Heat Exchanger Networks

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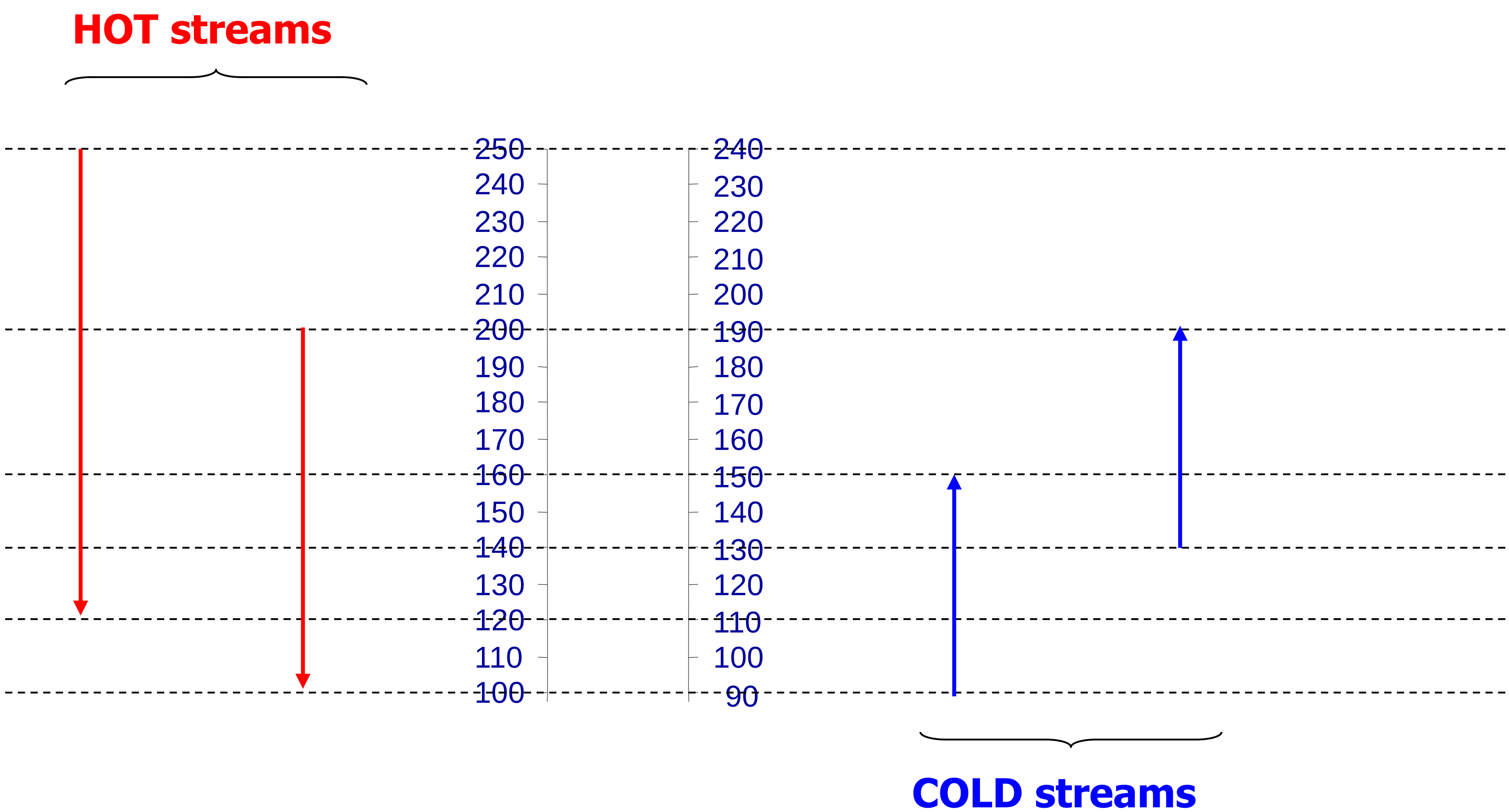
Lesson 3 of "Process Systems Engineering" – Master Degree in Chemical Engineering – Politecnico di Milano

Heat Exchanger Networks

Stream	Physical cond.	F Cp [kcal/h °C]	Tin	Tout	Available Q 1.E3 kcal/h
1	Hot	1,000	250	120	130
2	Hot	4,000	200	100	400
3	Cold	3,000	90	150	-180
4	Cold	6,000	130	190	-360
				TOTAL	**-10**

$$Q_i = F_i \cdot C_{p,i} \cdot (T_{in} - T_{out}) \qquad i = 1, \dots N_{\text{streams}}$$



Hohmann (1971)

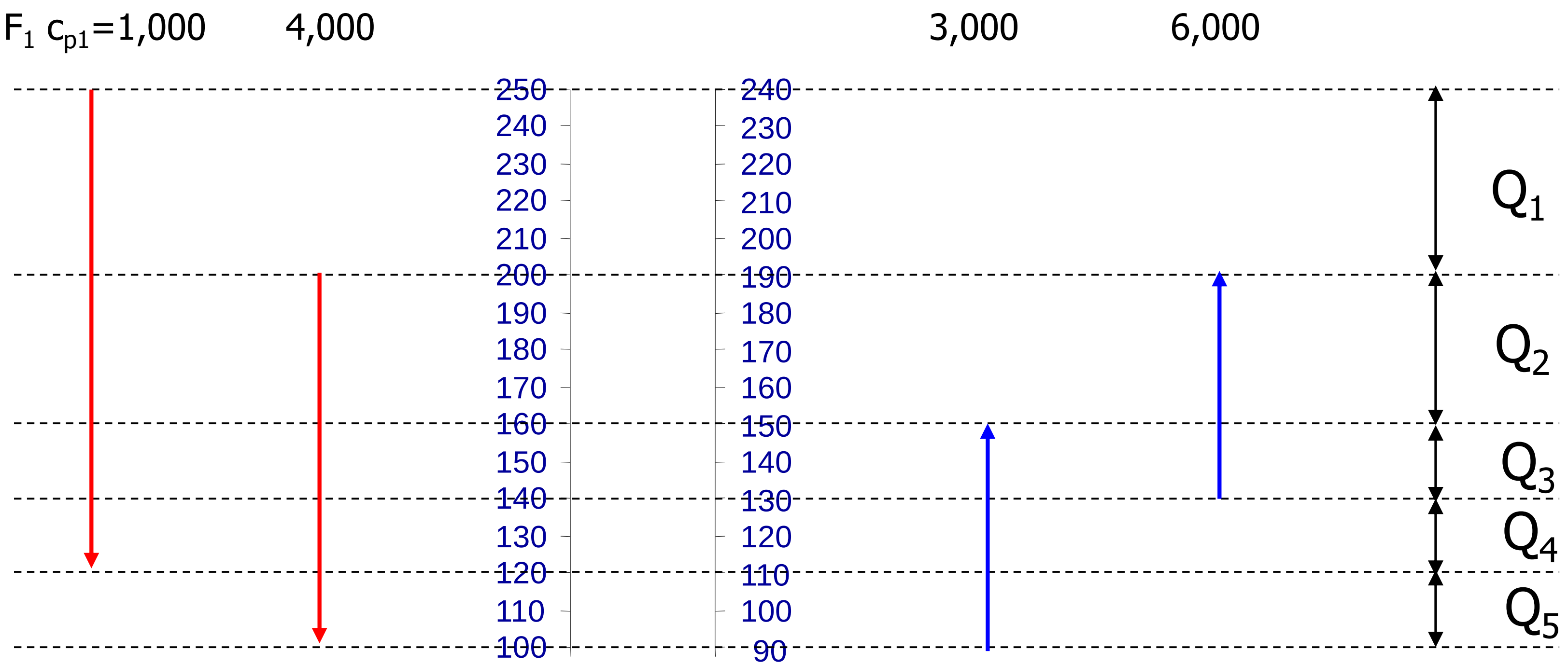
Umeda, Itoh and Shiroko (1978)

