IPESE
Industrial Process and Energy Systems Engineering

École Polytechnique Fédérale de Lausanne

Exercise 02: MER and problem table method Guidelines

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Outline

FINAL GOAL:

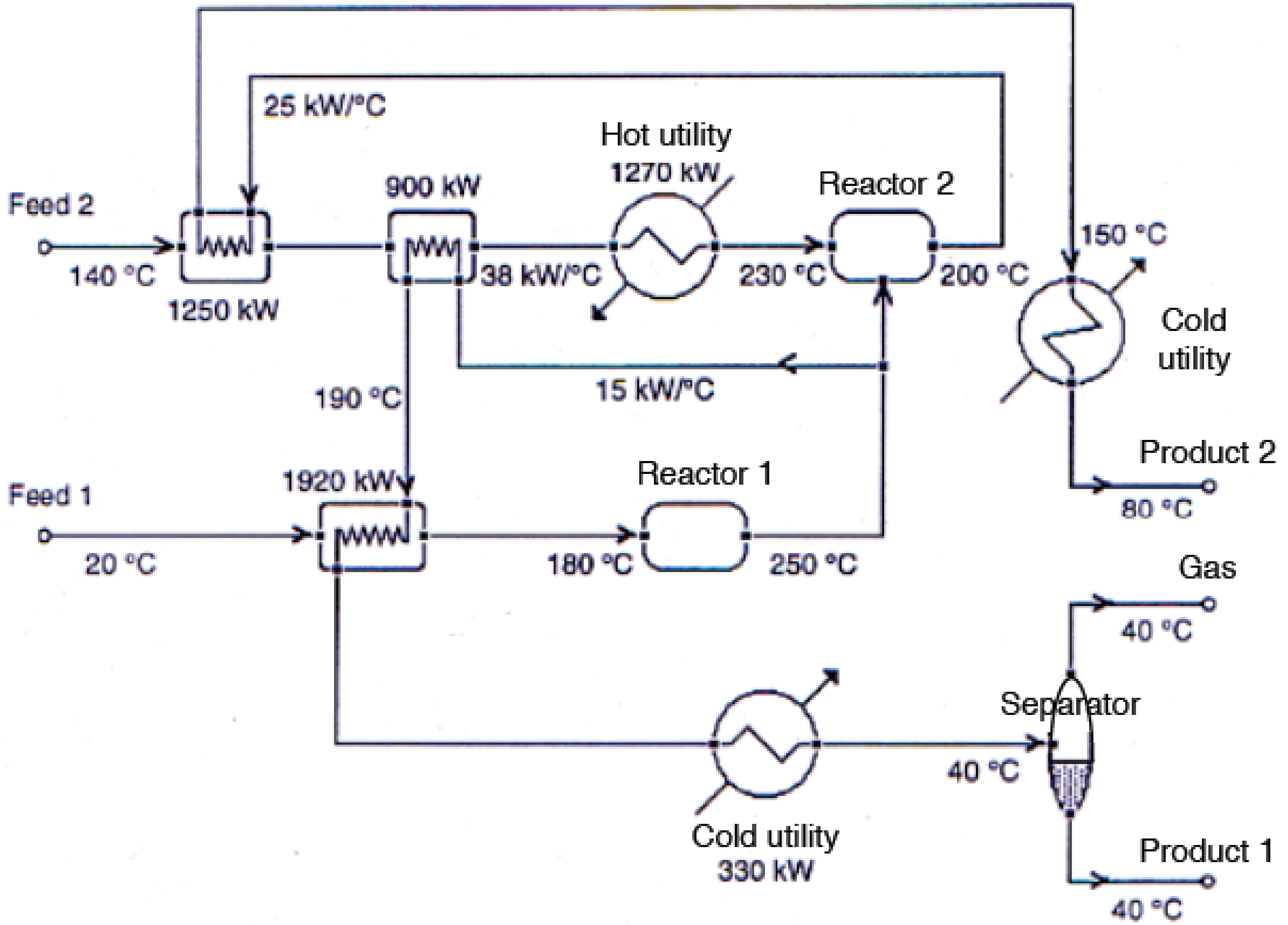
1. Estimate the energy bill of a process
2. Calculate the MER of a process by using the process table method
   - Draw the composite curves
   - Compute the heat cascade
   - Draw the grand composite curve
3. Estimate the possible energy saving under MER
4. Estimate the new energy bill under the MER
5. Identify the penalizing heat exchangers

Exercise 02

System under study

Industrial process composed by:

- 2 input feeds
- 2 output products + gas
- Heat exchanges
- Mixing/splitting
- Chemical reaction



