Pinch Analysis for Heat Integration

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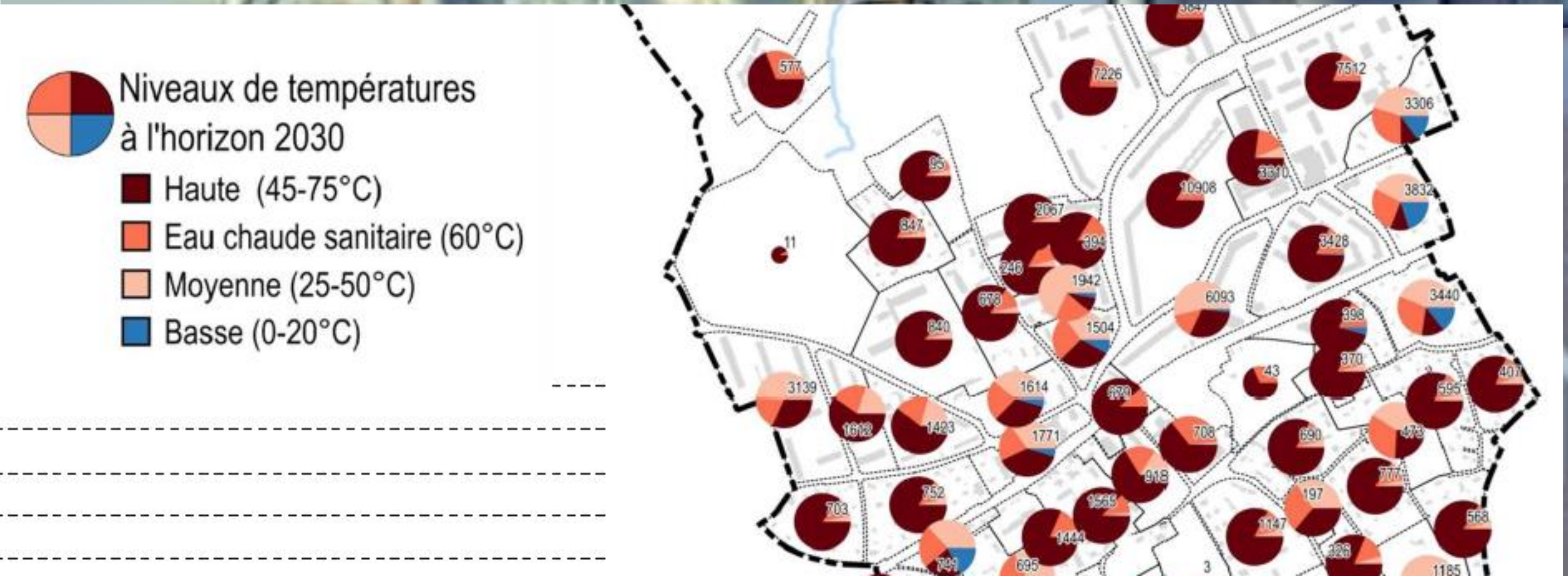
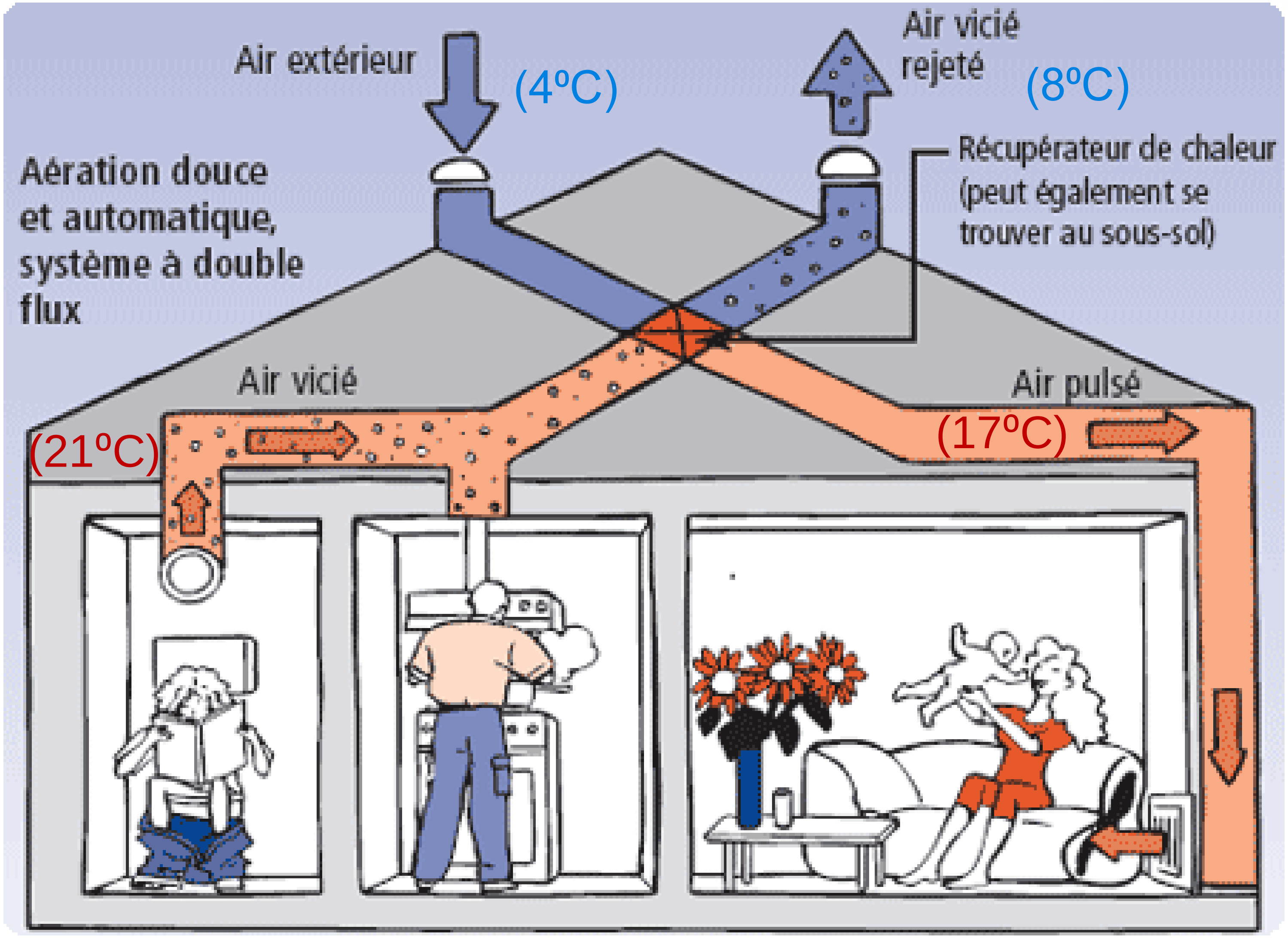


L. Girardin, "SIG pour la planification énergétique territoriale", 2014

Heat recovery: Space heating

Récupération de chaleur - Chauffage des locaux



Double flux avec récupération de chaleur

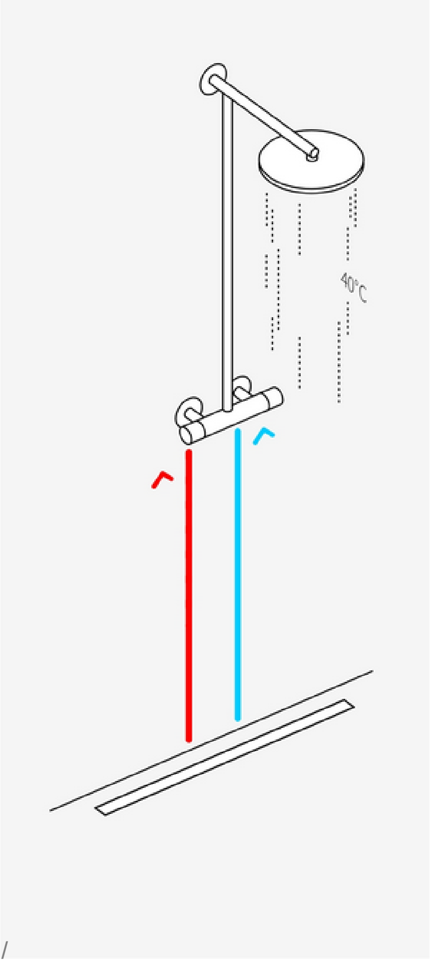
Komfortlüftung mit Wärmerückgewinnung

https://www.climamaison.com/conseil-expert/electricite-et-solution-tout-air-le-retour.htm

Heat recovery – Joulia shower
Récupération de chaleur - Douche Joulia

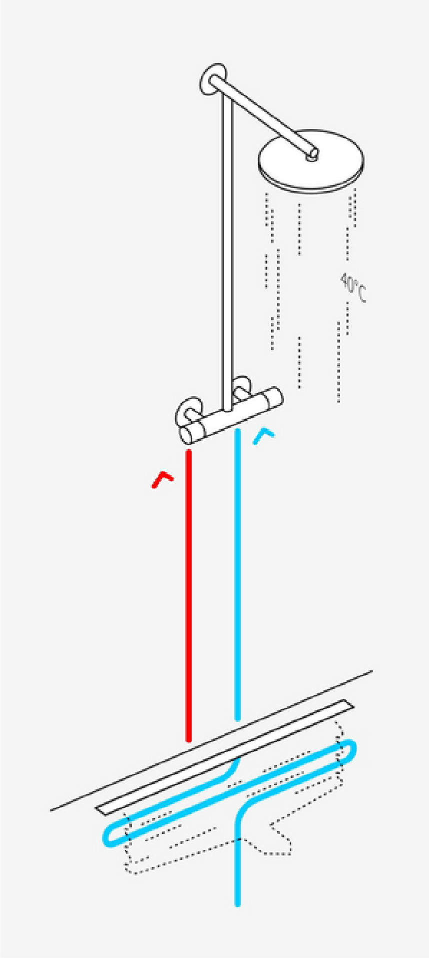
Before:

The cold and warm water is directly connected to the mixing valve. The used warm shower water regrettably flows into the sewerage system.



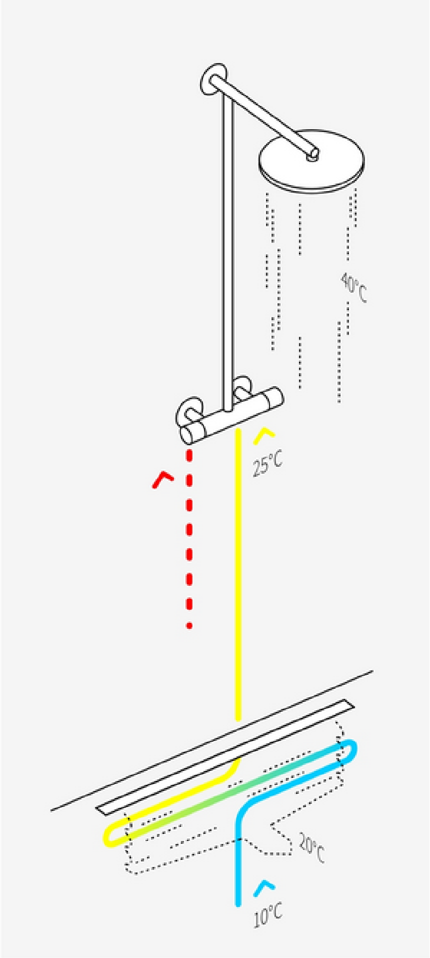
Thanks to the rerouting of the cold water…

The Joulia-Inline shower drain is directly connected to the cold water pipes. Thanks to the integrated heat recovery, the heat of the used water…



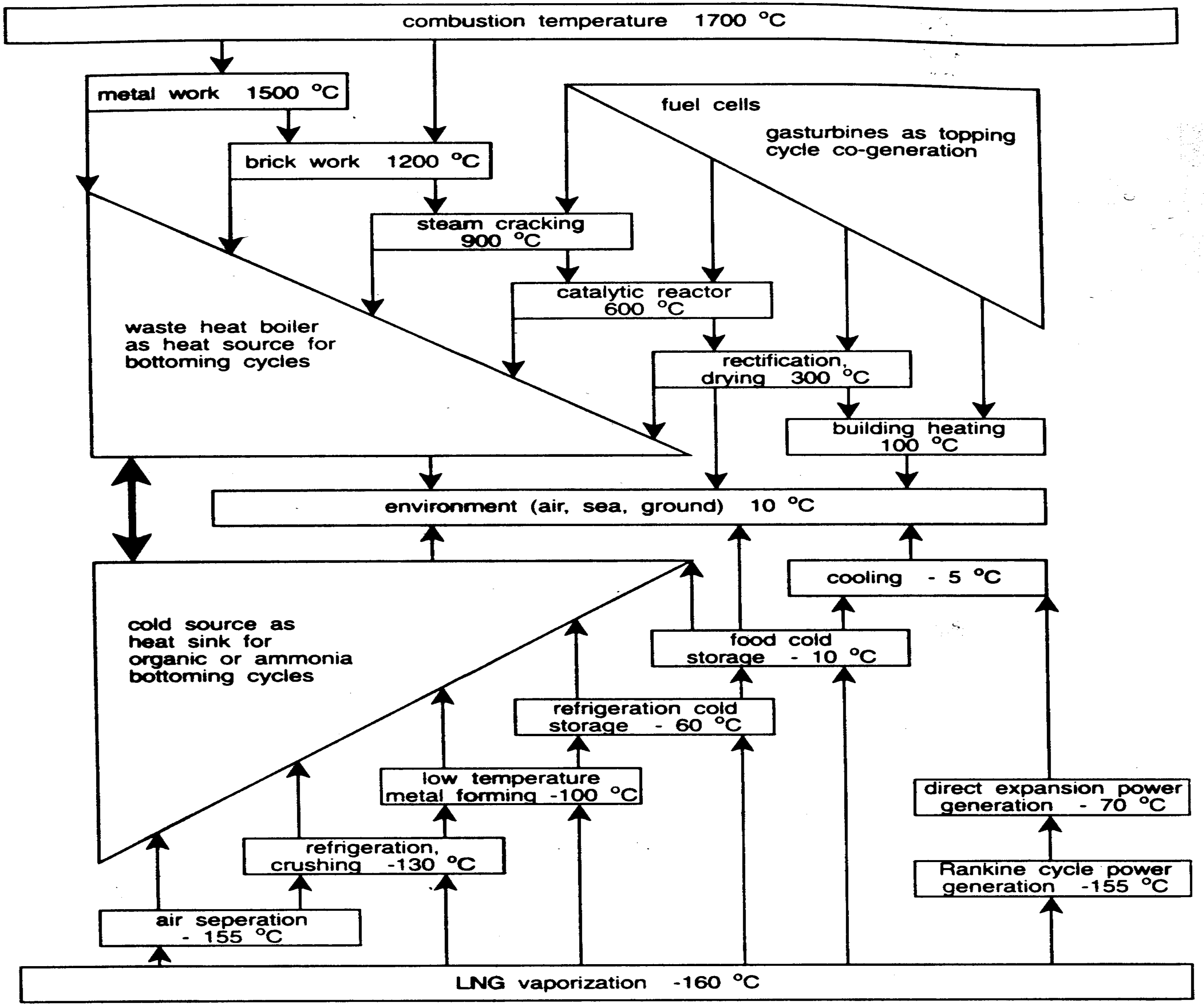
… the heat energy comes back!

…preheats the fresh cold water. Thereby less warm water is needed in the mixing valve and a lot of CO_2 and money can be saved.



https://joulia.com/en/

Minimizing energy losses by “cascading”



combustion temperature 1700 °C

metal work 1500 °C

brick work 1200 °C

steam cracking 900 °C

catalytic reactor 600 °C

rectification, drying 300 °C

building heating 100 °C

fuel cells

gasturbines as topping cycle co-generation

waste heat boiler as heat source for bottoming cycles

environment (air, sea, ground) 10 °C

cooling - 5 °C

food cold storage - 10 °C

refrigeration cold storage - 60 °C

low temperature metal forming -100 °C

refrigeration, crushing -130 °C

air seperation - 155 °C

cold source as heat sink for organic or ammonia bottoming cycles

direct expansion power generation - 70 °C

Rankine cycle power generation -155 °C

LNG vaporization -160 °C

Heat Integration

Pinch Technology

Course Introduction: Heat integration

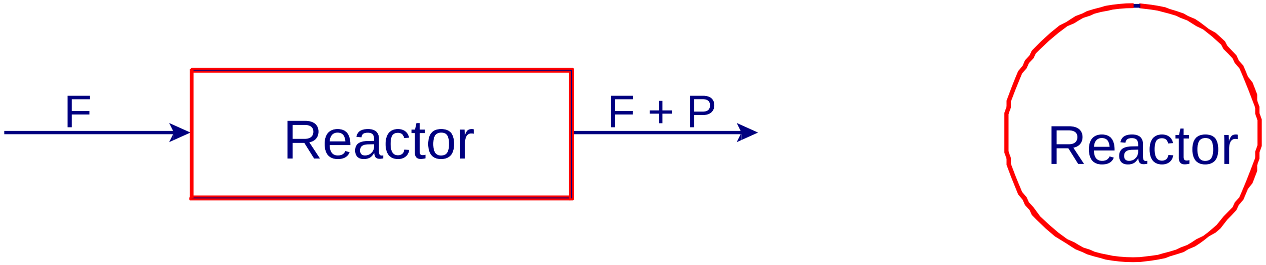
Objective	To introduce the problem of process heat recovery and Pinch analysis for solving this problem.
Scope	The course will focus on energy targets, the Pinch Design method, capital cost targeting and the integration of heat pumps.
Assumed Background	Basic thermodynamics
Recommended reading	Smith, *Chemical Process Design*, 1995, McGraw-Hill

Contents

Part 1

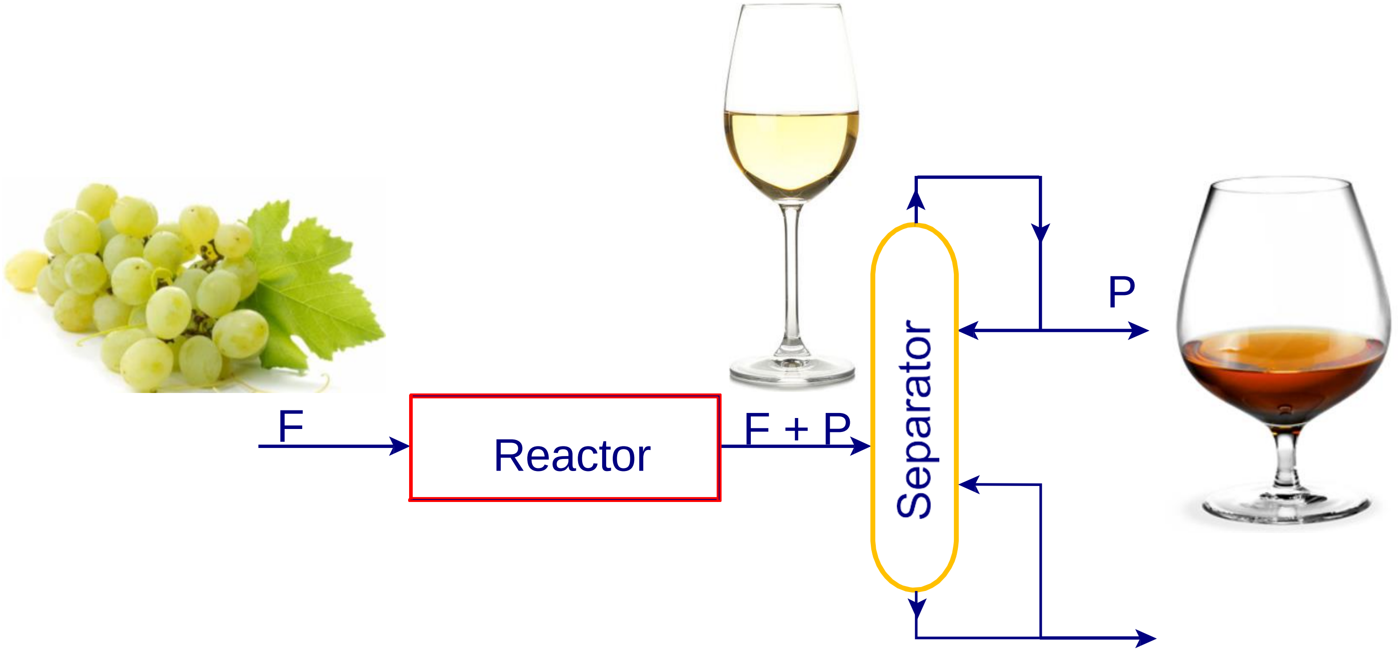
Introduction - Heat Integration

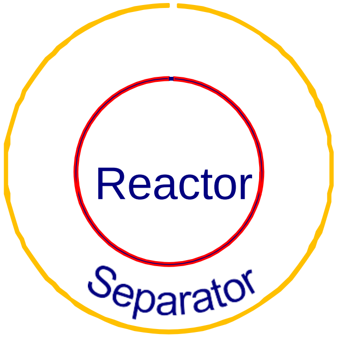
Let’s start by considering the hierarchy of process design



