054402 Design and Analysis

LECTURE 8: ADVANCED HEN SYNTHESIS

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Schedule - Day Two

- **Unit 4**. Loops and Splits
  - Minimum Number of Units by Loop Breaking
  - Class Exercise 5
  - Stream Split Designs
  - Class Exercise 6
- **Unit 5.** Threshold Problems
  - Class Exercise 7

Part Two: Objectives

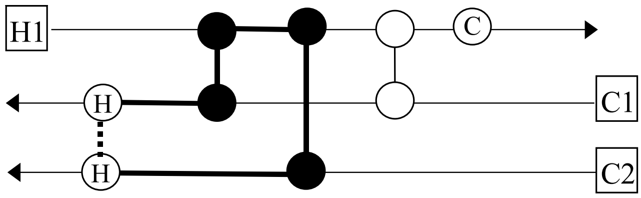
- This Unit on HEN synthesis serves to expand on what was covered last week to more advanced topics.
- Instructional Objectives - You should be able to:
  - Identify and eliminate "heat loops" in an MER design
  - Use stream splits to design for U_{min} and MER
  - Design a HEN for "Threshold Problems"

UNIT 4: Loops and Splits

The minimum number of units (U_{min}) in a network:

$$U_{Min} = N_{Stream} + N_{Util} - 1 \quad \text{(Hohman, 1971)}$$

A HEN containing U_{HEX} units ($U_{HEX} > U_{min}$) has ($U_{HEX} - U_{min}$) independent "heat loops".



The HEN above has 2 "heat loops"

Normally, when heat loops are "broken", heat flows across the pinch - the number of heat exchangers is reduced, but the utility loads are increased.

Class Exercise 5 (Linnhoff and Flower, 1978)

Example:

Stream	T^S (°C)	T^T (°C)	ΔH (kW)	CP (kW/°C)
H1	180	40	280	2.0
H2	150	40	440	4.0
C1	60	180	360	3.0
C2	30	130	260	2.6

ΔT_{min} = 10 °C.

Step 1: Temperature Intervals

(subtract ΔT_{min} from hot temperatures)

Temperature intervals:

180°C ⇒ 170°C ⇒140°C ⇒130°C ⇒60°C ⇒30°C

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Class Exercise 5 (Cont'd)

Step 2: Interval heat balances

For each interval, compute:

$\Delta H_i = (T_i - T_{i+1}) \times (\Sigma CP_{Hot} - \Sigma CP_{Cold})$

Interval	H1	H2	C1	C2	T_i	$T_i - T_{i+1}$	$\Sigma CP_{Hot} - \Sigma CP_{Cold}$	ΔH_i
1					180	10	–3.0	–30
2					170	30	–1.0	–30
3					140	10	3.0	30
4					130	70	0.4	28
5					60	30	3.4	102
6					30			

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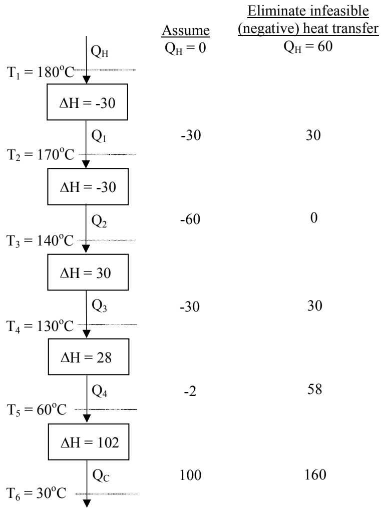
Class Exercise 5 (Cont'd)

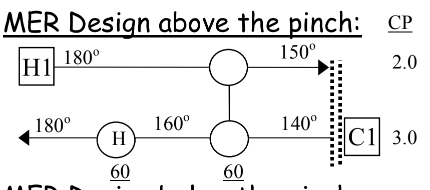
Step 3: Form enthalpy cascade.