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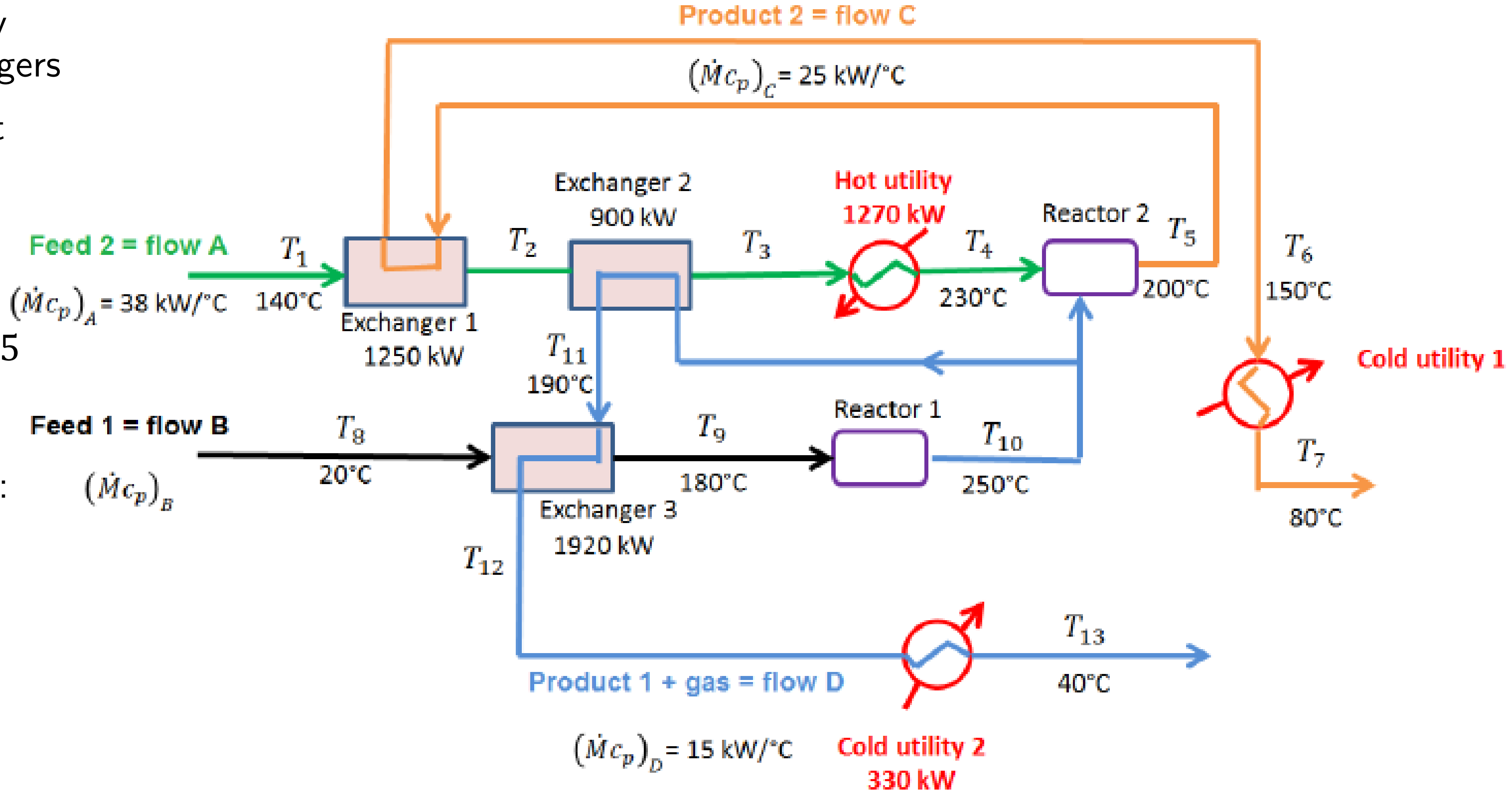
QUESTION 1: actual energy bill

- Determine the missing temperatures T_2, T_3, T_{12} by heat balance at the exchangers
- Determine the missing heat capacity $\left(\dot{M}c_p\right)_B$ by heat balance at Exchanger 3.
- Estimate the energy bill:

1. Hot utility: Boiler $\eta = 0.85$
   $OC_{boiler}\left[\frac{CHF}{y}\right]$?
2. Cold utility: cooling water:
   $T_{cw,in} = 25$ °C
   $T_{cw,out} = 35$ °C
   $c_{p,cw} = 4.18\ kJ/kg/K$
   $\rho_{cw} = 996\ kg/m^3$
   $OC_{cw,}\left[\frac{CHF}{y}\right]$?