Process design starts with the reactor

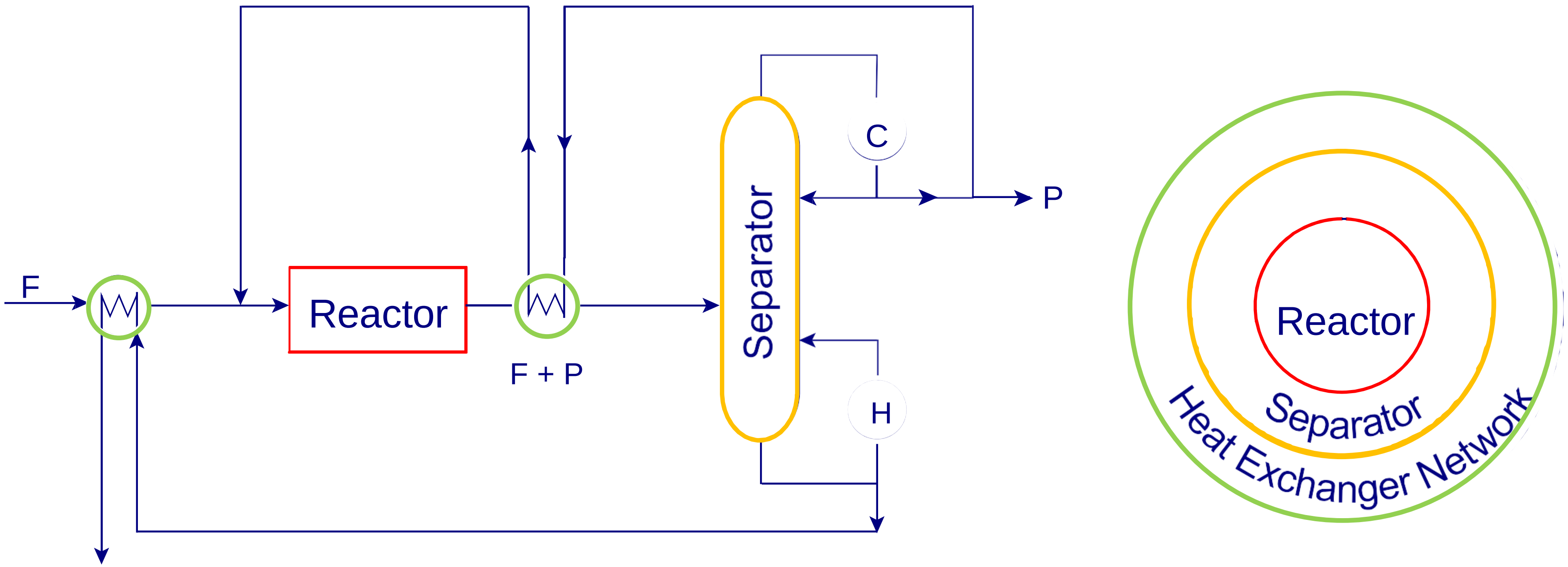
(Courtesy of University of Manchester)





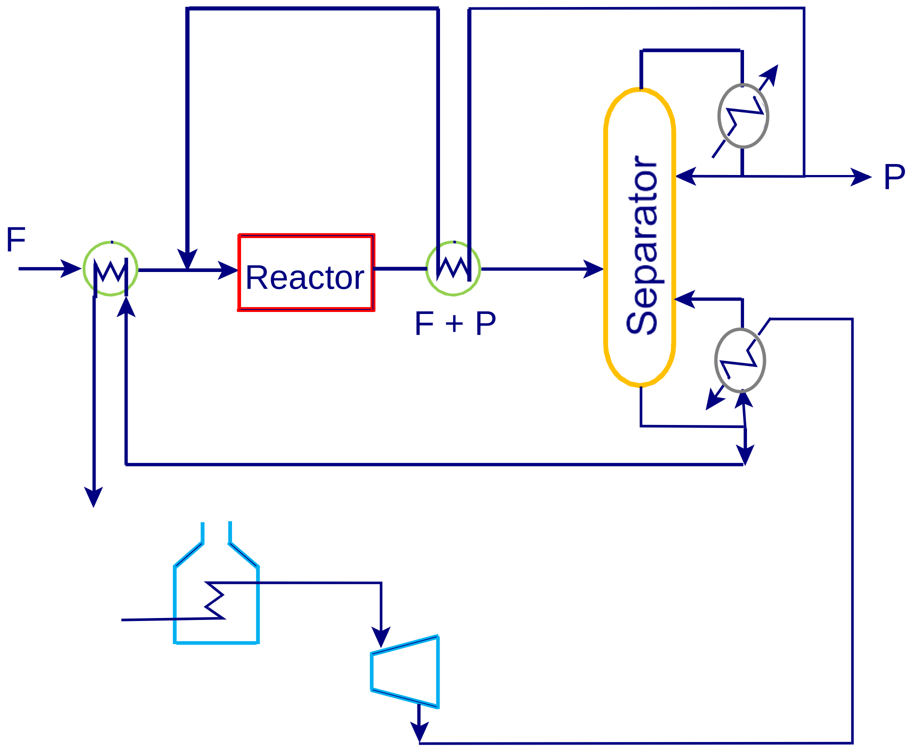
Once we know the reactor design,
we need to specify the separation system

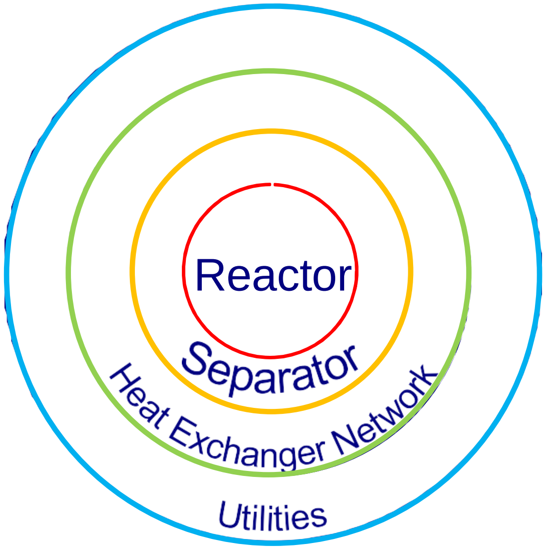
(Courtesy of University of Manchester)



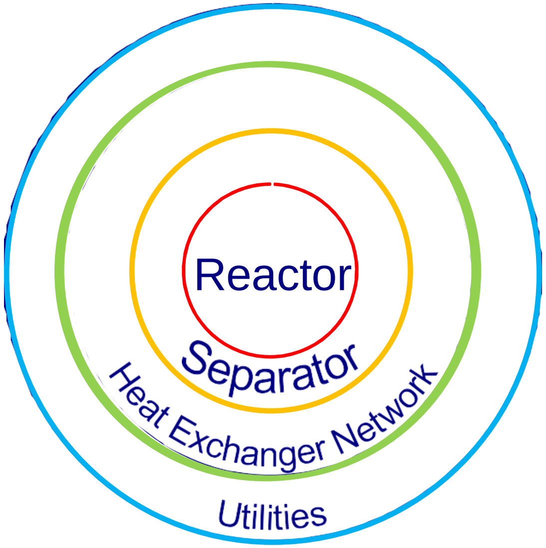
Once we know reactor and separator design, we know material and energy balance - Heat Exchanger Network

(Courtesy of University of Manchester)





(Courtesy of University of Manchester)



The "Onion" Diagram

(Courtesy of University of Manchester)

What is better process integration about?

- Better process design
- Increased throughput in retrofit
- Reduced utility costs
- Better utilisation of capital
- Reduced emissions

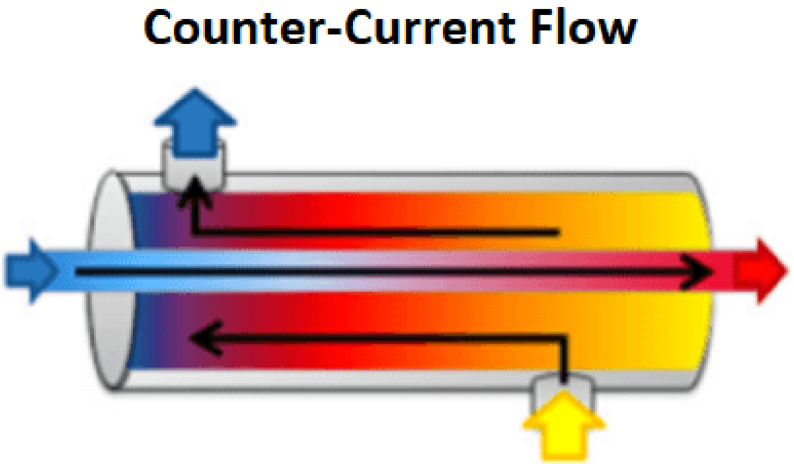
(Courtesy of University of Manchester)

The Basic Terminology

(Courtesy of University of Manchester)

Heat recovery: Heat exchanger

Echangeur de chaleur



https://www.google.com/search?q=counter-current+heat+exchanger&tbm=isch
https://www.filsonfilters.com/counter-flow-heat-exchanger/

Heat recovery:
Small versus large heat exchanger (here: counterflow)
Echangeur de chaleur – petit ou grand (ici: contre-courant)

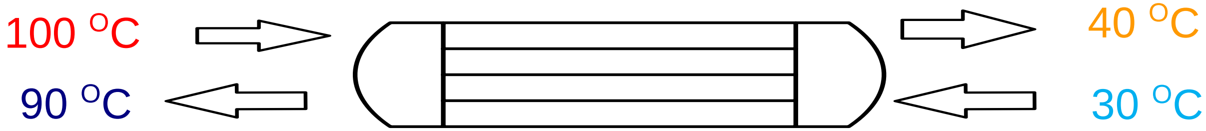
100 ^{O}C

70 ^{O}C

60 ^{O}C

30 ^{O}C

$$\Delta H = m \cdot c_P \cdot \Delta T$$



100 ^{O}C

90 ^{O}C

40 ^{O}C

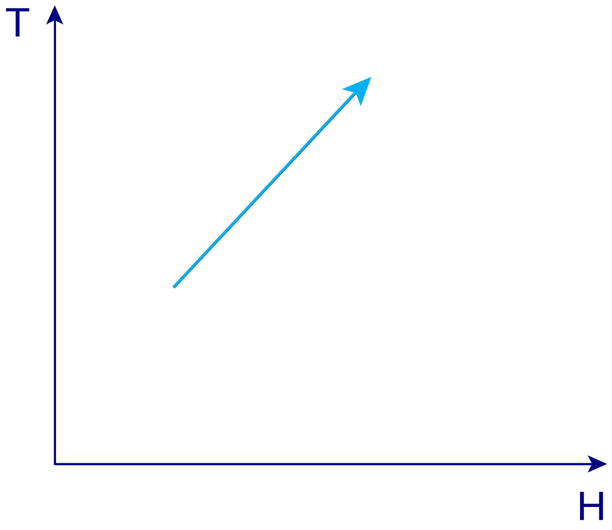
30 ^{O}C

→ Which heat exchanger would you prefer (for using waste heat at 100 ^{o}C)?

The Streams

" Cold " streams require heating

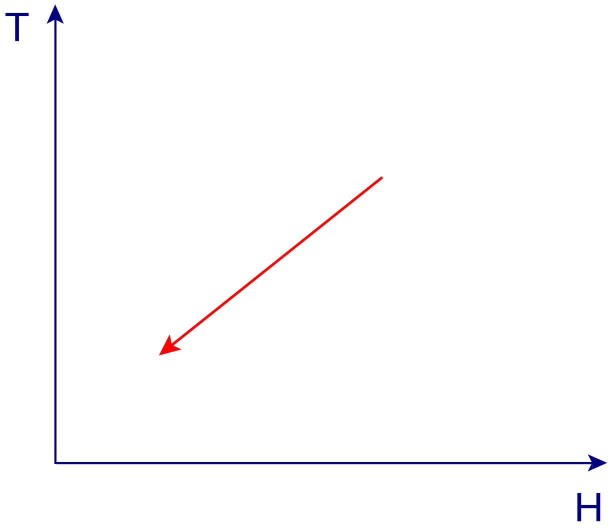
(Courants froids)



Example: Fresh milk needs to be heated up as part of the ultra-high temperature (UHT) treatment.

" Hot " streams require cooling

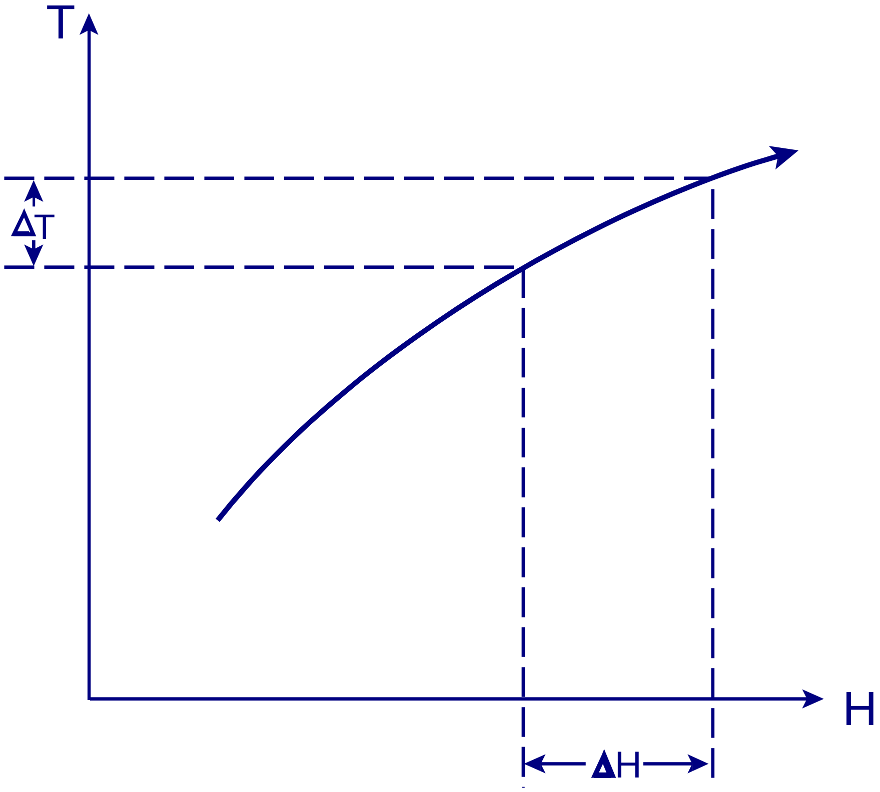
(Courants chauds)



Example: Milk that has undergone ultra-high temperature treatment needs to be cooled down before packaging.

(Courtesy of University of Manchester)

Temperature-Enthalpy Diagram



H = Stream Enthalpy (MW or kW)

(Courtesy of University of Manchester)

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Heat Duties (Charge thermique)

$$\Delta H = m \cdot c_P \cdot \Delta T$$

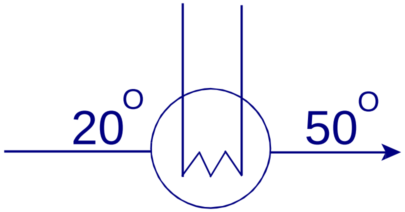
m [kg/s]

c_P [MJ/(°C·kg)]

ΔT [°C]

ΔH [MW]

$$CP = m \cdot c_P = \frac{\Delta H}{\Delta T}$$



CP = 0.5 [MW/°C]

$\Delta H = 0.5 \cdot 30$ [MW]

$$\boxed{\boldsymbol{\Delta H = CP \cdot \Delta T}}$$

Heat Capacity Flowrate ⟹ CP = Product of mass flow (m) (débit massique)

(débit de capacité de chaleur) and specific heat capacity (c_P) (chaleur spécifique)

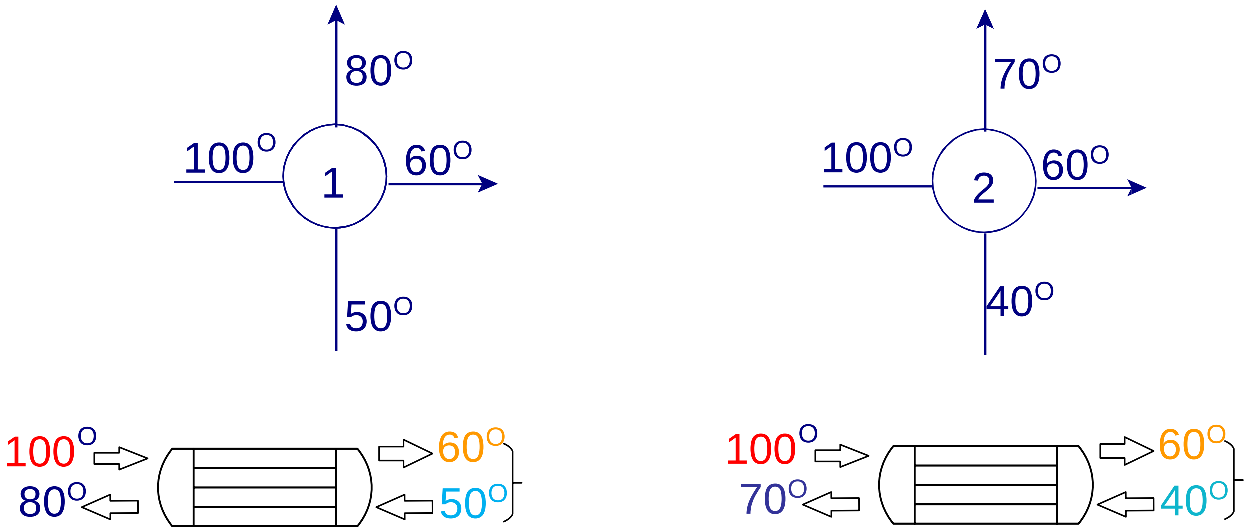
⟹ [MW/°C]

(Courtesy of University of Manchester)

ΔT_{min}

(Différence de température minimale)

Minimum Permissible Temperature Difference

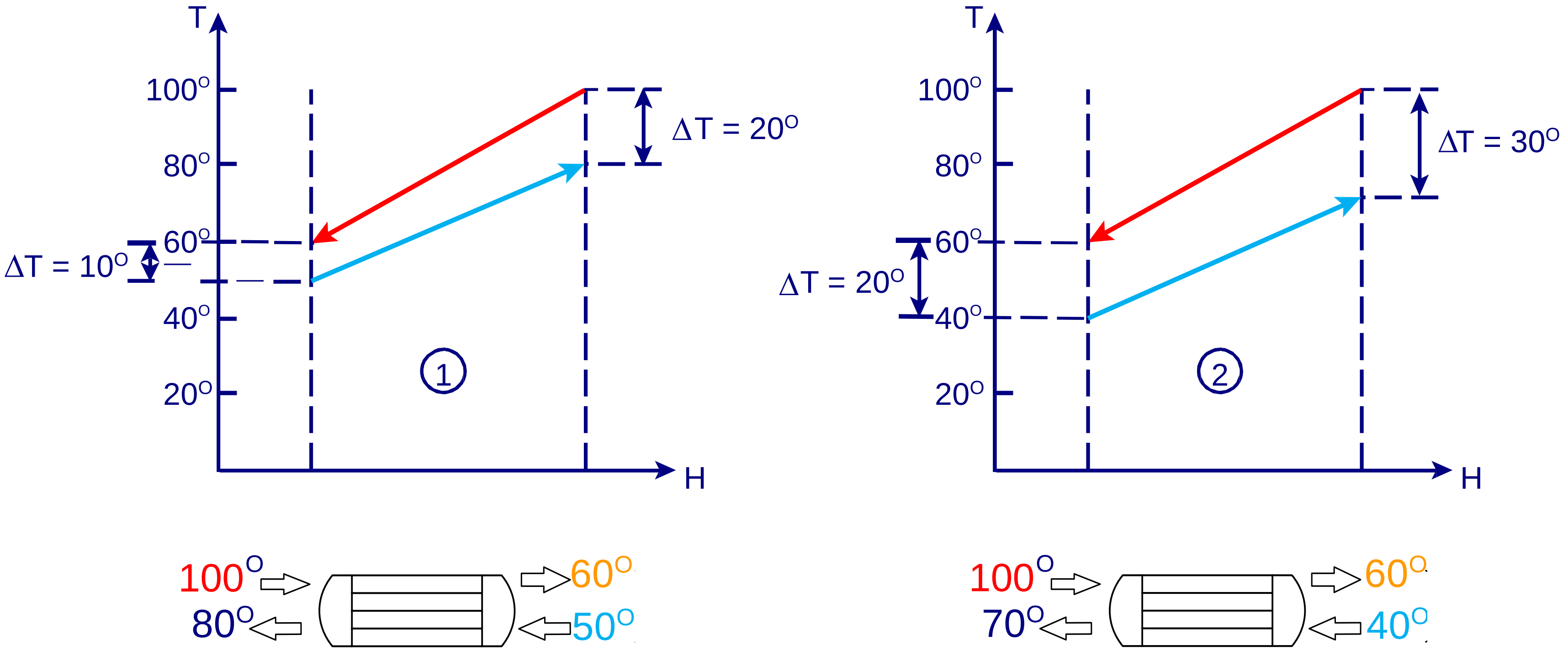


ΔT_{min} = 20°

Which heat exchanger violates ΔT_{min}?