This defines:
Cold pinch temp. = 140 °C
Q_{Hmin} = 60 kW
Q_{Cmin} = 160 kW

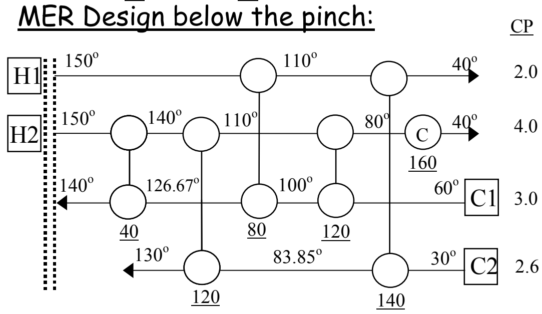
Class Exercise 5 (Cont'd)

MER Design above the pinch:



$U_{Min,MER} = N_{Stream} + N_{Util} - 1$
$= 2 + 1 - 1$
$= 2$ ✓

MER Design below the pinch:

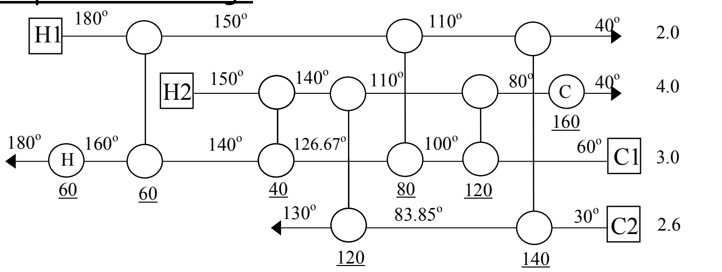


$U_{Min,MER} = 4 + 1 - 1$
$= 4$

MER design below pinch has 6 exchangers! i.e. There are two loops below pinch.

Class Exercise 5 (Cont'd)

Complete MER Design

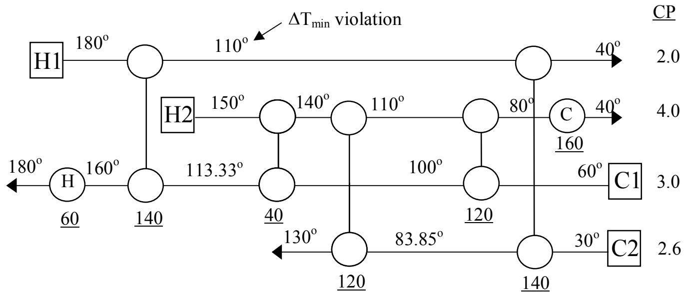


However, $U_{Min} = N_{Stream} + N_{Util} - 1$
$= 4 + 2 - 1$
$= 5$

The MER network has 8 units. This implies 3 independent "heat load loops". We shall now identify and eliminate these loops in order to design for U_{Min}

Class Exercise 5 (Cont'd)

Identification and elimination of 1st loop:

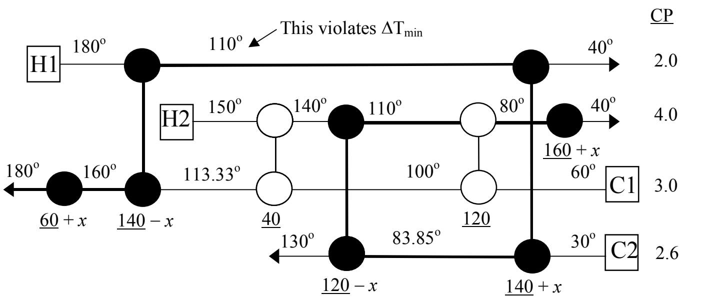


To reduce the number of units, the 80 kW exchanger is merged with the 60 kW exchanger. This breaks the heat loop, but also creates a ΔT_{min} volation in the network:

Class Exercise 5 (Cont'd)

Identification and elimination of 1st loop (Cont'd):

To restore ΔT_{min}, the loads of the exchangers must be adjusted along a "heat path" by an unknown amount x. A "heat path" is a path through the network that connects heaters with coolers.



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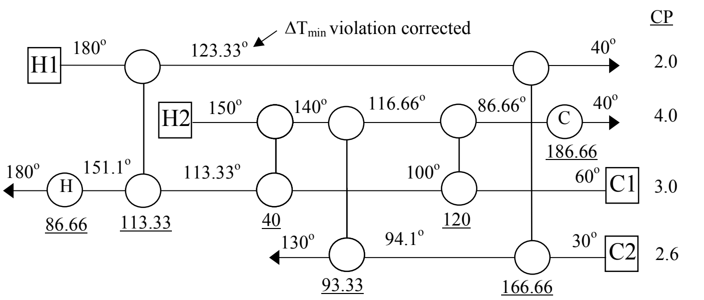
Class Exercise 5 (Cont'd)

Identification and elimination of 1st loop (Cont'd):

Performing a heat balance on H1 in the exchanger which exhibits the ΔT_{min} violation:

$$140 - x = 2(180 - 113.33 - \Delta T_{min}) \Rightarrow x = 26.66$$



This is called "**energy relaxation**"