Linnhoff and Flower (1978)

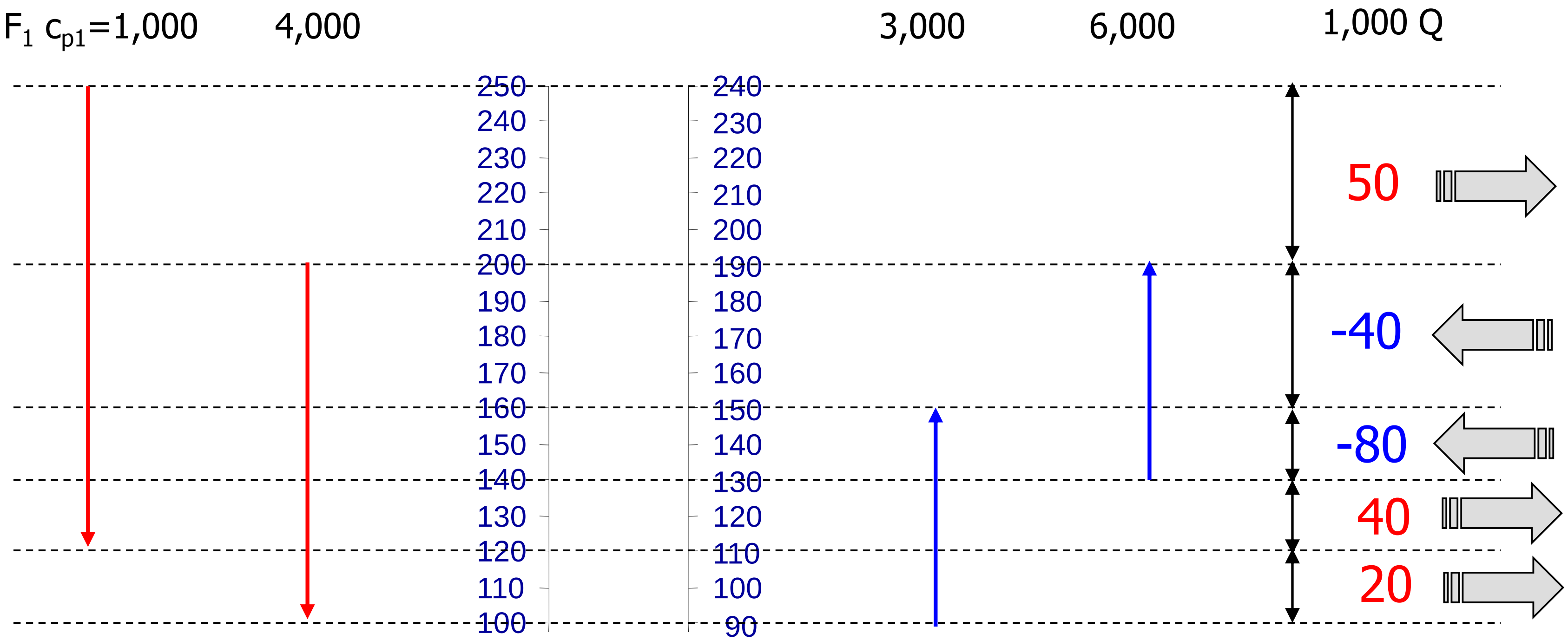
Linnhoff and Hindmarsh (1983)

Townsend and Linnhoff (1983)

Linnhoff, Dunford and Smith (1985)

