Chemical Process Design / Diseño de Procesos Químicos

Subject 8. Process synthesis: Heat Exchangers Network Synthesis (HENS)

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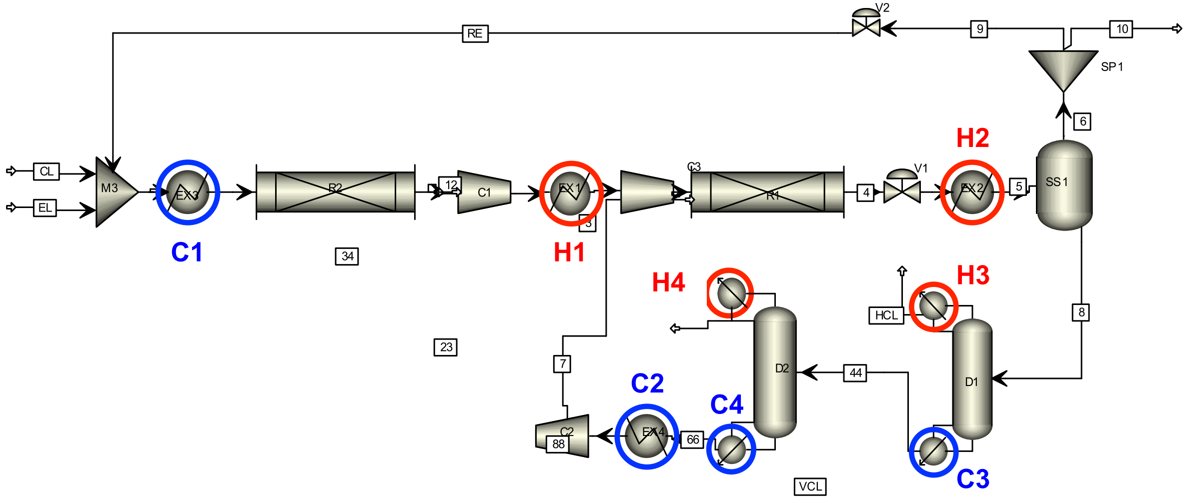
1.- Heat Exchanger Network Synthesis: Introduction

Objective: Recover Heat to reduce energy consumption



Cool Stream → C# Streams that need steam. Sinks heat.

Hot Stream → H# Streams that need cooling water. Sources heat.

Basic HENS problem

- **The Mass and heat Balances have been completed.**
- **Stream characteristics: Tinlet, Toutlet, heat capacity flowrate.**

$$f\ (KW/K) = F\ (kg/s) \cdot Cp\ (J/kg.K)\ ;\ Q\ (KW) = f\ \Delta Tp$$

- **Non-isothermal streams Tinlet ≠ Toutlet (no change of phase).**
- **Change of phase:**
  - **Pure components Tinlet = Toutlet isothermal streams (vaporize, condense). Assumptions: $\Delta Tp = 1$; $Q = f\Delta Tp$; $f = \Delta H$**
  - **Multicomponents $\Delta Tp = Tdew - Tbub$ → $Q = f\Delta Tp$; $f = \Delta H/\Delta Tp$**

1.- Heat Exchanger Network Synthesis: Introduction

HEN Problem

Given n_H hot streams and n_C cold streams

- **HOT** f_{Hi}, T_{Hi}^{in}, T_{hi}^{out}

  + Auxiliary utilities such as fuel, steam, cooling water, refrigeration

- **COLD** f_{Cj}, T_{Cj}^{in}, T_{Cj}^{out}

Find the network of countercurrent heat exchangers (single pass) to MINIMIZE total annualized Costs C_A (exchangers +utilities)

$$C_A = i_m\left(C_{CTI}\right) + C = C_A = i_m\left[\sum_i C_{P,I_i} + \sum_j C_{P,A_j}\right] + sF_S + (cw)F_{cw}$$

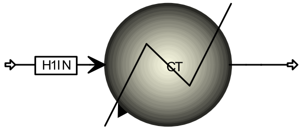
i_m: return of investment annually (0.33).
C_{CTI}: total Capital Investment.
C: annual Cost of utilities.
$C_{P,\,Ii}$: purchase cost of exchangers.
$C_{P,\,Aj}$: purchase cost of auxiliary network.
F_s, F_{cw}: annual flowrates of steam and cooling water.
s, cw: unit cost of steam and cooling water.

1.- Heat Exchanger Network Synthesis: Introduction

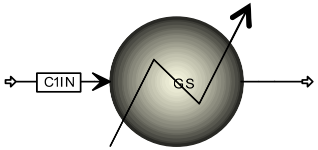
Alternatives (three): (1.- Extreme, 2.- Near Optimal, 3.- Optimal)

1. Extreme Alternative:

a) Every hot stream with cooling utility → Cooling Towers.



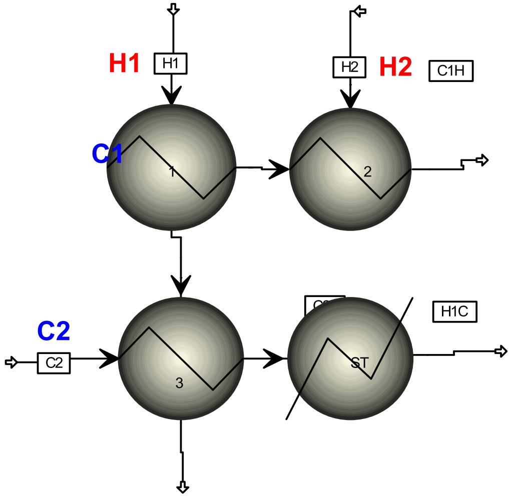
Every cold stream with heating utility → Generating steam.



Higher driving force → U↑ →A↓

→ Is the minimum possible interchange between streams.

b) Recover as much heat as possible using the least amount of utilities.



Optimal solution from a heat recovery point of view because only need heating (or cooling); This is the maximum possible heat interchange. Not always possible.

1.- Heat Exchanger Network Synthesis: Introduction

Alternatives

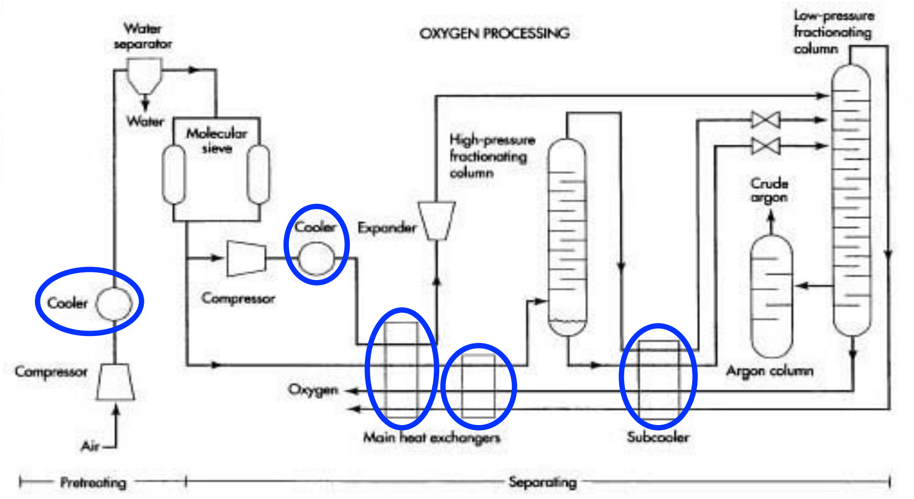
2. Near Optimal Network (two-step synthesis):

a) **Minimum Utility Cost (consumption) for a given DT_{min} (HRAT – heat recovery approach temperature) → Minimize Utility Costs e.g. HRAT = 10 K.**

b) **Fewest number of units (exchangers). The Mass and heat Balances have been completed → Minimize investment Costs.**

Pinch Analysis → 1.- Predict a) + b); 2.- Develop network structure to satisfy a) + b).

70´s. Linnhoff. Linde and other separation air industries use this methodology



http://www.madehow.com/Volume-4/Oxygen.html.

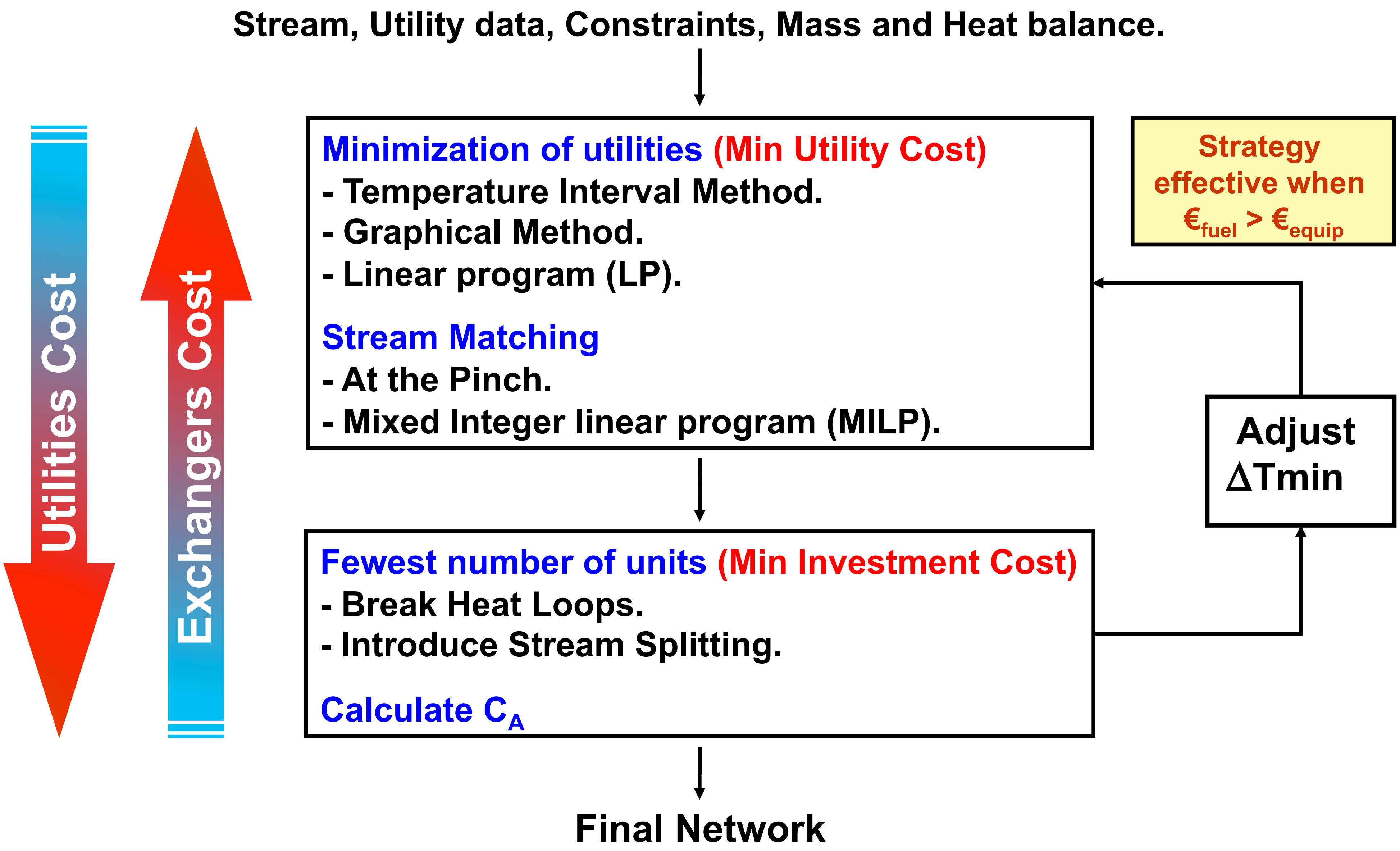
3. Optimal Network (one-step synthesis):

MINLP Optimization of C_A → Non Lineal $€ = \Phi (A^{\alpha}), \alpha < 1$; $C = C_0 (A / A_0)^{\alpha}$

$$\Delta T_{lm} = (\Delta T1 - \Delta T2) / \ln (\Delta T1 / \Delta T2)$$

1.- Heat Exchanger Network Synthesis: Introduction

2. Near Optimal Network (two-step synthesis):



Stream, Utility data, Constraints, Mass and Heat balance.