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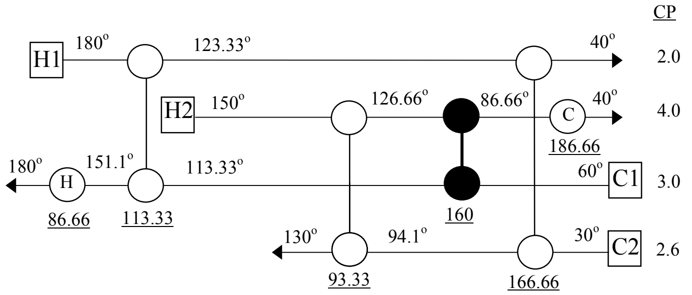
Class Exercise 5 (Cont'd)

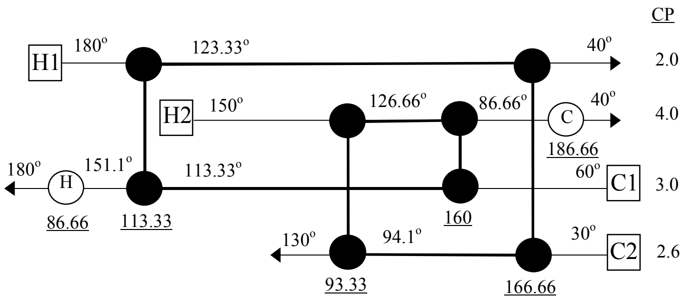
Identification and elimination of 2nd loop:



Since there is no ΔT_{min} violation, no adjustment of the loads of the exchangers is needed - we reduce the number of units by one with no energy penalty.

Class Exercise 5 (Cont'd)

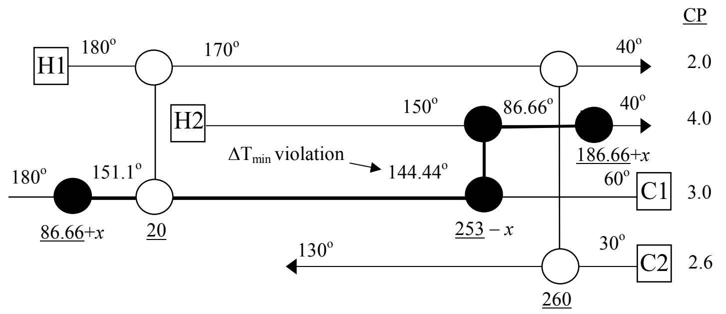
Identification and elimination of 3rd loop:



Shifting the load of the smallest exchanger (93.33 kW) around the loop, the network is reduced to…

Class Exercise 5 (Cont'd)

Identification and elimination of 3rd loop:

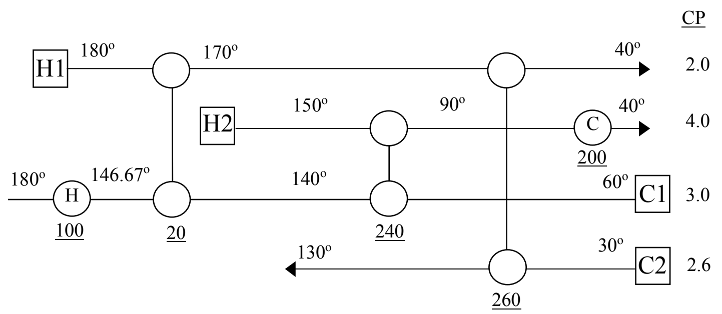


We use the heat path to restore ΔT_{min}:

$$253.33 - x = 3(150 - \Delta T_{min} - 60) \Rightarrow x = 13.33$$

Class Exercise 5 (Cont'd)

Therefore U_{min} Network is:



Loop Breaking - Summary

Step 1:

Perform MER Design for U_{HEX} units. Try and ensure that design meets $U_{Min,MER}$ separately above and below the pinch.

Step 2:

Compute the minimum number of units:

$$U_{Min} = N_{Stream} + N_{Util} - 1$$

This identifies $U_{HEX} - U_{min}$ independent "heat loops", which can be eliminated to reduce U.