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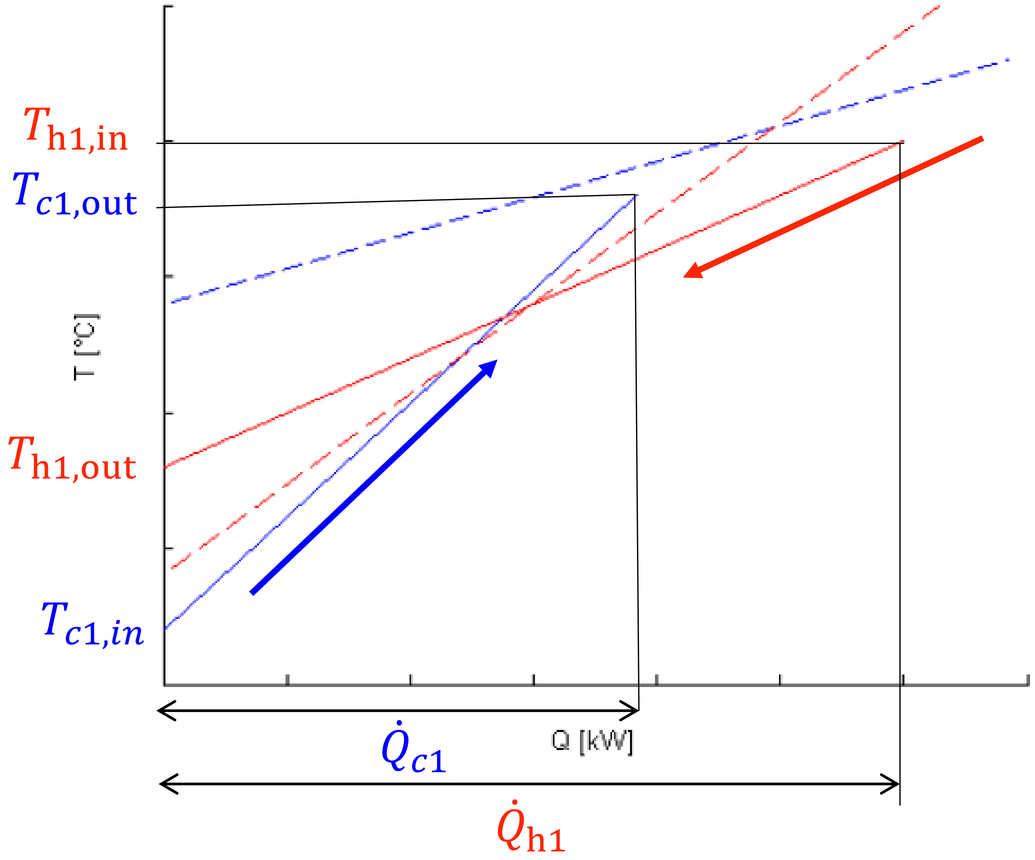
QUESTION 2: minimum energy requirements

1. Identify hot and cold streams: remember that an hot stream has to be cooled down while a cold stream has to be heated up.

Stream		T_{in} [°C]	T_{out} [°C]	$(\dot{M}c_p)$ [kW/°C]	$\dot{Q}$ [kW]
HOT					
COLD					