Minimization of utilities (Min Utility Cost)
- Temperature Interval Method.
- Graphical Method.
- Linear program (LP).

Stream Matching
- At the Pinch.
- Mixed Integer linear program (MILP).

Fewest number of units (Min Investment Cost)
- Break Heat Loops.
- Introduce Stream Splitting.

Calculate C_A

Final Network

Adjust
ΔTmin

Strategy
effective when
$€_{fuel} > €_{equip}$

2.- HENS: Minimum Utility Consumption

	f (KW/K)	Tin (K)	Tout (K)
H1	10	600	320
H2	20	540	320
C1	15	360	600
C2	13	300	450

At specified ΔT_{min}= HRAT

7200 Kw

5550 Kw

First Law Thermodynamics:
7200 – 5550 Kw =
1650 Kw cooling

Pinch Analysis: Use of the composite Streams (Hohmann Curves) to obtain HEN by Graphical Approach. Temperature interval method.

- **At HRAT specified → Q = fΔTp → ΔTp = Q/f → Slope 1/f**

  You specify that:

  Δt_{min} = HRAT = 0 → Area = ∞; ΔT_{min} = HRAT ↑↑ → Energy ↑↑ and A → 0.

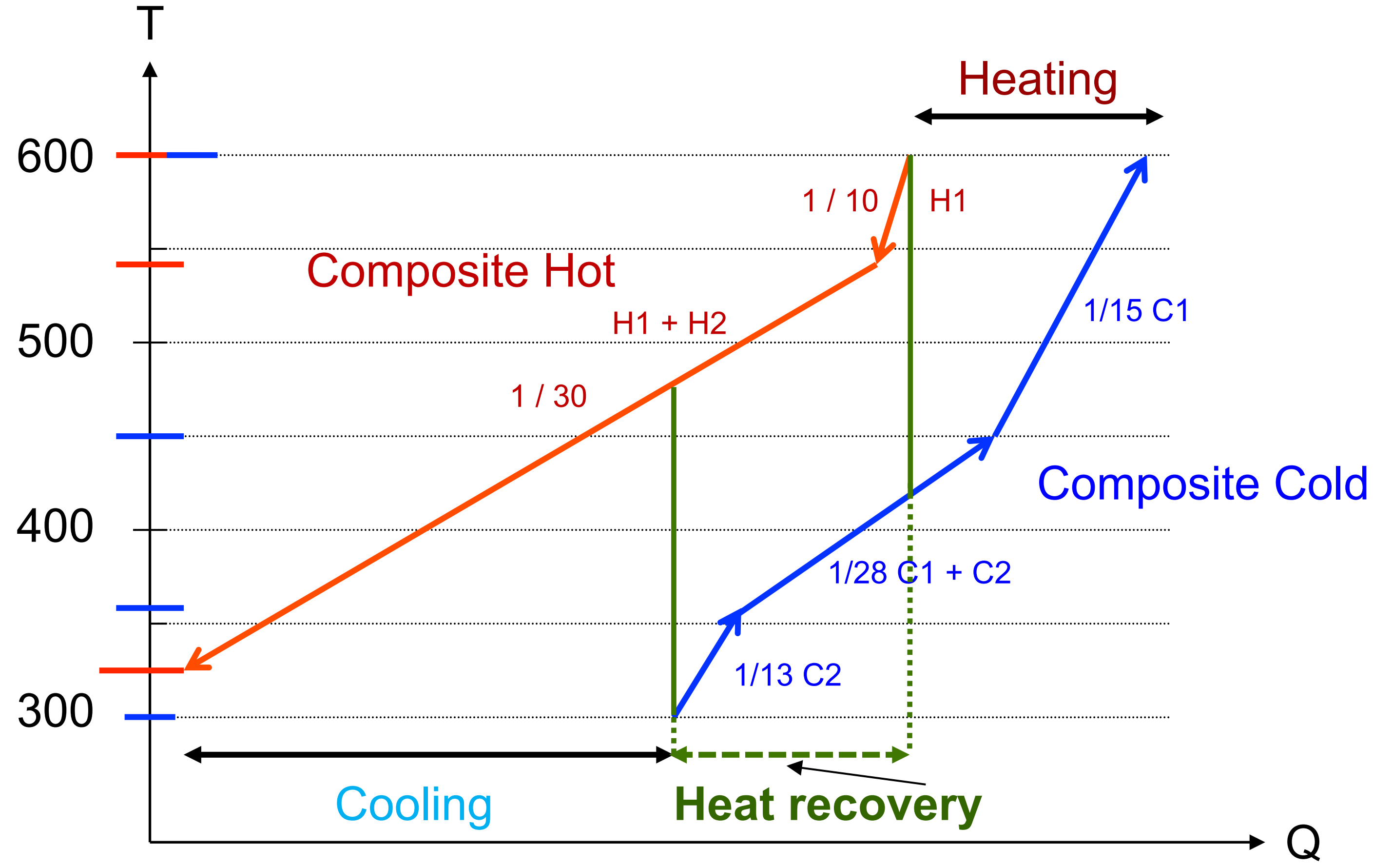
  - **Influence of the “Minimum Recovery Approach Temperature – HRAT” or “Approach Temperature – ΔT_{min}” ΔT_{min} = HRAT.**

- **Problem Table (Heat flow analysis) at HRAT = 20 K. Temperature intervals in order to guarantee feasible heat exchange based on the inlet Ts.**

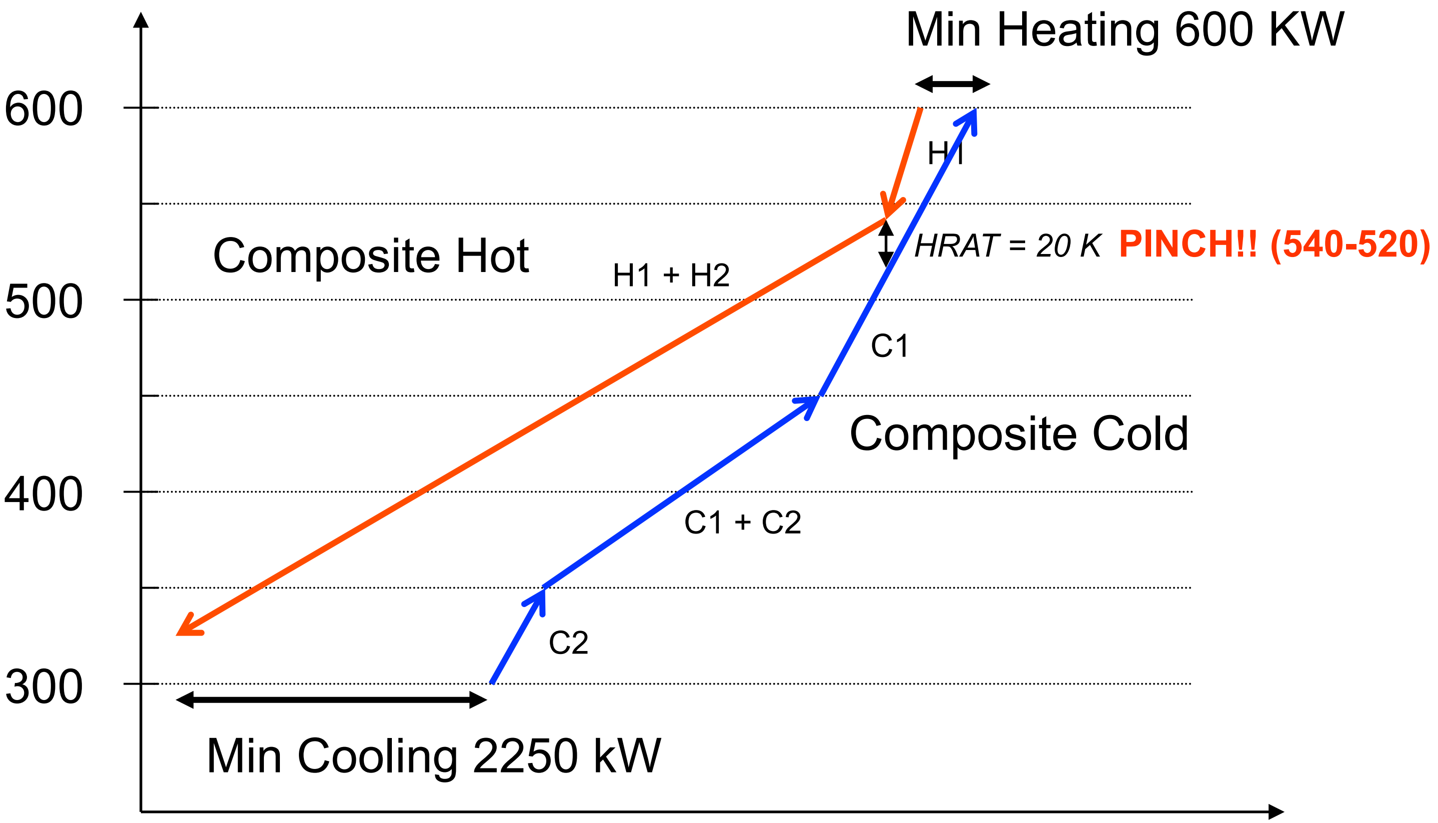
- **Final result from the Graphical and Interval approaches are the same.**

Pinch Analysis

	f (KW/K)	Tin (K)	Tout (K)
H1	10	600	320
H2	20	540	320
C1	15	360	600
C2	13	300	450

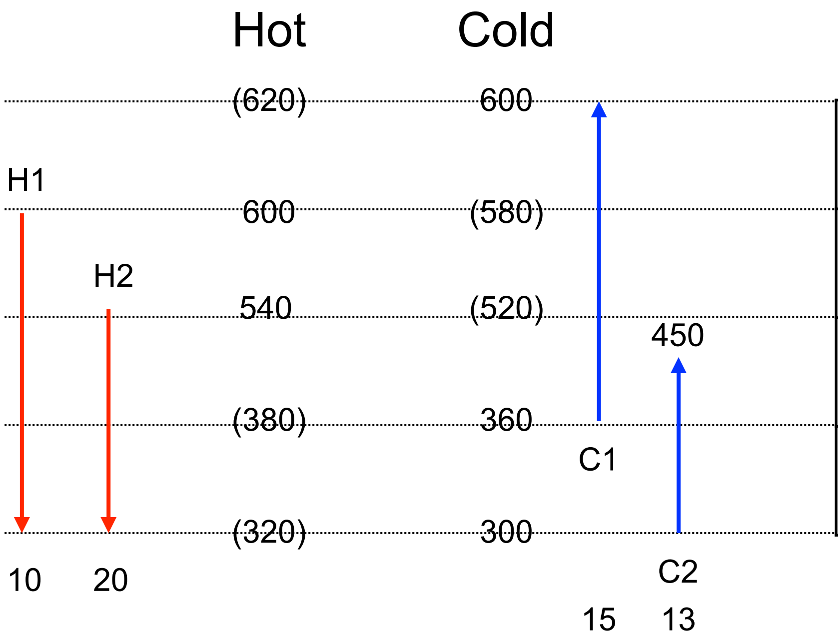


Target min heating / min cooling



Problem Table ΔT_{min} = HRAT = 20 K

Temperature intervals



Heat Surplus/ Deficit kW	Infeasible Cascade	Feasible Cascade
–300	–300	
–300	–600	
1230	630	
1020	1650	

	f (kW/K)	Tin(K)	Tout(K)
H1	10	600	320
H2	20	540	320
C1	15	360	600
C2	13	300	450

Problem Table ΔT_{min} = HRAT = 20 K

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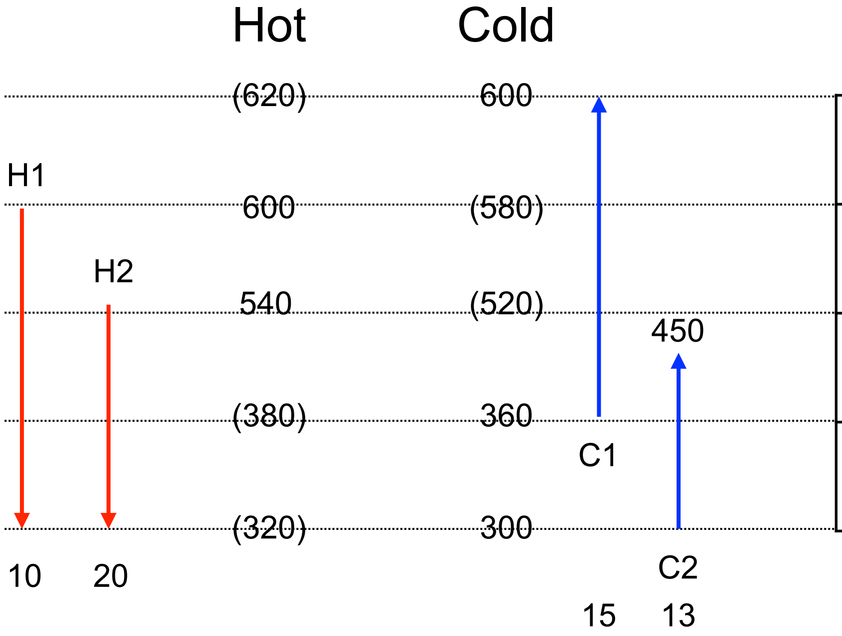