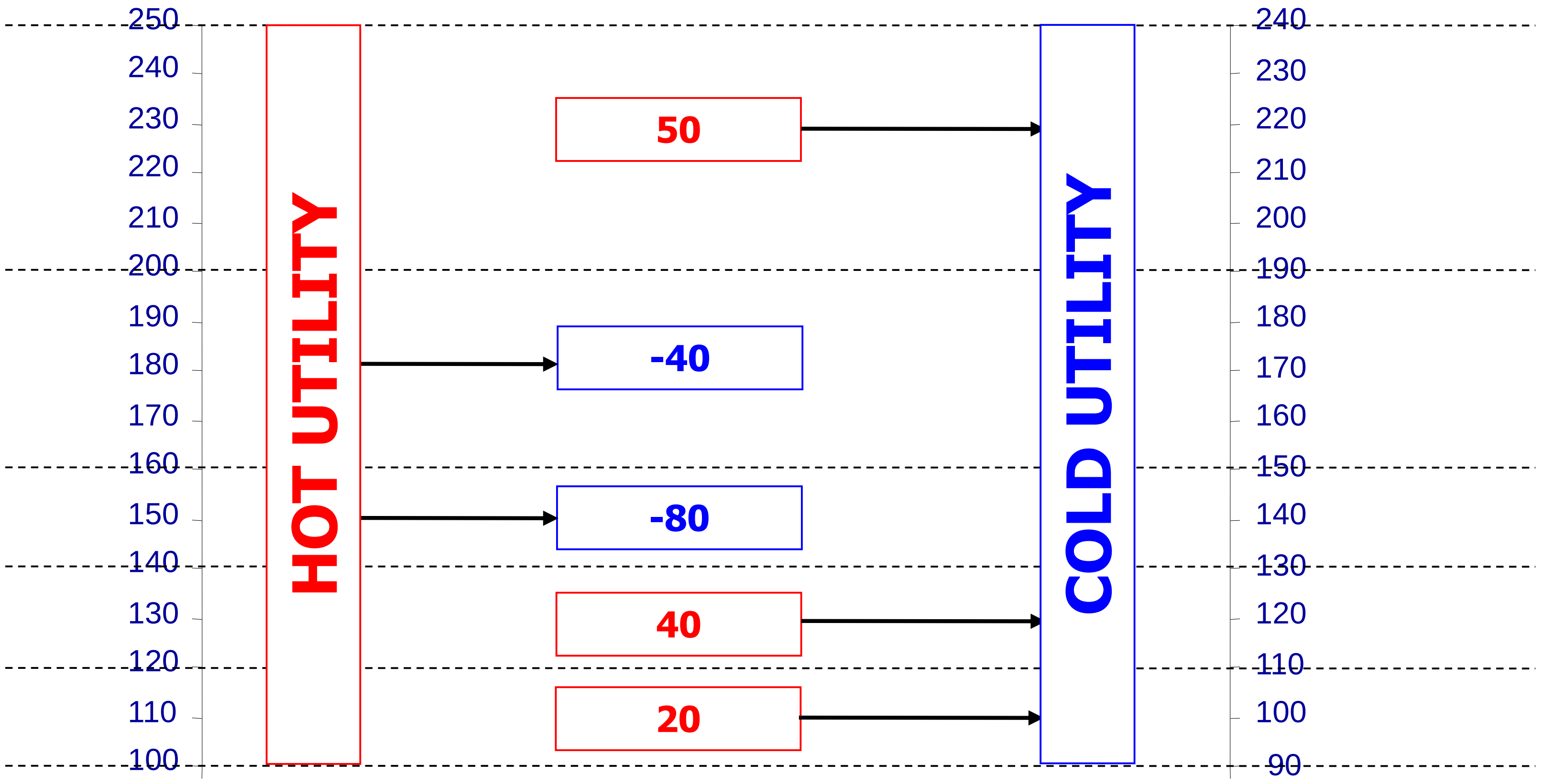


$$Q_i = \left[\sum_i \left(F \cdot C_p \right)_{HOT,i} - \sum_i \left(F \cdot C_p \right)_{COLD,i} \right] \cdot \Delta T_i \qquad i = 1, \ldots N_{\text{intervals}}$$



F1 cp1=1,000
4,000
3,000
6,000
1,000 Q
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
50
-40
-80
40
20

TOTAL = -10


250
240
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190
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HOT UTILITY
50
-40
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40
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COLD UTILITY
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120
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100
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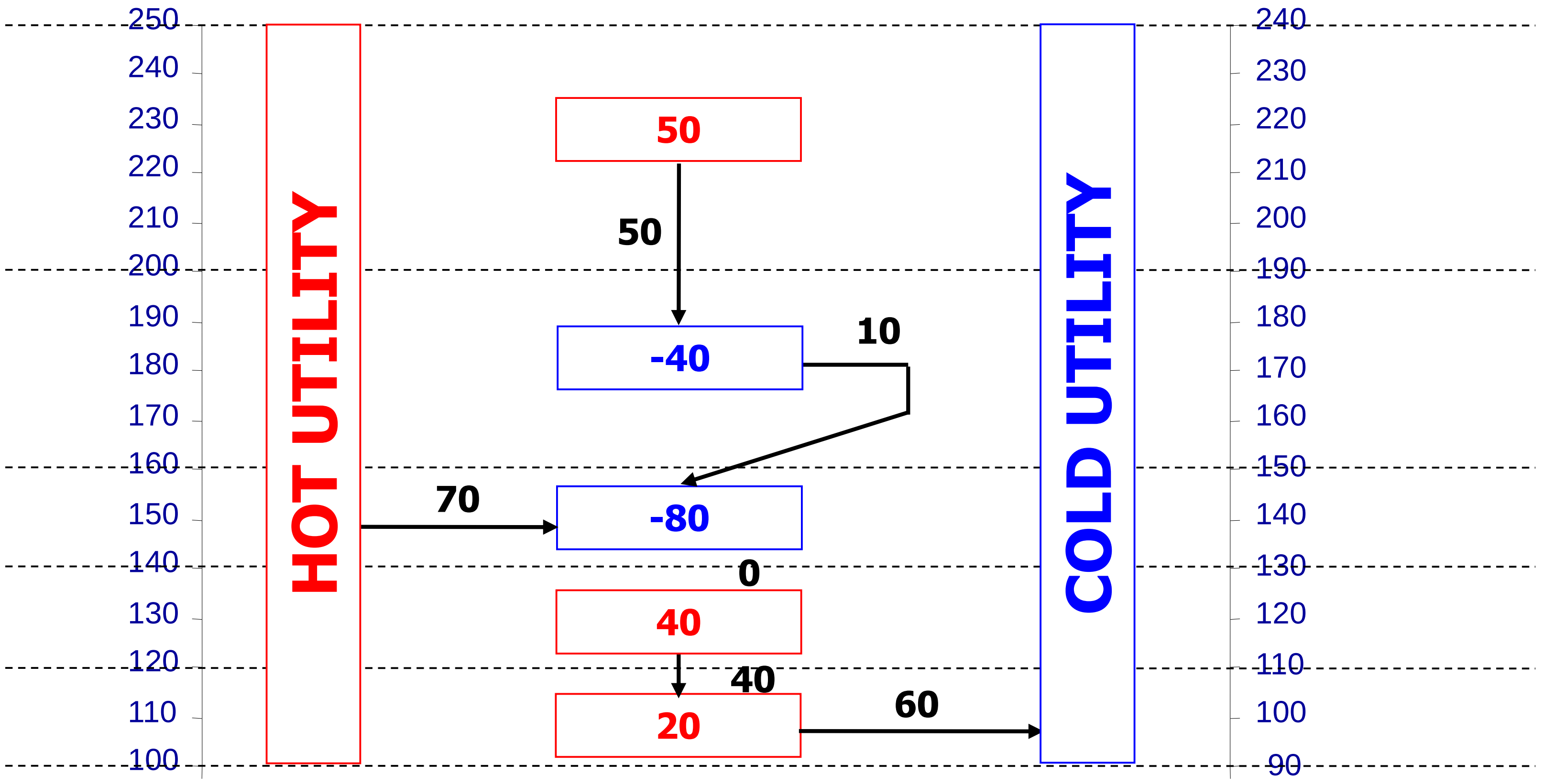
250
240
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130
120
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100
HOT UTILITY
50
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10
70
-80
0
40
40
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COLD UTILITY
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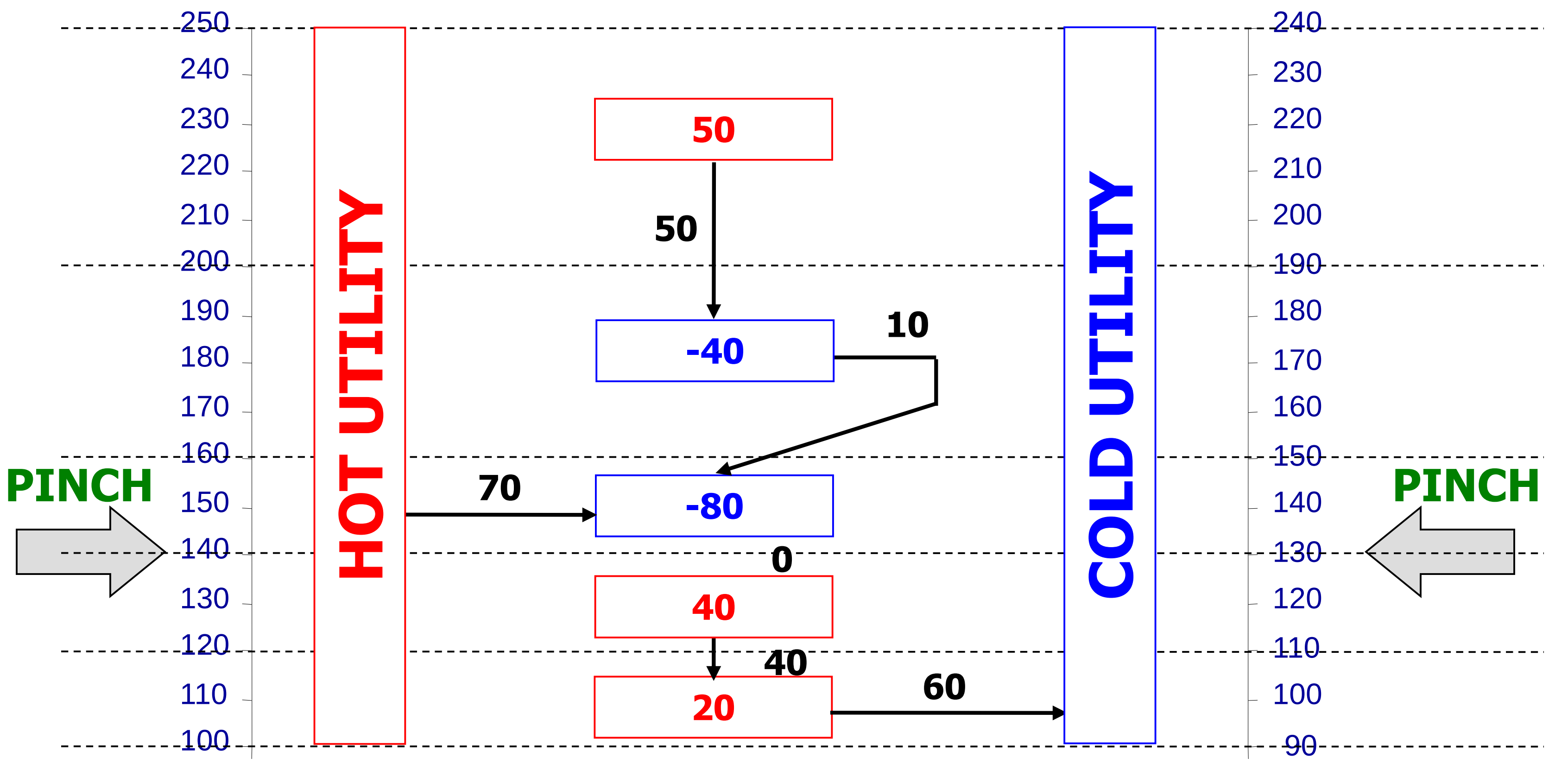
130
120
110
100
90