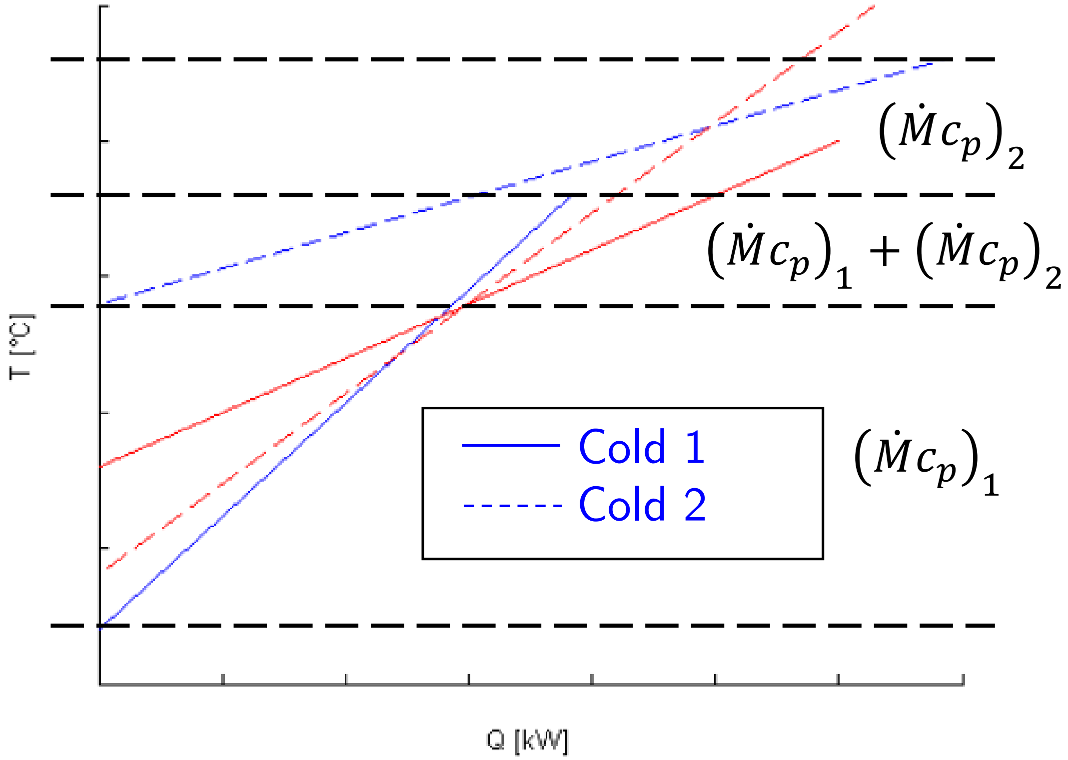
Exercise 02

QUESTION 2: minimum energy requirements

1. Identify hot and cold streams: remember that an hot stream has to be cooled down while a cold stream has to be heated up.

Stream		T_{in} [°C]	T_{out} [°C]	$(\dot{M}c_p)$ [kW/°C]	$\dot{Q}$ [kW]
HOT					
COLD					