Heat Surplus/ Deficit kW	Infeasible Cascade	Feasible Cascade
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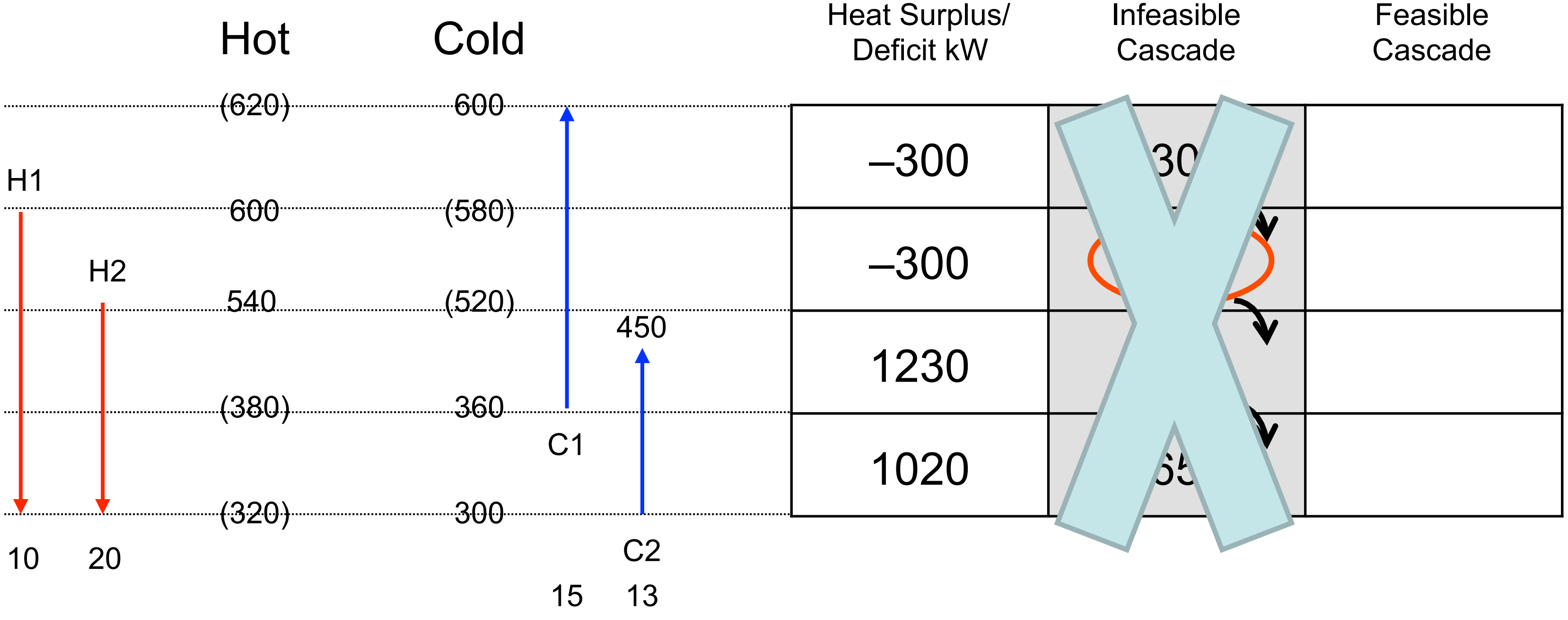

Heat Surplus/ Deficit kW	Infeasible Cascade	Feasible Cascade
–300	30	
–300		
1230		
1020	65	

	f (kW/K)	Tin(K)	Tout(K)
H1	10	600	320
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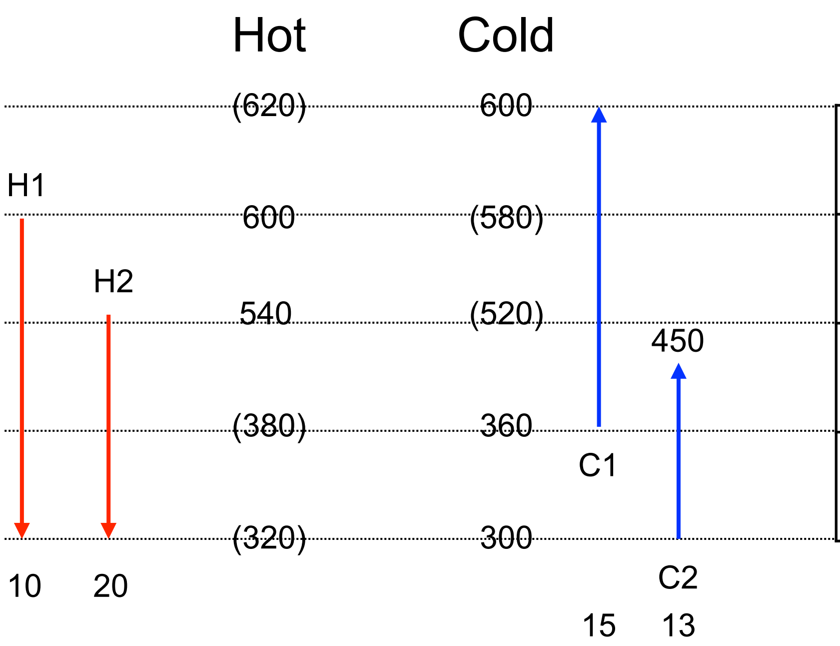
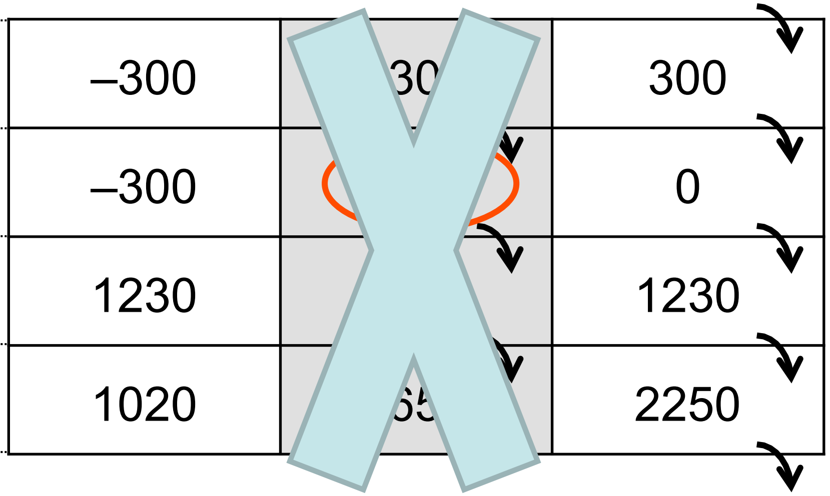
Problem Table ΔT_{min} = HRAT = 20 K

Temperature intervals





Heat Surplus/ Deficit kW	Infeasible Cascade	
–300	30	300
–300		0
1230		1230
1020	55	2250