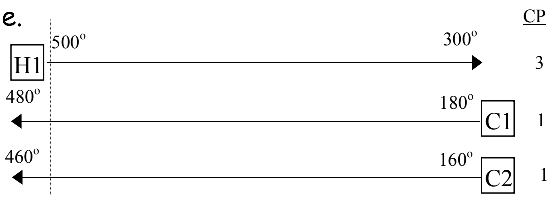
Step 3:

For each loop, eliminate a unit. If this causes a ΔT_{min} violation, identify the "heat path" and perform "energy relaxation" by increasing the duties of the cooler and heater on the heat path.

Loops improve energy recovery and heat load flexibility at the cost of added units ($>U_{min}$)

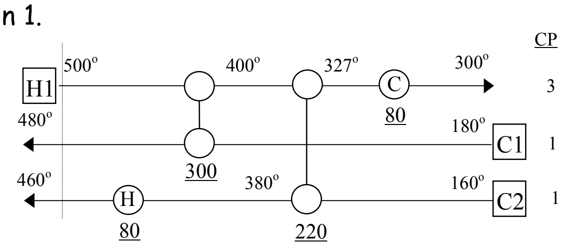
Stream Split Designs

Example.



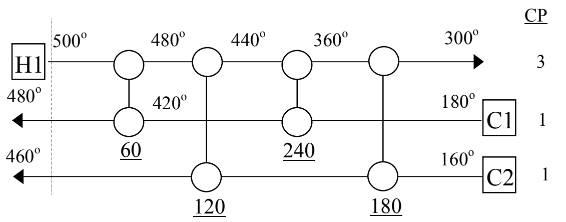
$Q_{Hmin} = 0$ $U_{Min} = 2$ $Q_{Cmin} = 0$

Option 1.

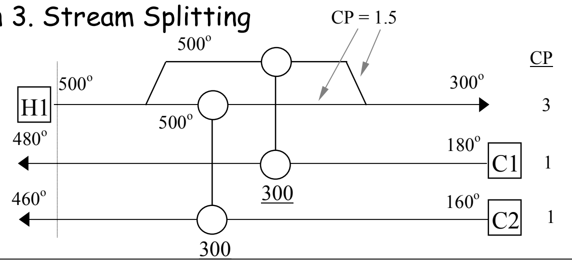


Stream Split Designs (Cont'd)

Option 2. Loops



Option 3. Stream Splitting



Loops vs. Stream Splits

Loops:

☺ Improved energy recovery (normally)

☺ Heat load flexibility (normally)

☹ $U > U_{Min}$ (by definition)

Stream Splitting:

☺ Maximum Energy recovery (always)

☺ Branch flowrate flexibility (normally)

☺ $U = U_{Min}$ (always)

Stream splitting is a powerful technique for better energy recovery

BUT - Don't split unless necessary

Stream Splitting Rules

1. Above the pinch (at the pinch):

❶ Cold utilities cannot be used (for MER). So, if $N_H > N_C$, MUST split COLD streams, since for feasibility $N_H \le N_C$

❷ Feasible matches must ensure $CP_H \le CP_C$. If this is not possible for every match, split HOT streams as needed. If Hot steams are split, recheck ❶

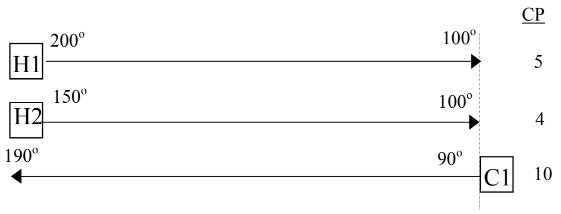
2. Below the pinch (at the pinch):

❶ Hot utilities cannot be used (for MER). So, if $N_C > N_H$, MUST split HOT streams, since for feasibility $N_C \le N_H$

❷ Feasible matches must ensure $CP_C \le CP_H$. If this is not possible for every match, split COLD streams as needed. If Cold steams are split, recheck ❶

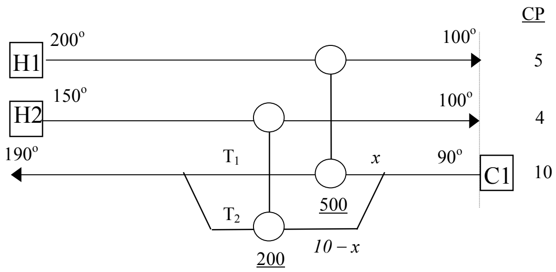
Class Exercise 6

Design a hot-side HEN, given the stream data below:



Solution:
Since $N_H > N_C$, we must split C1. The split ratio is dictated by the rule: $CP_H \le CP_C$ (necessary condition) and by a desire to minimize the number of units ("tick off "streams)

Class Exercise 6 (Cont'd)



x is determined by the following energy balances:

$$x(T_1 - 90) = 500$$

$$(10 - x)(T_2 - 90) = 200$$

subject to: $200 - T_1 \geq \Delta T_{min} = 10$

$150 - T_2 \geq \Delta T_{min} = 10$

Best to make $T_1 = T_2$. Here, this is not possible. Why?