(Échangeur de chaleur)

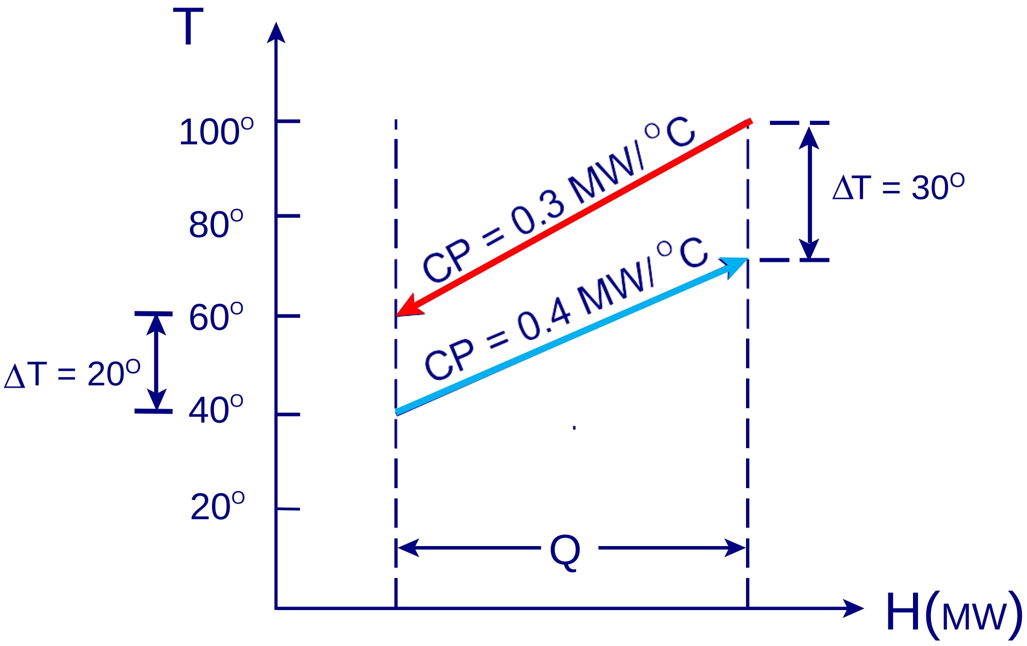
(Courtesy of University of Manchester)



$$\boxed{\Delta H = CP \cdot \Delta T}$$

(Courtesy of University of Manchester)

Heat Exchanger Duty



$$Q = |\Delta H| = CP \times \Delta T$$
$$= 0.3 \times 40$$
$$= 0.4 \times 30$$
$$Q = 12\ \mathrm{MW}$$

(Courtesy of University of Manchester)

Part 2

Setting Energy Targets

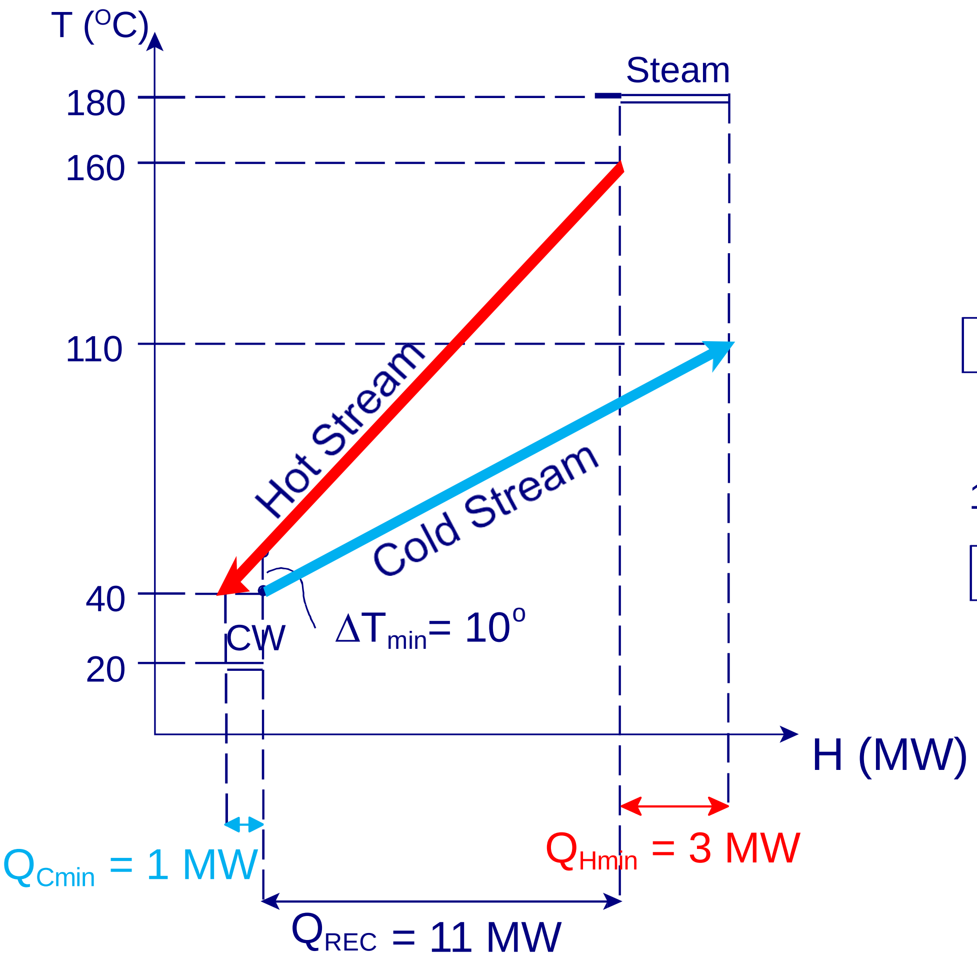
Two-Stream Heat Recovery Problem

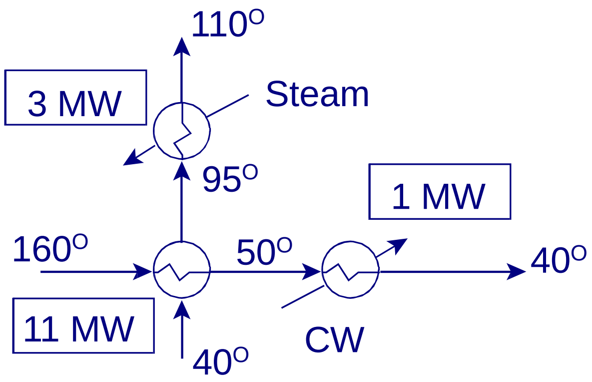
Stream	Type	Supply Temp. T (^oC)	Target Temp. T (^oC)	CP (MW/^oC)	ΔH (MW)
1	Cold	40	110	0.2	14
2	Hot	160	40	0.1	-12

$$\Delta \mathbf{H} = \mathbf{CP} \cdot \Delta \mathbf{T}$$

(Courtesy of University of Manchester)

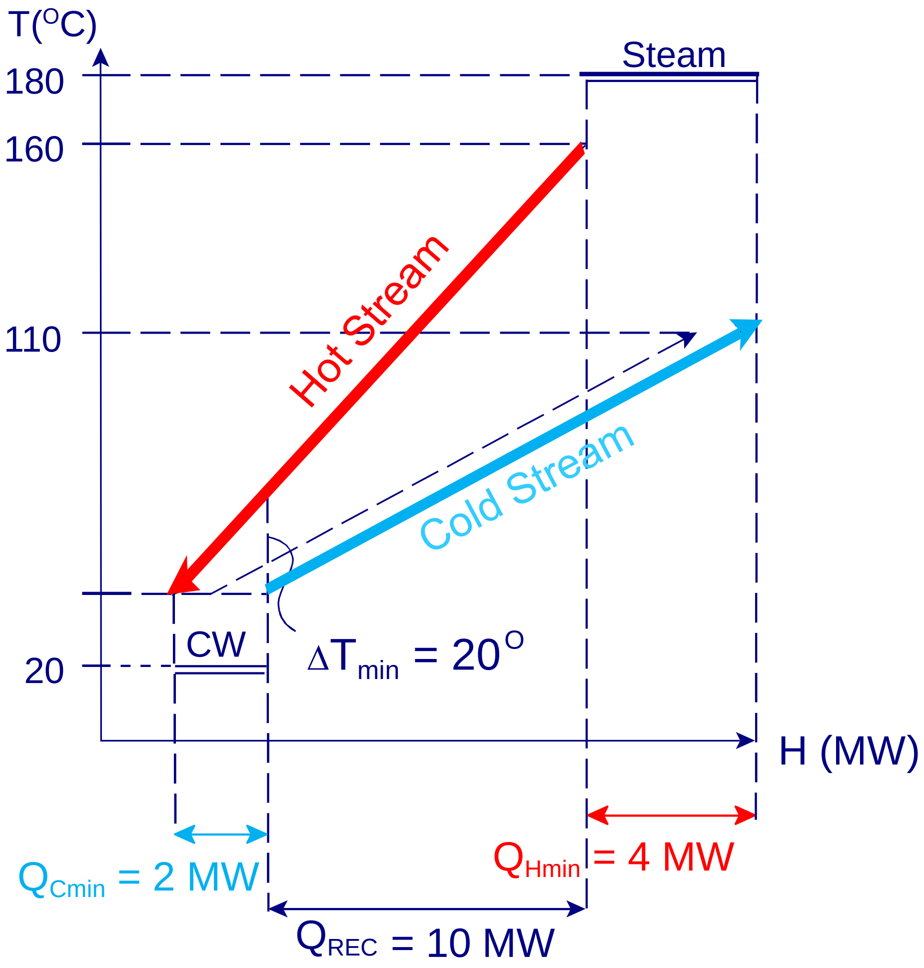
Two-Steam Heat Recovery Problem

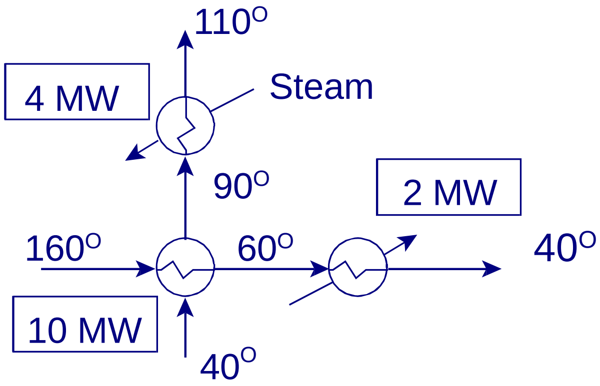




(Courtesy of University of Manchester)

Streams can be shifted horizontally





(Courtesy of University of Manchester)

Two Basic Facts

- Correlation between

ΔT_{min} and Q_{Hmin}, Q_{Cmin}

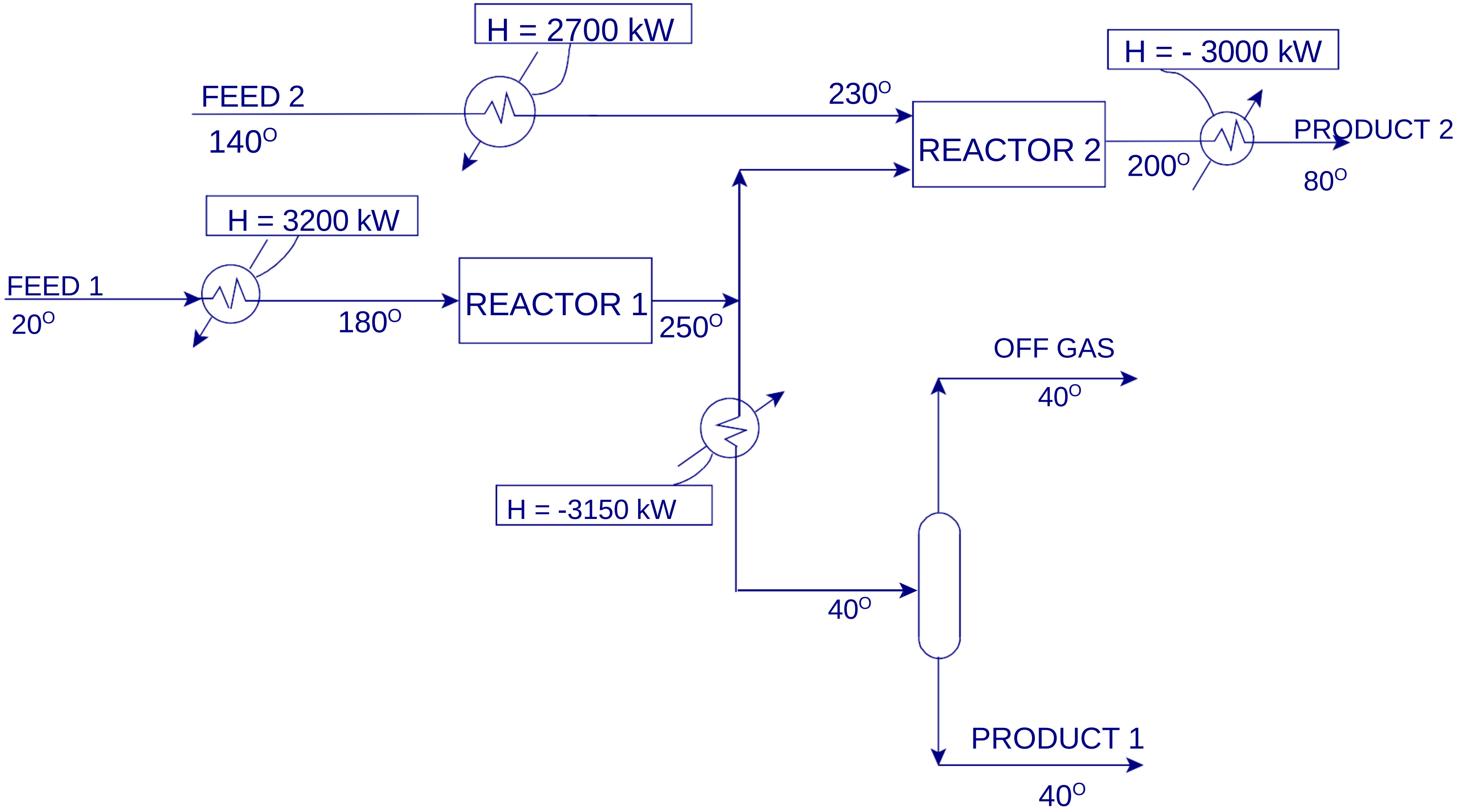
- More in, More Out !

$Q_{Hmin} + X \longrightarrow Q_{Cmin} + X$

(Courtesy of University of Manchester)

What if several hot and several cold streams?

Example 2



A simple flowsheet with two hot streams and two cold streams.