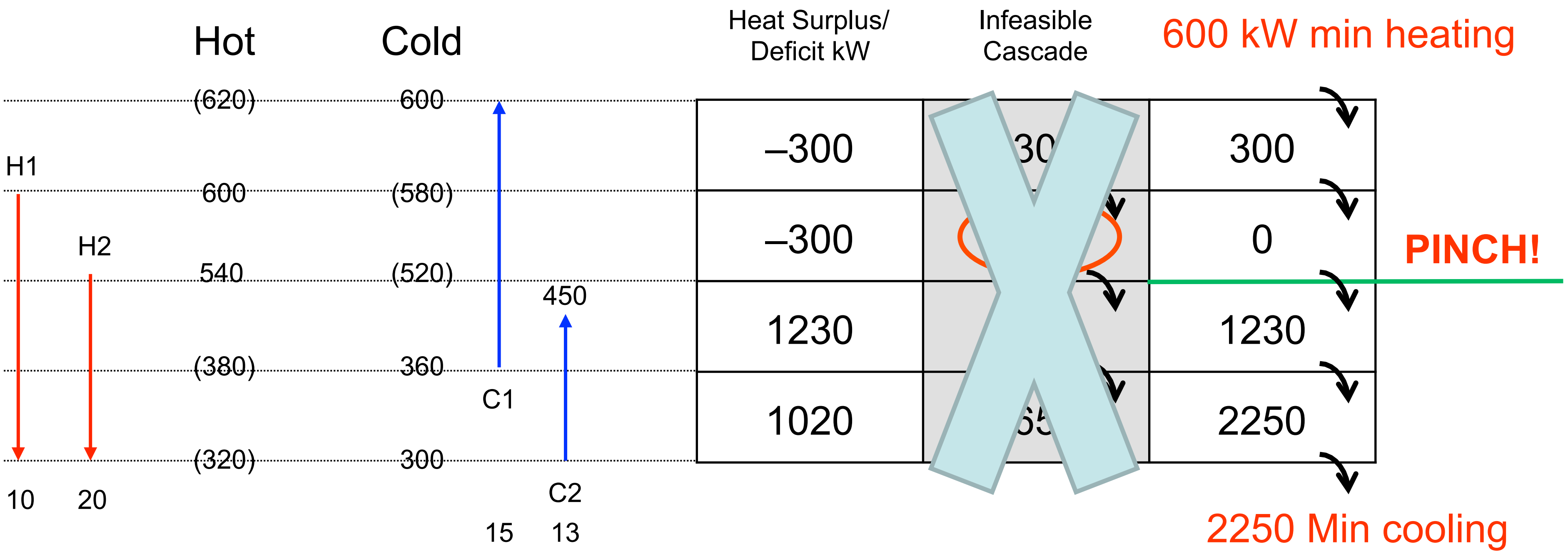
600 kW min heating

2250 Min cooling

	f (kW/K)	Tin(K)	Tout(K)
H1	10	600	320
H2	20	540	320
C1	15	360	600
C2	13	300	450

Problem Table ΔT_{min} = HRAT = 20 K

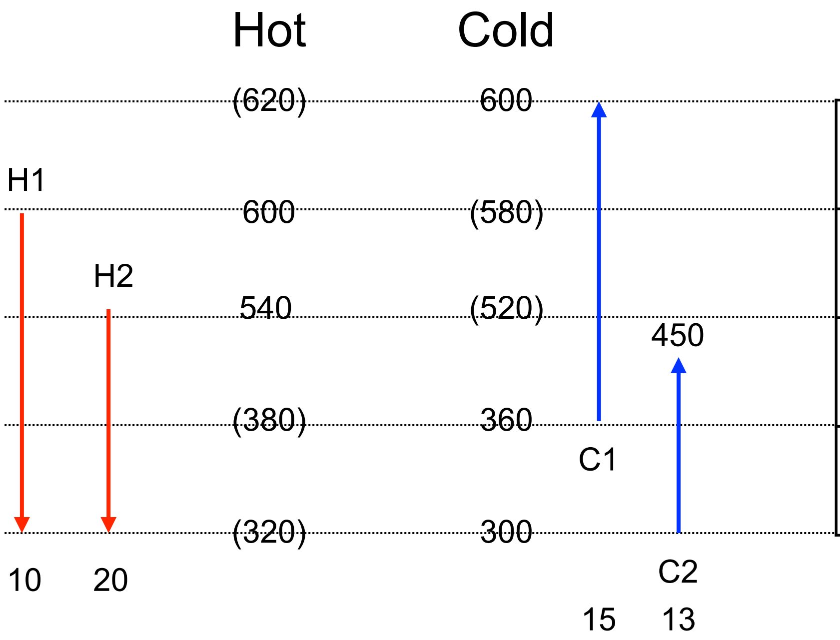
Temperature intervals

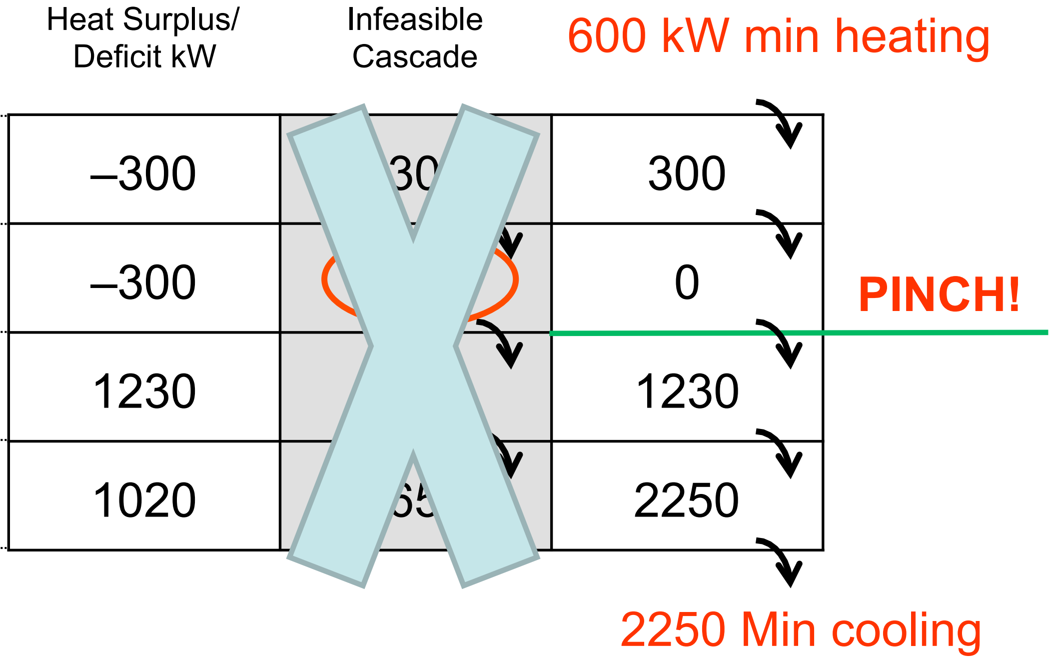


	f (kW/K)	Tin(K)	Tout(K)
H1	10	600	320
H2	20	540	320
C1	15	360	600
C2	13	300	450

Problem Table ΔT_{min} = HRAT = 20 K

Temperature intervals





Heat Surplus/ Deficit kW	Infeasible Cascade	600 kW min heating
–300	30	300
–300	[illegible]	0
1230	[illegible]	1230
1020	55	2250

PINCH!

2250 Min cooling

	f (kW/K)	Tin(K)	Tout(K)
H1	10	600	320
H2	20	540	320
C1	15	360	600
C2	13	300	450

Min heating	600 kW
Min cooling	2250 kW
Pinch	540-520 K

Heat Exchanger Network Synthesis

The Problem Table (Heat flow Analysis):

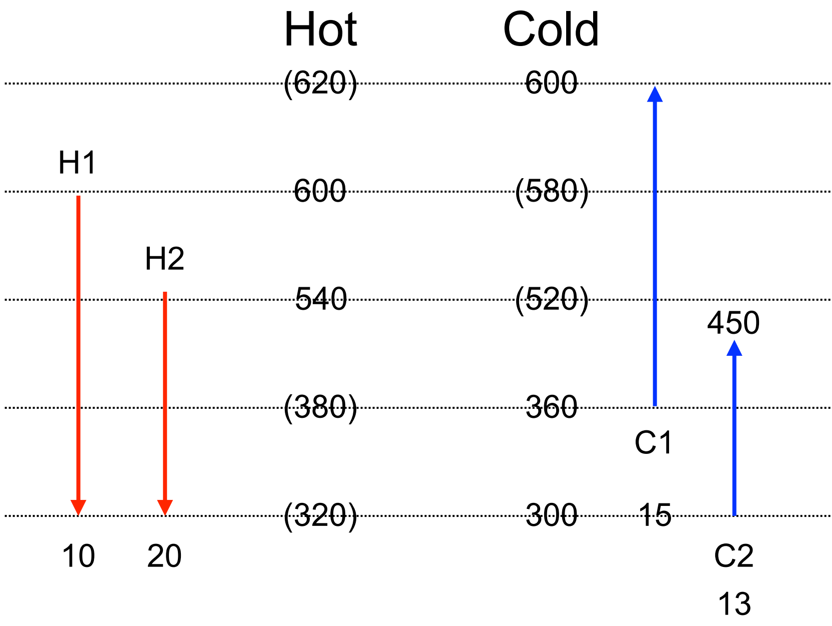
1. Determine Heat Surplus/Deficit in each interval.
2. Cascade heat with 0 Kw heating. Largest Deficit = Min Heating.
3. Cascade with Minimum Heating:
    - 3.1. Min Cooling at bottom.
    - 3.2. Temperature below position where 0 Kw entering interval → PINCH.

Not heat transfer below → Partition of Design between ABOVE + BELOW pinch.

Mathematical Optimization Models for HEN: Transshipment model (Papoulias and Grossmann, 1983)

Heat Content at HRAT = 20 K.

Temperature intervals

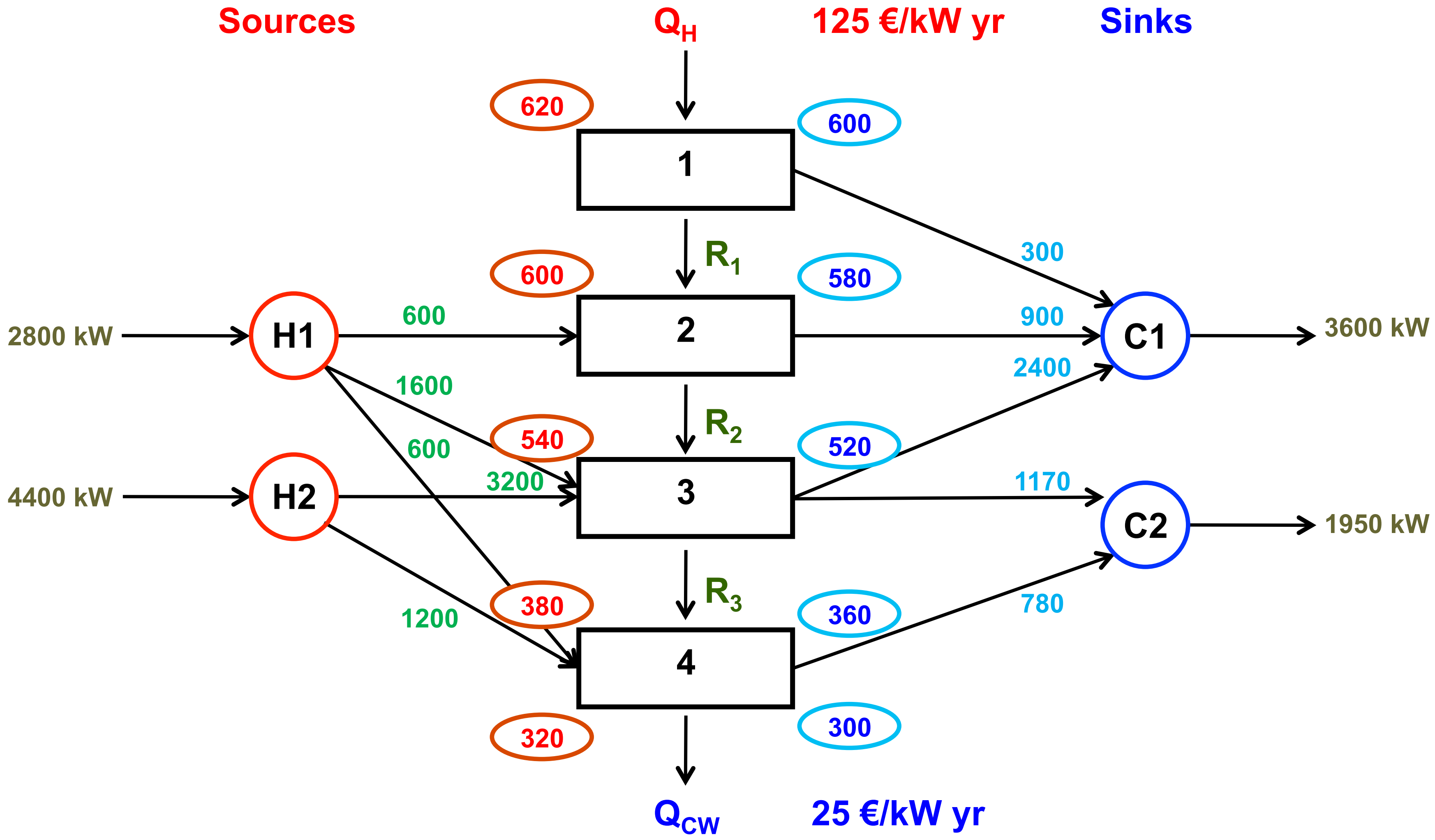


Heat Content (kW)

H1	H2	C1	C2
		300	
600		900	
1600	3200	2400	1170
600	1200		780
2800	4400	3600	1950

Mathematical Optimization Models for HEN: Transshipment model (Papoulias and Grossmann, 1983)

Heat Cascade Diagram at HRAT = 20 K.



Mathematical Optimization Models for HEN: Transshipment model (Papoulias and Grossmann, 1983)

Heat Balances

$R_1 + 300 = Q_H$

$R_2 + 900 = R_1 + 600$

$R_3 + 3570 = R_2 + 4800$

$Q_{CW} + 780 = R_3 + 1800$

4 eqs; 5 var $R_1, R_2, R_3, Q_H, Q_{CW}$

Linear programming problem (LP)

$$\text{Min } Z = 125\,Q_H + 25\,Q_{CW}$$

s.t.

$$R_1 - Q_H = -300$$

$$R_2 - R_1 = -300$$

$$R_3 - R_2 = 1230$$

$$Q_{CW} - R_3 = 1020$$

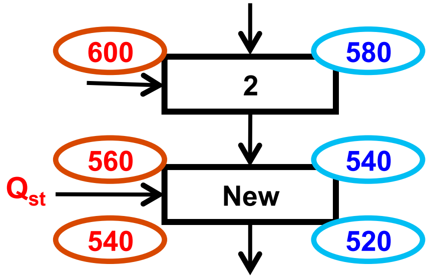
$R_1, R_2, R_3, Q_H, Q_{CW} \geq 0$

Solution:

$Q_H = 600$ kW; $Q_{CW} = 2250$ kw; $R_1 = 300$; $R_2 = 0$ → PINCH (540 – 520); $R_3 = 1230$; $Z = 131250$ €/yr

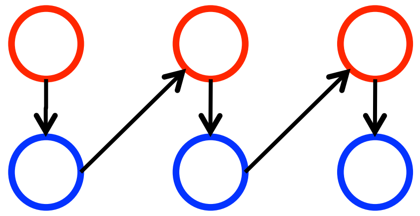
Remarks:

1. The approach can be easily extended to multiple utilities (e.g. use of steam at 560 K) by simply including in heat balance.
2. Can extend to forbidden matches (e.g. No H1-C1).