2. Define temperature intervals and sum up hot and cold streams respectively to obtain the **COMPOSITE CURVES**



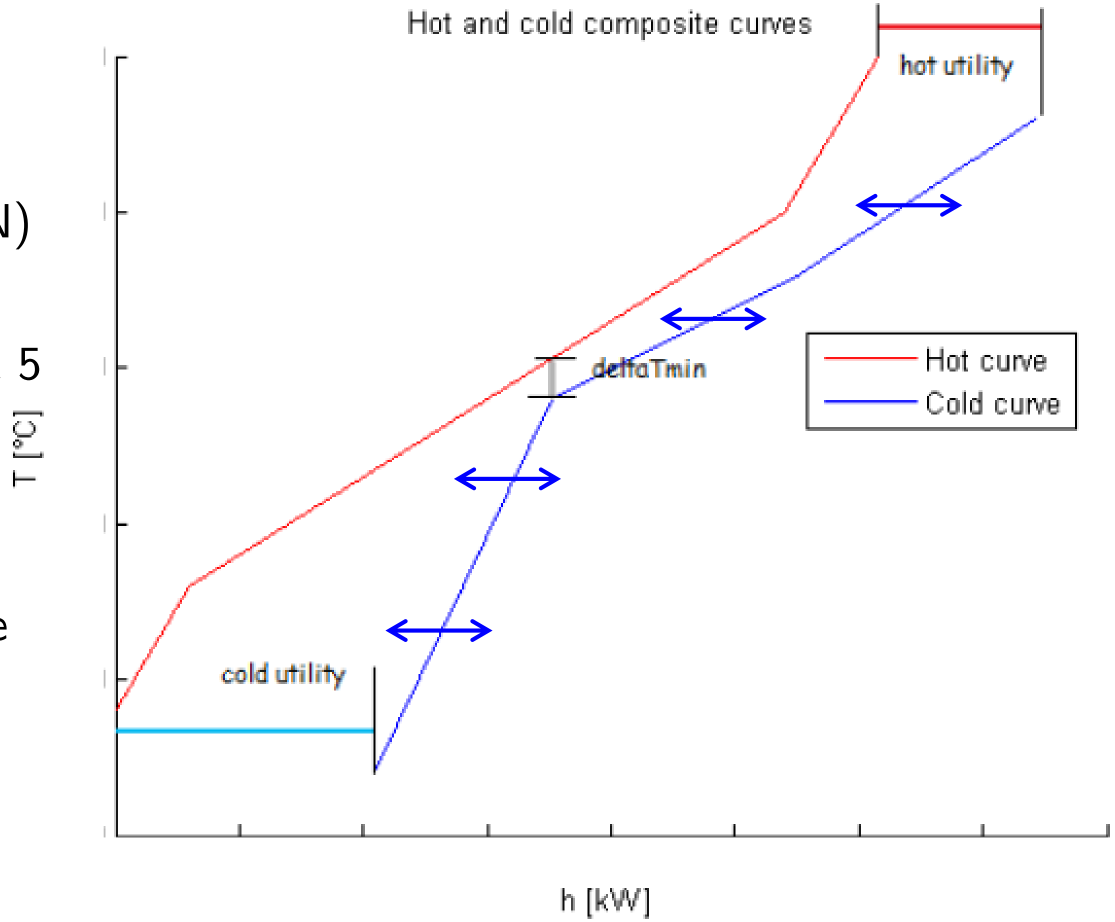
Exercise 02

QUESTION 2: minimum energy requirement

- Hot and cold composite curves can be shifted horizontally
- Once the ΔT_{min} is chosen hot and cold utility requirements are defined:

$\downarrow \Delta T_{min} \longrightarrow \uparrow$ heat recovery $\rightarrow$ $\downarrow$ Operating cost; $\uparrow$ Investment cost (HEN)

- ΔT_{min} is the result of an optimization: in this exercise test 5 values: 1, 3, 5, 10, 15 °C
- The minimum energy requirement can be estimated graphically
- Determine the MER more precisely with the problem table method



Exercise 02

QUESTION 2: minimum energy requirement (problem table method)

1. Shift the hot and cold composite curves vertically of $\Delta T_{min}/2$ so that they touch at the pinch point

Stream	T_{in} [°C]	T_{out} [°C]	T_{in}^* [°C]	T_{out}^* [°C]	$(\dot{M}c_p)$ $[kW/°C]$	$\dot{Q}$ $[kW]$
HOT 1			$T_{h1,in} - \Delta T_{min}/2$	$T_{h2,out} - \Delta T_{min}/2$		
HOT 2			$T_{h2,in} - \Delta T_{min}/2$	$T_{h2,out} - \Delta T_{min}/2$		
COLD 1			$T_{c1,in} + \Delta T_{min}/2$	$T_{c1,out} + \Delta T_{min}/2$		
COLD 2			$T_{c2,in} + \Delta T_{min}/2$	$T_{c2,out} + \Delta T_{min}/2$		

2. Build a table in terms of corrected temperatures intervals and check which streams are crossing each interval

Exercise 02

QUESTION 2: minimum energy requirement (problem table method)

T^* [°C]	$\Delta T_{r,r+1}$ [°C]	$(\dot{M}c_p)_{h1}$ $\left[\frac{kW}{°C}\right]$	$(\dot{M}c_p)_{h2}$ $\left[\frac{kW}{°C}\right]$	$(\dot{M}c_p)_{c1}$ $\left[\frac{kW}{°C}\right]$	$(\dot{M}c_p)_{c2}$ $\left[\frac{kW}{°C}\right]$	$(\dot{M}c_p)_{r,r+1} = \sum \dot{M}c_p$ $\left[\frac{kW}{°C}\right]$	$\Delta\dot{Q}_{r,r+1}$ $[kW]$	$\dot{R}_r^0$ $[kW]$	$\dot{R}_r$ $[kW]$
T_1^*								$\dot{R}_1^0 = 0$	
	$T_1^* - T_2^*$		$(\dot{M}c_p)_{h2}$		$(\dot{M}c_p)_{c2}$	$(\dot{M}c_p)_{h2} - (\dot{M}c_p)_{c2}$	$(\dot{M}c_p)_{1,2} \cdot \Delta T_{1,2}$		
T_2^*								$\dot{R}_2^0 = \dot{R}_1^0 + \Delta\dot{Q}_{1,2}$	

3. For each interval compute:

- The overall heat capacity $(\dot{M}c_p)_{r,r+1} = \sum(\dot{M}c_p)_h - \sum(\dot{M}c_p)_c$
- The heat load in each interval $\Delta\dot{Q}_{r,r+1} = (\dot{M}c_p)_{r,r+1} \cdot \Delta T_{r,r+1}$
- The heat cascaded to the lower temperature interval $\dot{R}_{r+1}^0 = \dot{R}_r^0 + \Delta\dot{Q}_{r,r+1}$
- Start with assumption $\dot{R}_1^0$=0

Exercise 02

QUESTION 2: minimum energy requirement (problem table method)