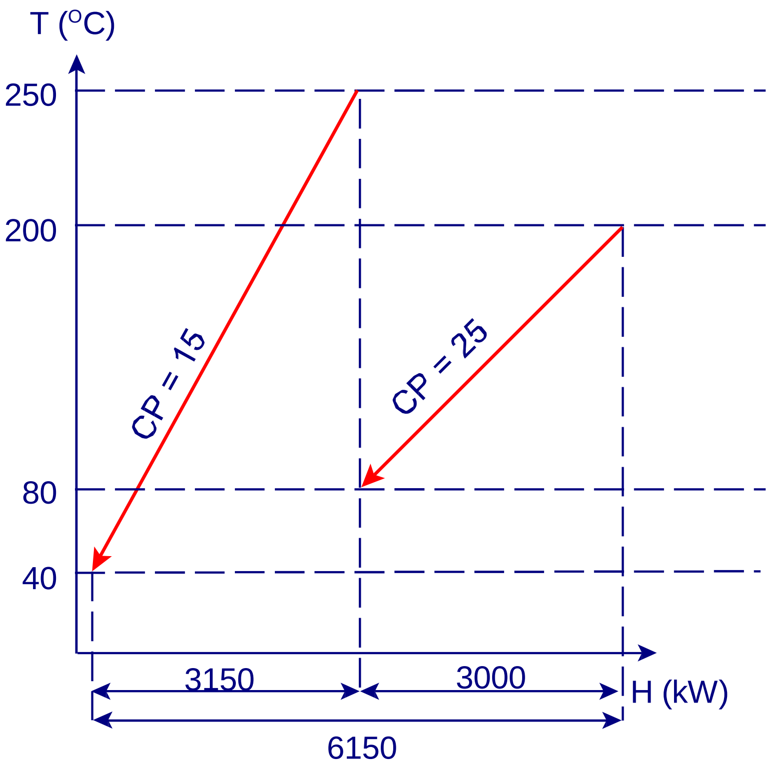
(Courtesy of University of Manchester)

Stream Data from the Flowsheet

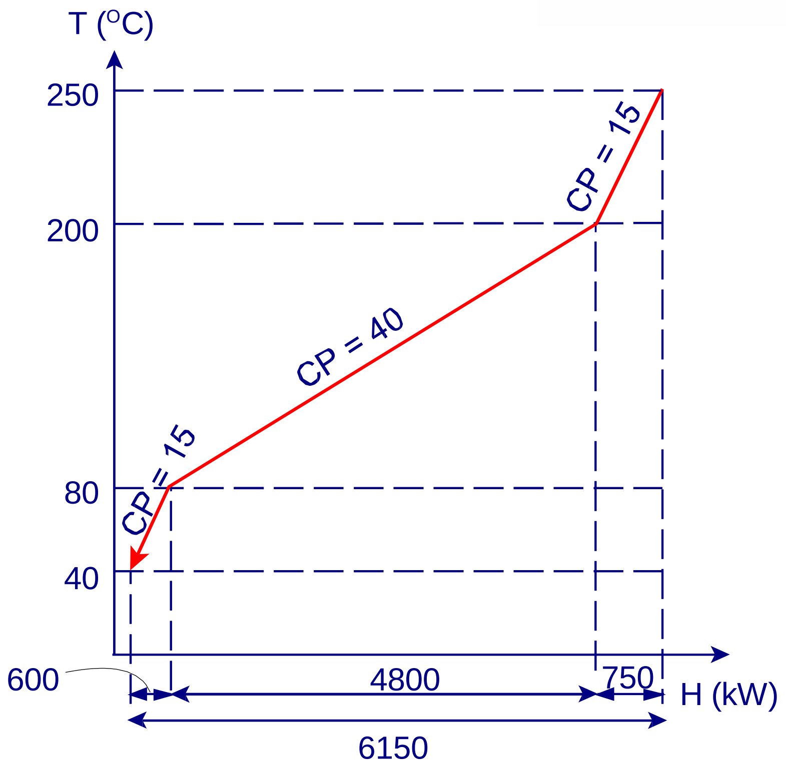
Stream	Type	Supply Temp. T_S (^OC)	Target Temp. T_T (^OC)	ΔH (kW)	Heat Capacity Flowrate CP (kW $^OC^{-1}$)
Reactor 1 feed	Cold	20	180	3200	20
Reactor 1 product	Hot	250	40	-3150	15
Reactor 2 feed	Cold	140	230	2700	30
Reactor 2 product	Hot	200	80	-3000	25

$$\boxed{\Delta \mathbf{H} = \mathbf{CP} \cdot \Delta \mathbf{T}}$$

(Courtesy of University of Manchester)



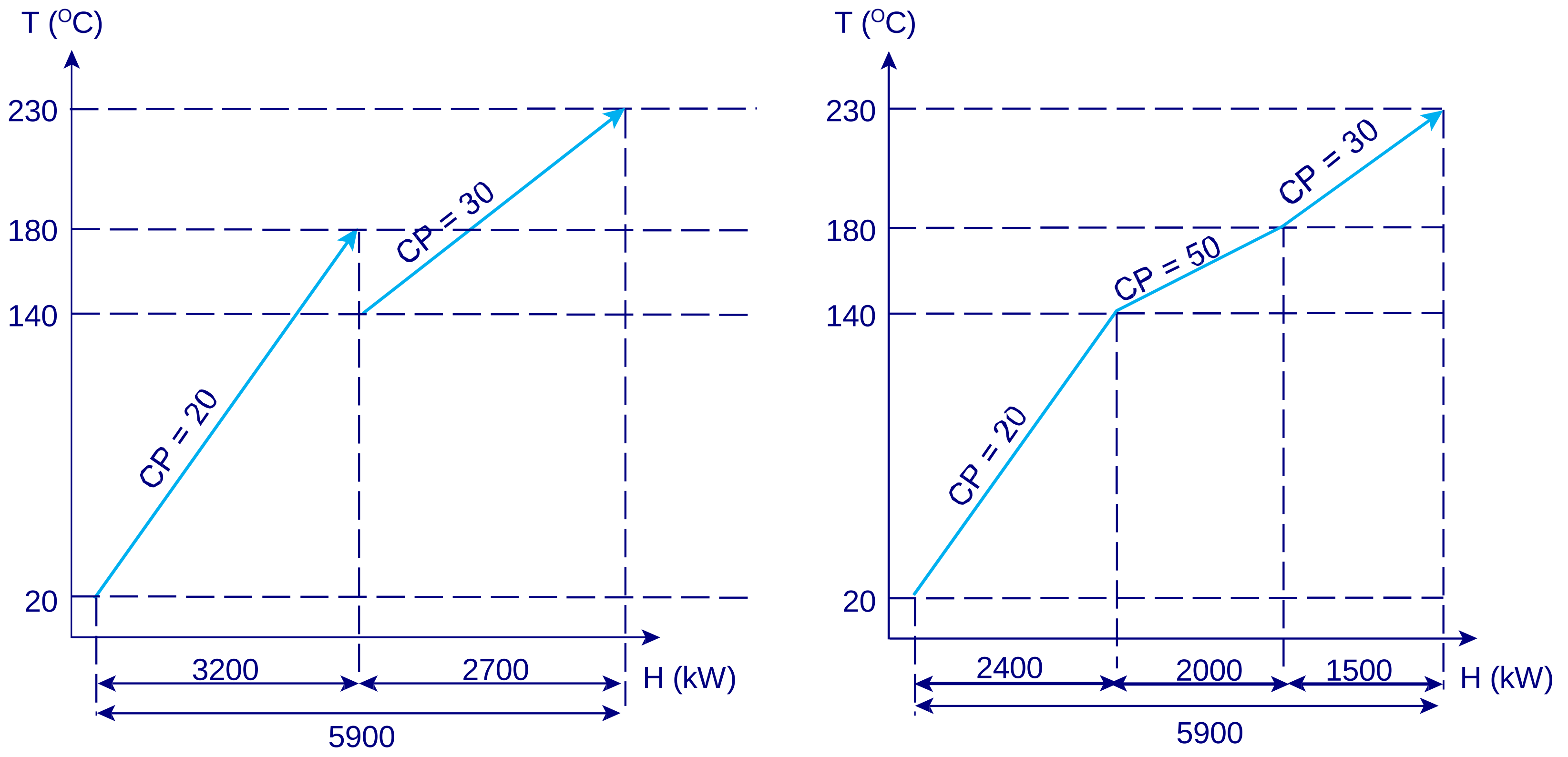
(a) The hot streams plotted separately



(b) Hot composite curve

Add the heat available in each temperature interval to form a composite curve.

(Courtesy of University of Manchester)

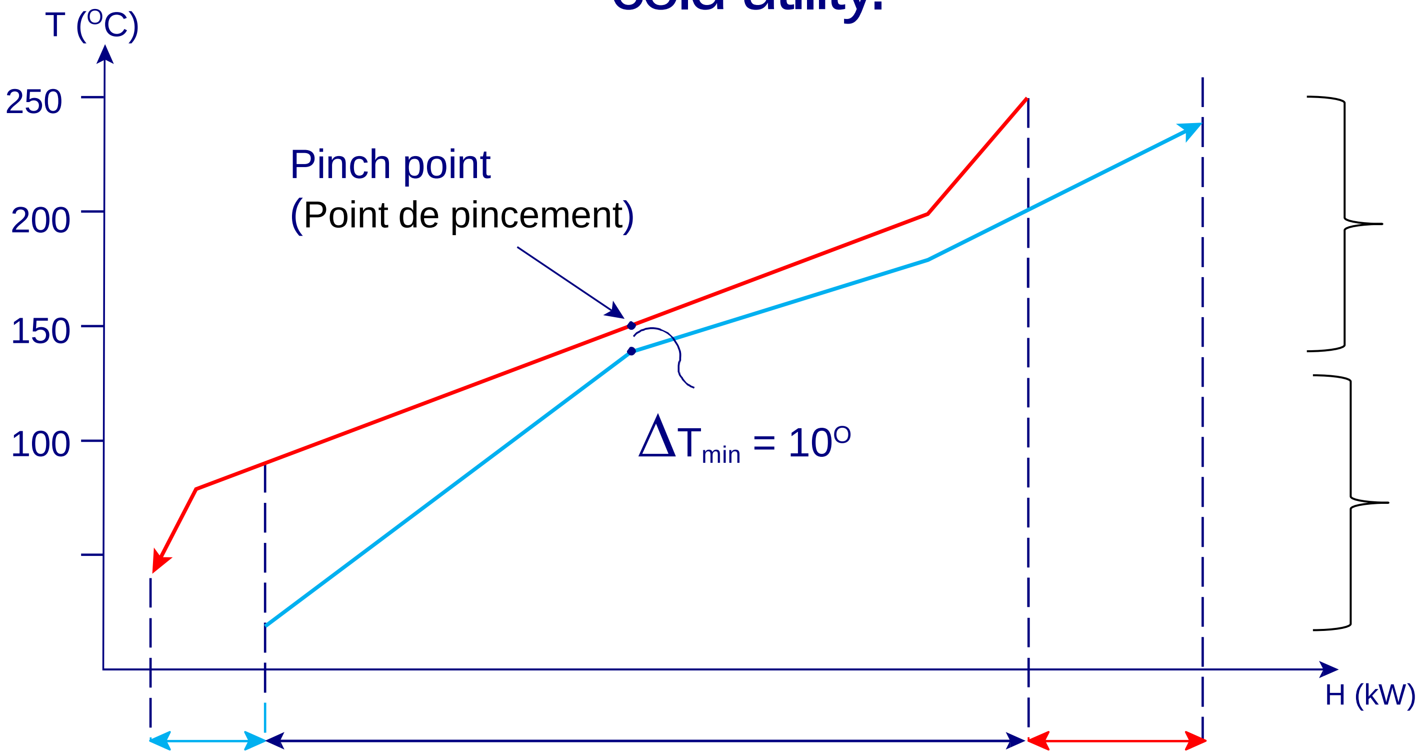


(a) The cold streams plotted separately (b) Cold composite curve

The cold streams can also be combined to obtain a composite cold stream.

(Courtesy of University of Manchester)

Plotting the hot and cold composite curves together gives the targets for hot and cold utility.



Above Pinch:
Heat sink,
i.e. heat is
valuable

Below Pinch:
Heat source,
i.e. heat is a
burden,
cooling is
aimed for

$Q_{Cmin} = 1000$

Besoin minimum de refroidissement

$Q_{REC} = 5150$

Potentiel maximal de récupération d’énergie

$Q_{Hmin} = 750$

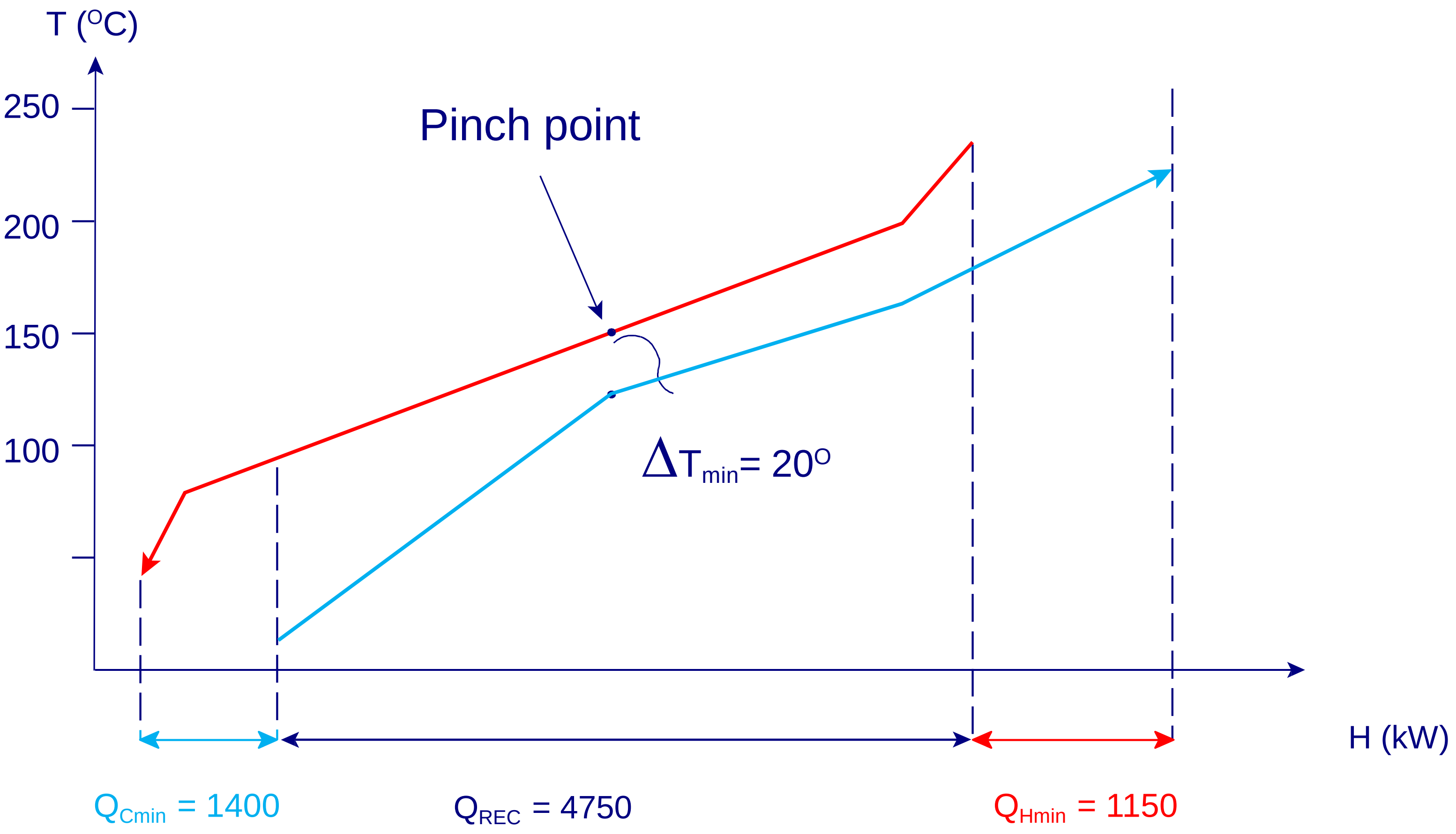
Besoin minimum de chauffage

(Courtesy of University of Manchester)

Golden rules:

- Don’t transfer heat across the pinch (from hot to cold area)
- Don’t use cold utilities above the pinch
- Don’t use hot utilities below the pinch

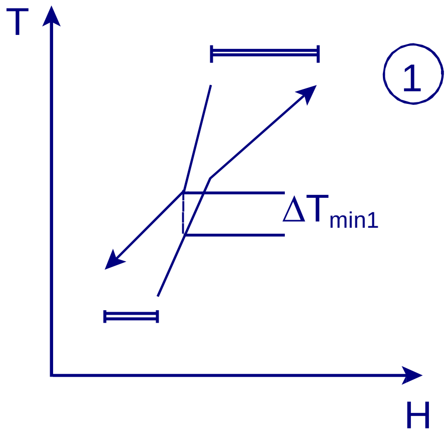
Now increase ΔT_{min} to 20°C

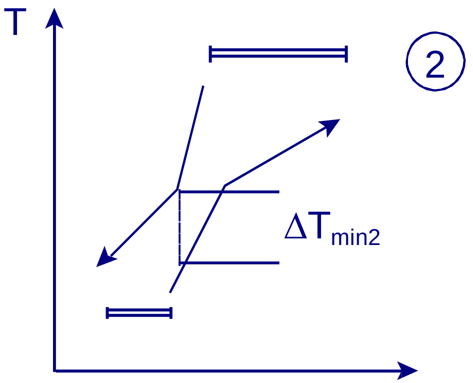


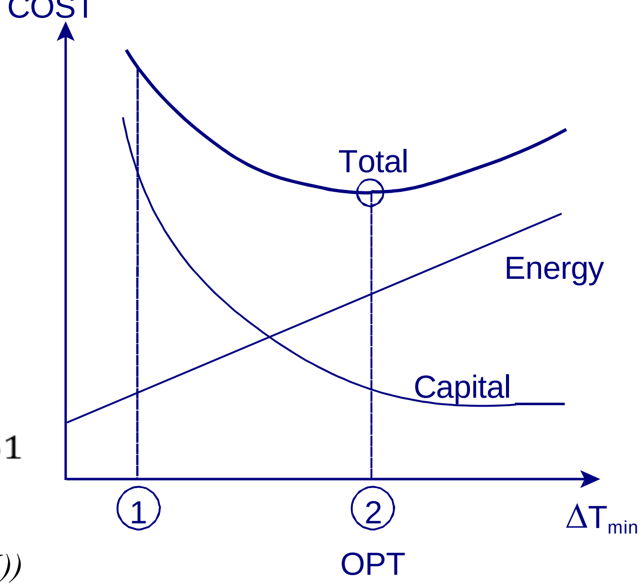
Q_{Hmin} and Q_{Cmin} increase correspondingly

(Courtesy of University of Manchester)

Choice of ΔTmin is nowadays subject to economic trade-off







On the one hand:
smaller ΔT min
→ less heating and cooling (①,②)

On the one hand:
smaller ΔT min
→ smaller heat flow in heat exchanger
→ H. exch. must be larger
→ H. exch. becomes more expensive

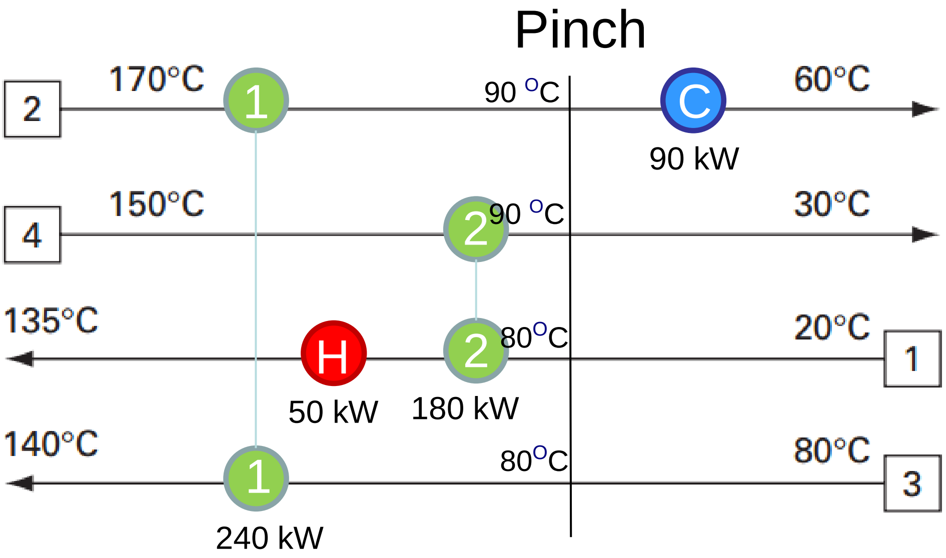
$$Q_{saved} = U \cdot A \cdot \Delta T_{min}$$

$$Cost_{exch} = 1957.8 * [A]^{0.551}$$

U = Overall heat transfer coefficient (W/(m^2•K))
A = Surface area (m^2)
ΔT_{min} = minimum (pre-set) temperature difference

(Courtesy of University of Manchester)

How do you design the network with your common sense?