3.- HENS: Minimum Number of Units. Stream matching at the pinch

For each subnetwork (Above/below the pinch) assume at least one stream is exhausted in each match:



Hot streams / Utilities

Cold Streams / Utilities

Given a graph with **n** nodes.

the minimum links = **n – 1.**

For each subnetwork: $N_{min} = n_{cold} + n_{hot} + n_{utility} - 1$

<u>In our Example we can predict the n° of exchangers</u>:

Above pinch: H1, C1, Steam → $N_{min} = 1 + 1 + 1 - 1 = 2$ units.

Below pinch: H1, H2, C1, C2, Cooling Water → $N_{min} = 2 + 2 + 1 - 1 = 4$ units.

Total $N_{min} = 2 + 4 = 6$ units.

Q_H = 600 kW heating at 125 €/kW yr.

Q_{CW} = 2250 kw cooling at 25 €/kW yr.

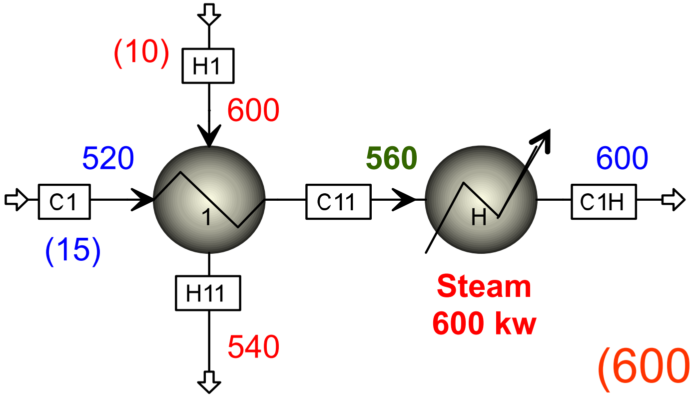
Pinch: 540-520 K.

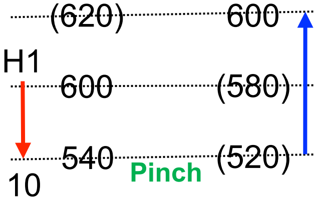
€ = 131.250 €/yr to HRAT = 20 K.

3.- HENS: Minimum Number of Units. Stream matching at the pinch

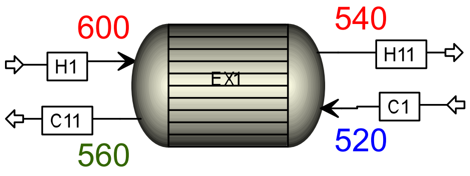
Derivation of the Network (Non-systematic. Only optimization is systematic):

Above pinch (Only H1, C1, Stream)

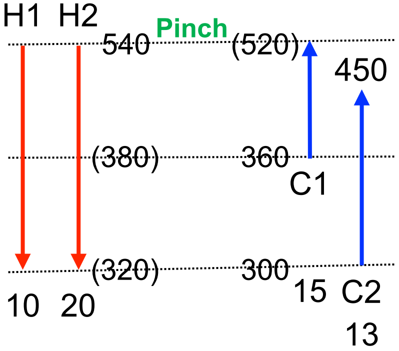


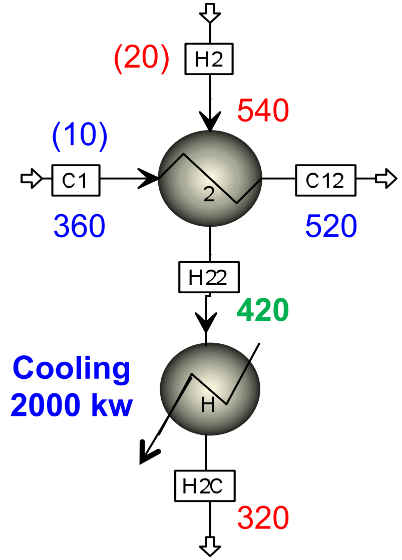


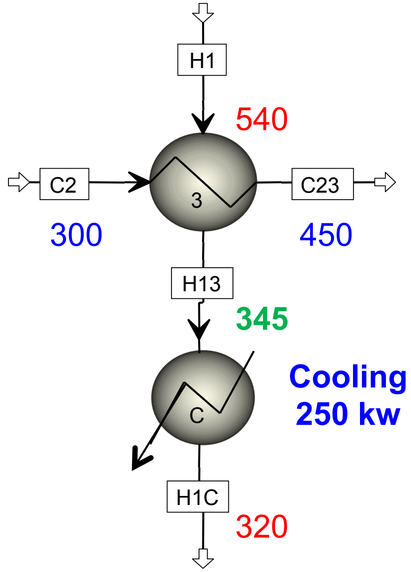
Check if the interchange is feasible



(600 – 540) · 10 = 600 = (T – 520) · 15 → T = 560







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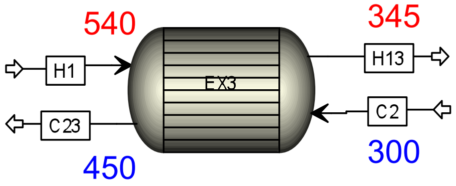
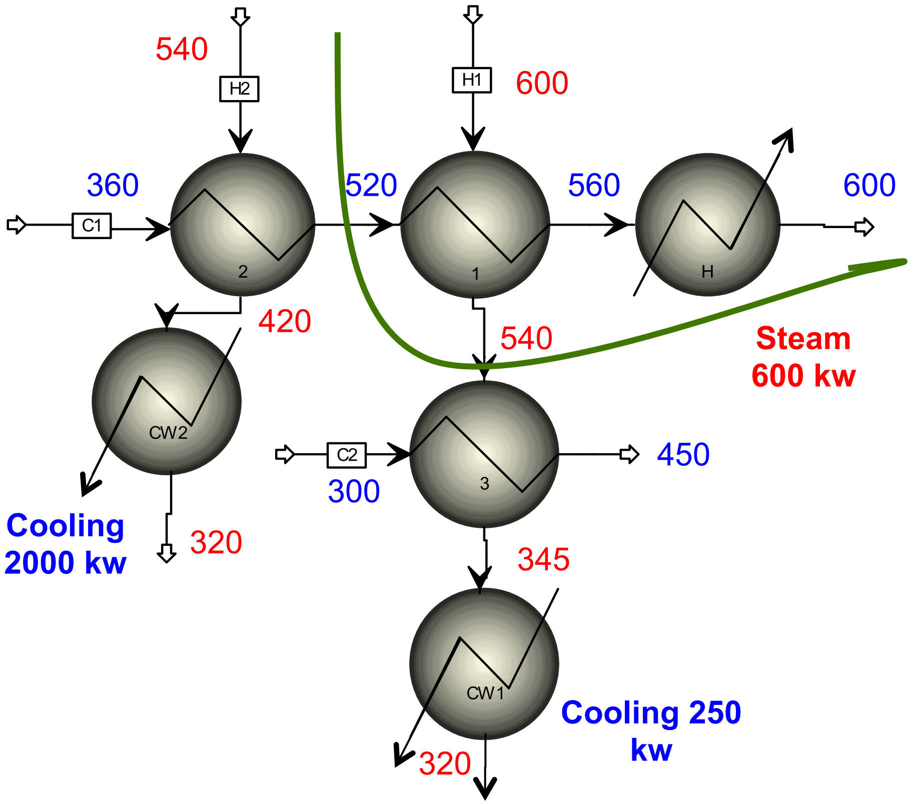


3.- HENS: Minimum Number of Units. Stream matching at the pinch

Final Network Structure.



Consider

$U_{exchangers}$ = 0.8 kw/m^{2}K

$U_{heaters}$ = 1.2 kw/m^{2}K

Total Area = 217 m^2

Investment Cost = 72,960 €/yr

Cost Exchangers = 1,500 A$^{0.6}$ €/y

Utility Cost = 131,250 €/y

TOTAL: 204,210 €/y

By Optimization the TOTAL: 184,750 €/y

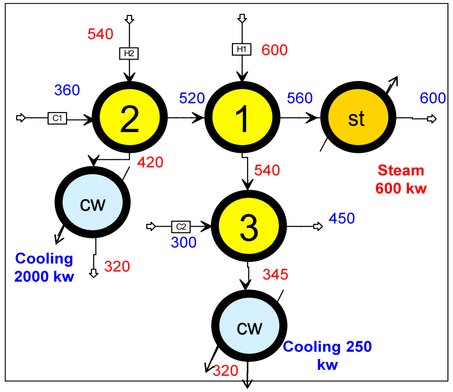
Not too far because the utilities are low.

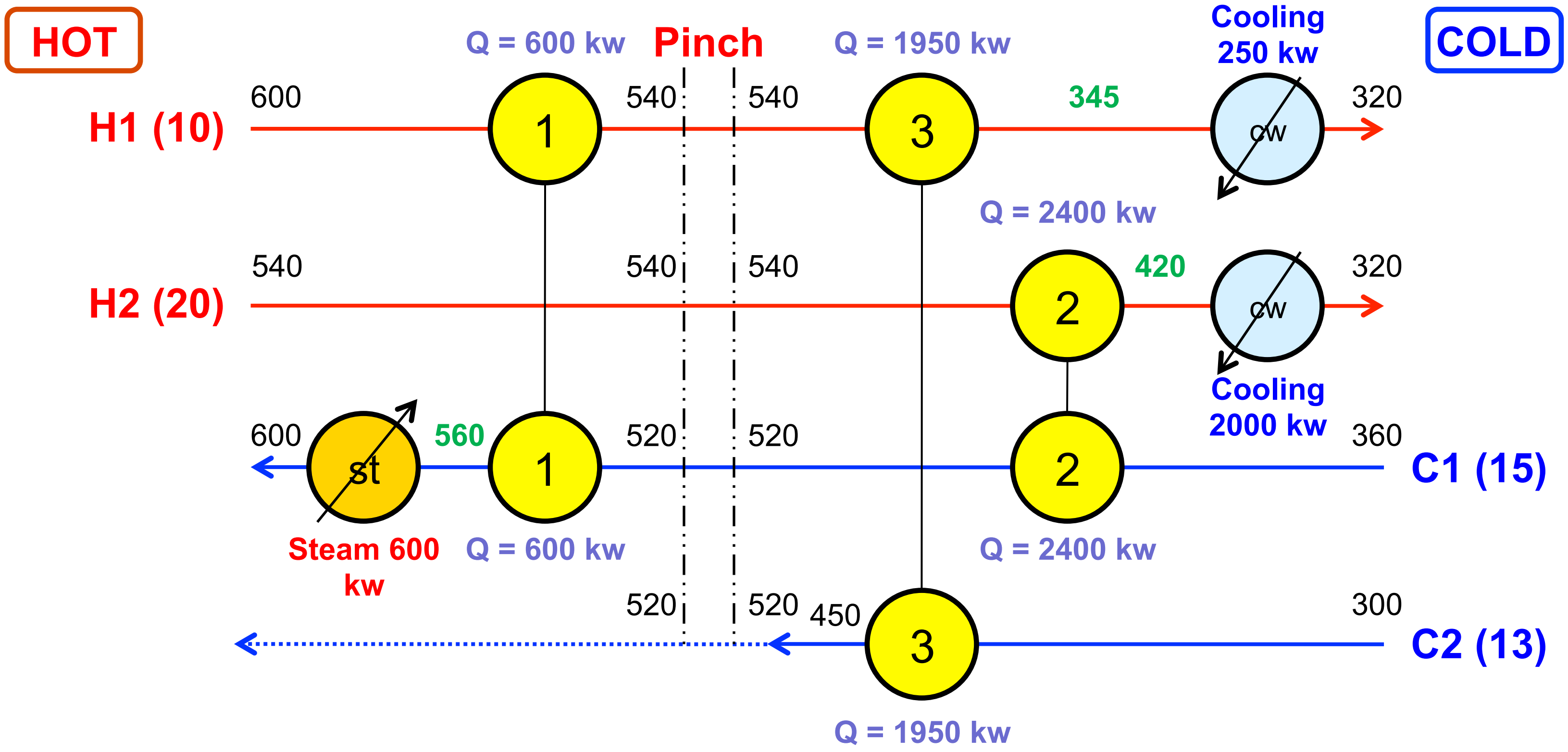
3.- HENS: Minimum Number of Units. Stream matching at the pinch

Representation of the HEN, with stream, f, T, pinch, units (exchangers and utilities), heat interchanged, Matches.

