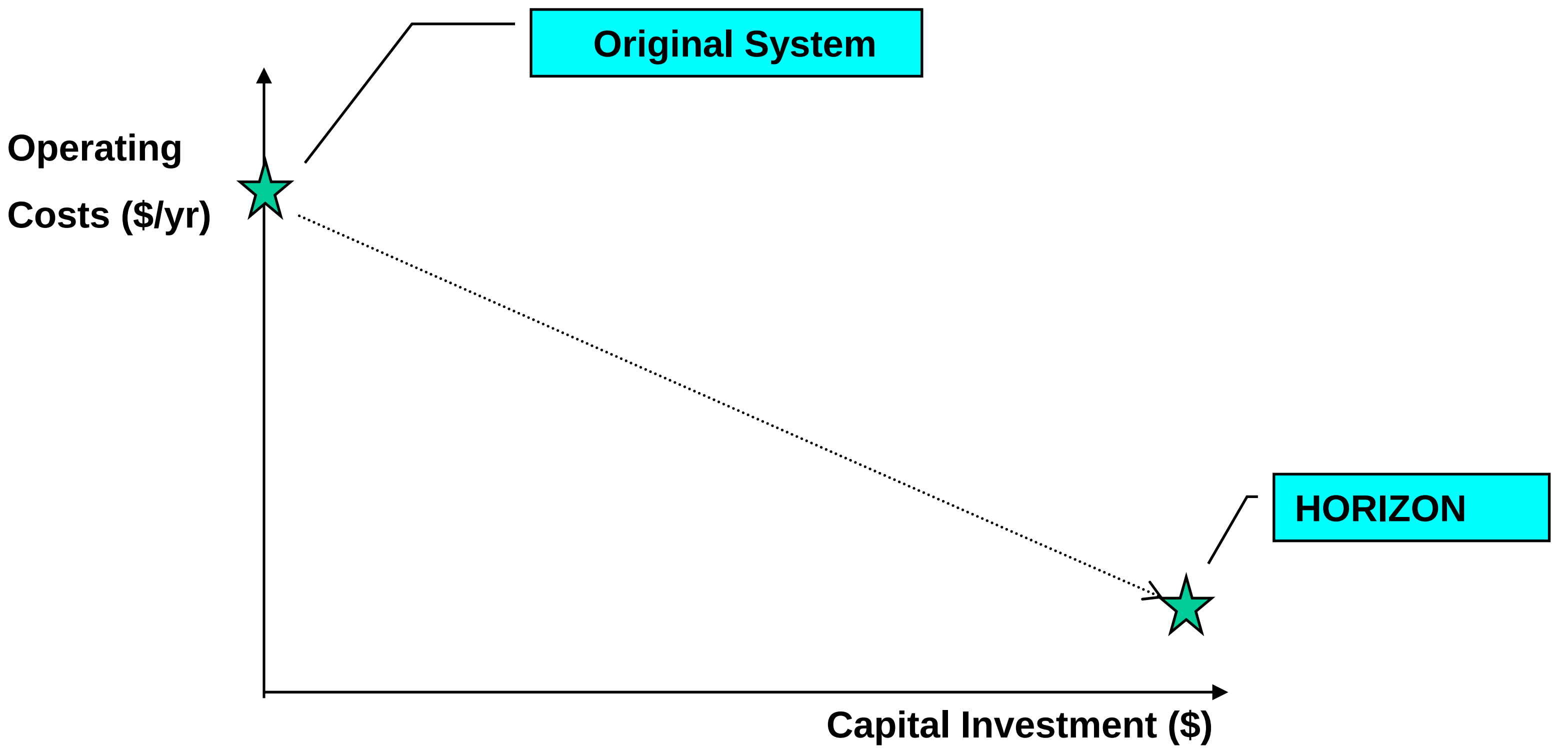
- The two-branch design…
  - Is efficient for all feedstocks proposed.
  - Consumes only a few more millions Btu/hr
  - Has many solutions of similar energy consumption.
- Complexity can be reduced at a relatively small energy increase and with some reduction of capital.
- All these models suggest that there is a lot of flexibility to perform an effective retrofit because there are these many options of similar cost to explore.

PART 9

RETROFIT
AND
TOTAL SITE INTEGRATION

RETROFIT

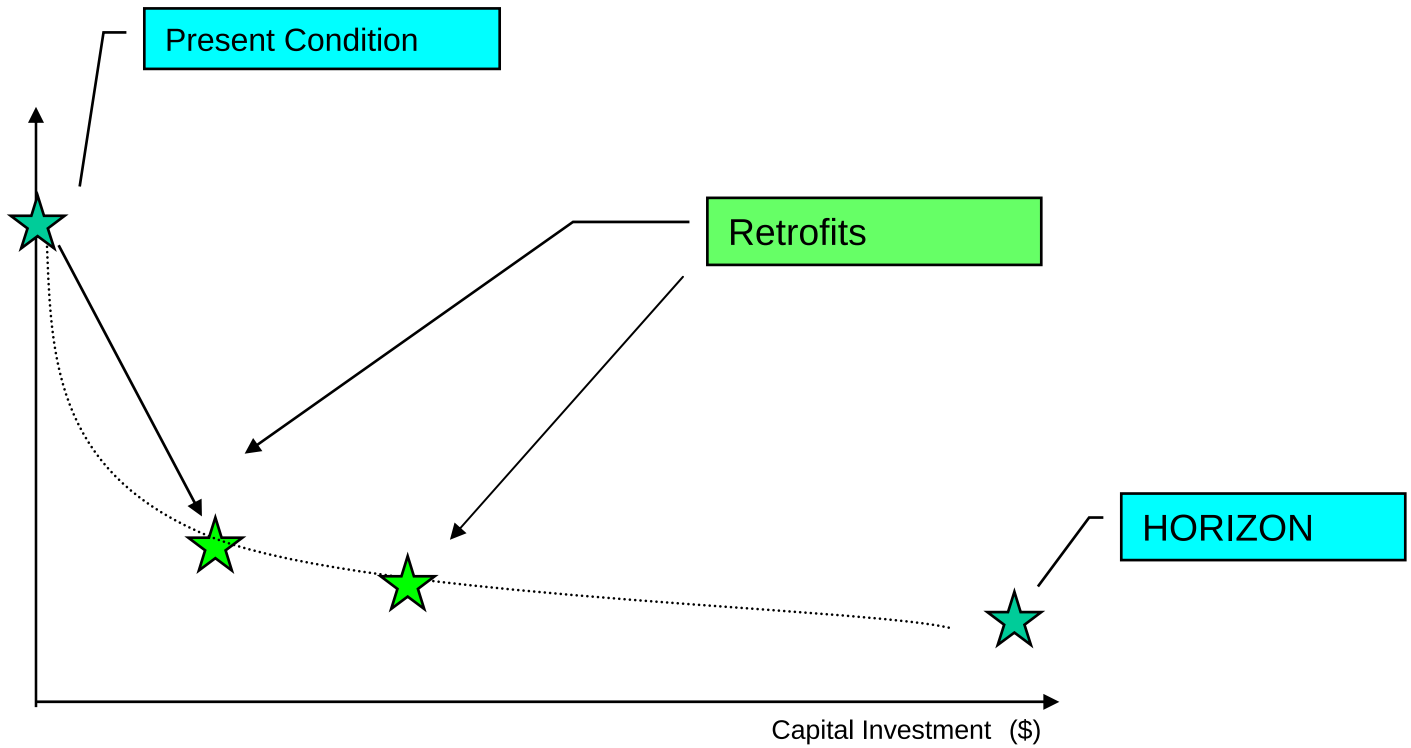
The big question in trying to do a retrofit of a HEN is whether one really wants to achieve maximum efficiency.



Usually retrofits are too expensive and have a long payout.