250
240
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210
200
190
180
170
160
150
140
130
120
110
100
HOT UTILITY
50
50
-40
10
PINCH
70
-80
0
40
40
20
60
COLD UTILITY
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
PINCH

Temperature-Enthalpy diagrams

We introduce the reference enthalpy (equal to 0) at the LOWEST temperature of the HOT streams.

HOT Streams

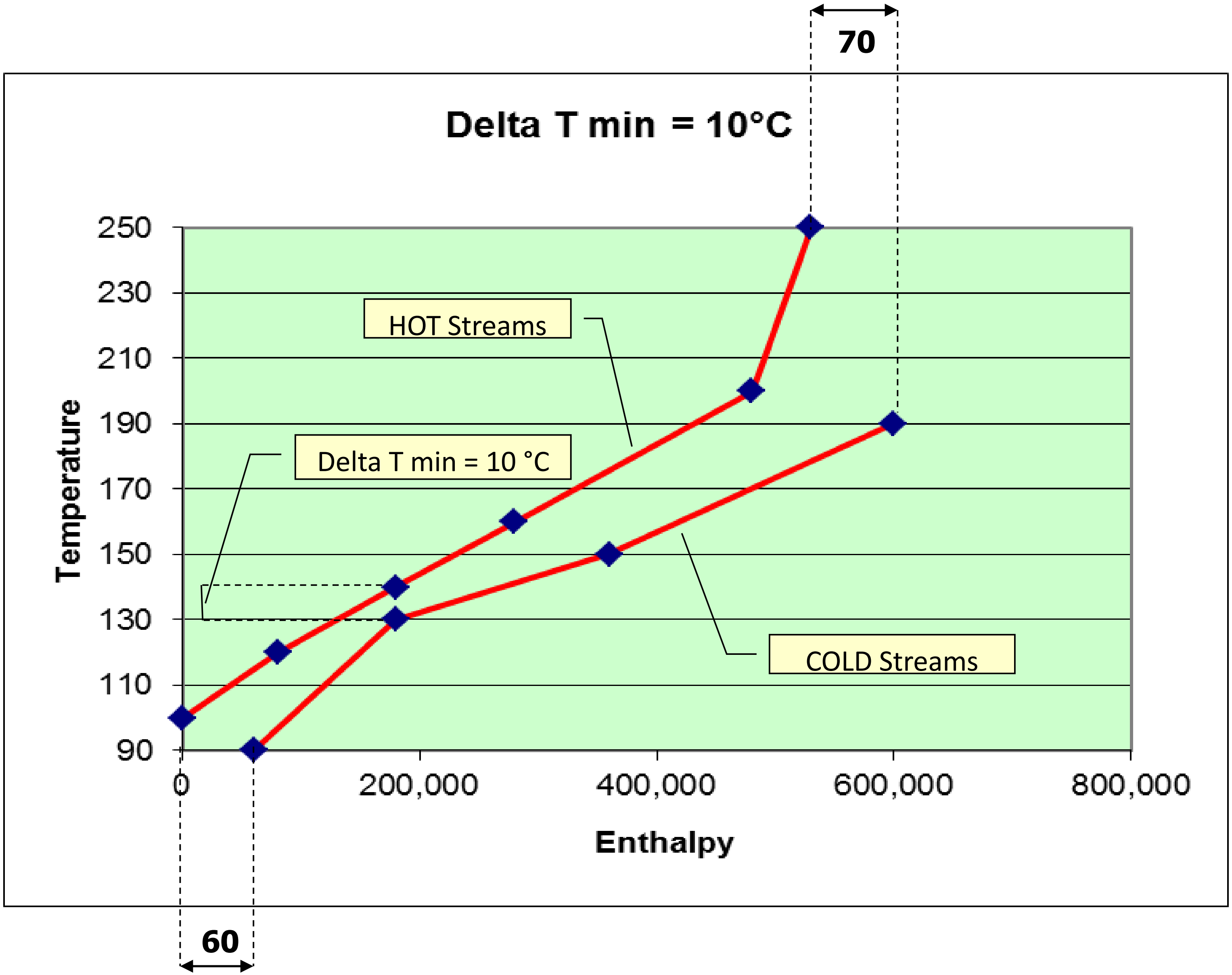
T	F Cp1	F Cp2	(F Cp)tot	H	H cumulative
100				**0**	0
120		4,000	4,000	80,000	80,000
140	1,000	4,000	5,000	100,000	180,000
160	1,000	4,000	5,000	100,000	280,000
200	1,000	4,000	5,000	200,000	480,000
250	1,000		1,000	50,000	530,000