1. Diagram.
2. Matches 1, 2, 3.
3. Utilities.
4. T and Kw.

	f (KW/K)	Tin (K)	Tout (K)
H1	10	600	320
H2	20	540	320
C1	15	360	600
C2	13	300	450

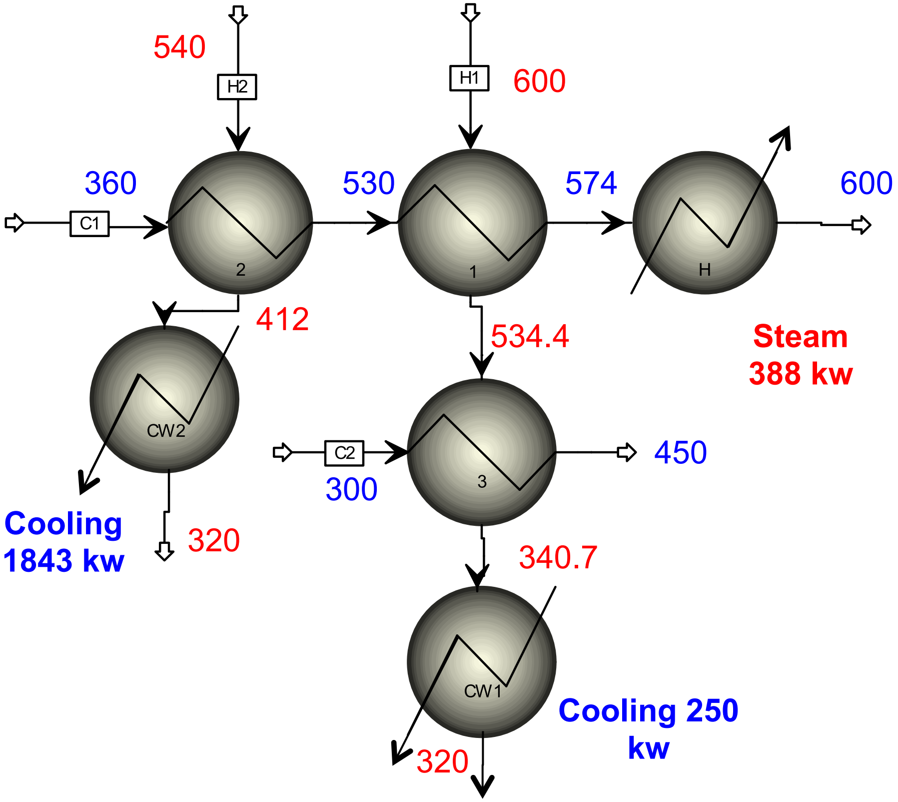




3.- HENS: Minimum Number of Units. Stream matching at the pinch

Optimum Network Structure.

The same structure as the previous one



Consider

$U_{exchangers}$ = 0.8 kw/m^2K

$U_{heaters}$ = 1.2 kw/m^2K

Total Area = 238 m^2

Investment Cost = 72,960 €/yr

Cost Exchangers = 1,500 $A^{0.6}$ €/y

Exchanger Cost = 87,237 €/y

Utility Cost = 97,515 €/y

TOTAL (optimization): 184,750 €/y vs. TOTAL (Pinch) 204,210 €/y

Same Structure of units but different temperatures.

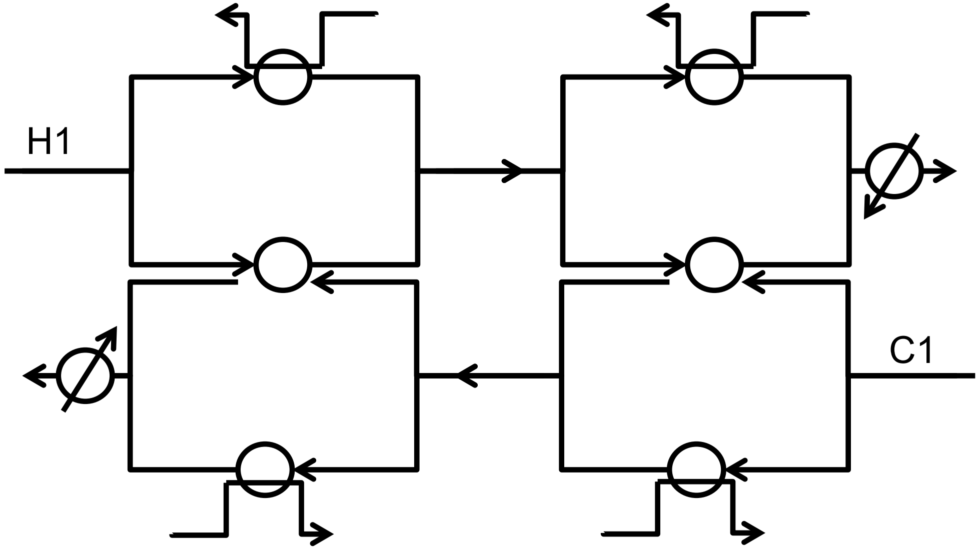
3.- Automatic Synthesis at HENS: Mathematical Optimization Models for HEN (Papoulias and Grossmann, 1983 b,c)

- **Objective:**

Simultaneous Optimization at: Heat Recovery + Selection of matches to minimize Total Annual Costs → Investment Costs Exchangers + Utility Costs.

- **Procedure:**

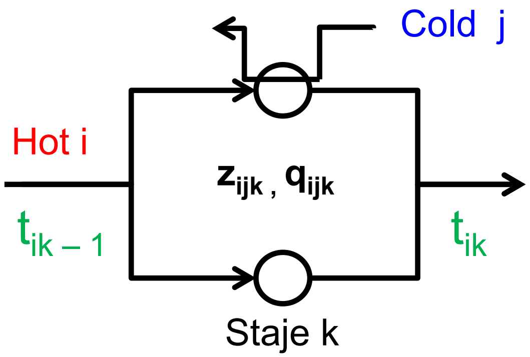
1. Postulate Staged Superstructure at alternative configurations.
2. Model as a Mixed-Integer NonLinear Program (MINLP).
3. Determine solution by solving the MINLP problem.



Each exchanger may be selected or not (0 – 1).

Specific configurations are obtained by finding values at 0 – 1 variables, plus heat loads and temperatures.

3.- Mathematical Optimization Models for HEN: MINLP model



z_{ijk}: 1 selected; 0 not selected.

q_{ijk}: Heat load.

t_{ik}: T stage k.

min Z = Fixed Cost exchangers + Cost areas + Cost utilities

s.t. heat balances for energy stream, each stage monotonic decrease T (left → right).

Logic constraints:

a) If $z_{ijk} = 0 \rightarrow q_{ijk} = 0$ linear ineq. $Q_{ijk} \leq \Omega\, z_{ijk}$, $q_{ijk} \geq 0$

b) If $z_{ijk} = 1 \rightarrow$ positive driving force $t_{ik} - t_{jk} \geq \Delta T_{min} - M\,(1 - z_{ijk})$

Note:

1. **Need to specify number of stages (e.g. n° stages = max {°n hot, n° cold}).**
2. **Nonconvex MINLP → can be trapped in local solutions. To avoid bad solutions can add constraint → Heating utility ≤ $Q_{target,\ HRAT}$; $Q_{target,\ HRAT}$ from LP transshipment model.**

Model implemented in PC based software (SYNHEAT):

- **Automatically interfaces with GAMS.**
- **Includes LP transshipment.**

4.- Optimum "Minimum Recovery Approach Temperature-HRAT" or "Approach Temperature – ΔTmin" *(Mínima diferencia de temperatura permitida)*

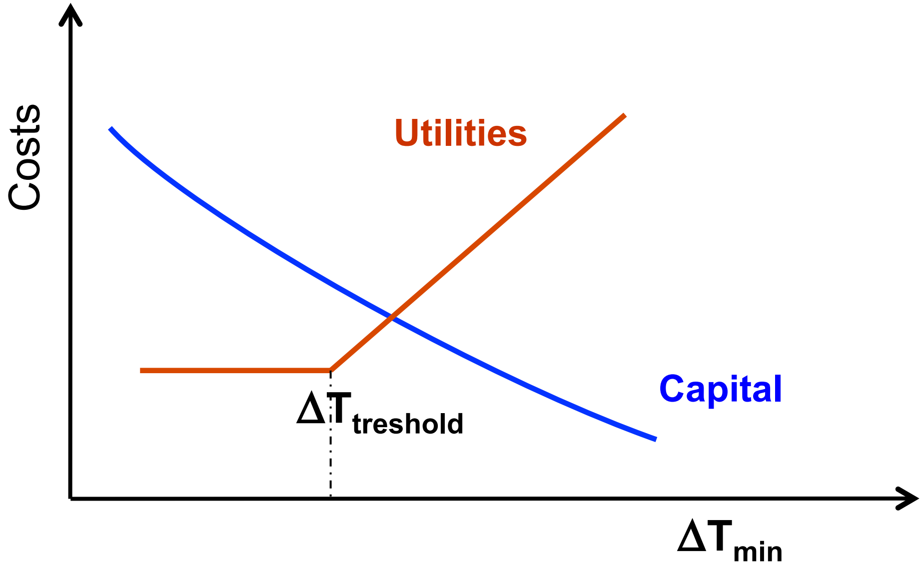
ΔT_{min} → 0 A → ∞

Utility requirements → Absolute minimum.

ΔT_{min} → ∞ A → 0

Utility requirements → Maximum (not heat exchange between process stream).

$\Delta T_{treshold}$ Critical ΔT_{min} below which no pinch exists (Threshold Approach T Difference).



Designing HEN → Consider effect of ΔT_{min}

5.- Heat integration

Flows and temperatures in a process can be adjusted to improve heat recovery.

5.1. Readjusting pressures and temperatures:

- **5.1.1. Distillation columns (highly energy-intensive).**
- **5.1.2. Multiple-effect distillation.**

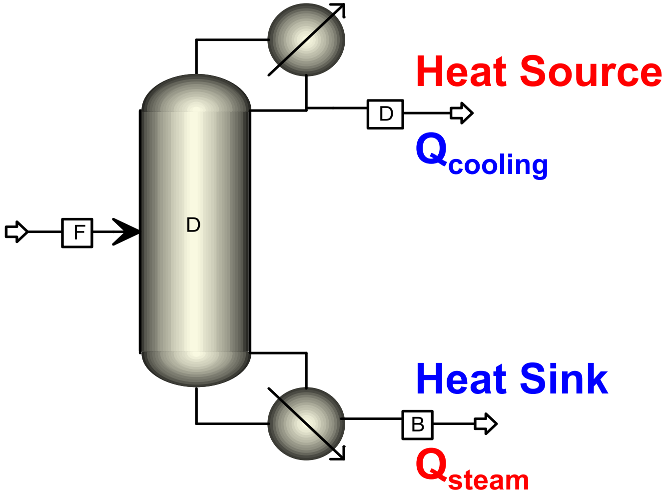
5.2. Readjusting flows:

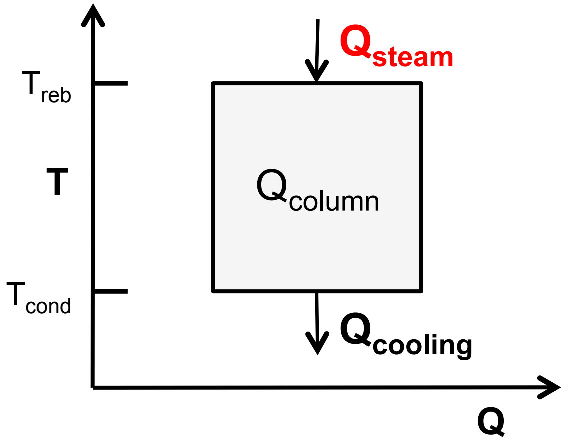
- **5.2.1 Recycles .**

5.1.1.- Readjustment P´s in distillation columns:

Assume heat load similar in Condenser and in reboiler → $Q_{cooling} \approx Q_{steam}$

(reasonable approximation if saturated liquids and $T_{cond} < T_F < T_{reb}$)