RETROFIT

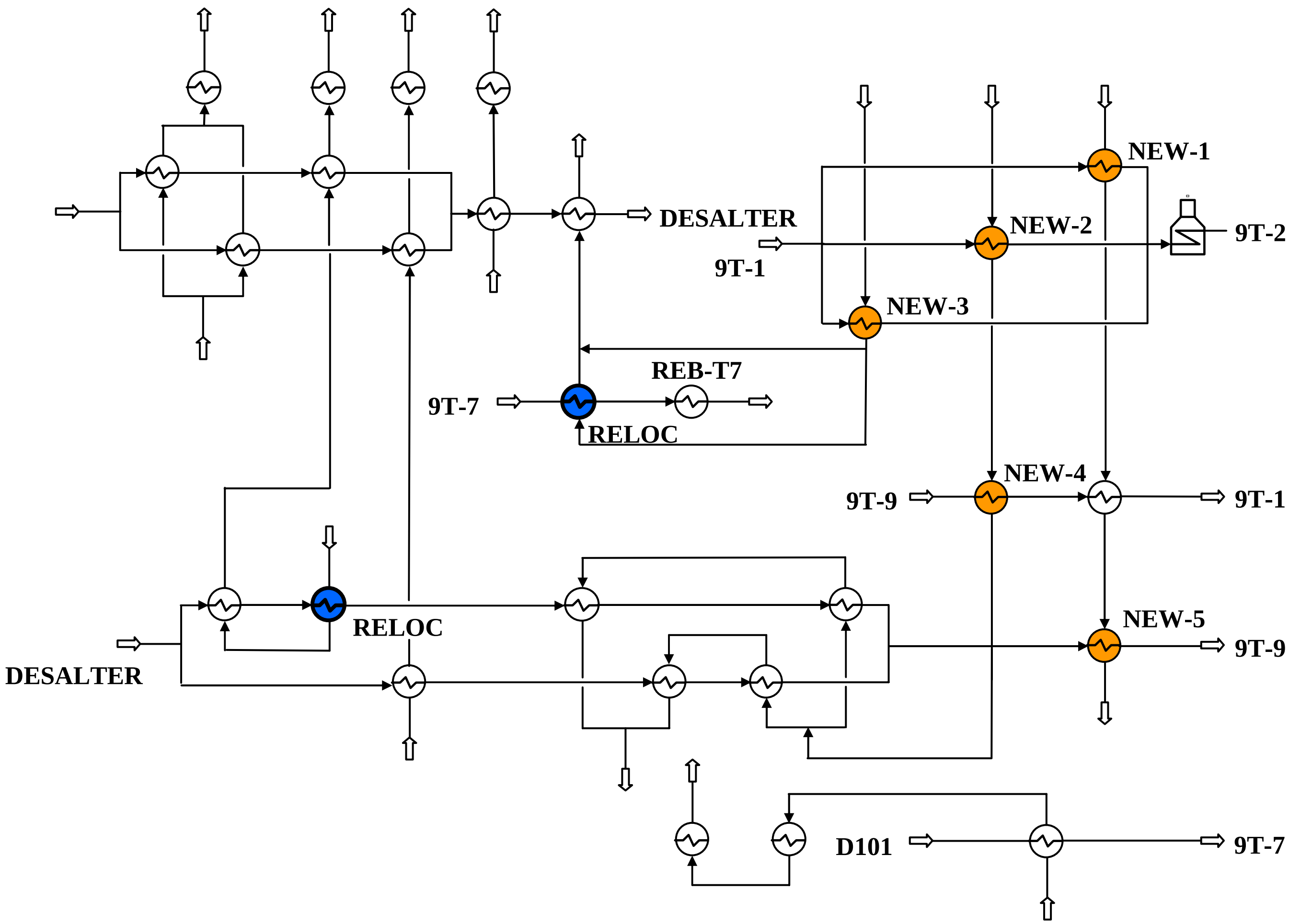
It is desired to produce the largest reduction of cost with the smallest capital investment



The question is how to identify the most profitable.

EXAMPLE

Retrofits involve a) relocation, and b) addition of new units.



This particular study produced a) 700,000 annual savings with 1.2 years payoff, b) __Additional__ 12% capacity (not counted in the $700,000 savings)

TYPES OF RETROFIT

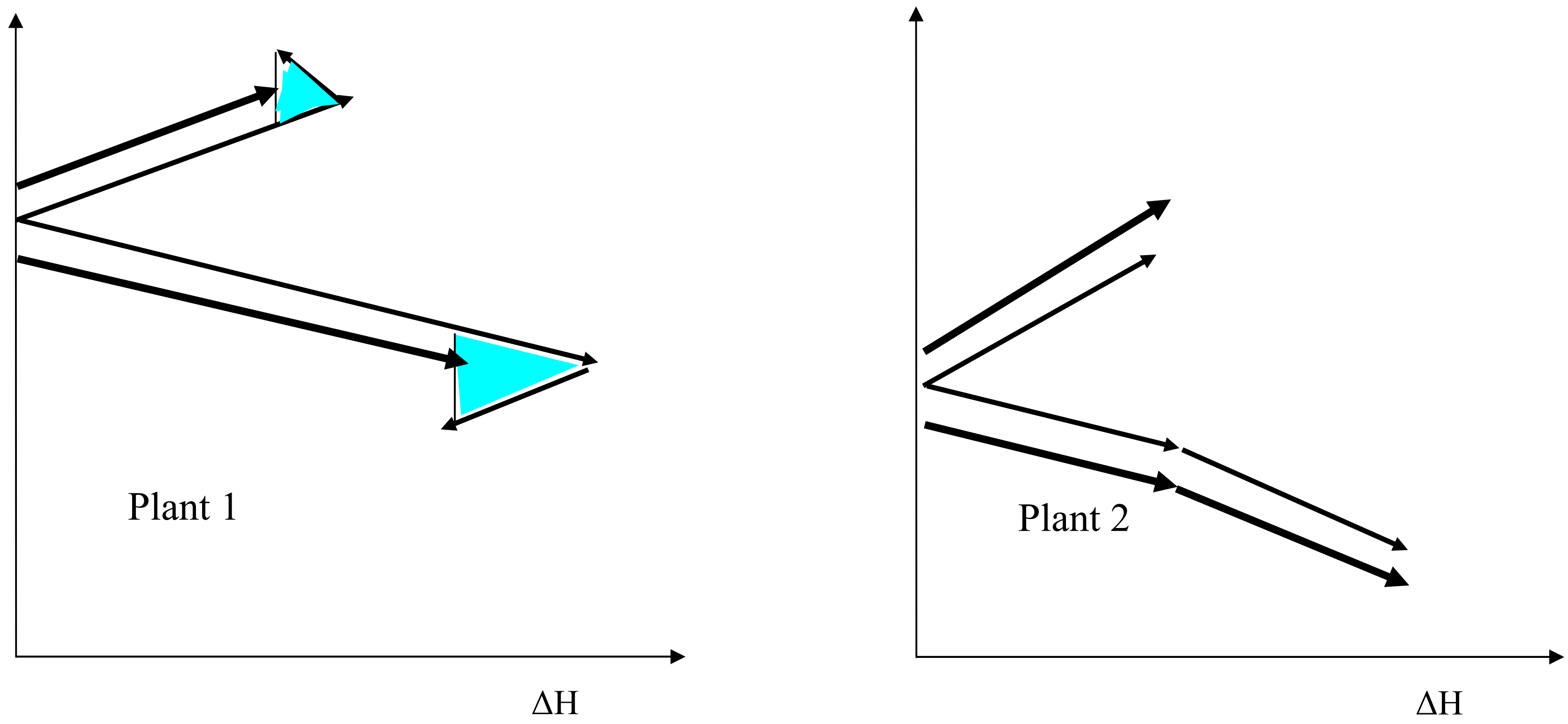
- By inspection. Perform pinch design or pseudo pinch design and determine heat exchangers to add
- Systematic methods using tables and graphs exist They are outside the scope of this course.
- Mathematical programming approaches also exist but they have not passed the test of usability and friendliness