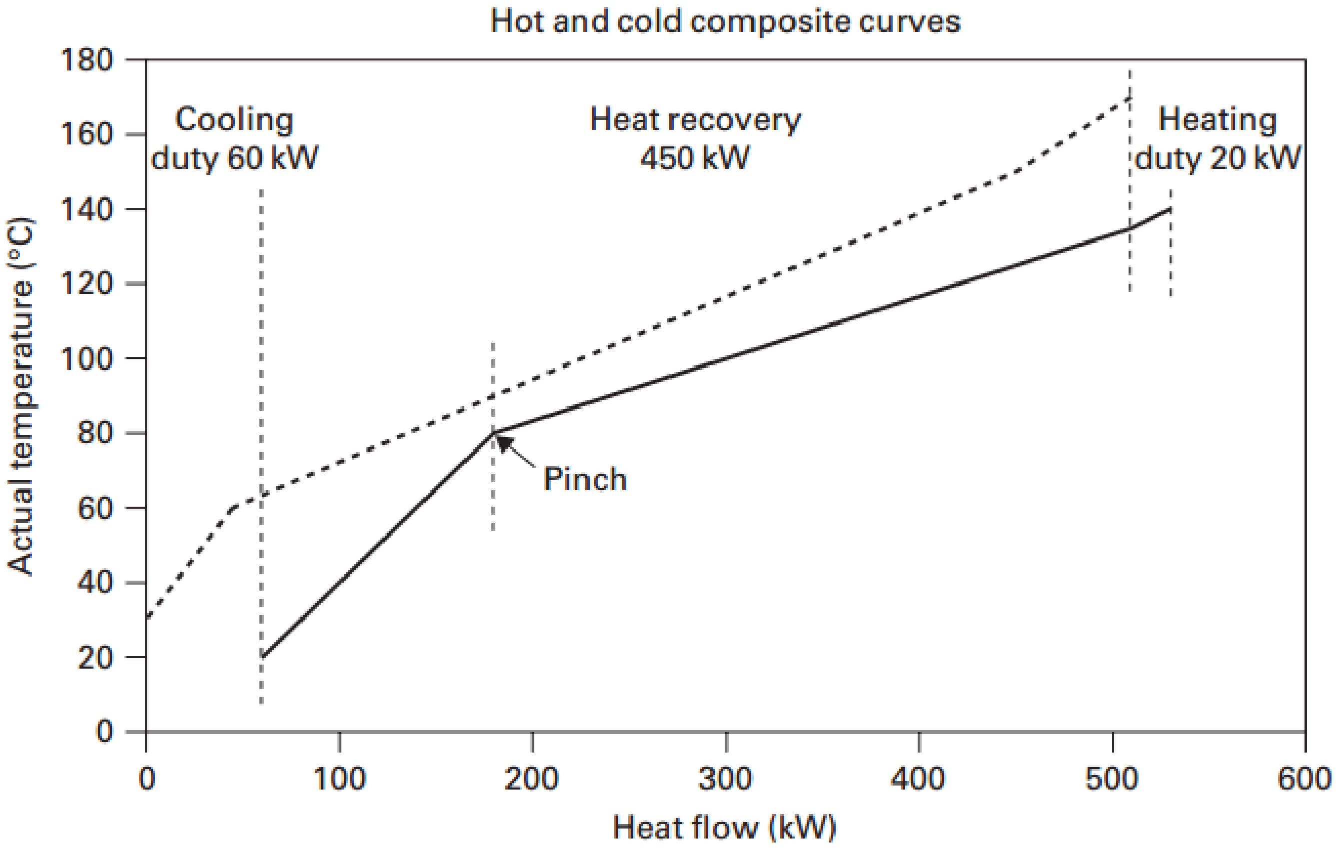
CP (kW/°C)	Δ*H* (kW)	Δ*H* Above/below pinch
3.0	+330	240/90
1.5	+180	90/90
2.0	−230	−110/−120
4.0	−240	−240/0

Above: 240+90-110-240 = -20
Below: =90+90-120-0 = 60

30 kW is being transferred across the pinch!
“Traditional” heat exchanger network designs are almost invariably off-target

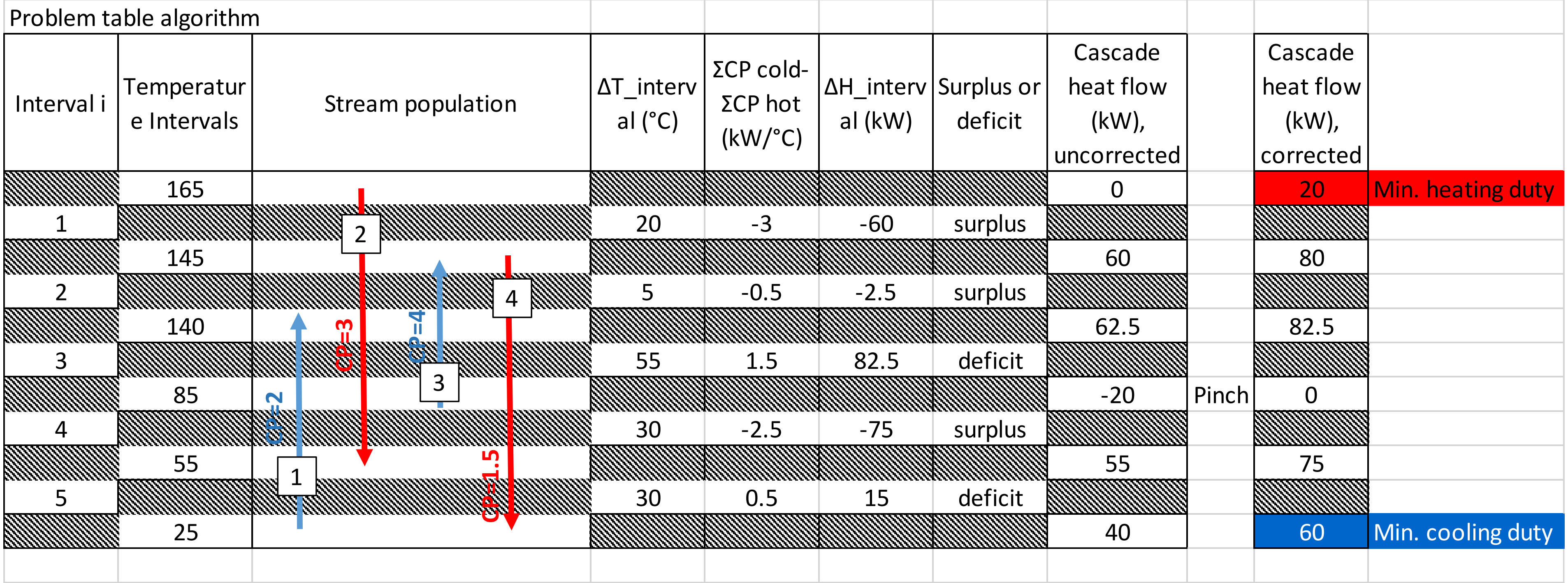
(Courtesy of University of Manchester)

How much energy would the ideal network have needed? (1/2)



(Courtesy of University of Manchester)

How much energy would the ideal network have needed? (2/2)



Problem table algorithm

Interval i	Temperature Intervals	Stream population	ΔT_interval (°C)	ΣCP cold-ΣCP hot (kW/°C)	ΔH_interval (kW)	Surplus or deficit	Cascade heat flow (kW), uncorrected		Cascade heat flow (kW), corrected	
	165						0		20	Min. heating duty
1			20	-3	-60	surplus				
	145						60		80	
2			5	-0.5	-2.5	surplus				
	140						62.5		82.5	
3			55	1.5	82.5	deficit				
	85						-20	Pinch	0	
4			30	-2.5	-75	surplus				
	55						55		75	
5			30	0.5	15	deficit				
	25						40		60	Min. cooling duty

(Courtesy of University of Manchester)

Summary

- Temperature-enthalpy diagrams can be used to determine heat recovery potential
- Composite curves can be used to simultaneously analyze a set of hot streams and cold streams
- Energy targets are determined based on energy balance and ΔTmin.
- Energy targets can be varied by changing ΔTmin.

Part 3

The Problem Table Algorithm and Grand Composite Curve

Stream Data, ΔT_{min}

"Composite Curves"

Energy Targets

But Composite Curves are complicated

An Alternative:

"The Problem Table"

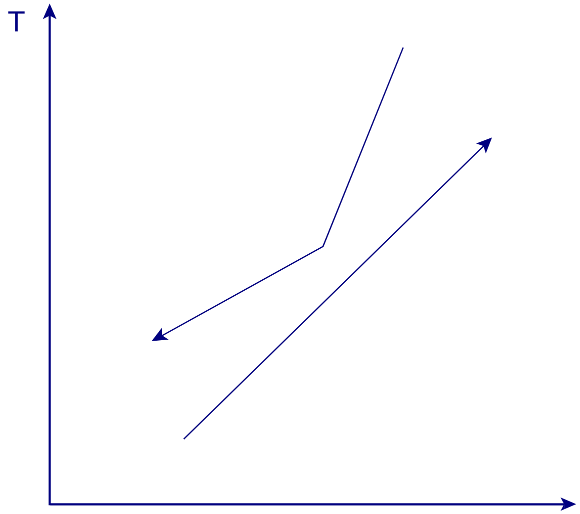
Example 2

Stream Data Table

No	Stream	Type	Supply Temp. T_S (^OC)	Target Temp. T_T(^OC)	Enthalpy change ΔH (kW)	Heat Capacity Flowrate CP (kW $^OC^{-1}$)
1	Reactor 1 feed	Cold	20	180	3200	20
2	Reactor 1 product	Hot	250	40	-3150	15
3	Reactor 2 feed	Cold	140	230	2700	30
4	Reactor 2 product	Hot	200	80	-3000	25

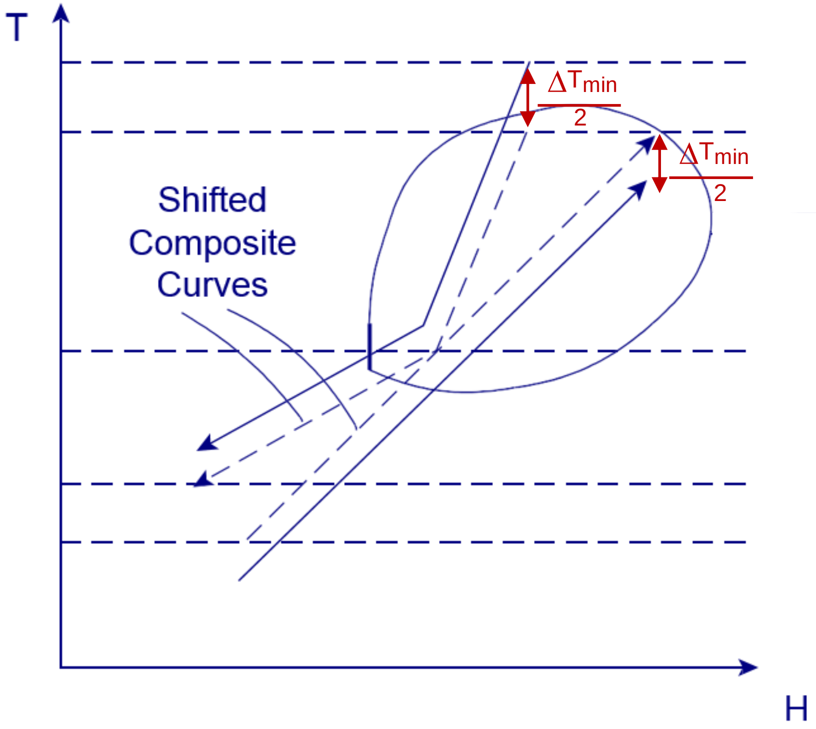
(Courtesy of University of Manchester)

Shift Composite Curves



(Courtesy of University of Manchester)

Shift Composite Curves



(Courtesy of University of Manchester)

Shifting rule:

Cold streams $+ \dfrac{\Delta T_{min}}{2}$

Hot streams $- \dfrac{\Delta T_{min}}{2}$

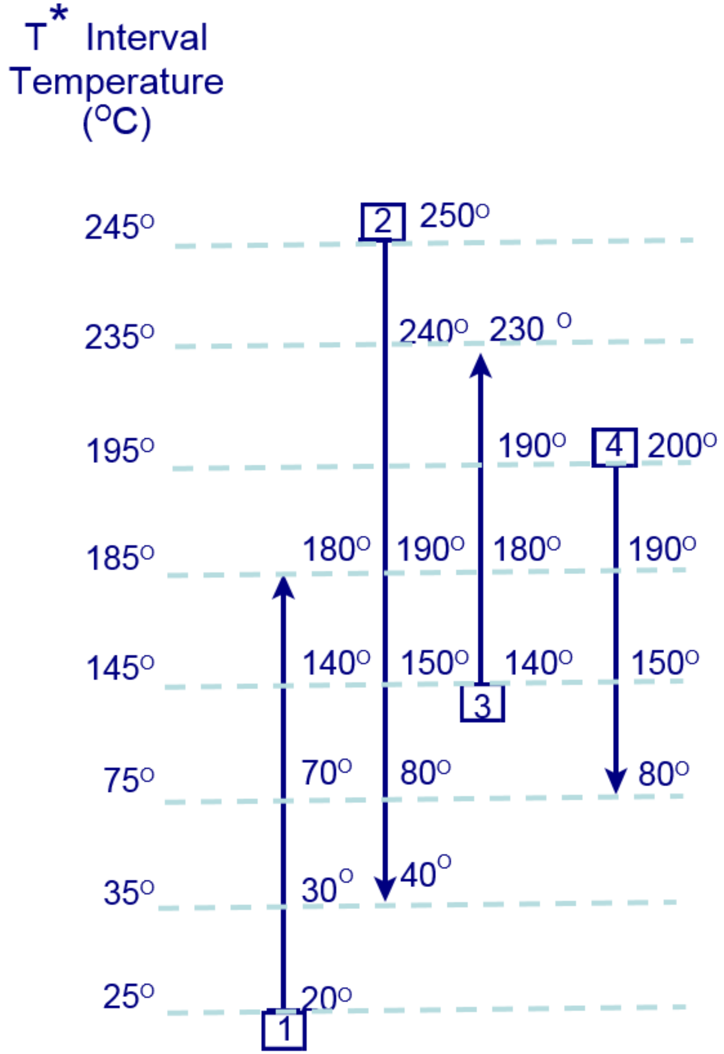
(Courtesy of University of Manchester)

Stream data for our example:

Stream No	Type	T_S (°C)	T_T (°C)	T_S^* (°C)	T_T^* (°C)
1	Cold	20	180	25	185
2	Hot	250	40	245	35
3	Cold	140	230	145	235
4	Hot	200	80	195	75

(Courtesy of University of Manchester)

Shifted temperature intervals



(Courtesy of University of Manchester)

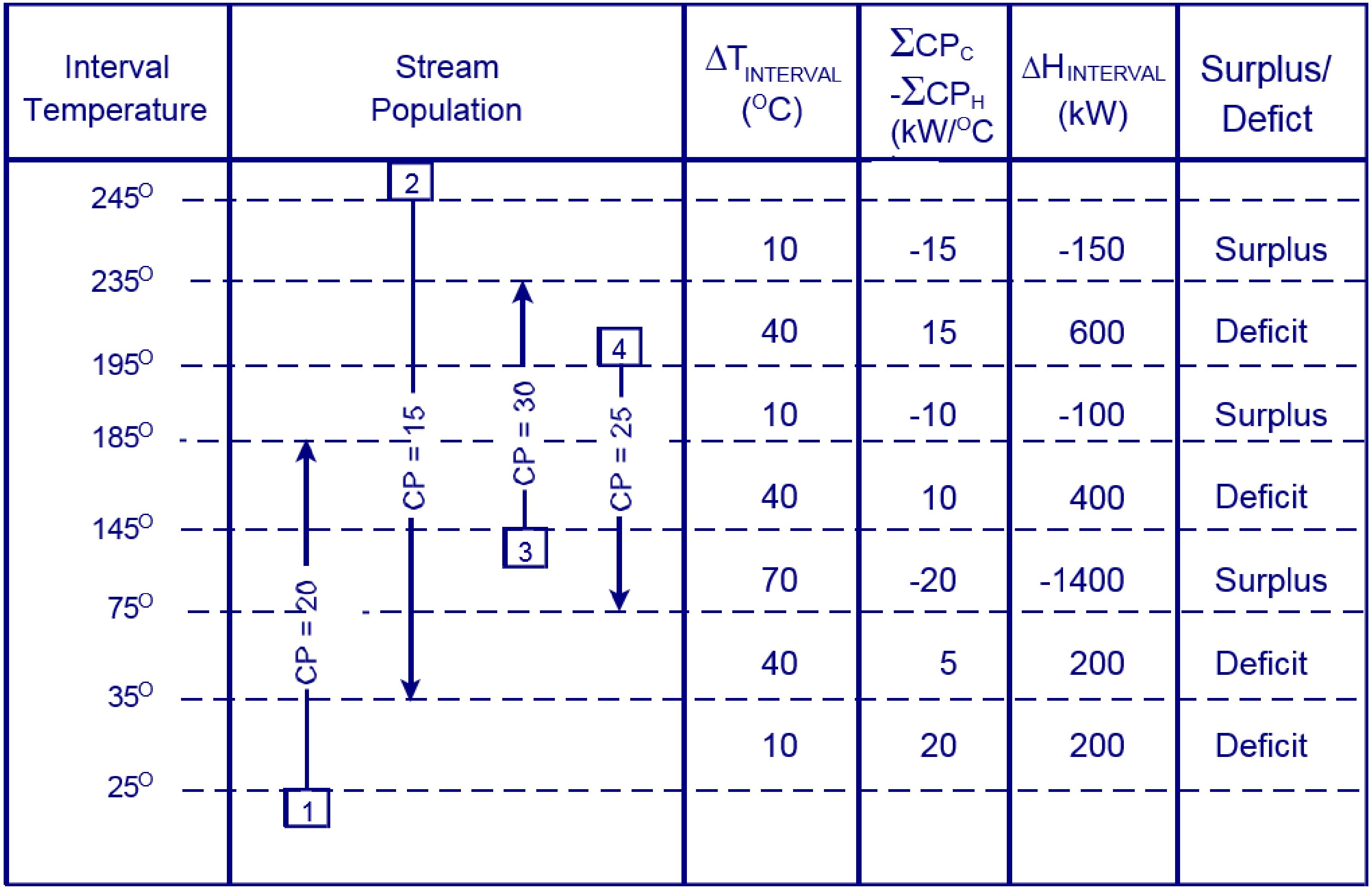
In each shifted temperature interval,
calculate a simple energy balance from

$$\Delta H_i = (\underset{\text{All cold streams}}{\Sigma\ CP_C} \ - \ \underset{\text{All hot streams}}{\Sigma\ CP_H})_i \, \Delta T_i$$

- ΔH_i = heat balance for interval
- ΔT_i = temperature difference across interval

(Courtesy of University of Manchester)

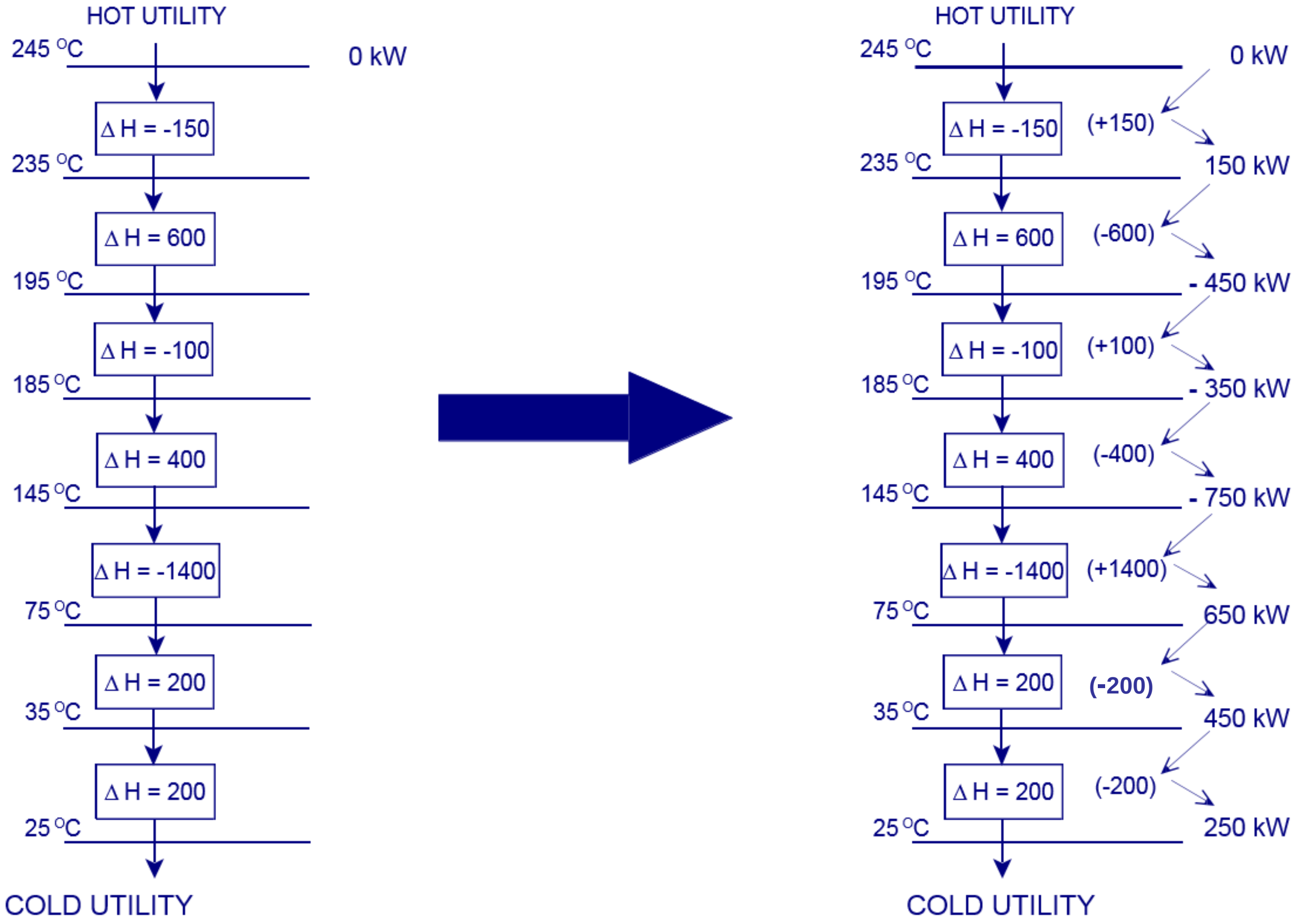
Problem table (for Temperature Interval Heat Balance)