We shall make $T_2 = 140$ (why?)

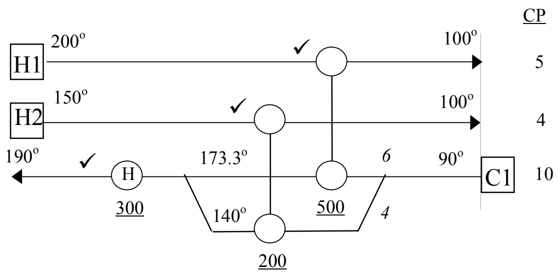
Class Exercise 6 (Cont'd)

A possible solution is therefore:

$(10 - x)(140 - 90) = 200 \Rightarrow x = 6$

$T_1 = 90 + 500/x = 173.33$ (satisfies constraint)

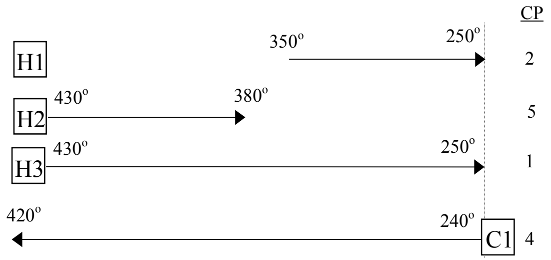
Complete solution is:



This is an MER design which also satisfies U_{Min} (U_{Min} = 3).

Practice Exercise 1

Design a hot-side network for MER and U_{Min} given the stream data below.



Practice Exercise 2

Data:

Stream	T^S (°F)	T^T (°F)	ΔH 10^4kBtu/h	CP (10^4 kBtu/h °F)
H1	400	120	280	1.0
H2	340	120	440	2.0
C1	160	400	360	1.5
C2	100	300	260	1.3

ΔT_{min} = 20 °F

❶ Determine Q_{Hmin}, Q_{Cmin} and the pinch location.

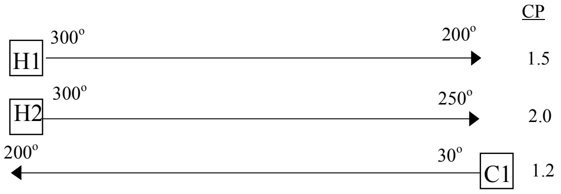
❷ Design an MER network which satisfies energy targets

❸ Design a network for U_{Min} by eliminating the heat loops in the network and performing energy relaxation.

UNIT 5: Threshold Problems

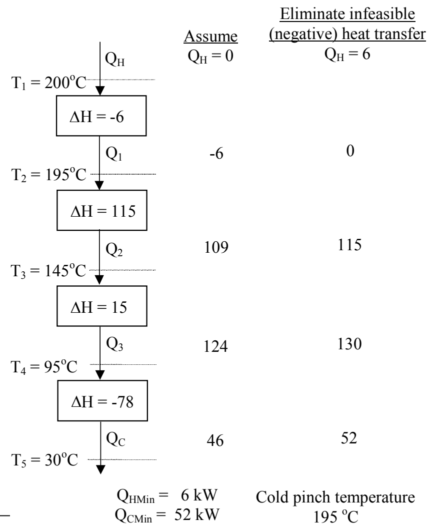
Networks with excess heat supply or heat demand may have MER targets with only one utility (i.e., either $Q_{Hmin} = 0$ or $Q_{Cmin} = 0$). Such designs are not separated at the pinch, and are called "Threshold Problems"

Example - Consider the problem

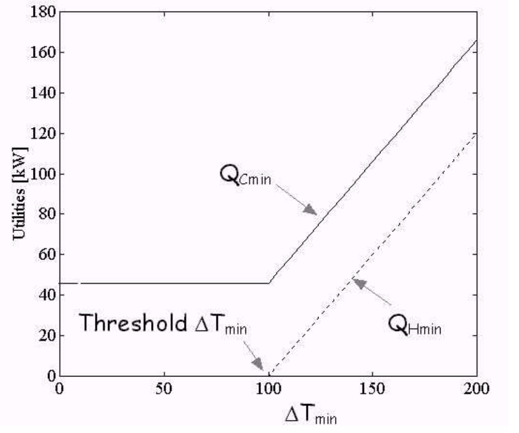


Threshold Problems (Cont'd)