RECENT WORK ON RETROFIT

- Asante, N. D. K.; Zhu, X. X. *An Automated and Interactive Approach for Heat Exchanger Network Retrofit*. Chem.Eng. Res. Des. 75 (A), 349-360 (1997).
- Briones, V.; Kokossis, A. C. Hypertargets: *A Conceptual Programming Approach for the Optimisation of Industrial Heat Exchanger Networks II. Retrofit Design.* Chem. Eng. Sci. 54, 541-561 (1999).
- Barbaro, Bagajewicz, Vipanurat, Siemanond. *MILP formulation for the Retrofit of Heat Exchanger Networks*. Proceedings of Pres 05. (2005)

TOTAL SITE INTEGRATION

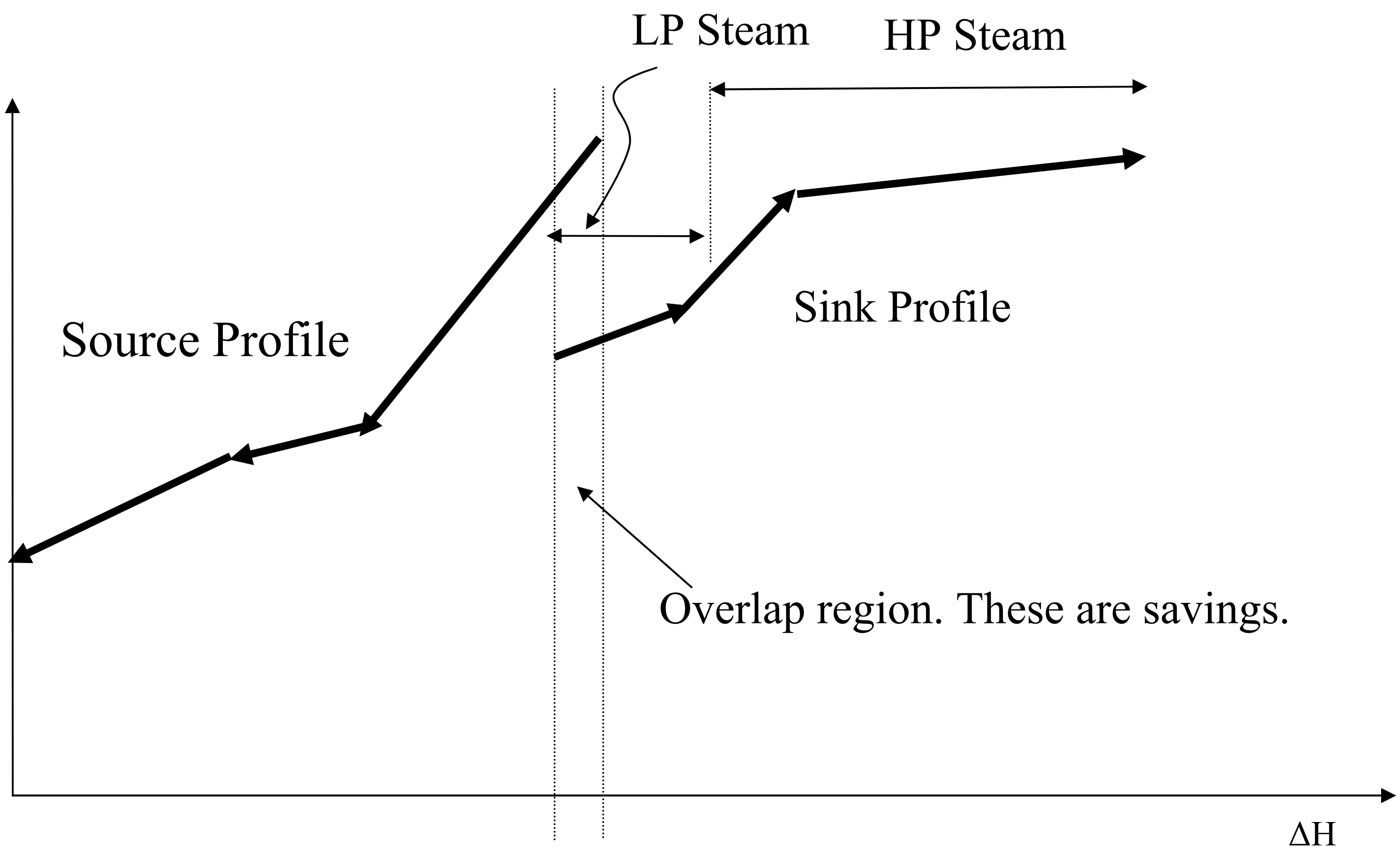
- **USE OF GRAND COMPOSITE CURVES TO PLACE UTILITIES.**



Pockets are eliminated and curves are shifted

TOTAL SITE INTEGRATION

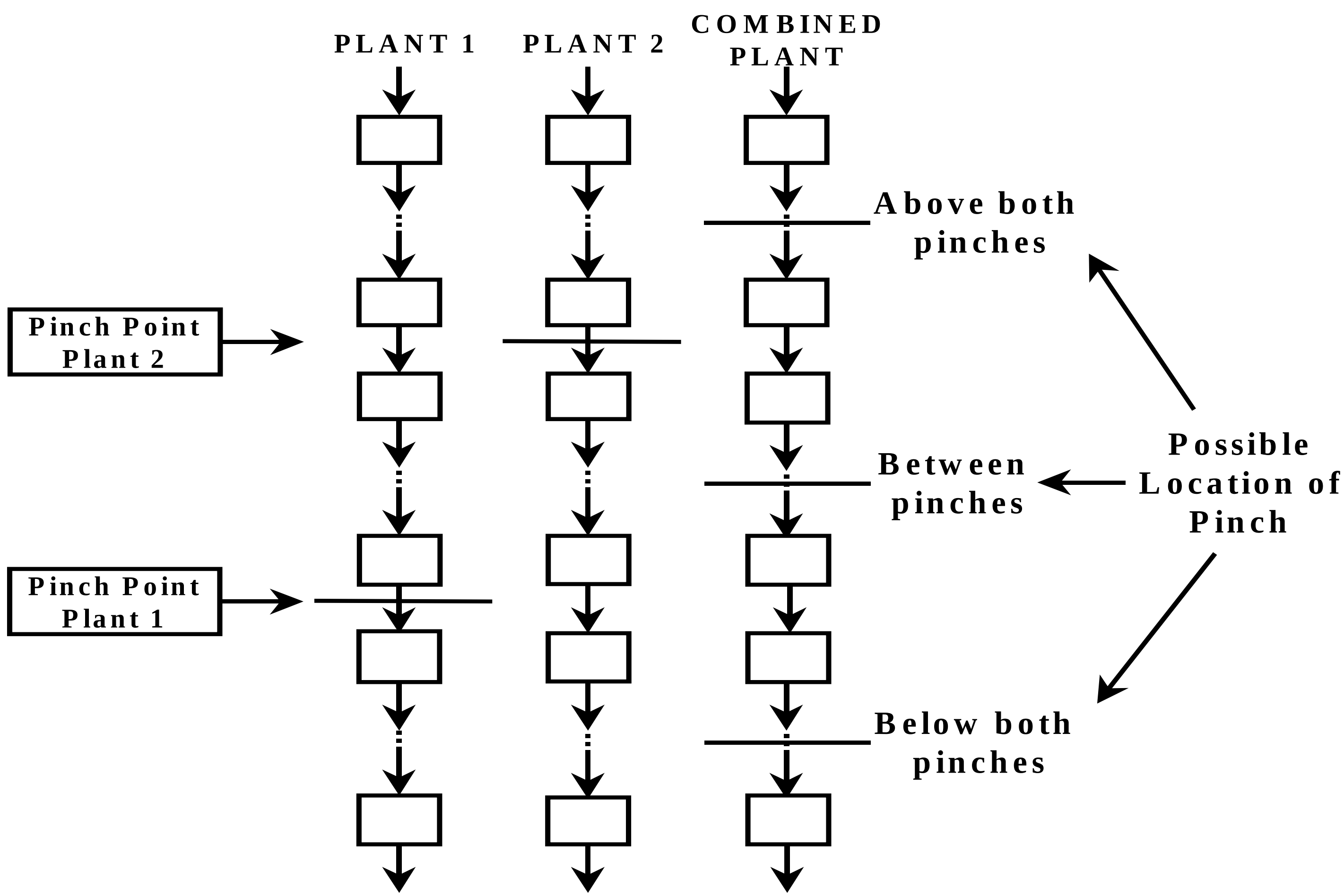
- **Site sink and source profiles are constructed.**