Interval Temperature	Stream Population	$\Delta T_{INTERVAL}$ (°C)	$\Sigma CP_C - \Sigma CP_H$ (kW/°C)	$\Delta H_{INTERVAL}$ (kW)	Surplus/ Deficit
245°					
		10	-15	-150	Surplus
235°					
		40	15	600	Deficit
195°					
		10	-10	-100	Surplus
185°					
		40	10	400	Deficit
145°					
		70	-20	-1400	Surplus
75°					
		40	5	200	Deficit
35°					
		10	20	200	Deficit
25°					

(Courtesy of University of Manchester)

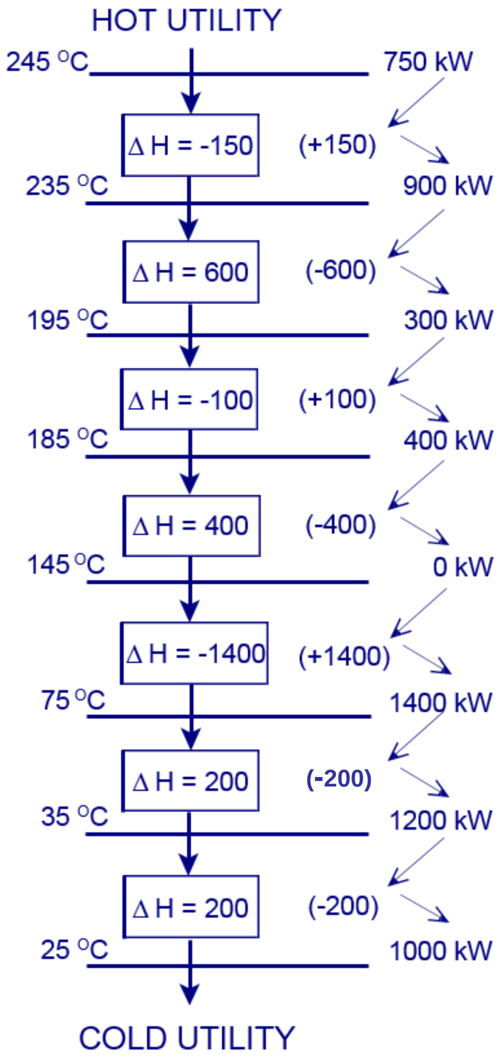
Cascade any surplus heat from high to low temperature



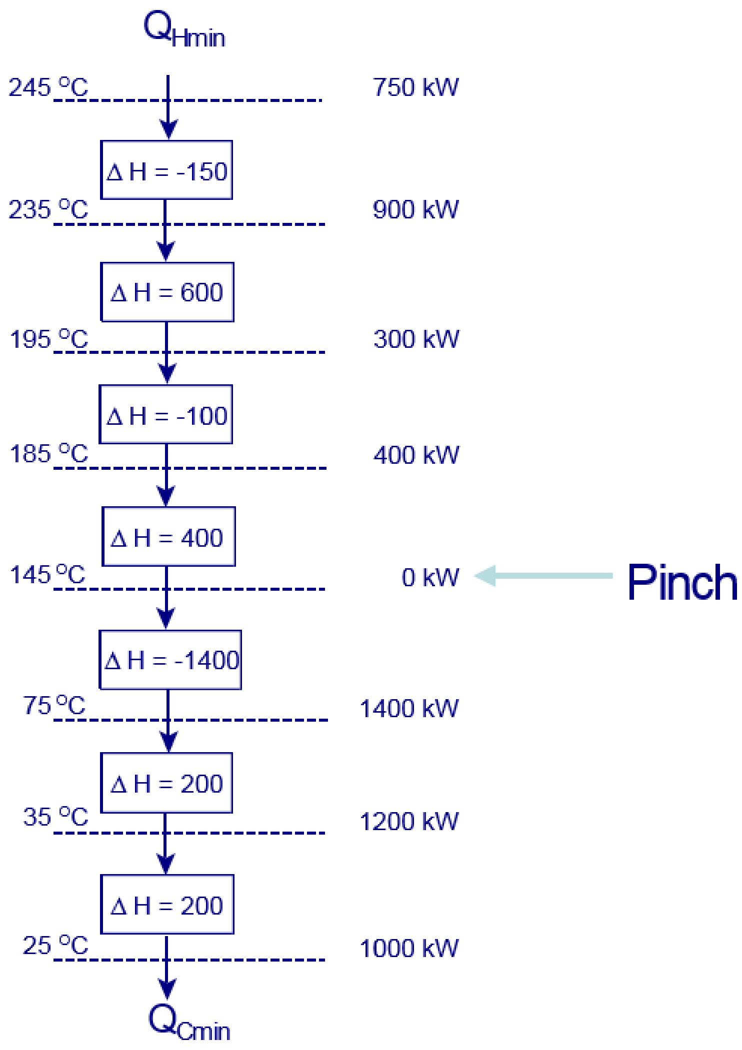
Problem table cascade

(Courtesy of University of Manchester)

Heat flows cannot be negative! Add heat to make them at least 0!



(Courtesy of University of Manchester)



Q_{Hmin}

245 °C — 750 kW

ΔH = -150

235 °C — 900 kW

ΔH = 600

195 °C — 300 kW

ΔH = -100

185 °C — 400 kW

ΔH = 400

145 °C — 0 kW ← Pinch

ΔH = -1400

75 °C — 1400 kW

ΔH = 200

35 °C — 1200 kW

ΔH = 200

25 °C — 1000 kW

Q_{Cmin}

T^*pinch = 145°C
T pinch = 150°C for hot streams T
pinch = 140°C for cold streams

(Courtesy of University of Manchester)

Summary

- The problem table algorithm:
  - STEP 1
  - Adjust For ΔT_{min}
  - STEP 2
  - Set Up Temperature Intervals
  - STEP 3
  - Calculate Interval Heat Balances
  - STEP 4
  - Cascade For Positive Heat Flows
- Q_{Hmin}, Q_{Cmin} and pinch location without drawing graphs

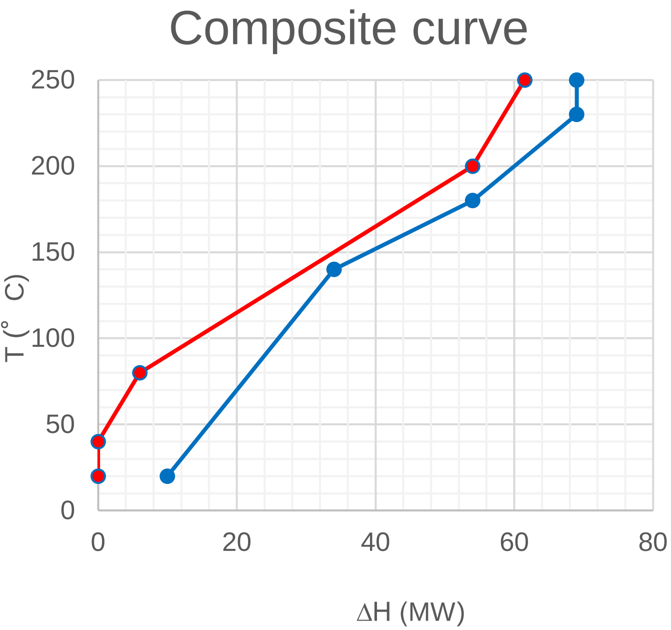
(Courtesy of University of Manchester)

How do we target for the best mix of utilities?

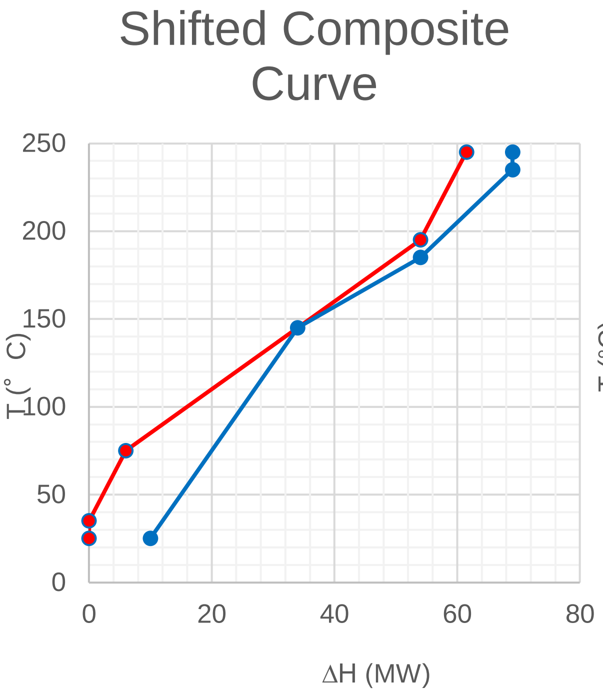
- The Grand Composite Curve

(Courtesy of University of Manchester)

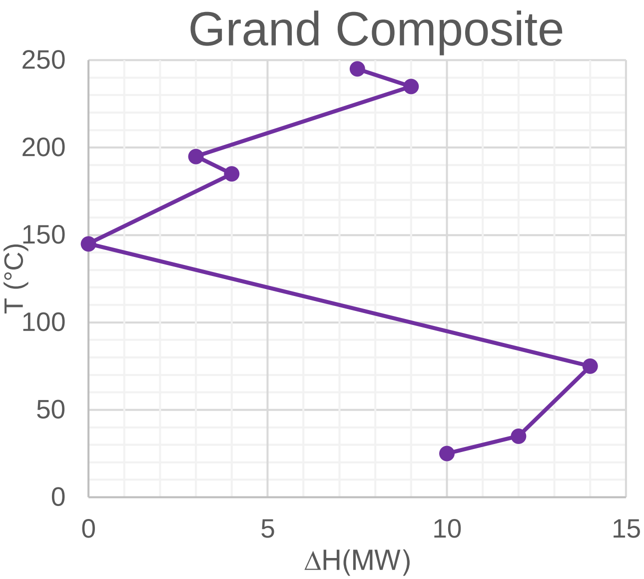
Construction of the Grand Composite Curve (GCC)



(Courbes composites)



(Courbes composites déplacées)

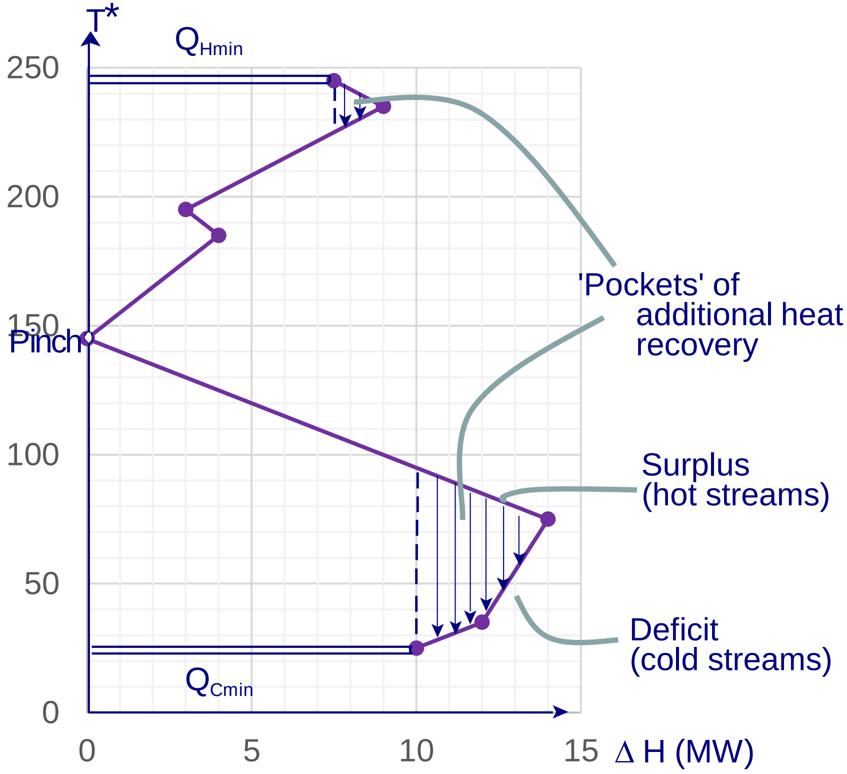


(Courbe grand composite)

Source: Pinch Analysis:
For the Efficient Use of Energy, Water & Hydrogen. Natural resources Canada. 2003

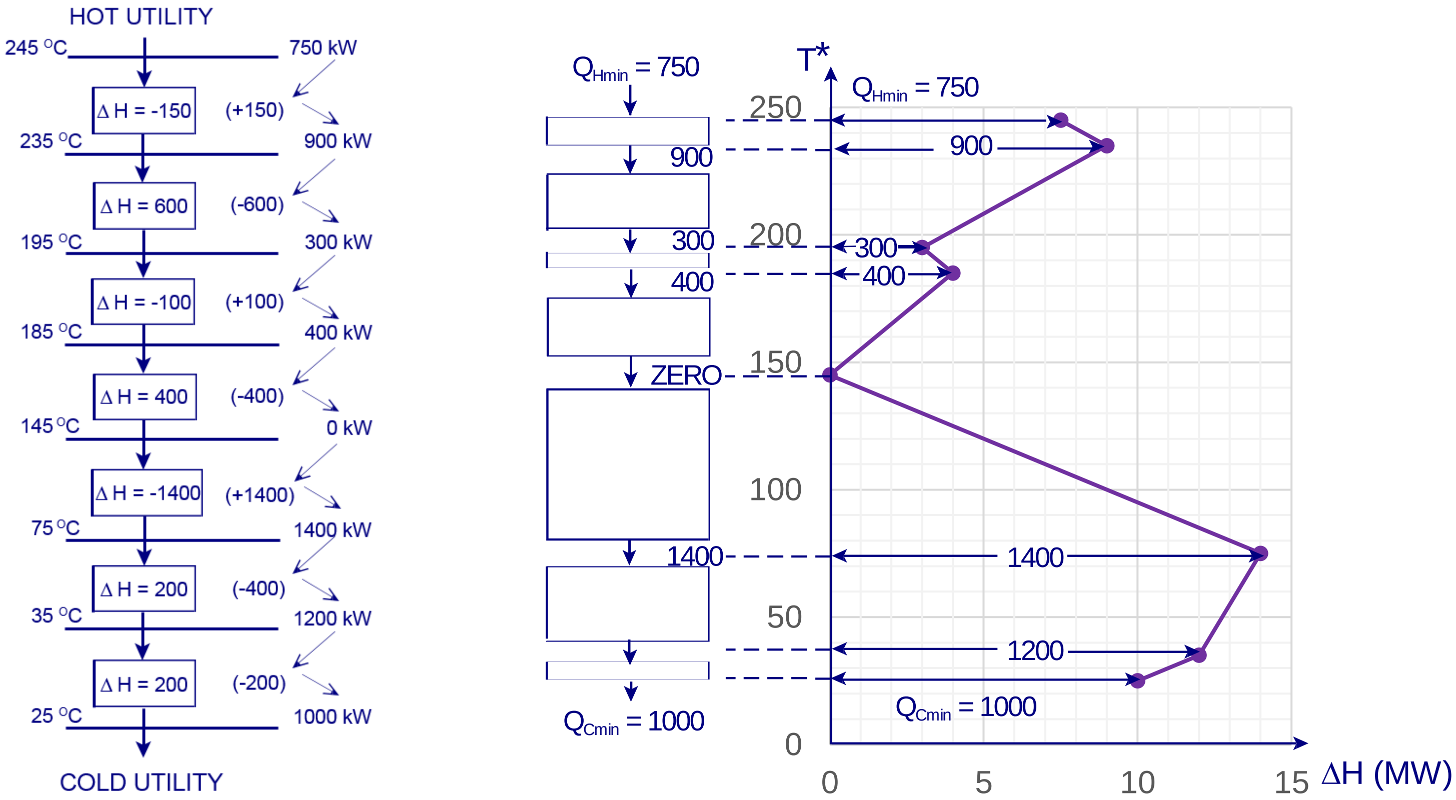
(Courtesy of University of Manchester)

The “Grand Composite Curve”

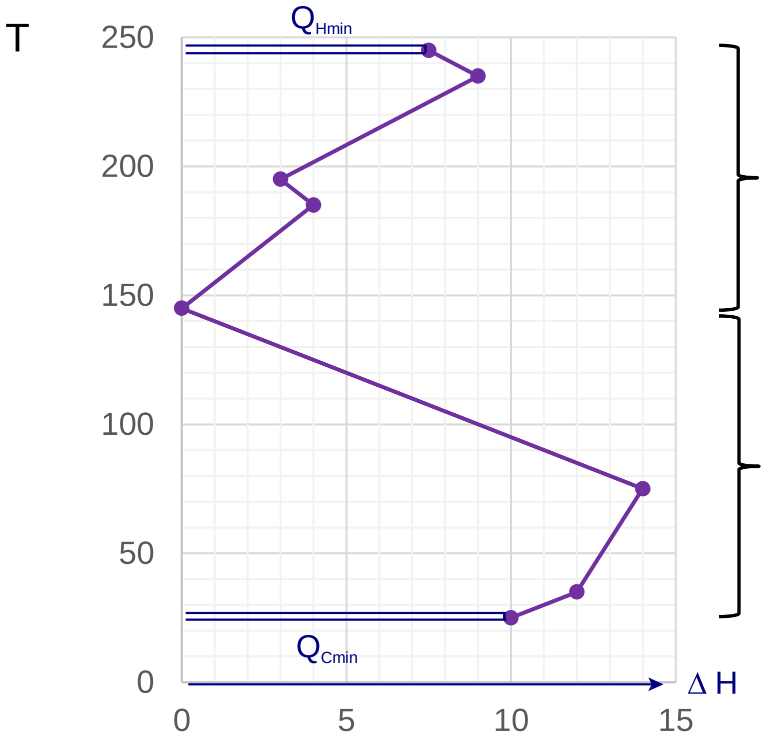


(Courtesy of University of Manchester)

The Problem Table



(Courtesy of University of Manchester)



Heat Sink
(puits de chaleur)