Assuming a value of ΔT_{min}= 105 °C:

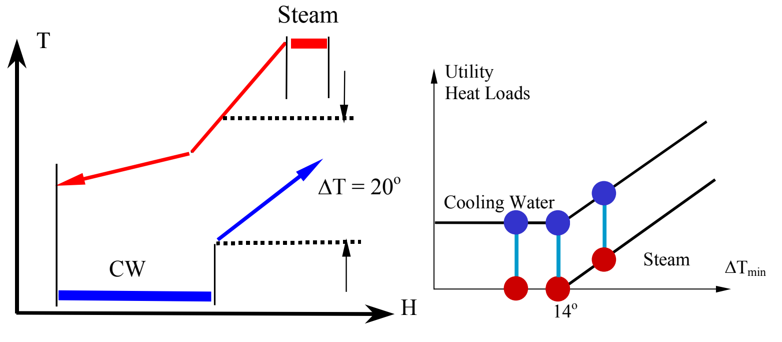


Threshold Problems (Cont'd)



Threshold problems do not have a pinch, and have non-zero utility duties only at one end.

Threshold Problems (Cont'd)



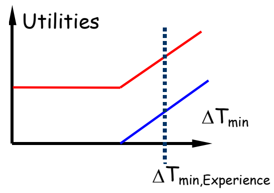
However, increasing driving forces beyond the **Threshold Value** leads to additional utility requirements.

Threshold Design Guidelines

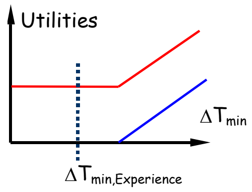
1. Establish the threshold ΔT_{min}
2. Note the common practice values for ΔT_{min}:

Application	Refrigeration	Process	Boiler
$\Delta T_{min,\ Experience}$	1-2 °C	10 °C	20-30 °C

3. Compare the threshold ΔT_{min} to $\Delta T_{min,Experience}$
Classify as one of the following:



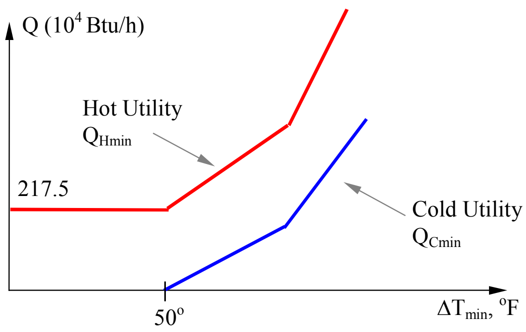
Pinched - treat as normal pinched problem



Threshold - must satisfy target temperatures at the "no utility end"

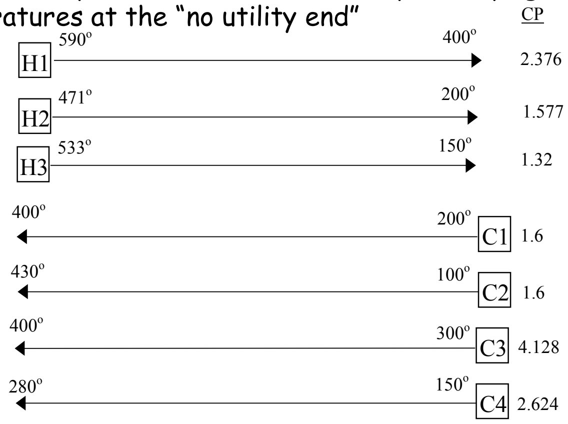
Class Exercise 7

The graph shows the effect of ΔT_{min} on the required levels of Q_{Hmin} and Q_{Cmin} for a process consisting of 3 hot and 4 cold streams.



Class Exercise 7 (Cont'd)

Design a network for U_{min} and MER for the process.
Hint: Identify two essential matches by satisfying target temperatures at the "no utility end"



$Q_{Hmin} = 217.5$ $Q_{Cmin} = 0$

Advanced HEN Synthesis - Summary

- **Unit 4. Loops and Splits**
  - Minimum Number of Units by Loop Breaking - U_{min}
  - Stream Split Designs - U_{min} and MER
- **Unit 5. Threshold Problems**
  - Problems with only hot or cold utilities (no pinch!)