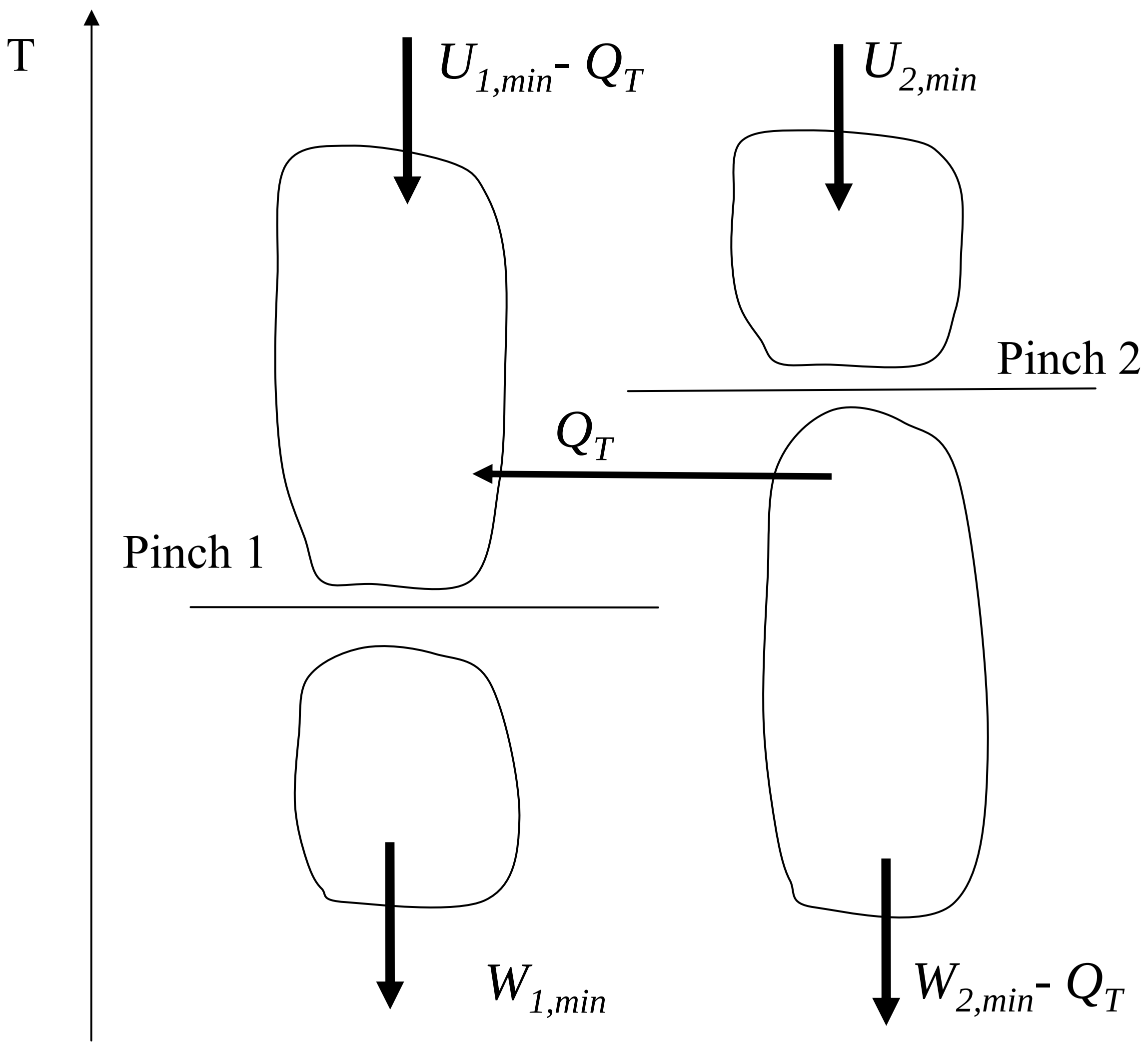
Energy integration is performed by placing utilities. We will see how this method can be wrong.

TOTAL SITE INTEGRATION

- Consider two plants. We would like to know under what conditions one can send heat from one plant to the other.



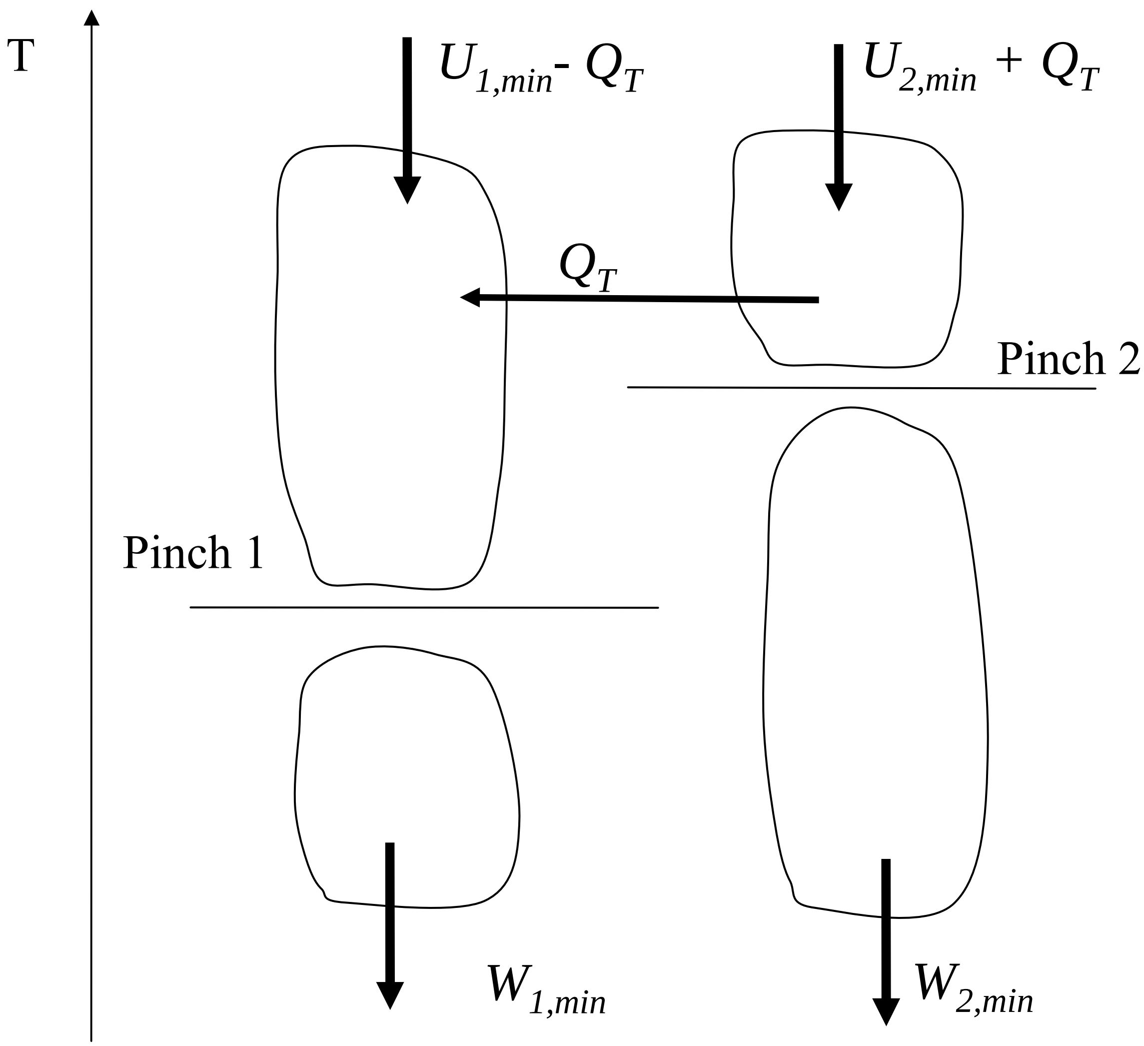
TOTAL SITE INTEGRATION



Effective integration takes place between pinches.