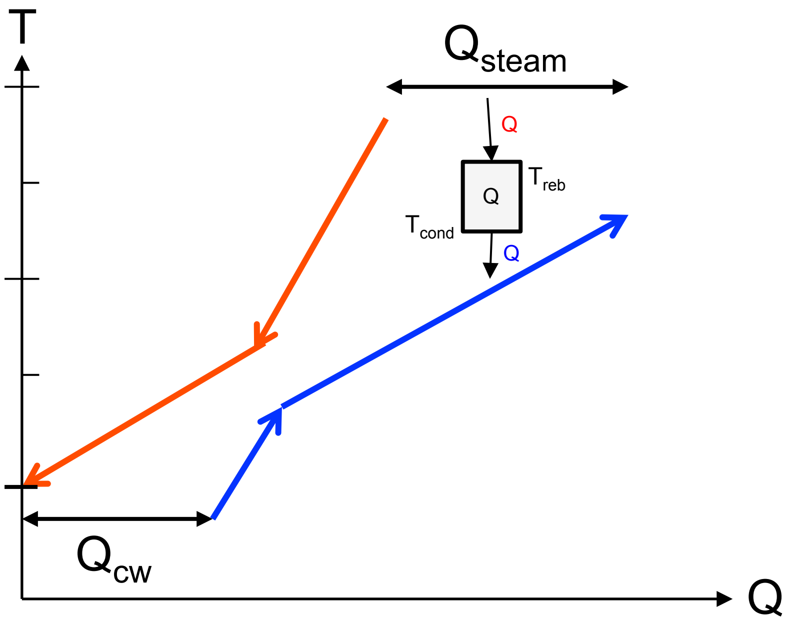
5.1. Readjustment P´s in distillation columns

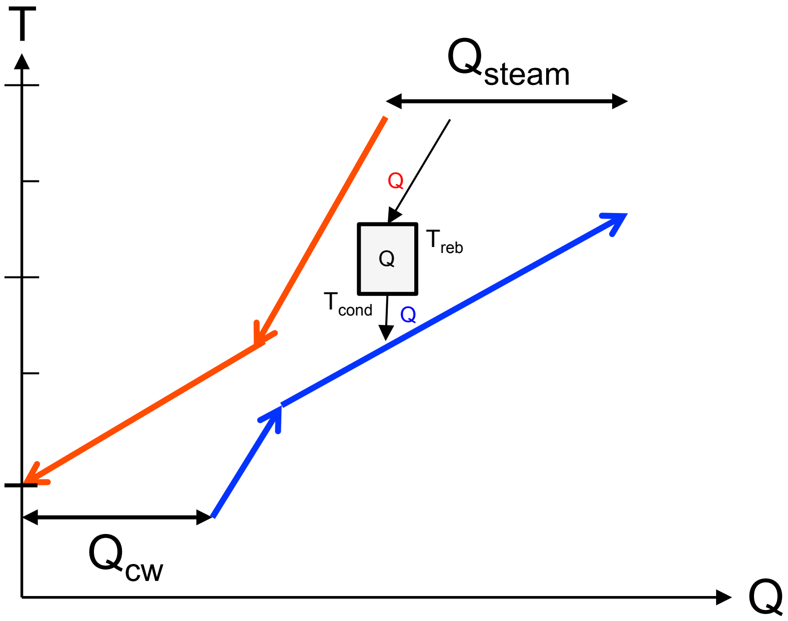
The heat duty Q ≈ $Q_{cooling}$ ≈ Q_{steam} is related directly to the reflux ratio. When Q is reduced (high cost of fuel) the N° trays increases →

→ Tradeoffs {Operating costs *vs.* Capital Costs}.

Heat integration:

a) Adjustment of the P level of the column to position its T-Q rectangle to lie below the hot composite and above the cold composite curves.

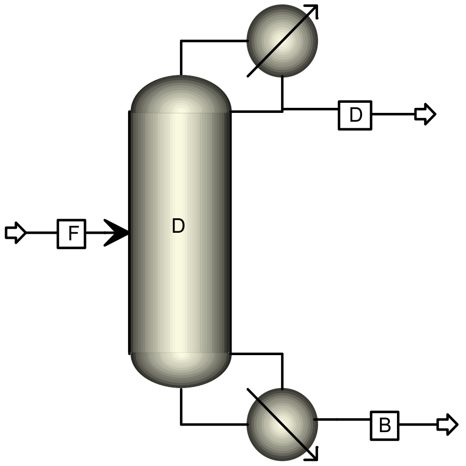


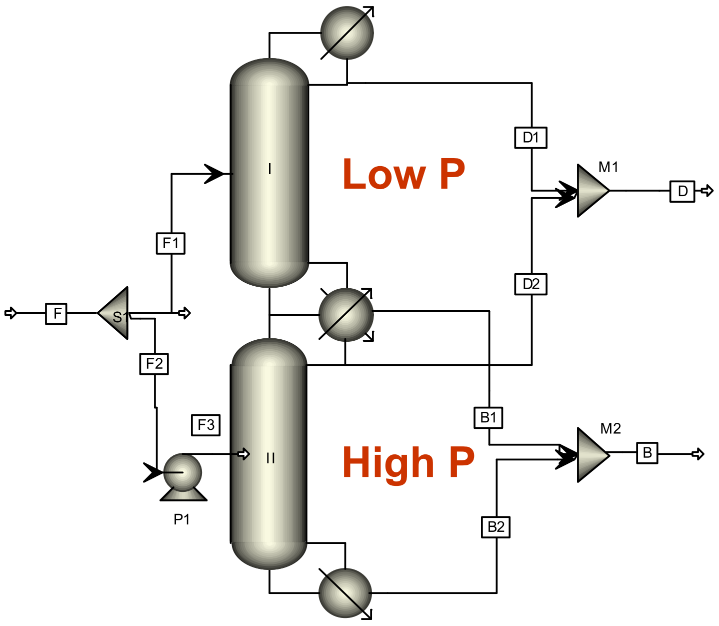


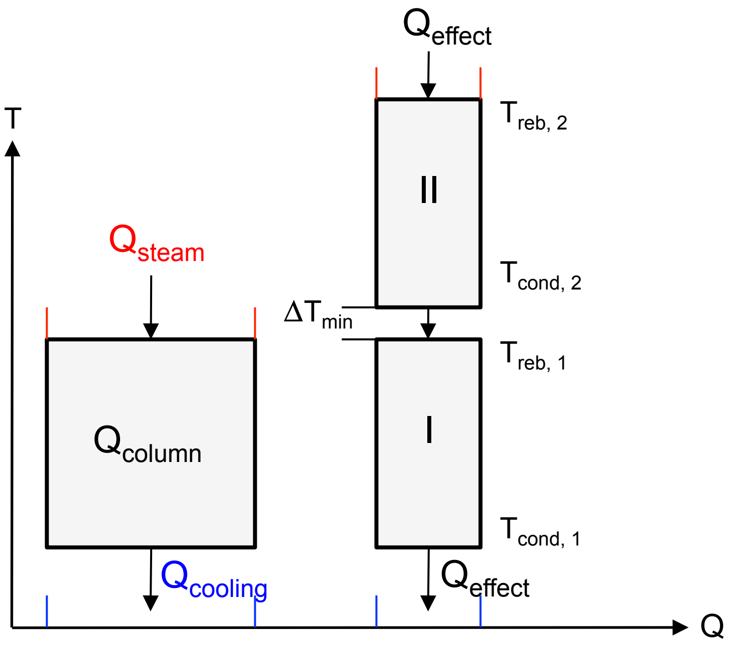
b) The P of the column is adjusted and the column positioned so that the reboiler receives its energy from a hot utility and the condenser rejects its energy to the cold process streams above the pinch.

5.1.2. Multiple-effect distillation

Separations where T – Q rectangle cannot be positioned under hot composite curves and above cold composite curves → Multiple effect distillation.







50% reduction in steam but higher investment + higher grade steam

P ↑ in (Neff – 1) columns ←→ steam cost ↓ (Qeff ≈ Q/Neff)

↑ € pumping.
↑ € equipment (thickness).
↑ € α↓→ n° trays↑ → H↑ ***vs.*** **↓ € steam.**
↑ € higher grade steam.
↑ € high investment.

5.2. Readjusting flows

5.2.1.- Recycles:

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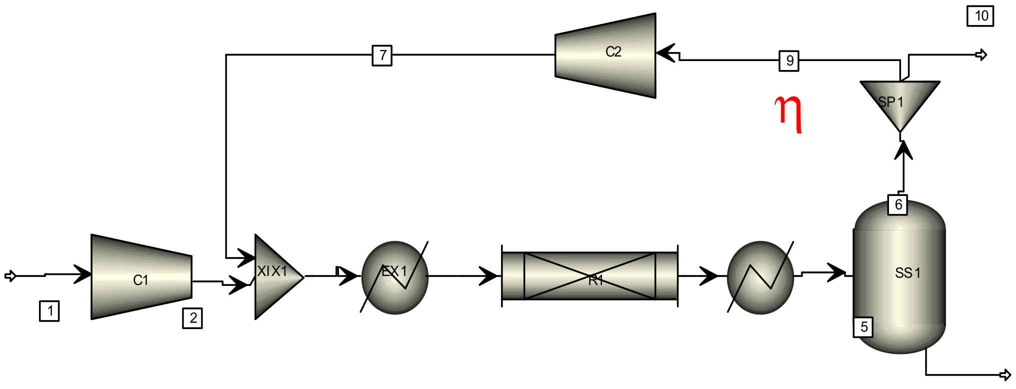

1. **With heat integration → curve shifted to right to higher η → higher overall conversion.**
2. **Trade-off: Energy Cost *vs.* raw material Cost.**

Procedure:

1. **Fix η.**
2. **Calculate mass + heat balance.**
3. **Determine minimum utility cost.**
4. **Total Cost = Raw material + Compression + minimum utility cost.**
5. **Repeat for different values at η to select minimum cost solution.**

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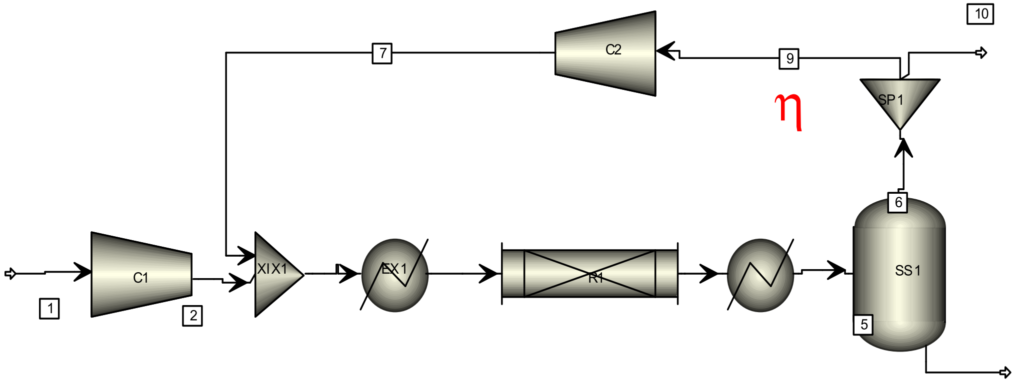