Once the QcMIN is known (minimum heat to be subtracted by a utility) we fix it as the reference enthalpy for the COLD streams at their MINIMUM temperature.

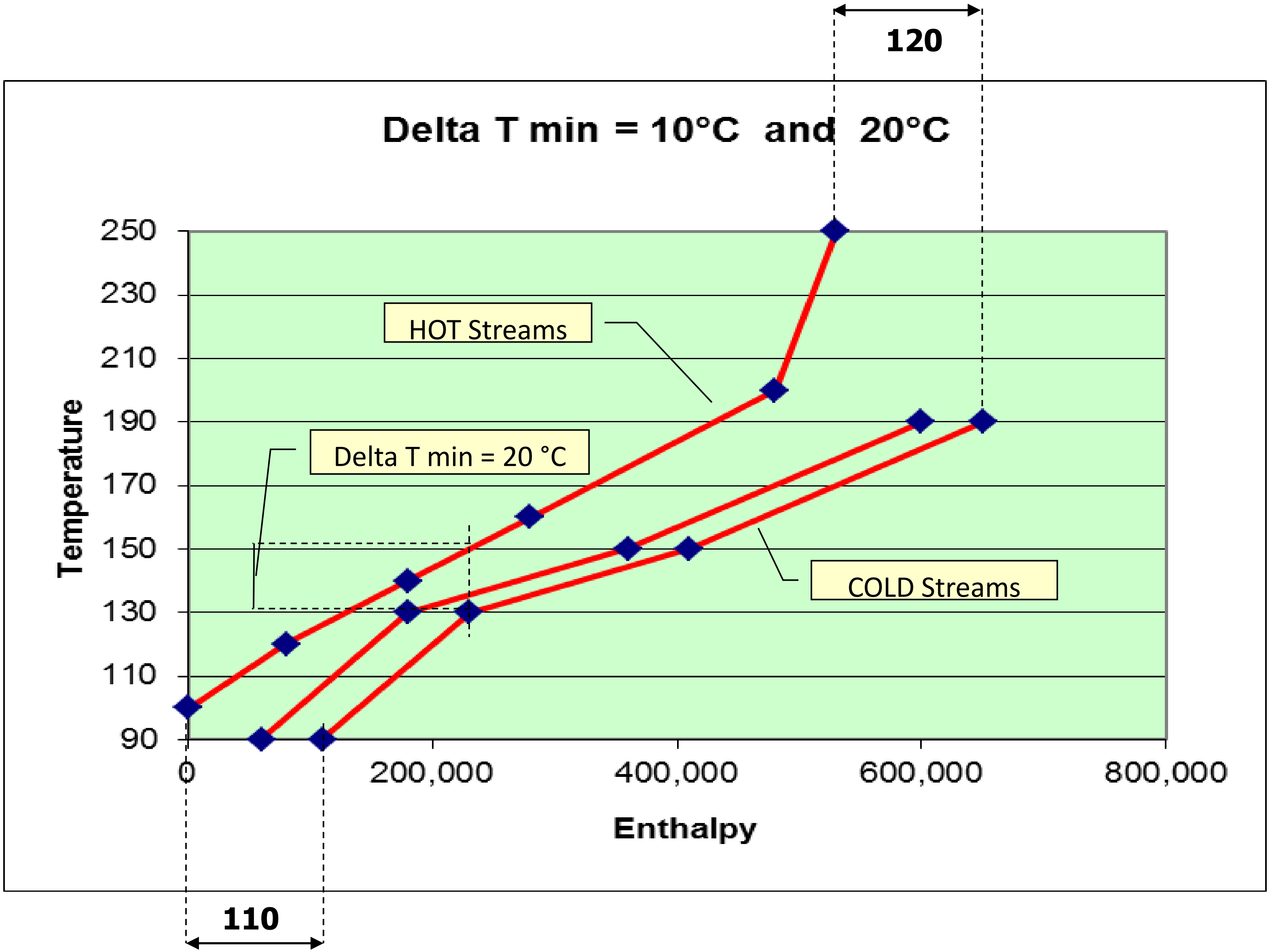
COLD Streams

T	F Cp3	F Cp4	(F Cp)tot	H	H cumulative
90				**60,000**	60,000
130	3,000		3,000	120,000	180,000
150	3,000	6,000	9,000	180,000	360,000
190		6,000	6,000	240,000	600,000