T^* [°C]	$\Delta T_{r,r+1}$ [°C]	$(\dot{M}c_p)_{h1}$ $\left[\frac{kW}{°C}\right]$	$(\dot{M}c_p)_{h2}$ $\left[\frac{kW}{°C}\right]$	$(\dot{M}c_p)_{c1}$ $\left[\frac{kW}{°C}\right]$	$(\dot{M}c_p)_{c2}$ $\left[\frac{kW}{°C}\right]$	$(\dot{M}c_p)_{r,r+1} = \sum \dot{M}c_p$ $\left[\frac{kW}{°C}\right]$	$\Delta\dot{Q}_{r,r+1}$ $[kW]$	$\dot{R}_r^0$ $[kW]$	$\dot{R}_r$ $[kW]$
T_1^*								$\dot{R}_1^0 = 0$	
	$T_1^* - T_2^*$		$(\dot{M}c_p)_{h2}$		$(\dot{M}c_p)_{c2}$	$(\dot{M}c_p)_{h2} - (\dot{M}c_p)_{c2}$	$(\dot{M}c_p)_{1,2} \cdot \Delta T_{1,2}$		
T_2^*								$\dot{R}_2^0 = \dot{R}_1^0 + \Delta\dot{Q}_{1,2}$	
	$T_2^* - T_3^*$	$(\dot{M}c_p)_{h1}$				$(\dot{M}c_p)_{h1}$	$(\dot{M}c_p)_{2,3} \cdot \Delta T_{2,3}$		
T_3^*								$\dot{R}_3^0 = \dot{R}_2^0 + \Delta\dot{Q}_{2,3}$	
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	
T_r^*									
	$\Delta T_{r,r+1}$						$(\dot{M}c_p)_{r,r+1} \cdot \Delta T_{r,r+1}$		
T_{r+1}^*								$\dot{R}_{r+1}^0 = \dot{R}_r^0 + \Delta\dot{Q}_{r,r+1}$	

Exercise 02

QUESTION 2: minimum energy requirement (problem table method)

$\dot{R}_r^0$ [kW]	$\dot{R}_r$ [kW]
$\dot{R}_1^0 = 0$	$\dot{R}_1 = \dot{R}_1^0 + \lvert \dot{R}_{j+1}^0 \rvert$
$\dot{R}_2^0 = \dot{R}_1^0 + \Delta\dot{Q}_{1,2}$	$\dot{R}_2 = \dot{R}_2^0 + \lvert \dot{R}_{j+1}^0 \rvert$
$\dot{R}_3^0 = \dot{R}_2^0 + \Delta\dot{Q}_{2,3}$	
$\dot{R}_{j+1}^0 = \dot{R}_j^0 + \Delta\dot{Q}_{j,j+1} = \min \dot{R}_r^0$	$\dot{R}_{j+1} = \dot{R}_{j+1}^0 + \lvert \dot{R}_{j+1}^0 \rvert = 0$
$\dot{R}_{r+1}^0 = \dot{R}_r^0 + \Delta\dot{Q}_{r,r+1}$	

- Take the most negative value in the heat cascade
- Sum up this value to the heat cascaded at each interval (in absolute value)
- All $\dot{R}_k$ will be positive
- The temperature at which $\dot{R}_r = 0$ is the pinch point
- $\dot{R}_1$ defines the hot utility requirement
- $\dot{R}_{last}$ defines the cold utility requirement
- The plot $\dot{\boldsymbol{R}}_{\boldsymbol{r}}$ vs $\boldsymbol{T}^*$ is the **GRAND COMPOSITE CURVE**

$$\boxed{\text{MER} = \dot{R}_1 + \dot{R}_{last}}$$

Exercise 02

QUESTION 3: possible energy savings

- For each ΔT_{min} the corresponding MER can be calculated
- Energy saving can be computed as the difference between the current energy requirement (from QUESTION 1) and the MER
- The energy recovered in each scenario can be computed as the difference between the total heat needed by the cold streams and the heat provided by the hot utility or the total heat that has to be removed from the hot streams and the one removed by the cold utility

ΔT_{min} [°C]	$\dot{Q}_{hot}$ $[kW]$	$\dot{Q}_{cold}$ $[kW]$	$\dot{Q}_{recovered}$ $[kW]$
Actual			
1			
3			
5			
10			
15			

Exercise 02

QUESTION 4: new energy bill

- Making the same assumption as for QUESTION 1, calculate the new energy bill for each ΔT_{min}