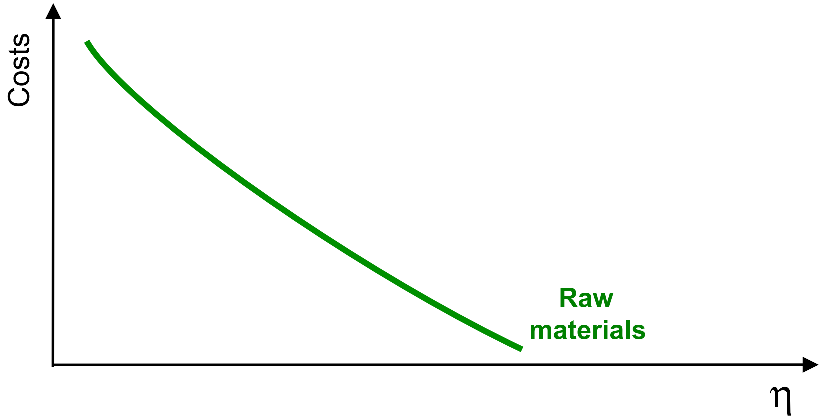

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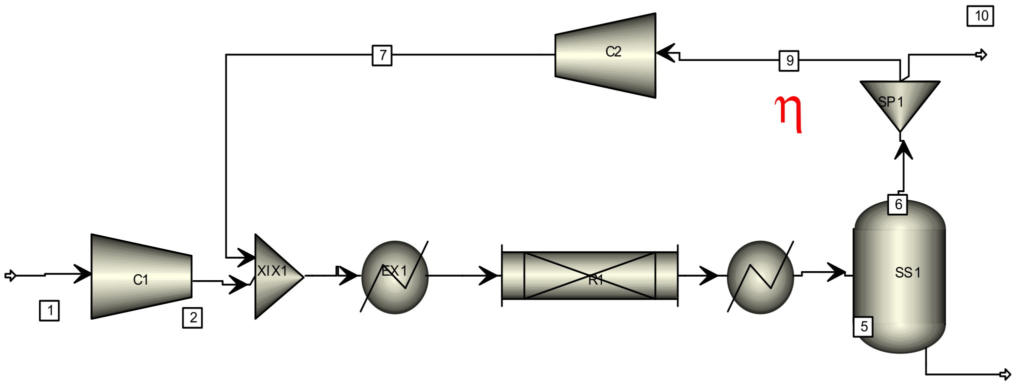

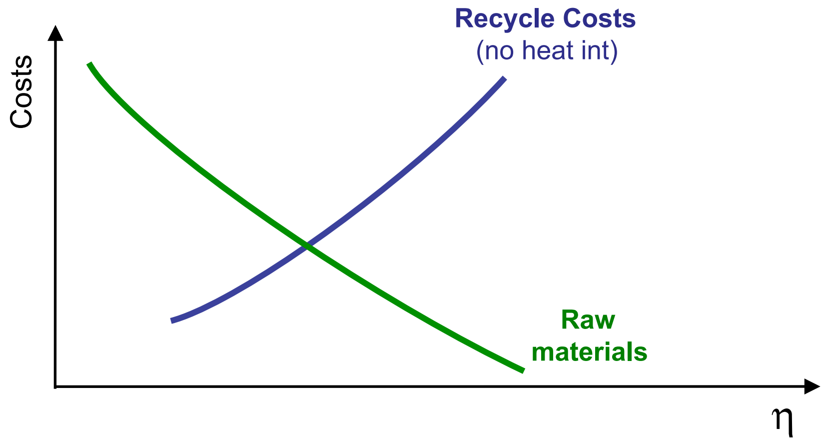

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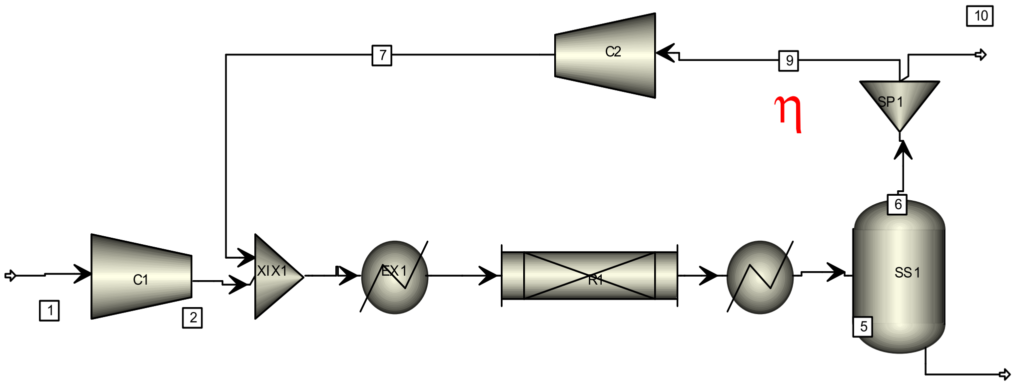

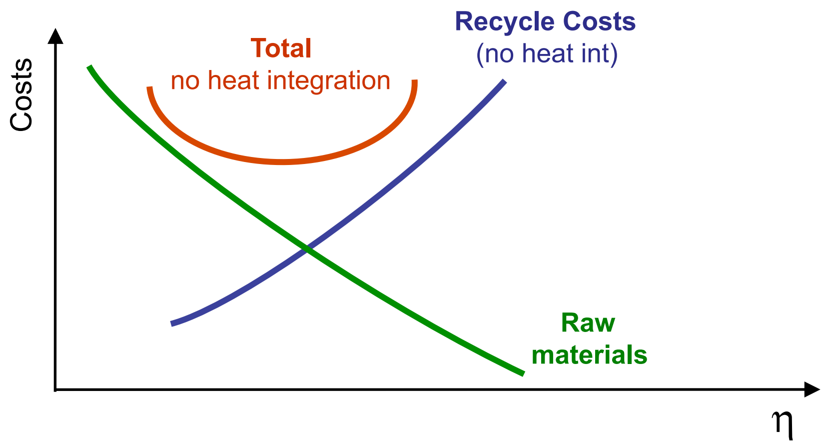

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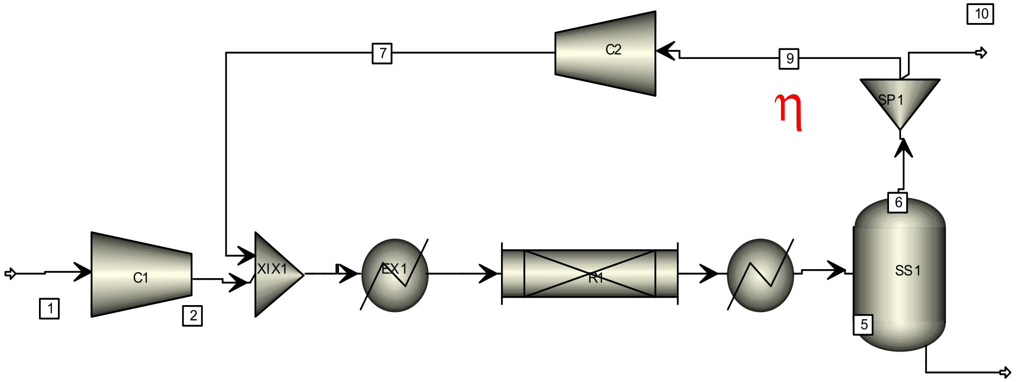

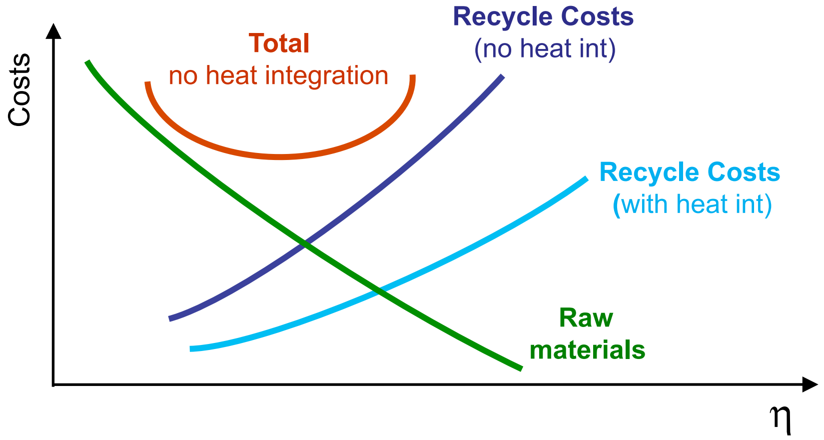

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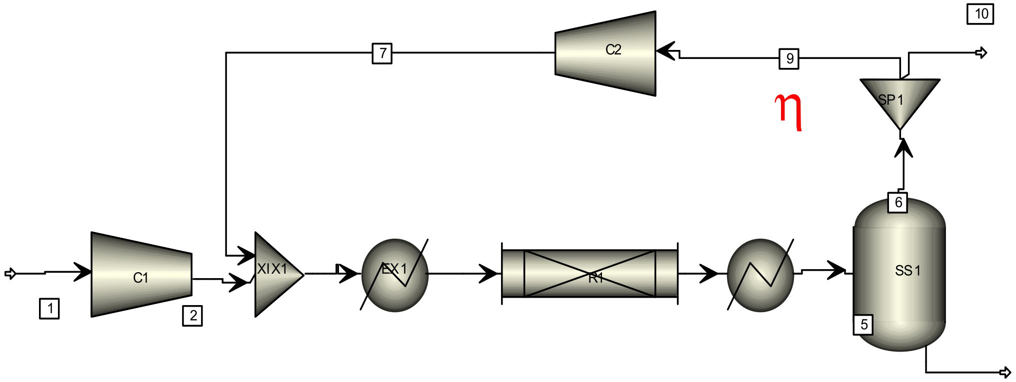

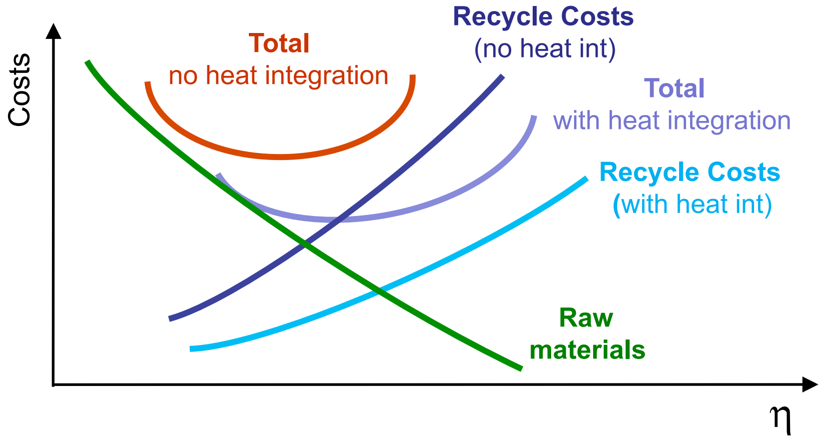

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6.- Further Reading and References

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PRACTICAL CHAPTER

- **Examples of HEN: Composite curve, Cascade of temperatures.**

RELEVANT TO LEARNING (I)

- **Where are the sources and sinks of heat in a chemical process?**
- **Heat Exchange Network (HEN):**
  - **What is the Cost?**
  - **Alternatives to doing HEN synthesis.**
  - **Algorithm to obtain a network.**
- **Obtain the PINCH and Min. Heating and Cooling needs by means of:**
  - **Composite curves.** ***Dada una representación T vs. H indicar toda la información que se puede extraer respecto del diseño de una red de intercambio de calor.***
  - **Feasible cascade.**
- **To draw a grid diagram of a HEN.**
- **Meaning of ΔT_{min}**
- **How to do heat integration in distillation columns.**

RELEVANT TO LEARNING (II)

- **Given a set of hot and cold streams, assume that the result obtained from a heat exchange network, working at 10 K HRAT, is a prediction of minimum services of 1800 kW of heating and of 2400 kW of cooling. Assume that HRAT is changed to a value of 20 K and then 2200 kW of heating and 2600 kW of cooling are predicted. Determine whether or not these results make sense and why.**

- ***Dado un conjunto de corrientes calientes y frías, suponer que se obtiene como resultados de una red de intercambio de calor, trabajando a HRAT de 10 K, una predicción de unos mínimos servicios de 1800 kW de calentamiento y de 2400 kW de enfriamiento. Suponer que se cambia HRAT a un valor de 20 K y entonces se predice 2200 kW de calentamiento y 2600 kW de enfriamiento. Determinar si estos resultados tienen sentido o no.***

RELEVANT TO LEARNING (II)

- **In a heat exchange network there may be more than two pinch points. Explain this briefly.**
- ***¿En una red de Intercambio de calor pueden existir más de dos puntos pinch?. Explicarlo brevemente*.**

- **A two-stage strategy for designing and optimizing a heat exchange network is better than a single-stage global optimization strategy. Discuss.**
- ***Una estrategia de diseño y optimización de una red de intercambio de calor en dos etapas es mejor que una estrategia de optimización global en una sola etapa.***