Temperature-Enthalpy diagrams



Temperature-Enthalpy diagrams



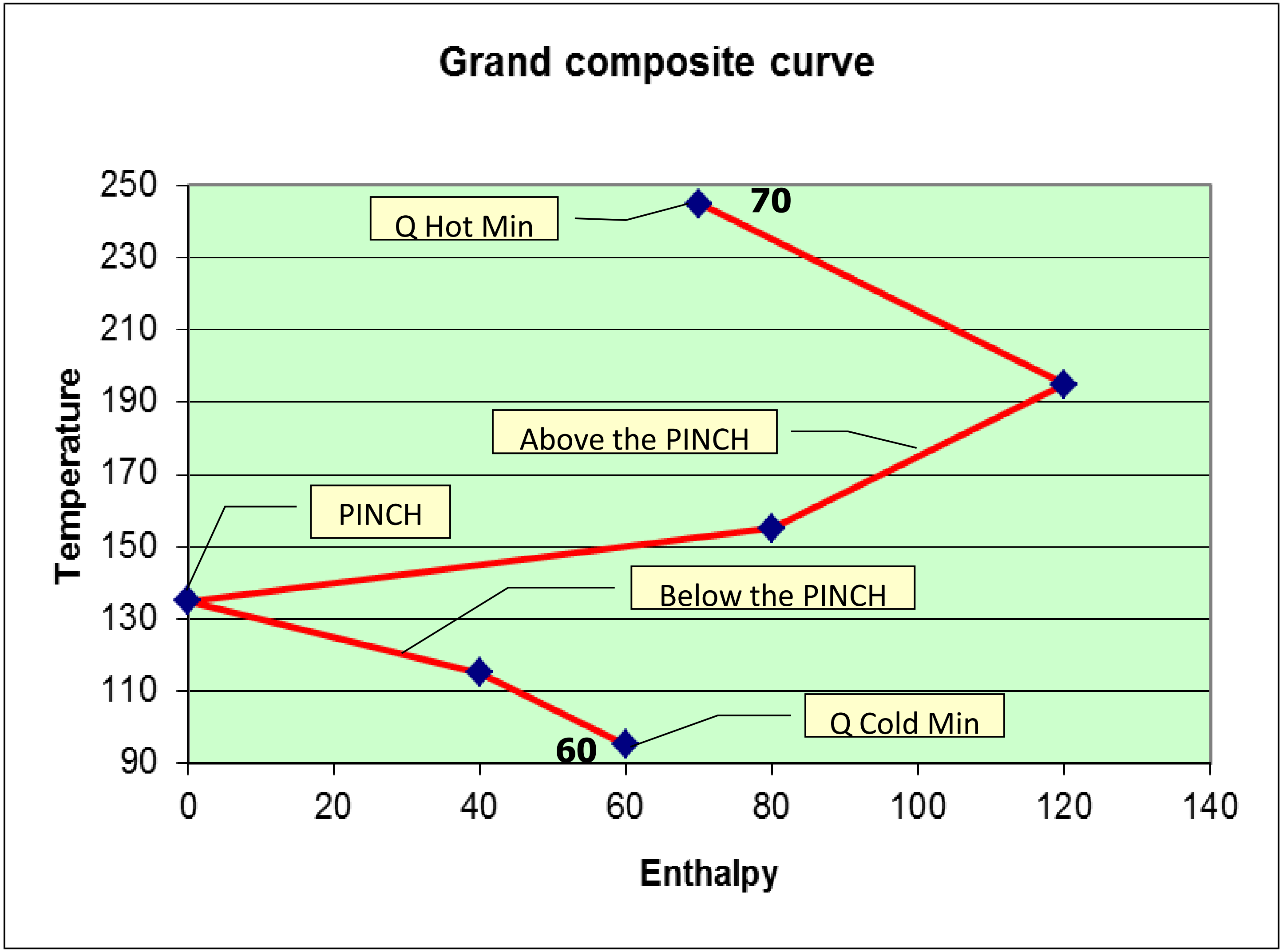
Grand composite curve

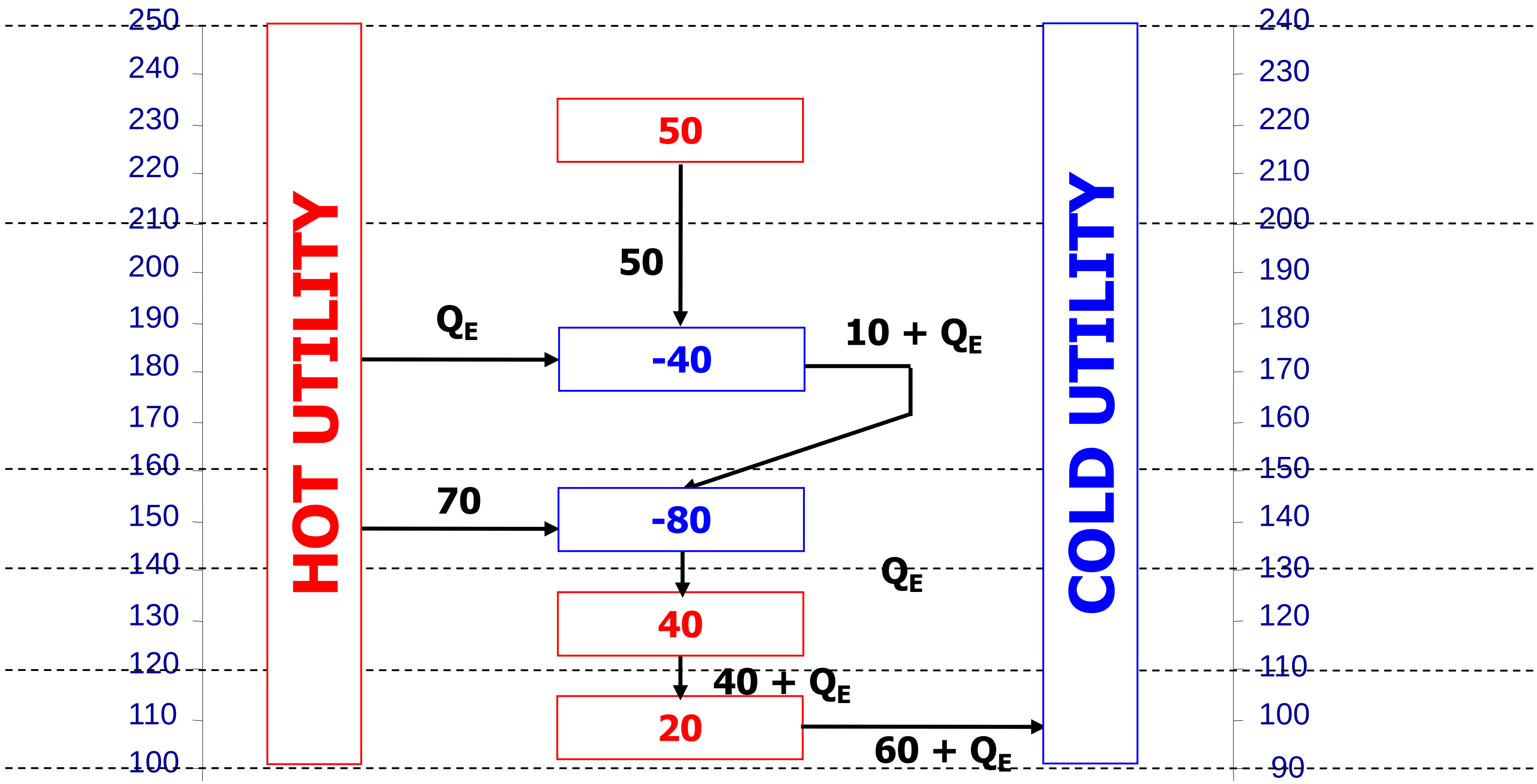
Cumulative values start symmetrically from the pinch condition

Data from the cascade diagram. Use the values of the enthalpies for the hot and cold streams.