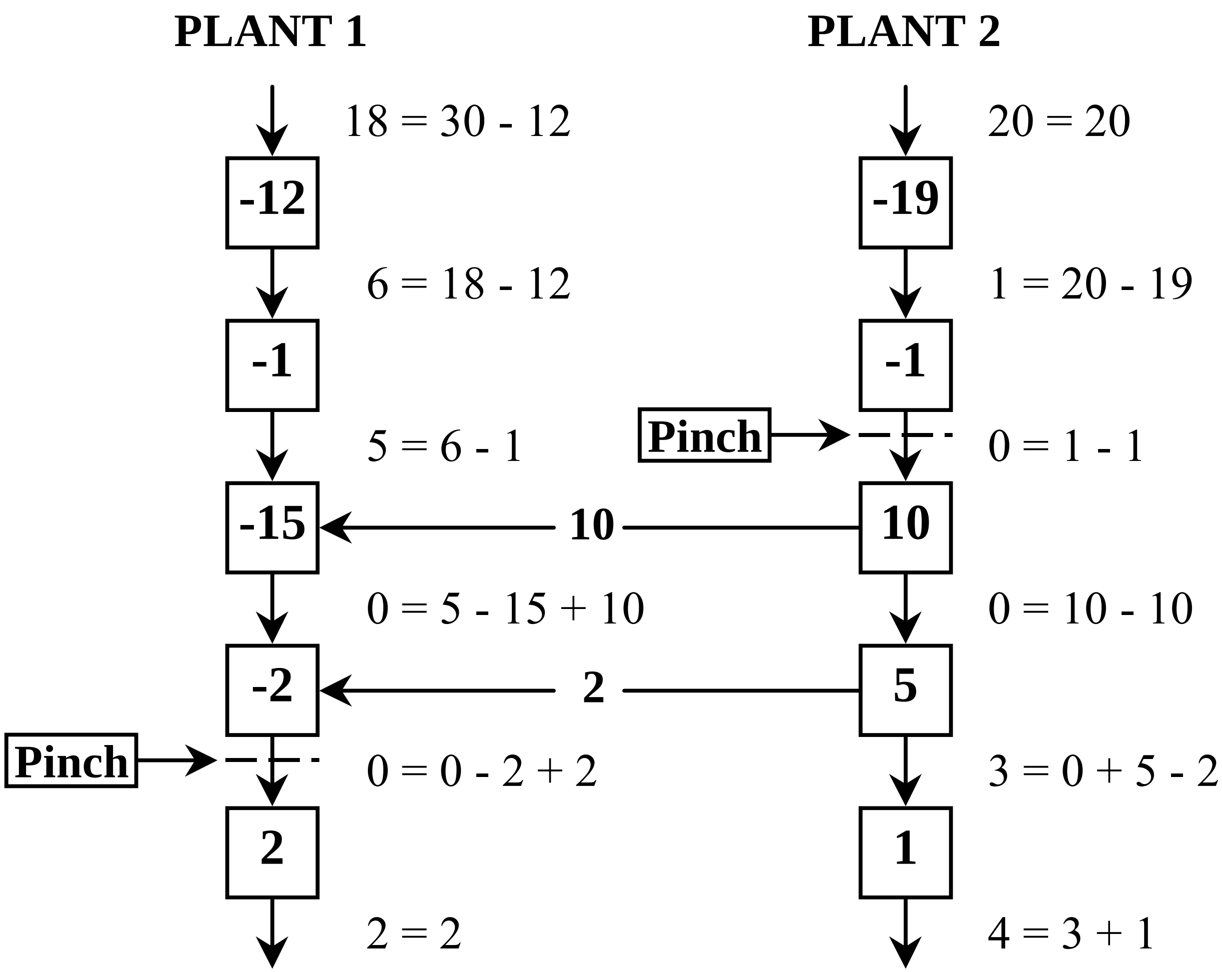
From where plant 2 is heat source to where plant 1 is heat sink.

TOTAL SITE INTEGRATION

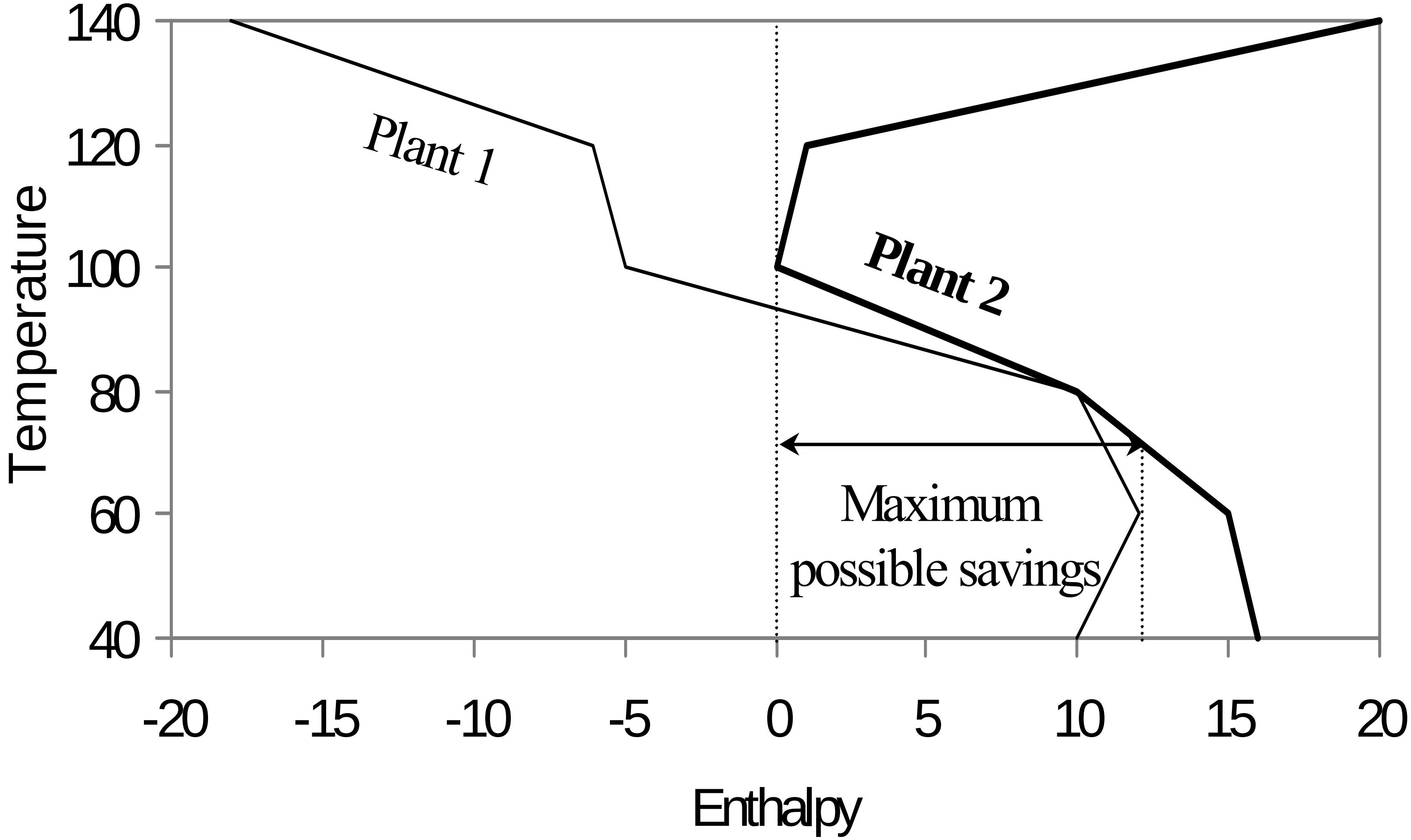


Integration outside the inter pinch region leads to no effective savings.