Heat is valuable

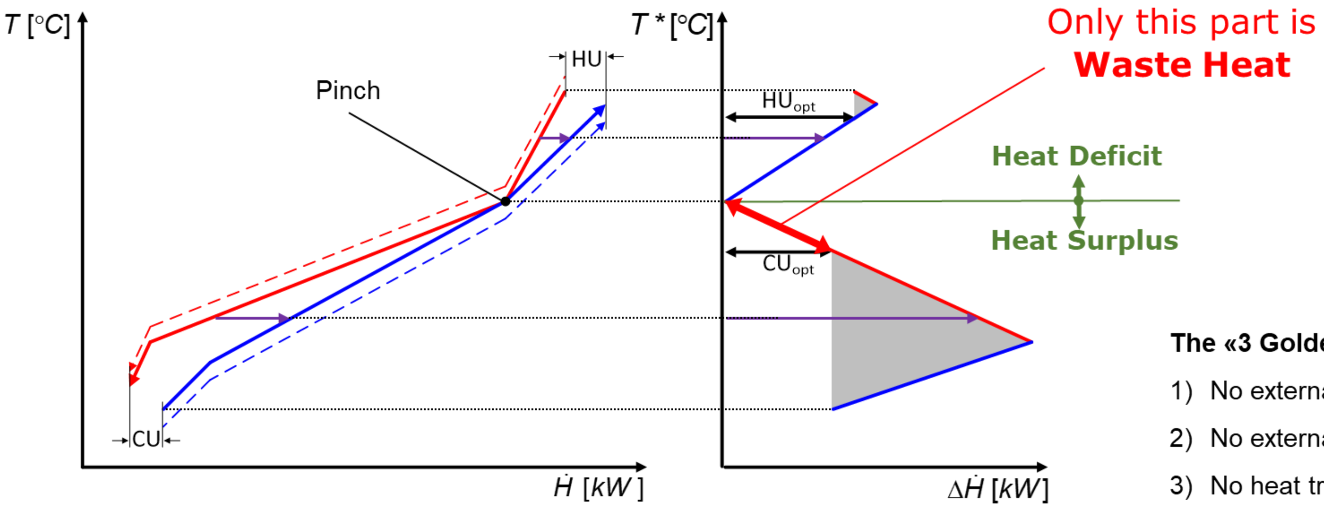
Heat source
(source de chaleur)

Heat is a burden

(Courtesy of University of Manchester)

Grand Composite Curve (GCC)

- Shows the heat deficit and surplus as a function of temperature
- Enables the optimization of the utility supply system (HU_{opt}, CU_{opt})
- **Identifies and characterizes the waste heat** (and excess heat)



Only this part is **Waste Heat**

Heat Deficit

Heat Surplus

The «3 Golden Rules» of Pinch Analysis

1) No external cooling above the pinch
2) No external heating below the pinch
3) No heat transfer over the pinch

(Hochschule Luzern Engineering and Architecture)

Example 2

Stream Data Table

No	Stream	Type	Supply Temp. T_S (^OC)	Target Temp. T_T(^OC)	Enthalpy change ΔH (kW)	Heat Capacity Flowrate CP (kW $^OC^{-1}$)
1	Reactor 1 feed	Cold	20	180	3200	20
2	Reactor 1 product	Hot	250	40	-3150	15
3	Reactor 2 feed	Cold	140	230	2700	30
4	Reactor 2 product	Hot	200	80	-3000	25

(Courtesy of University of Manchester)

CP Table

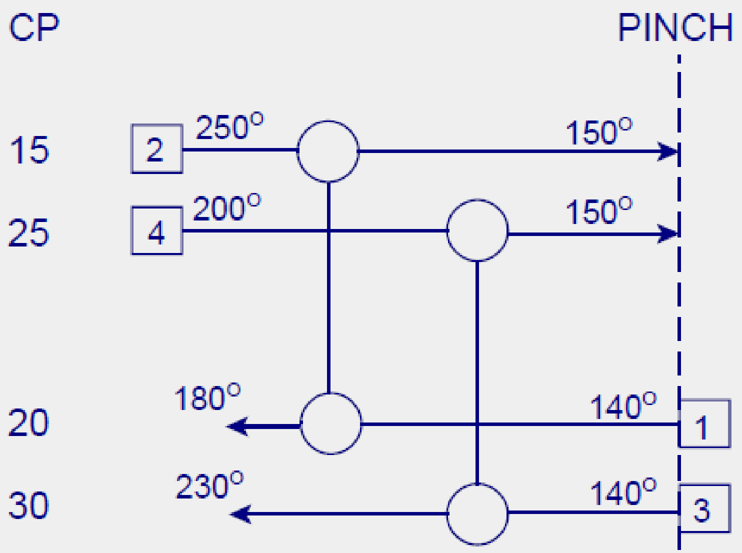
CP's in descending order ↓

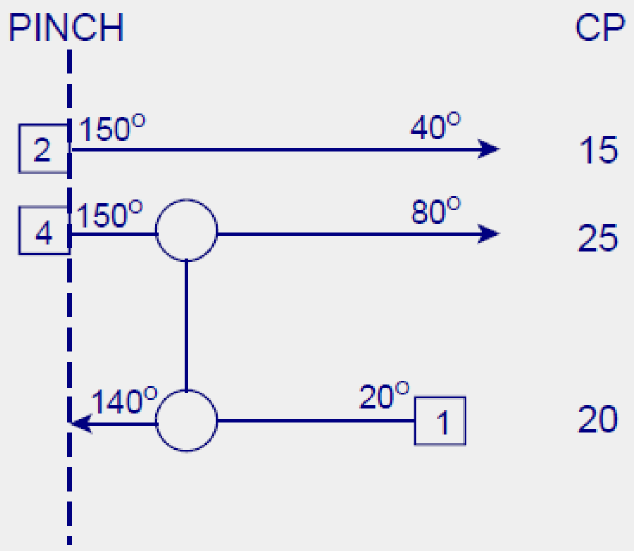
(a) ABOVE PINCH

CP_H	< CP_C
25	30
15	20

(b) BELOW PINCH

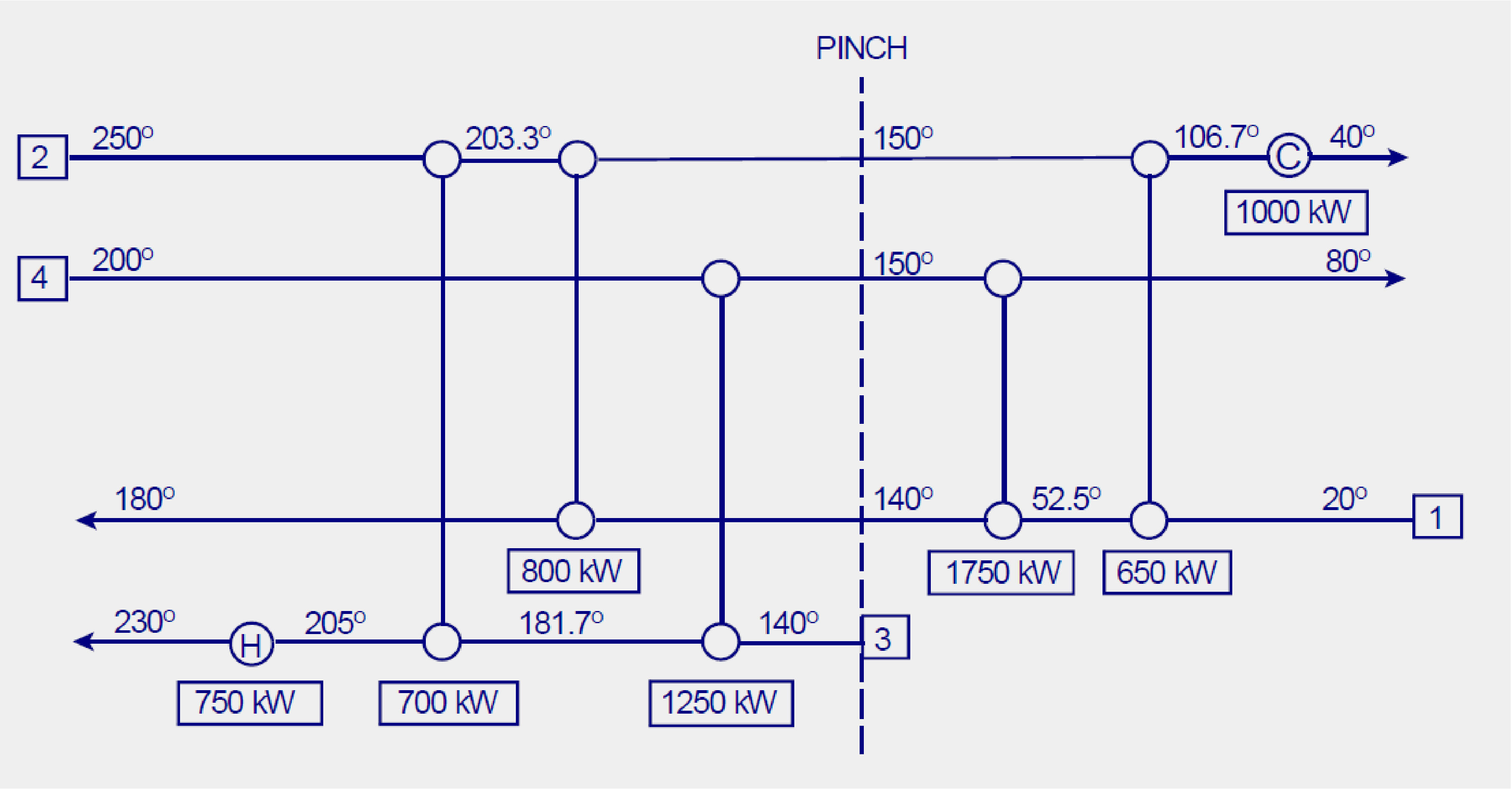
CP_H	> CP_C
25	20
15	





(Courtesy of University of Manchester)

Grid diagram of the Completed Design



(Courtesy of University of Manchester)

Summary

- Composite curve is a graphical approach while problem table algorithm uses a calculation based approach.
- The grid diagram determine the final matching between the heat exchanger and their sizes.

(Courtesy of University of Manchester)

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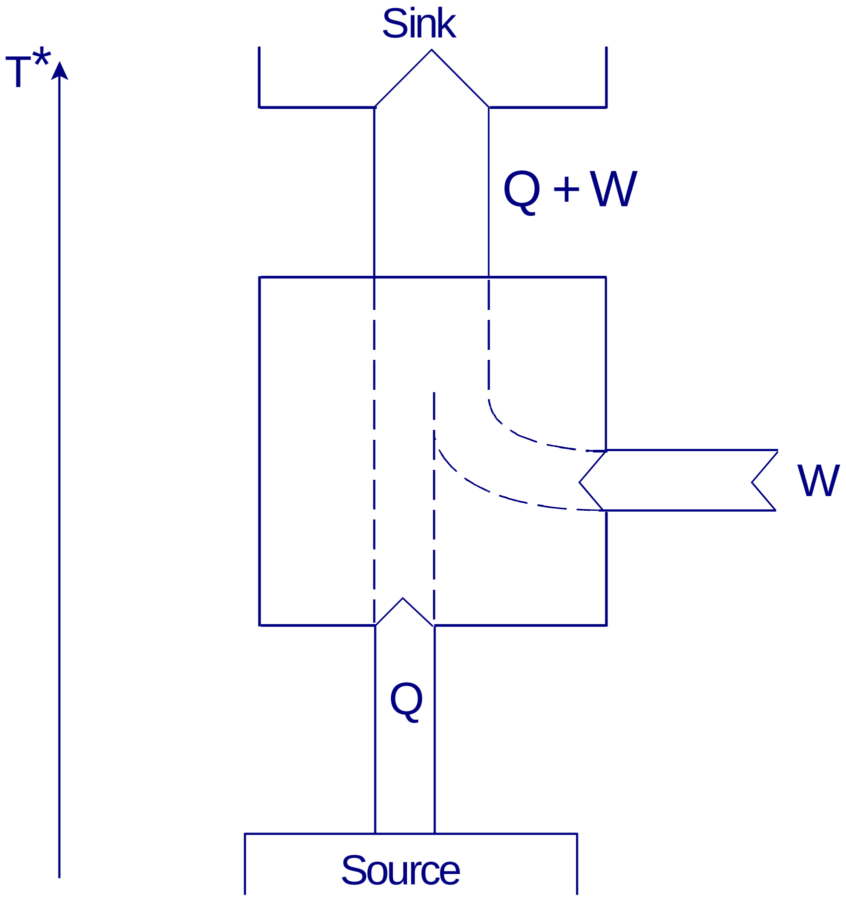
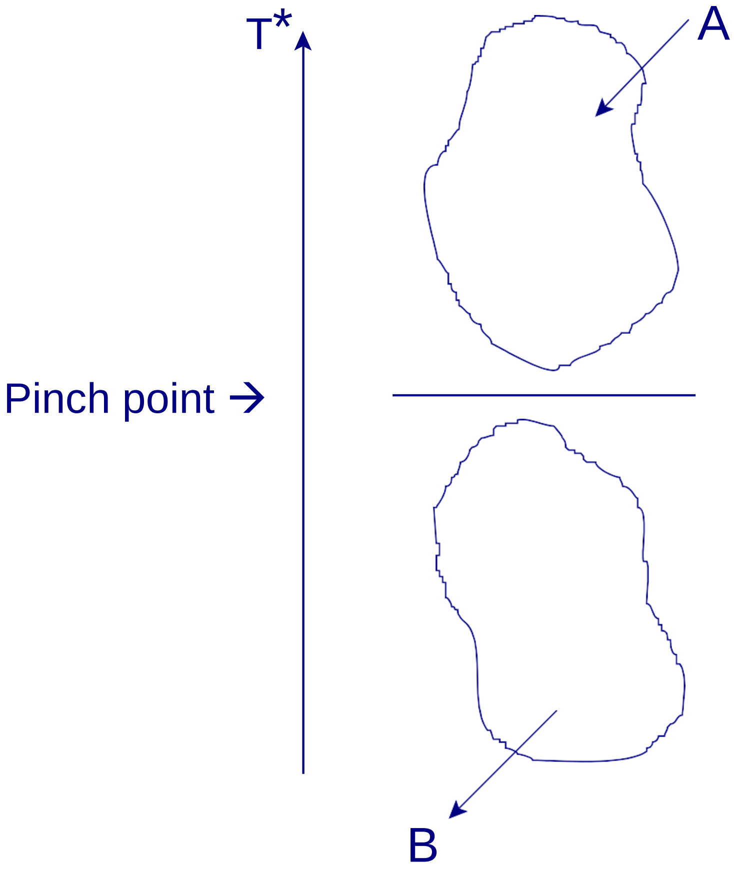
Part 4

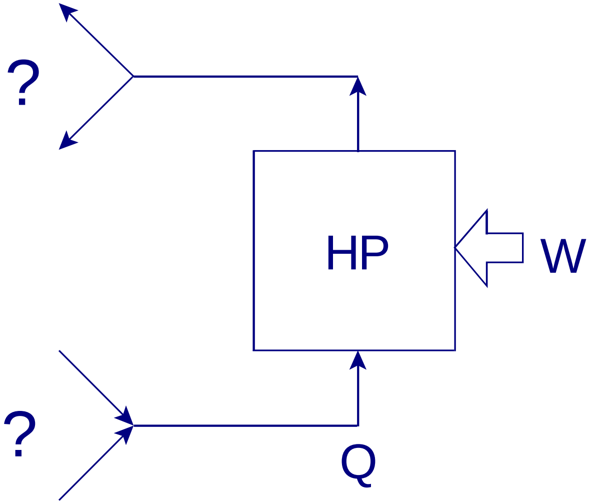
Heat Integration of Heat Pumps

Heat pump (Pompes à chaleur)



(Courtesy of University of Manchester)

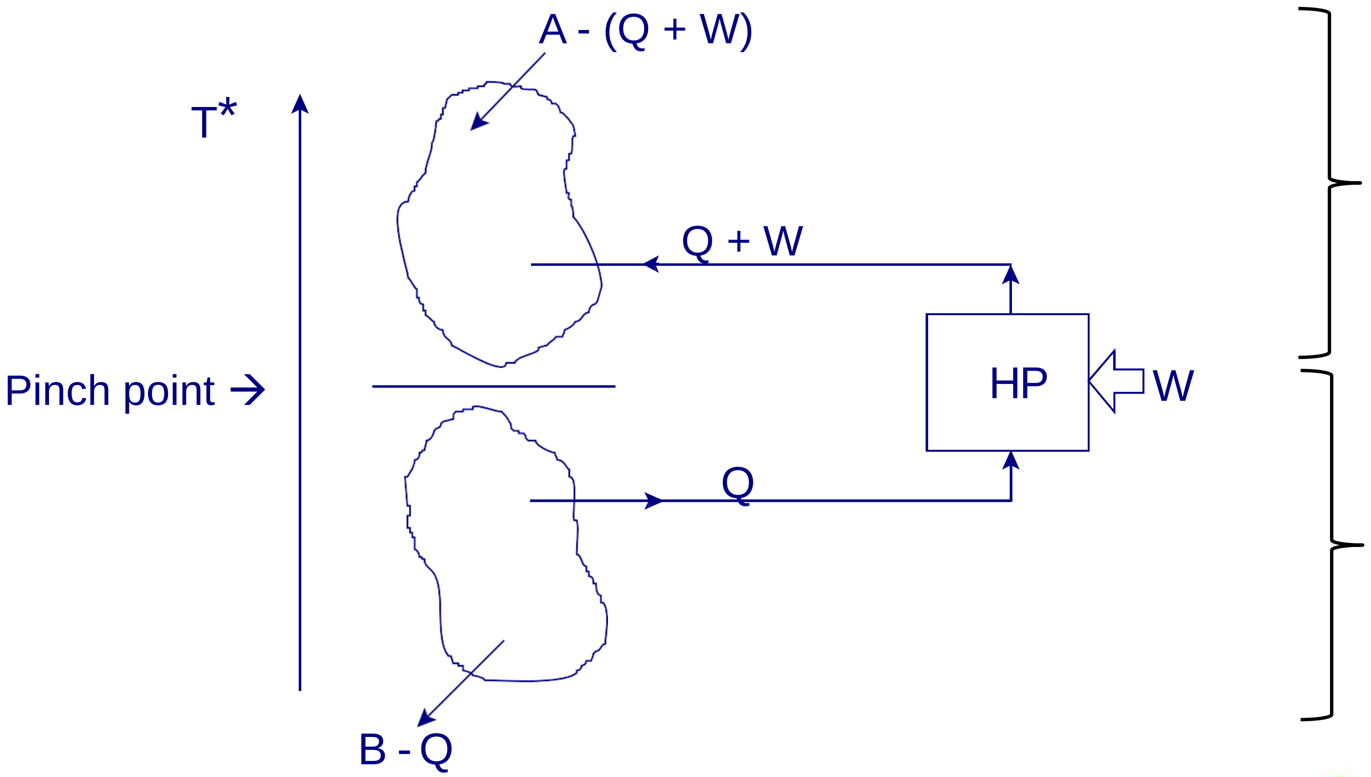




How should we integrate a heat pump ?