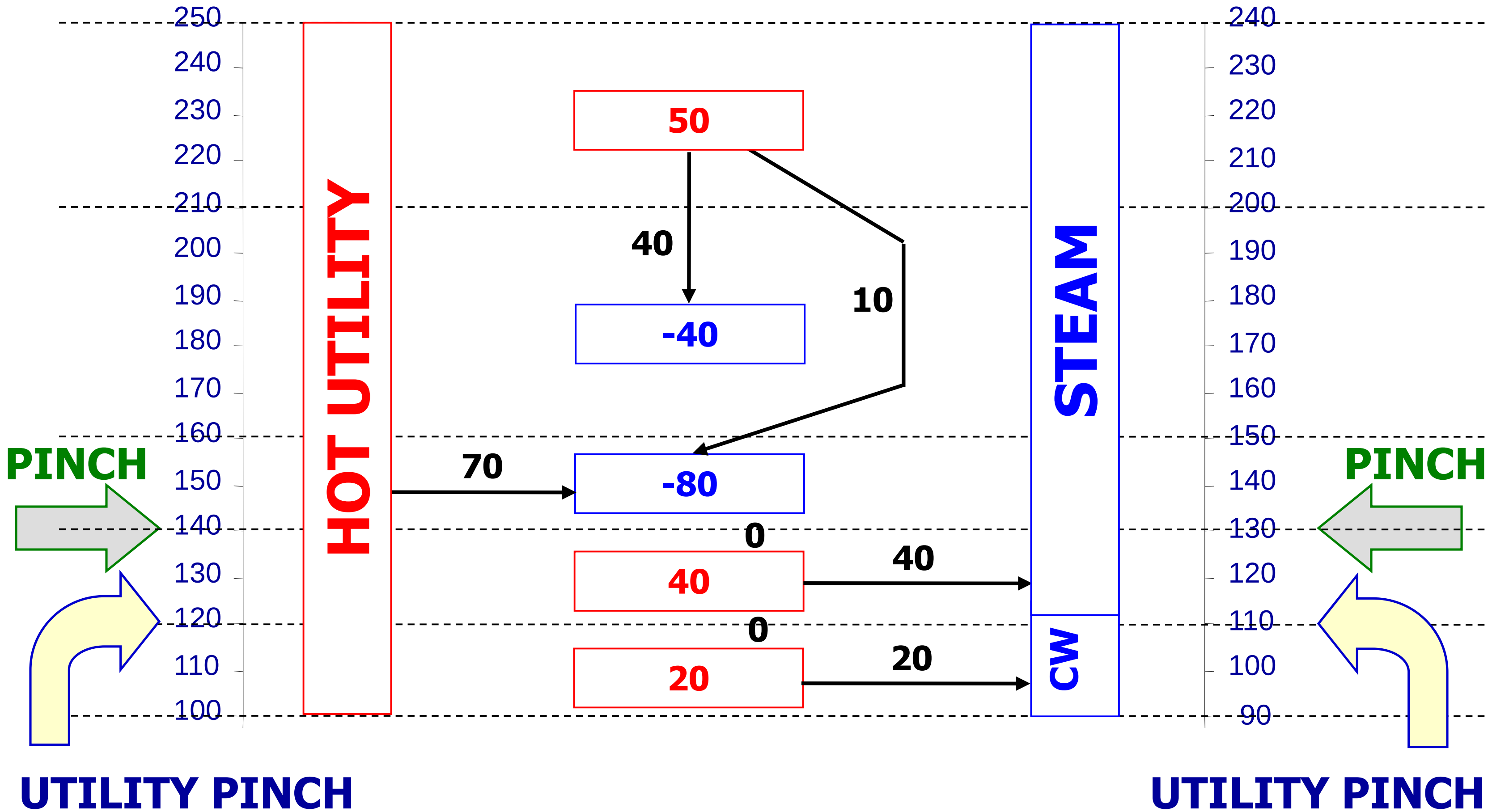
T Hot	T Cold	T Med	H	H cumulative
100	90	95	20	60
120	110	115	40	40
140	130	135	**0**	0
160	150	155	80	80
200	190	195	40	120
250	240	245	-50	70

Grand composite curve



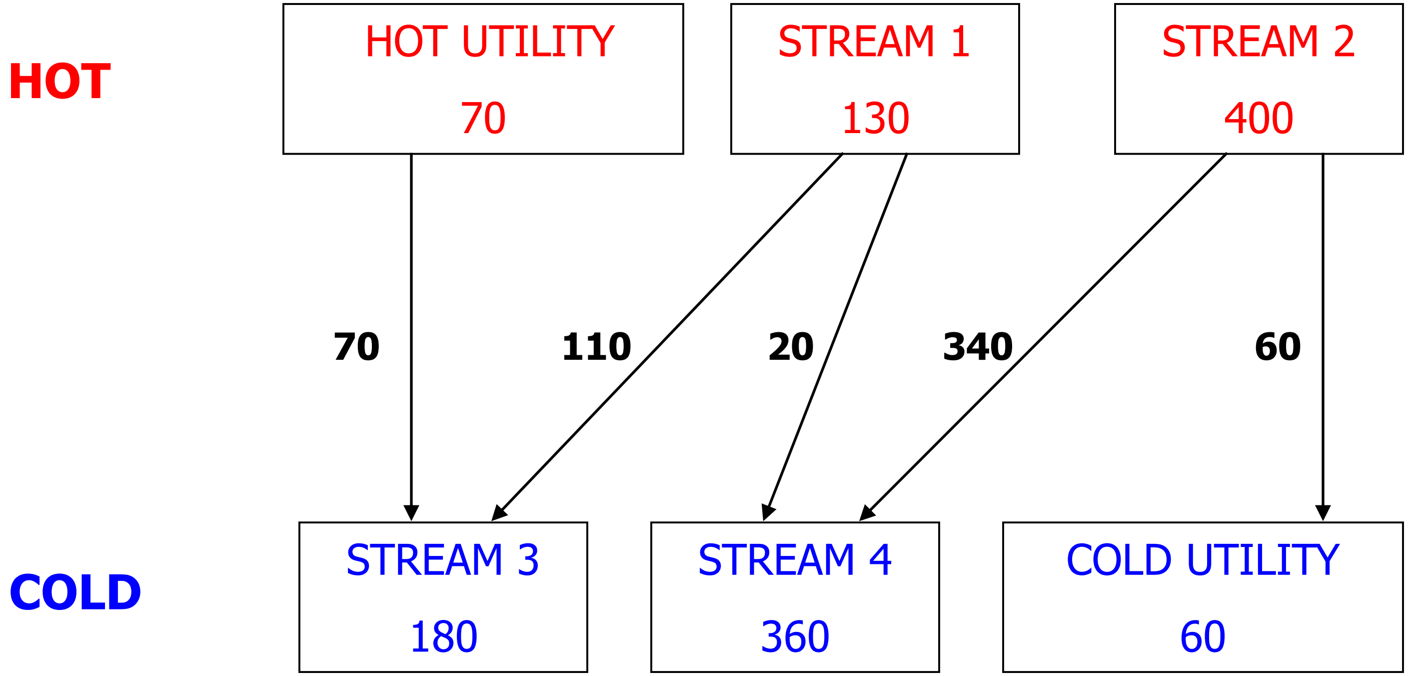


- DO NOT transfer heat across the PINCH
- Add heat only ABOVE the PINCH
- Remove heat only BELOW the PINCH