GRAND COMPOSITE CURVES

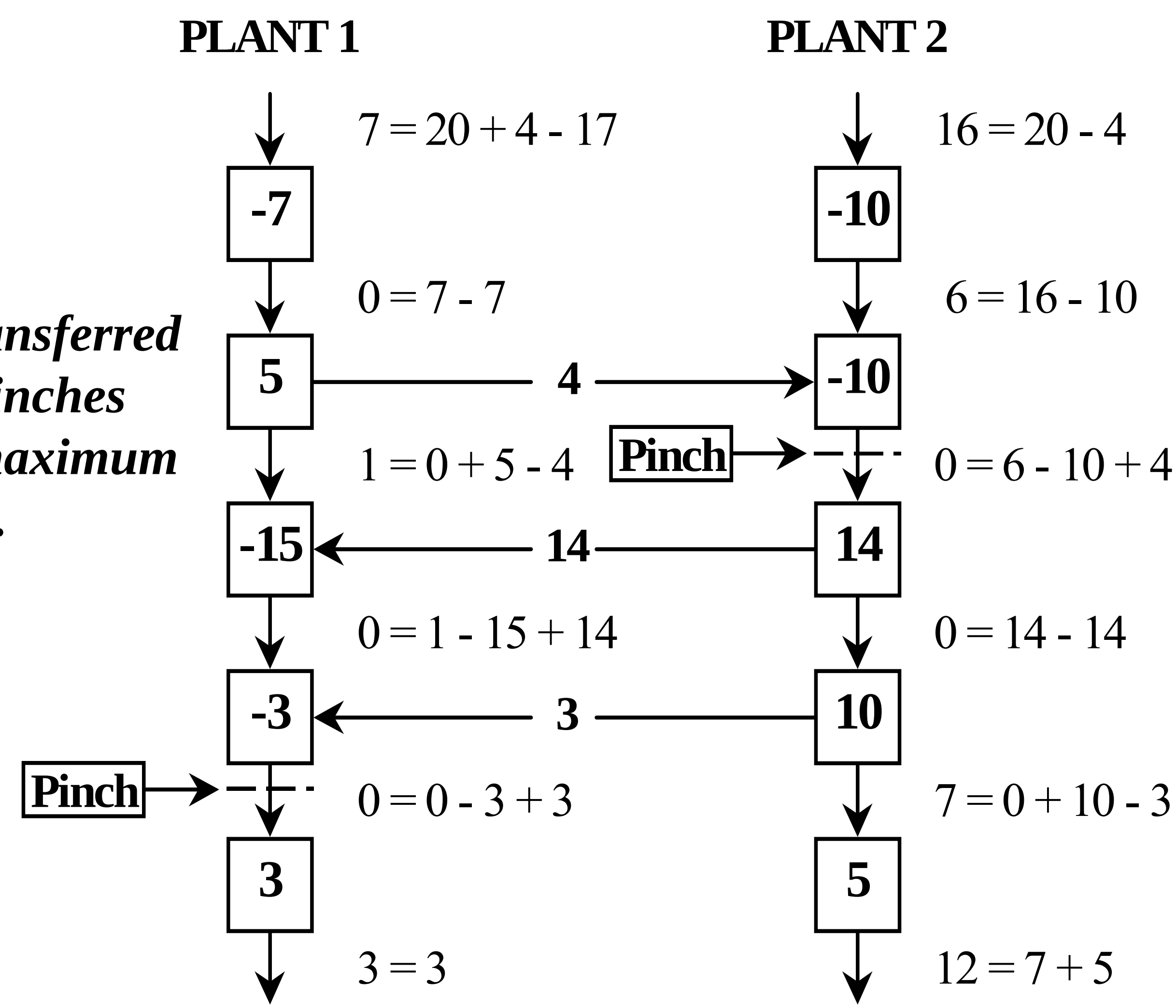


GRAND COMPOSITE CURVES

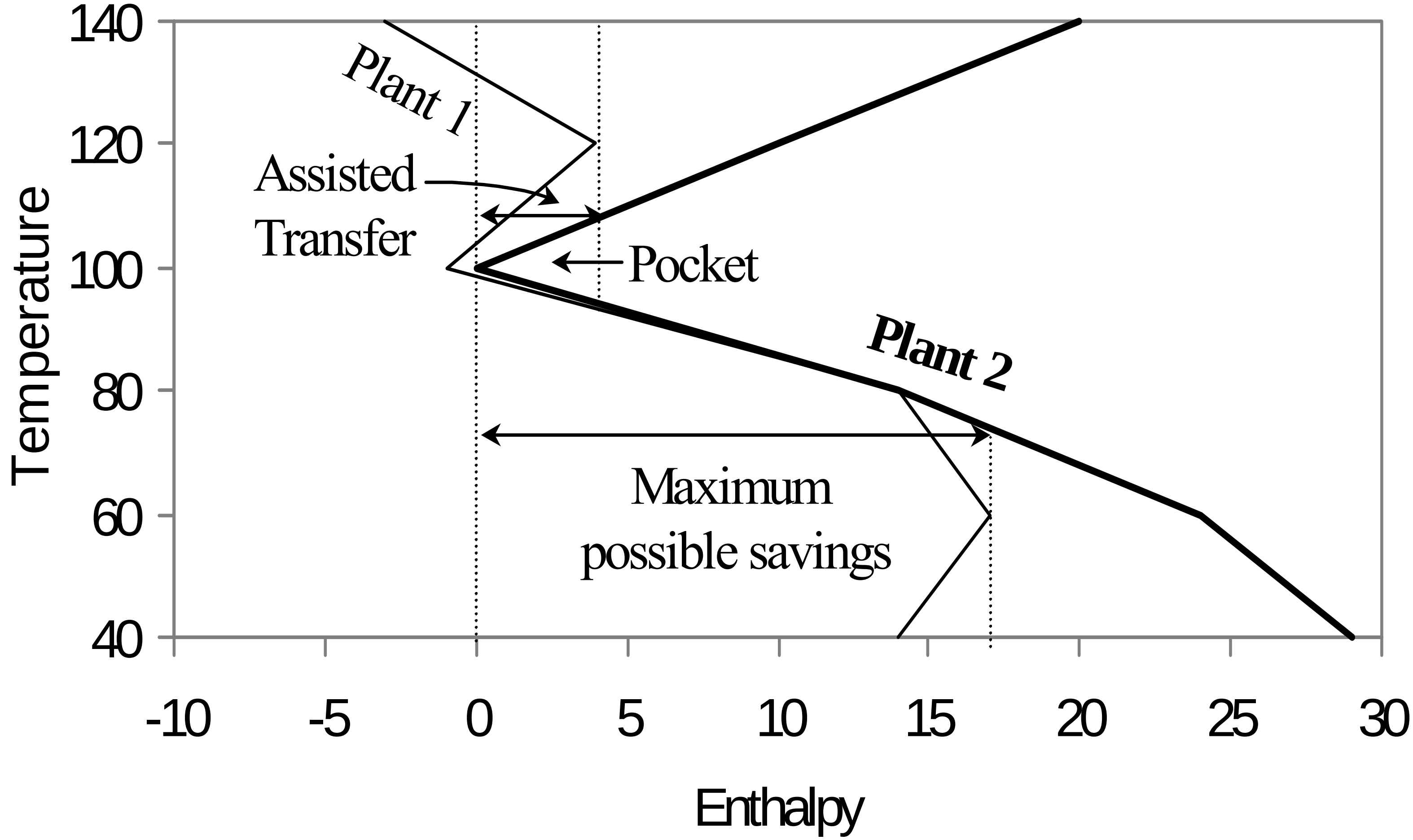


ASSISTED HEAT TRANSFER

If heat is not transferred above the two pinches only 13 of the maximum 17 can be saved.