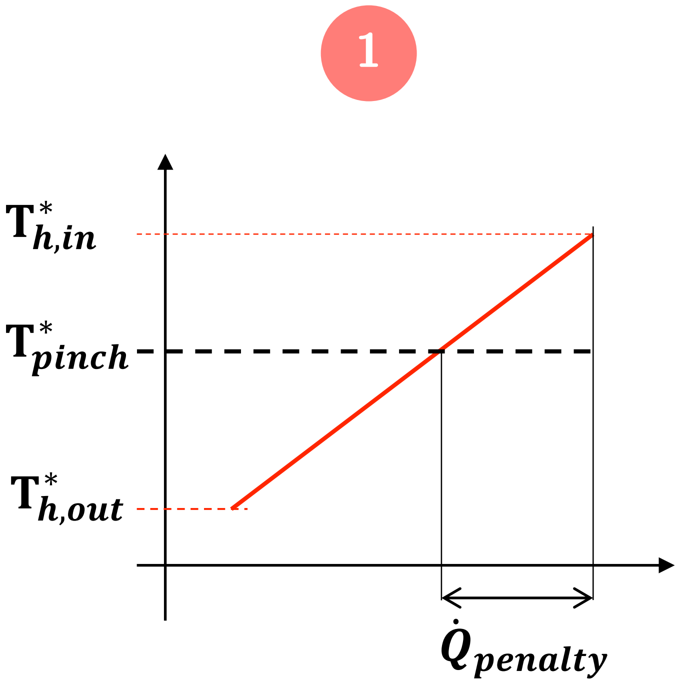
ΔT_{min} [°C]	OC_{hot} $[CHF/y]$	OC_{cold} $[CHF/y]$	OC $[CHF/y]$
Actual			
1			
3			
5			
10			
15			

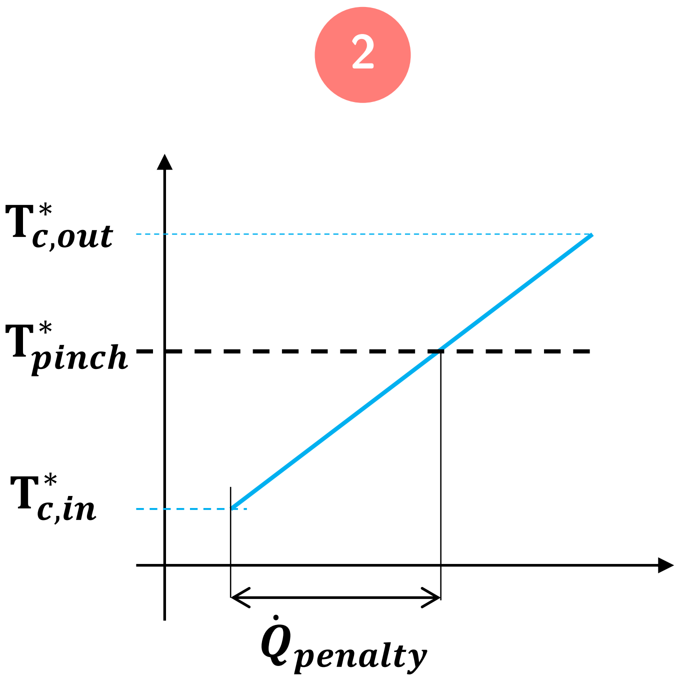
Exercise 02

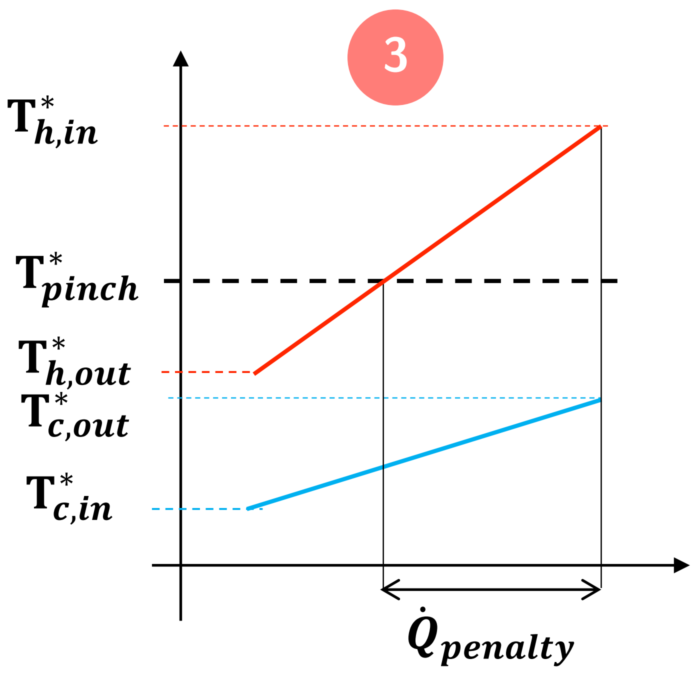
QUESTION 5: penalizing heat exchangers

- The pinch point devides the system into two subsystems
- Once the pinch point is identified 3 rules must be checked:

1. **NO COLD UTILITY ABOVE THE PINCH POINT** → they will just increase the hot utility requirement
2. **NO HOT UTILITY BELOW THE PINCH POINT** → they will just increase the cold utility requirement
3. **NO HEAT EXCHANGERS ACROSS THE PINCH POINT** → they will increase the excessive heat below and reduce the available heat above







Exercise 02

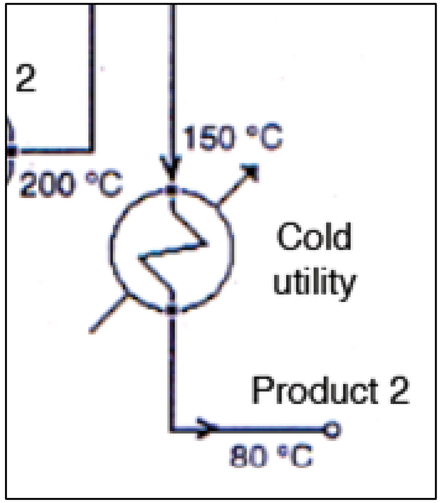
QUESTION 5: penalizing heat exchangers

- The pinch point devides the system into two subsystems
- Once the pinch point is identified 3 rules must be checked:

1. **NO COLD UTILITY ABOVE THE PINCH POINT** → they will just increase the hot utility requirement

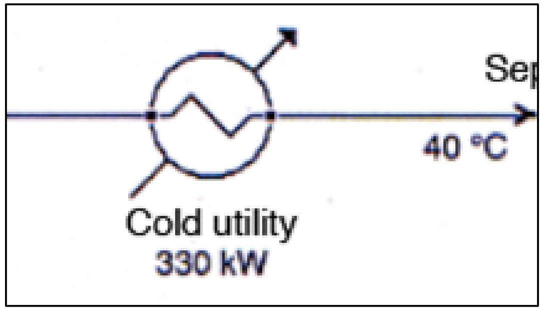
For all cold utilities check that the process hot stream inlet T is NOT above the pinch:

1. COLD UTILITY 1: $T_{c,in} = 25$ [°C] $T_{c,out} = 25$ [°C] $T_{h,in} = 150$ [°C] $T_{h,out} = 80$ [°C]



ΔT_{min} [°C]	T^*_{pinch} [°C]	$T^*_{h,in}$ [°C]	$T^*_{h,out}$ [°C]	**Penalizing? yes/no**
1				
3				
5				
10				
15				

2. COLD UTILITY 2: $T_{c,in} = 25$ [°C] $T_{c,out} = 25$ [°C] $T_{h,in} = \cdots$ [°C] $T_{h,out} = 40$ [°C]



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QUESTION 5: penalizing heat exchangers

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- Once the pinch point is identified 3 rules must be checked:

1. **NO COLD UTILITY ABOVE THE PINCH POINT** → they will just increase the hot utility requirement
2. **NO HOT UTILITY BELOW THE PINCH POINT** → they will just increase the cold utility requirement

   For all hot utilities check that the process cold stream outlet T is not below the pinch

3. **NO HEAT EXCHANGERS ACROSS THE PINCH POINT** → they will increase the excessive heat below and reduce the available heat above

Exercise 02

QUESTION 5: penalizing heat exchangers

- The pinch point devides the system into two subsystems
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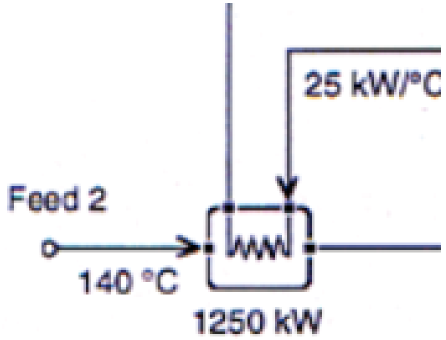
3. **NO HEAT EXCHANGERS ACROSS THE PINCH POINT** → they will increase the excessive heat below and reduce the available heat above

For each HEX check that none of the stream is crossing the pinch

ΔT_{min} [°C]	T^*_{pinch} [°C]	$T^*_{c,in}$ [°C]	$T^*_{c,out}$ [°C]	$T^*_{h,in}$ [°C]	$T^*_{h,out}$ [°C]	**Penalizing? yes/no**
1						
3						
5						
10						
15						



Exercise 02

Conclusions

- The problem table method is a systematic and powerful procedure to analyze complex thermal processes
- Set ΔT_{min} between hot and cold streams the minimum energy requirements (and therefore the maximum energy recovery) can be estimated
- Energy savings compared to the current scenario can be estimated as well as the new operating cost
- The optimal value of ΔT_{min} is the result of an optimization: best trade-off between operating and investment cost

Questions?

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