(Courtesy of University of Manchester)

Integrate **HP** across the pinch



A - (Q + W)

T*

Q + W

Pinch point →

HP

W

Q

B - Q

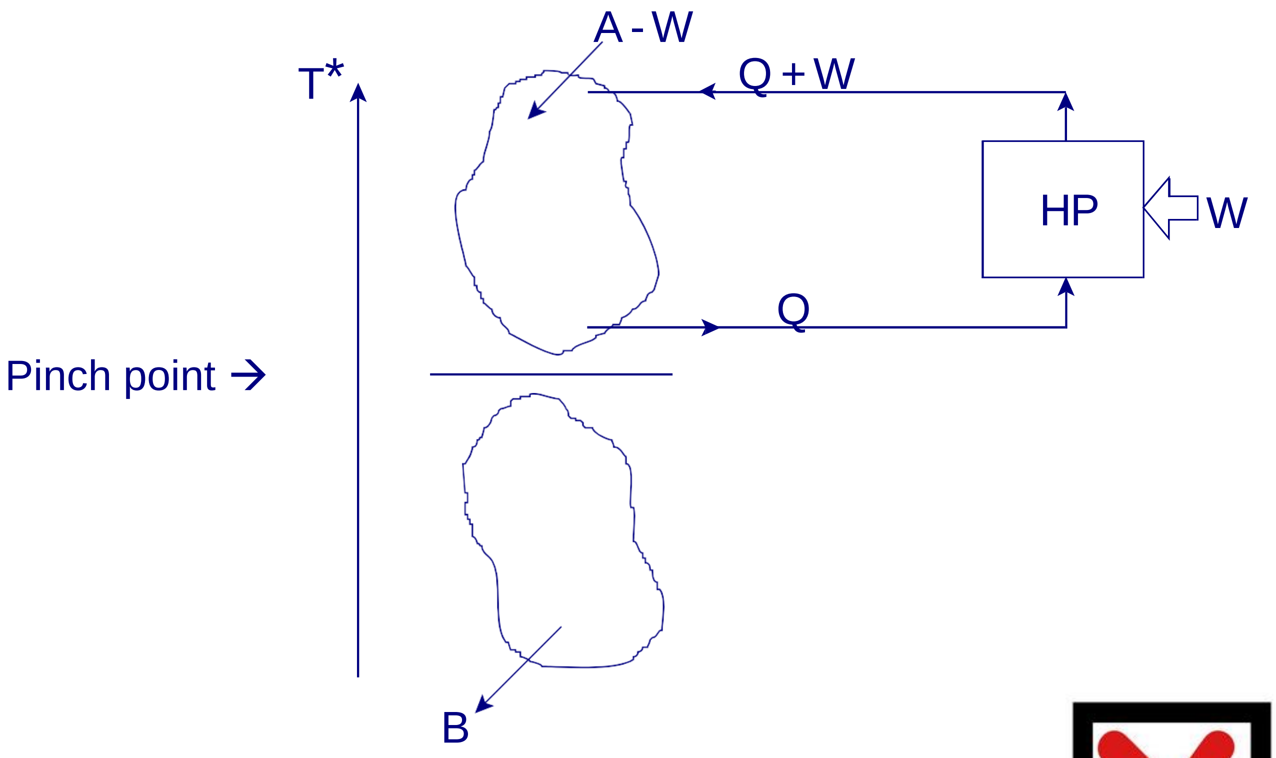
Heat is
valuable

Heat is
a burden

Saves hot and cold utility ☑

(Courtesy of University of Manchester)

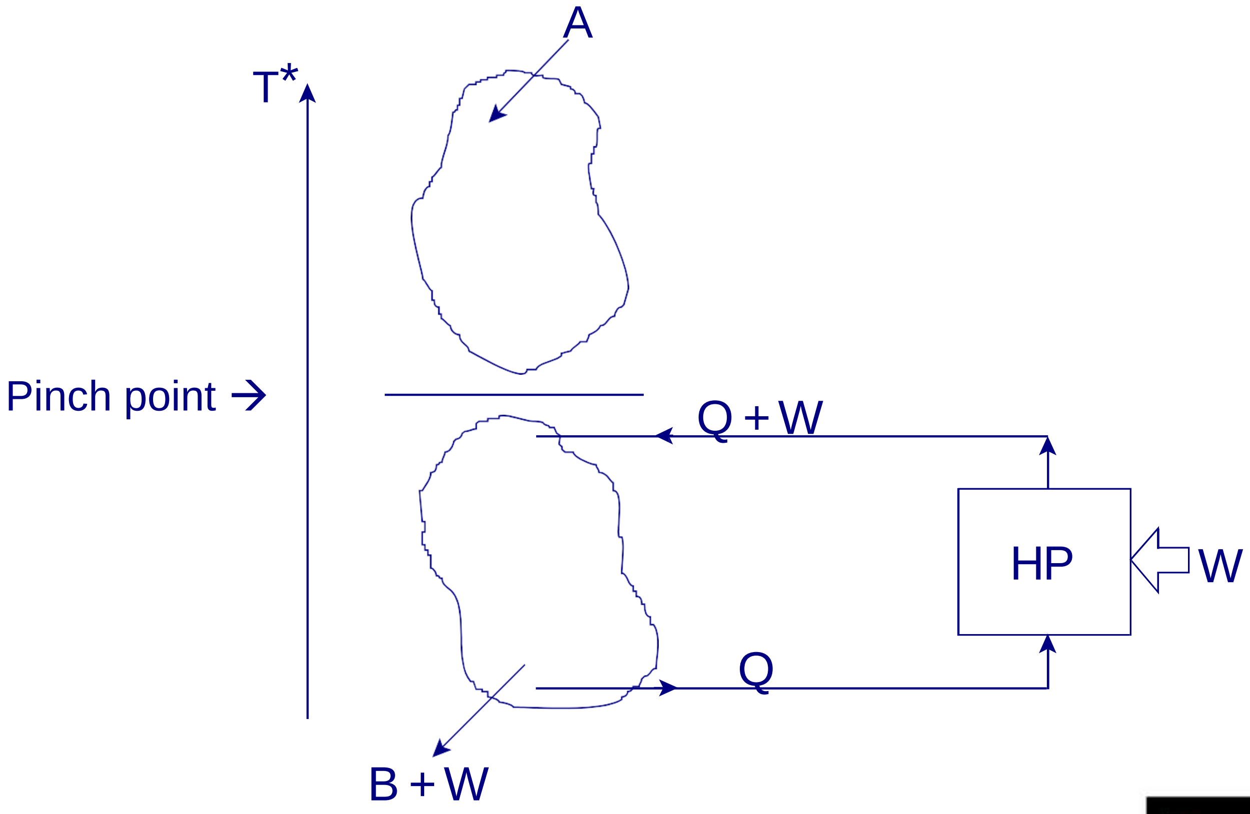
Integrate above the pinch



Power → Heat ☒

(Courtesy of University of Manchester)

Integrate below the pinch



Power ⟶ Waste Heat ☒

(Courtesy of University of Manchester)

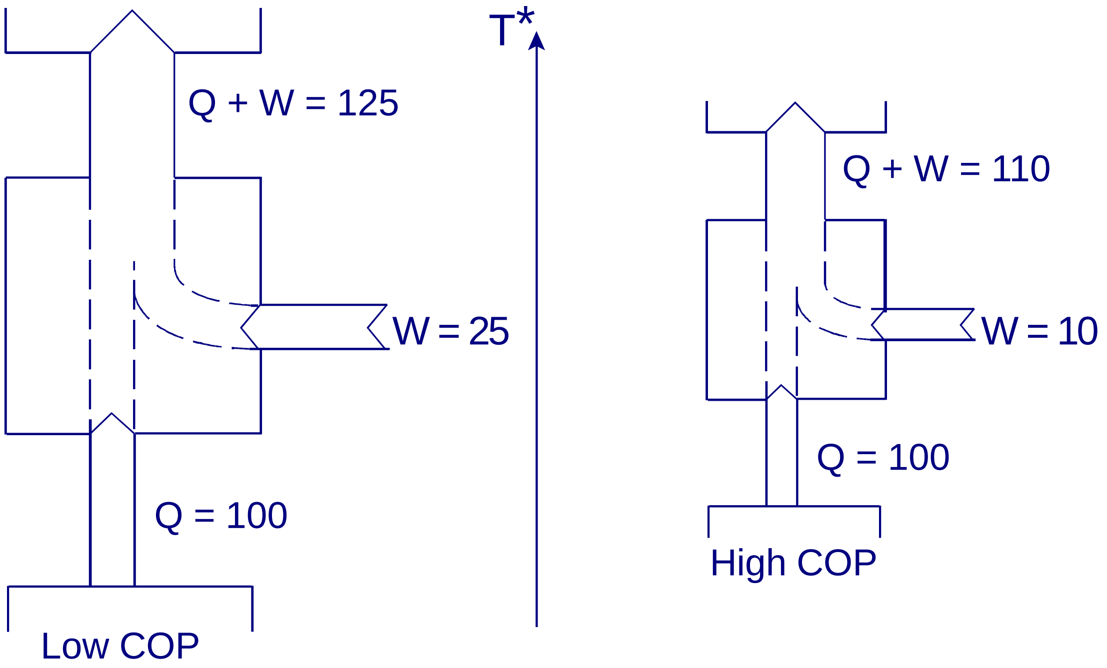
Appropriate Placement of Heat Pumps:

ACROSS THE PINCH

(à travers du point de pincement)

(Courtesy of University of Manchester)

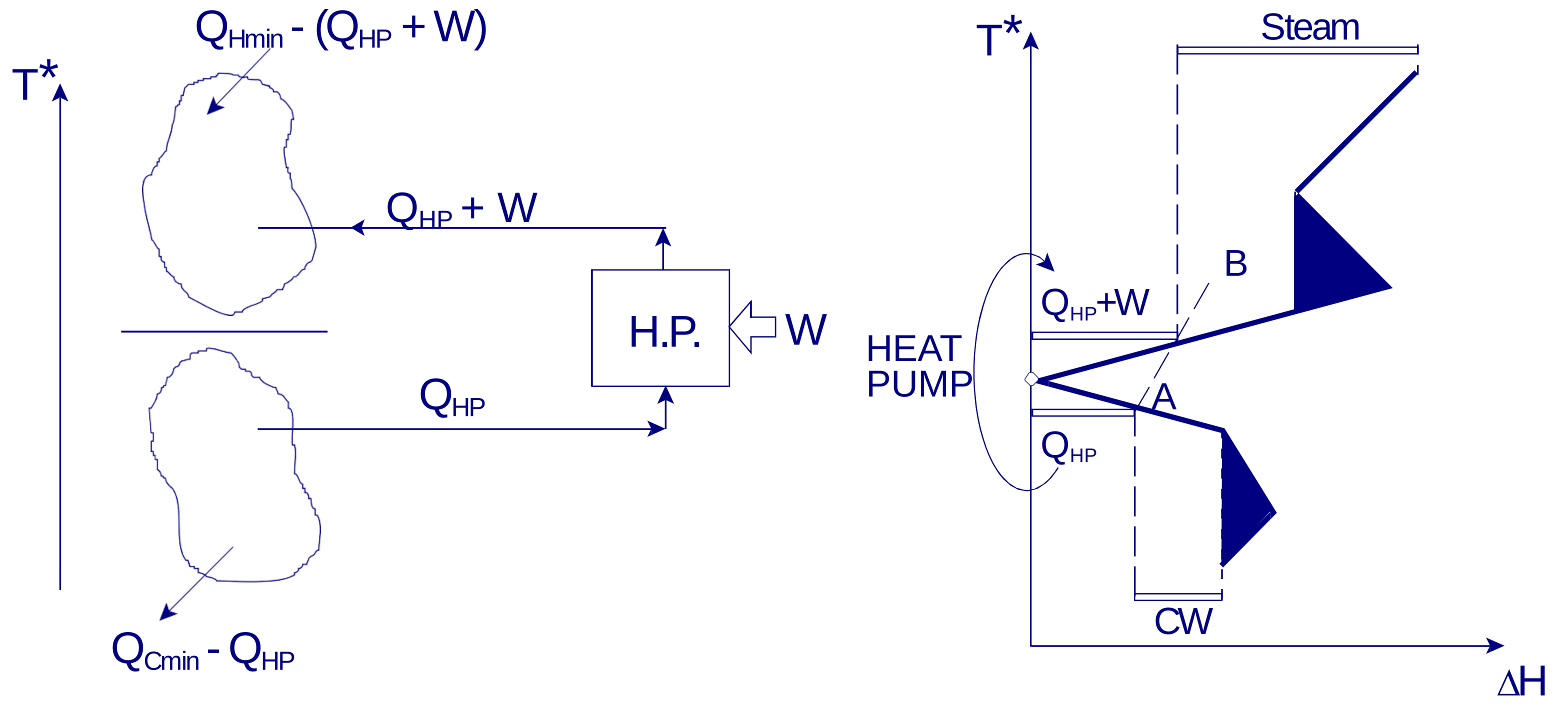
Coefficient of Performance



$$COP = \frac{Q + W}{W} = f(\Delta T)$$

Try and use Heat Pump across small ΔTs

(Courtesy of University of Manchester)



The grand composite curve allows heat pump cycles to be sized

(Courtesy of University of Manchester)

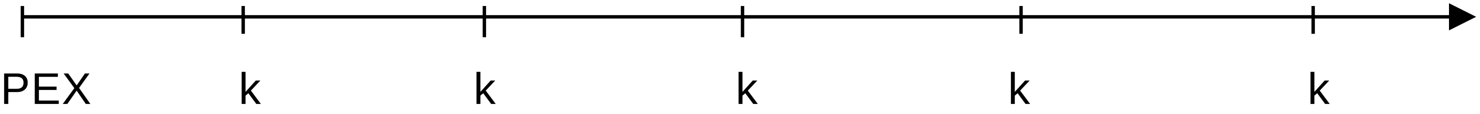
Summary

- Appropriate placement of heat pumps is fundamental
- Match profiles against the grand composite curve

Reminder

Economic assessment

Annuity method (1/2)



CAPEX k k k k k

$$\text{CAPEX} = \frac{k}{(1+r)} + \frac{k}{(1+r)^2} + \frac{k}{(1+r)^3} + \ldots$$

$$\text{CAPEX} = \frac{k}{(1+r)} * \left[1 + \frac{1}{(1+r)} + \frac{1}{(1+r)^2} + \ldots \right]$$

$$\text{CAPEX} = \frac{k}{(1+r)} * \left[1 + q + q^2 + \right]$$

$$\text{CAPEX} = \frac{k}{(1+r)} * \left[\frac{q^n - 1}{q - 1} \right]$$

$$\mathbf{CAPEX} = \mathbf{k} * \frac{(1+r)^n - 1}{(1+r)^n * r}$$

$1/\alpha$

k: yearly investment cost
CAPEX: Capital expenditure
α: Annuity factor
r: Interest rate
L: Lifetime or period of depreciation

Annuity method (2/2)

Investment costs k (per year)

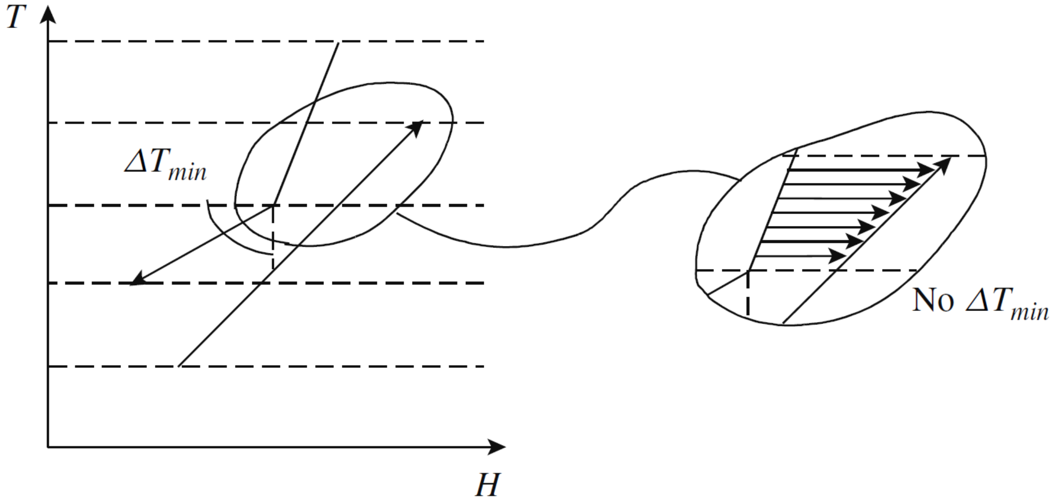
$$k = \alpha * \text{CAPEX}$$

$$\alpha = \frac{r}{1 - (1 + r)^{-n}}$$

r = interest rate (discount rate)
n = (economic) lifetime of the investment
(= period of depreciation)
α = annuity factor

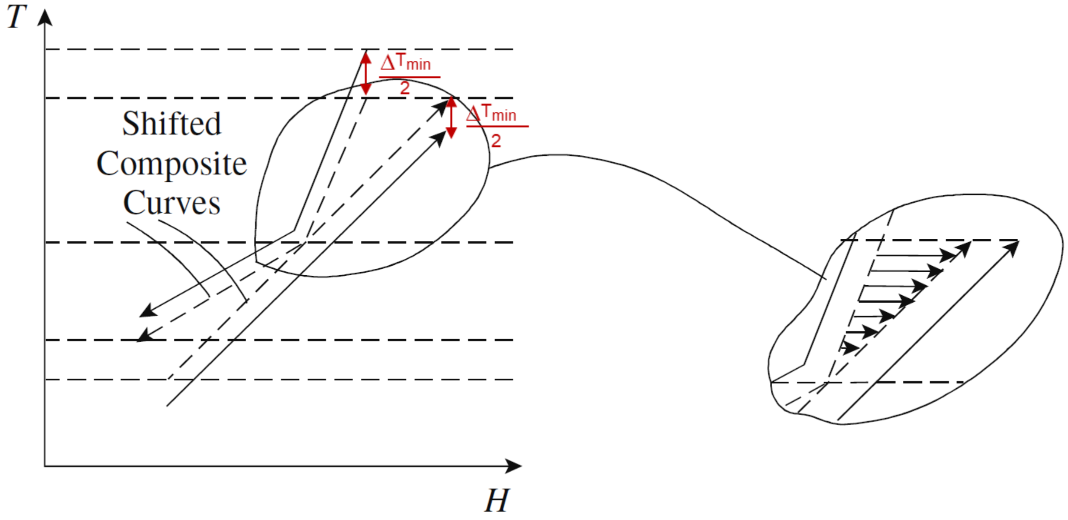
Additional slides

Original Composite Curves



(a) Driving forces not feasible within each interval.

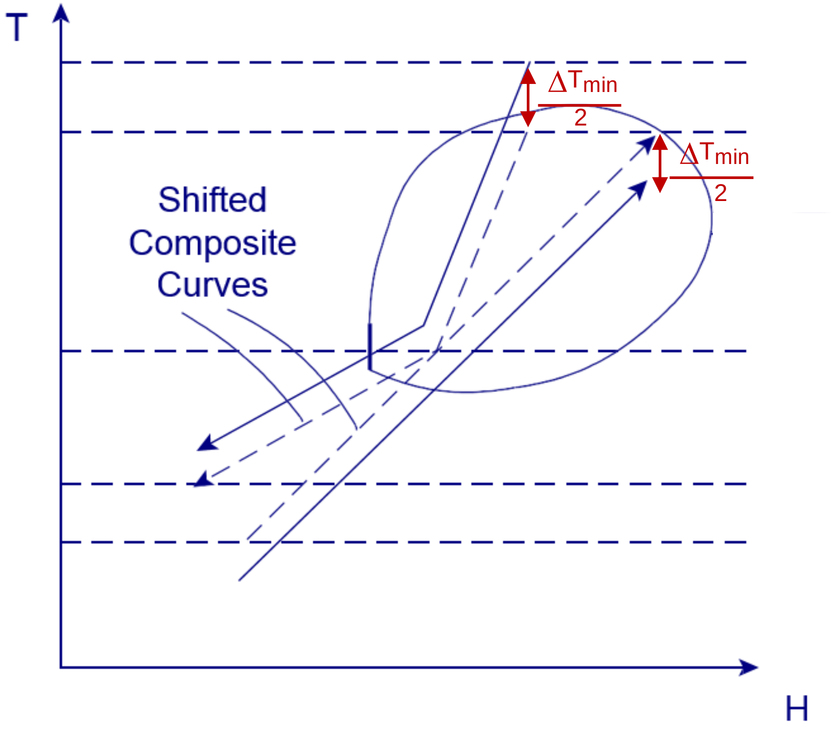
Shifted Composite Curves



(b) Heat transfer within temperature intervals now feasible.

Smith, 2005 (p.392)

Shift Composite Curves



(Courtesy of University of Manchester)