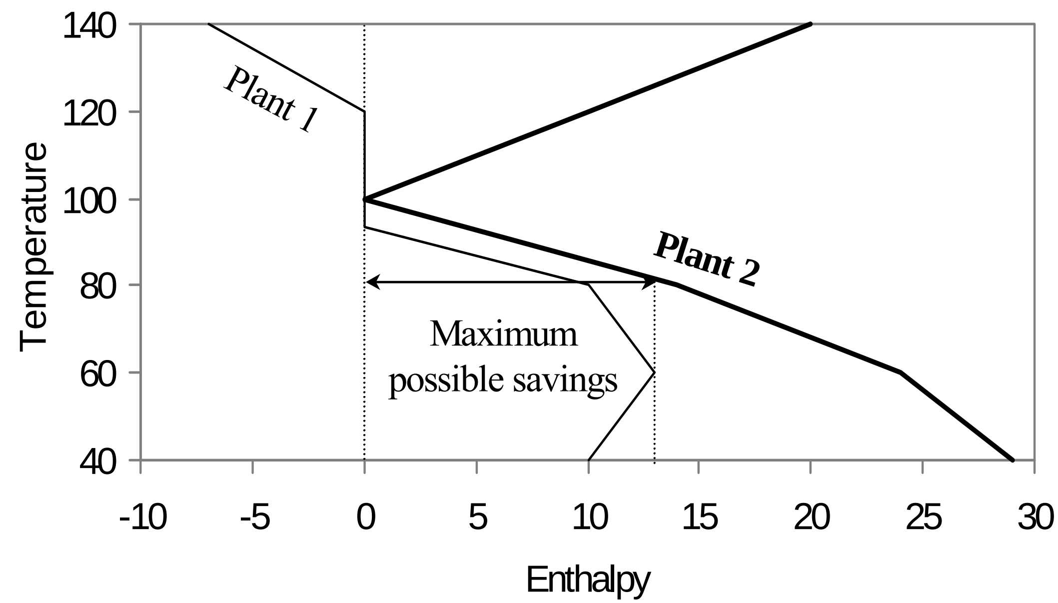


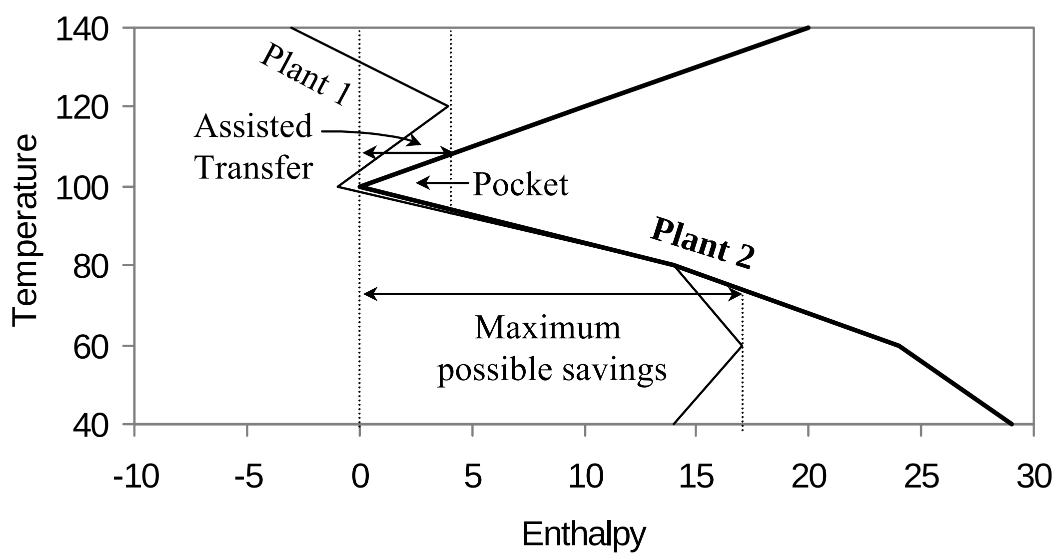
ASSISTED HEAT TRANSFER



ASSISTED HEAT TRANSFER

Typical solutions call for "sealing the pocket" preventing thus the savings.

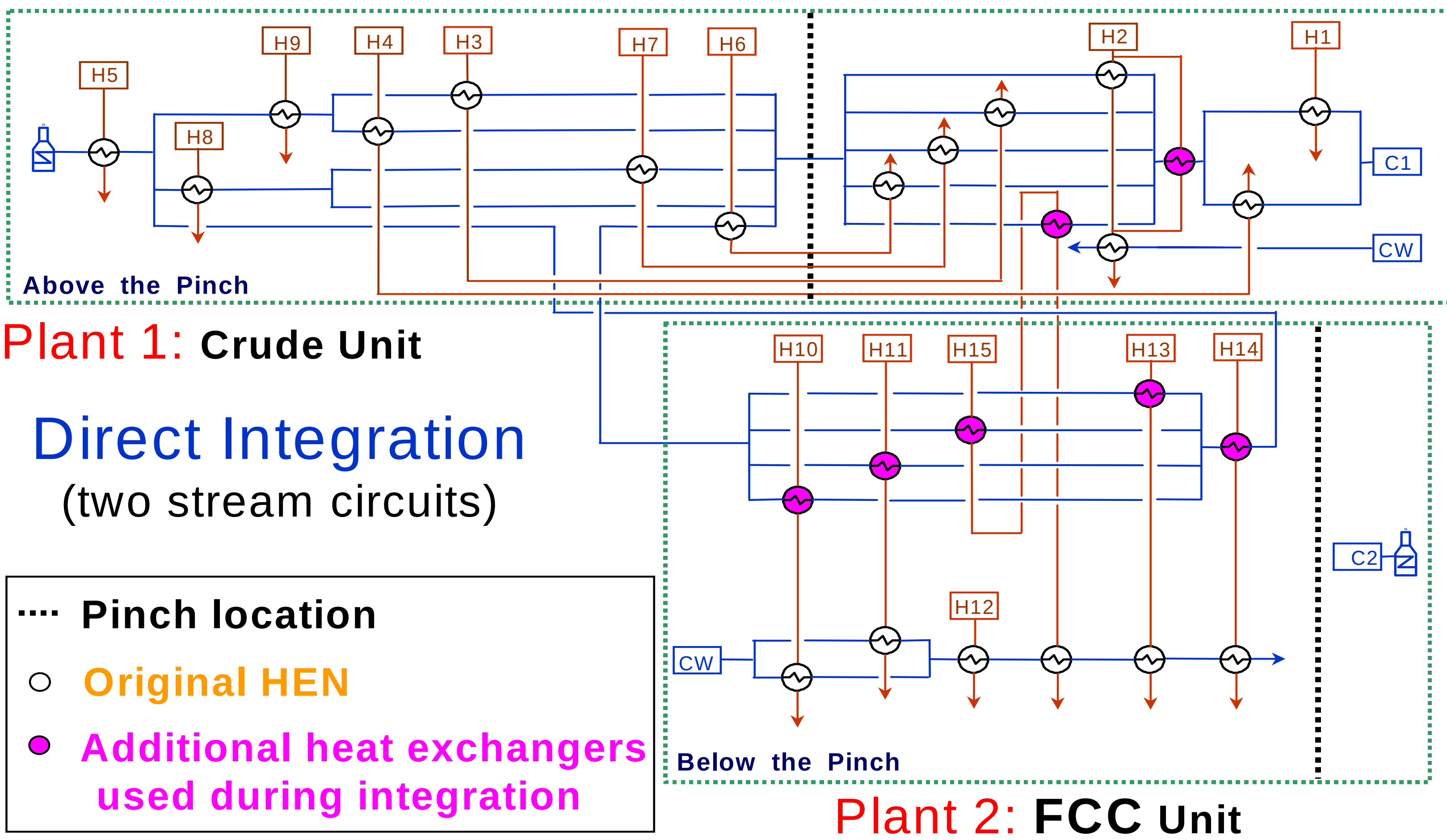




HEAT EXCHANGER NETWORKS

Heat Exchanger networks should be such that both plants can work at maximum efficiency when integrated and when they stand alone.

We now show a result of a case study. An integration between a Crude unit (heat sink) and an FCC unit (heat source).



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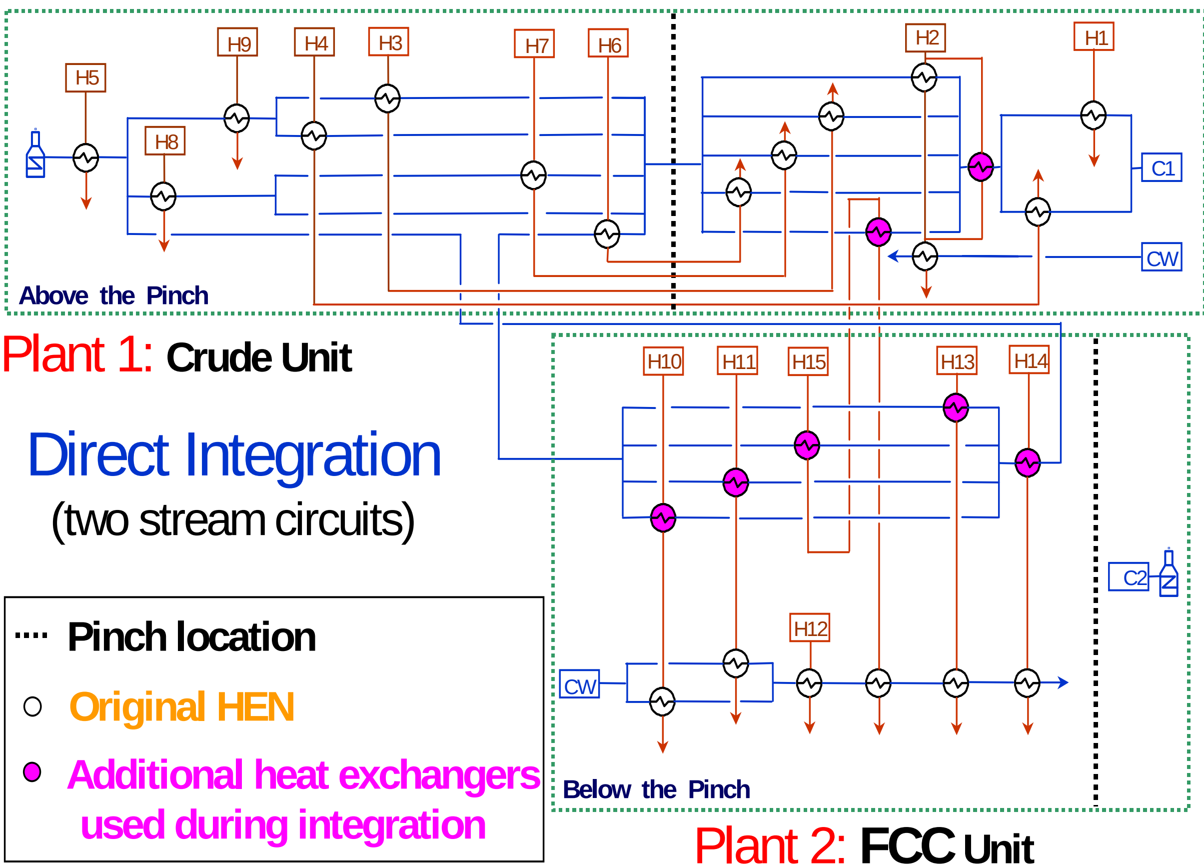


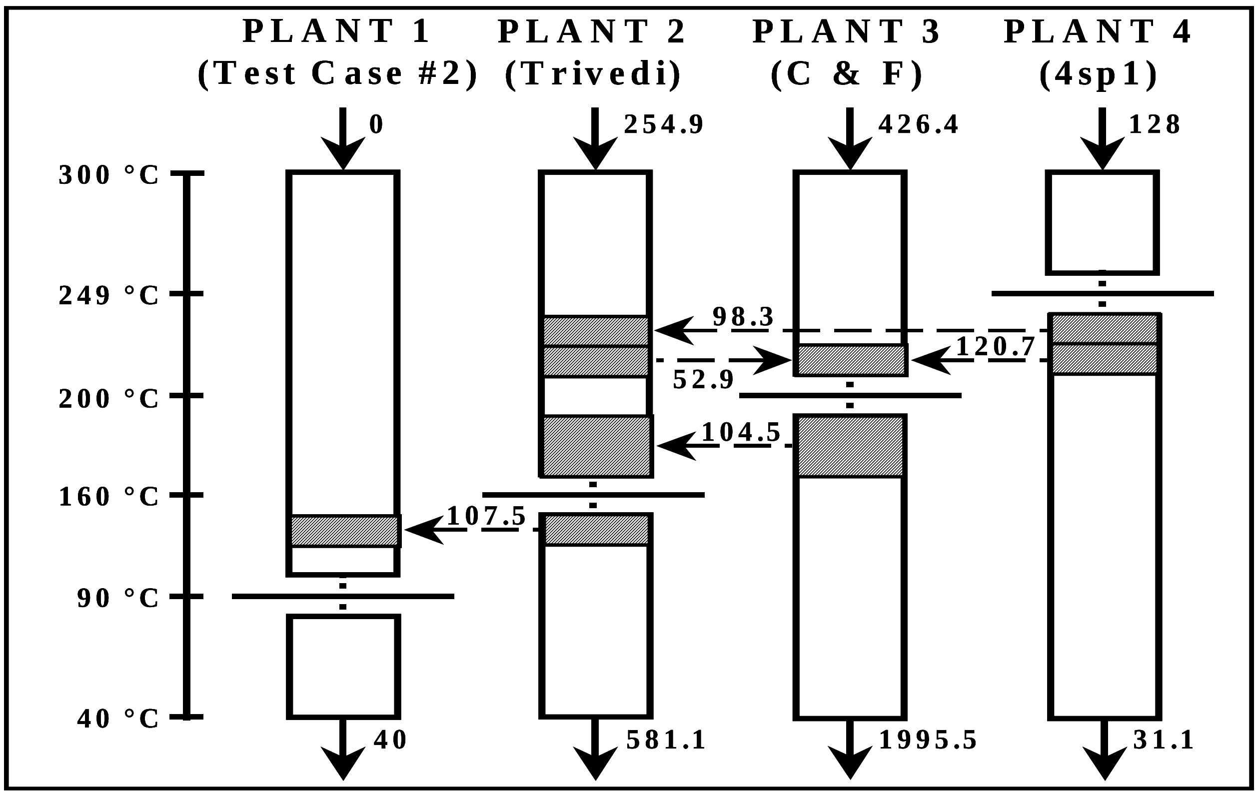
	Utility (MMBtu/hr)	
	Heating	Cooling
No Integration	252.9	147.7
Direct Integration	201.4	96.2

Savings	***1,000,000 $/year***

TOTAL SITE INTEGRATION

Multiple plants can also be analyzed. We show below one example of such studies.

- ***Alternative solutions exists.***
- ***Grand composite curves cannot be used anymore.***



FUTURE TRENDS

- Mathematical programming will be the dominant tool.
- Software companies are struggling to make the proper choice of existing methods for each case and most important numerically <u>reliable</u>.
- The best option for the time being is to intelligently interact with experts while using existing software.