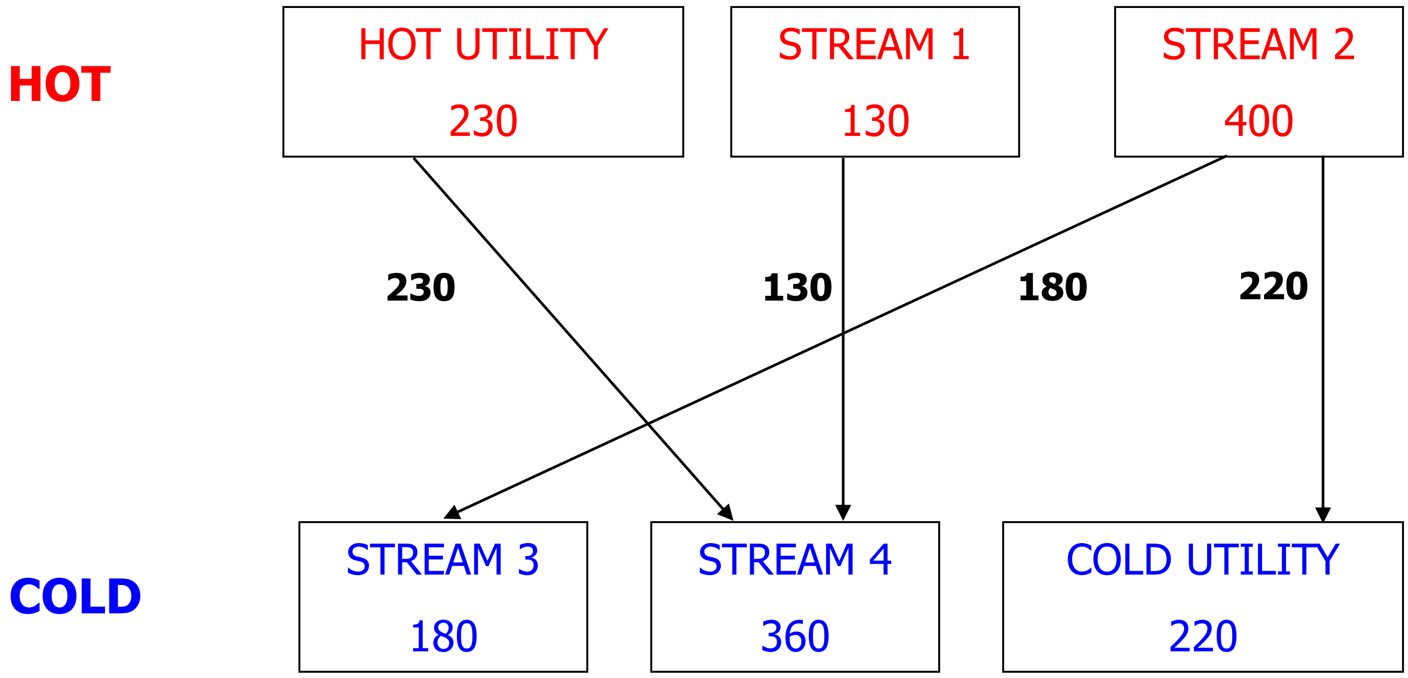
CW = **C**old **W**ater

- Always add heat at the lowest possible temperature level relative to the PINCH
- Always remove heat at the highest possible temperature level relative to the PINCH



Number of exchangers = (Number of streams) + (Number of utilities) – 1 = 4 + 2 – 1 = 5

N.B.: this equation is **not** always correct…

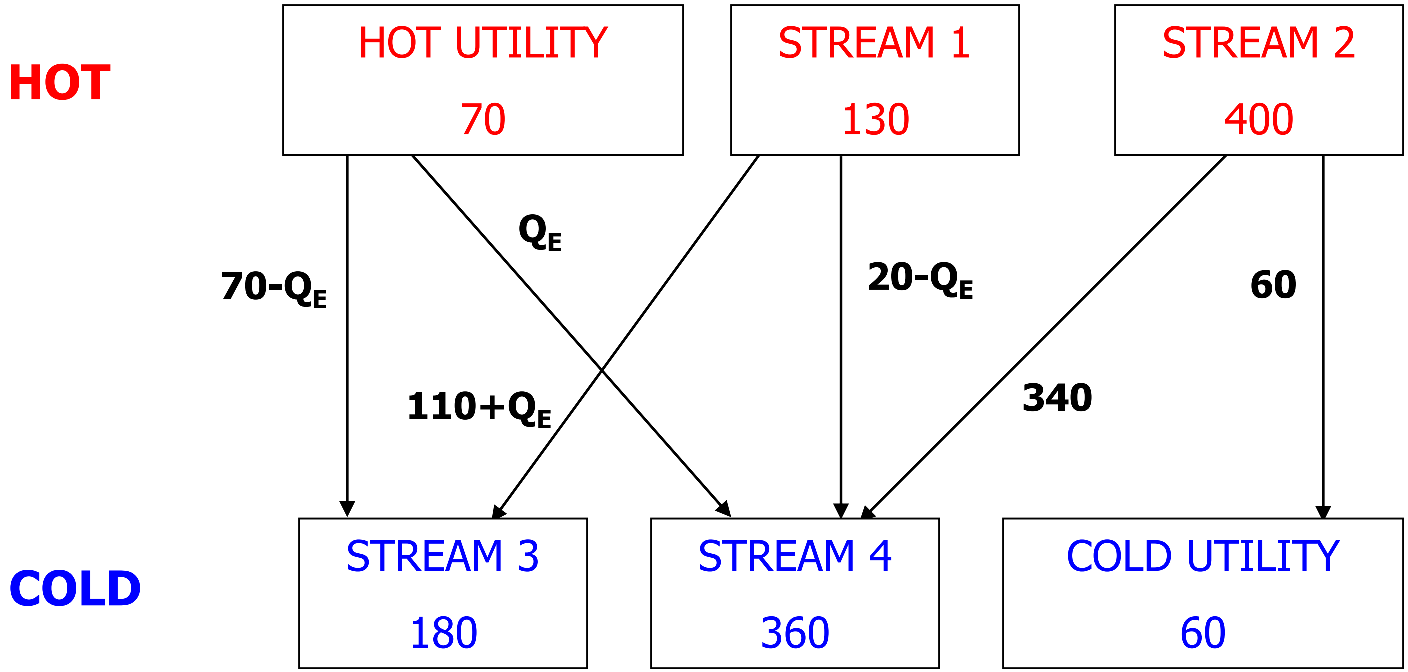


Number of exchangers = (N. streams) + (N. utilities) – (N. independent problems)

In this example, the independent problems are 2.

We have these groups: (2 + 3 + Cold Util.) and (Hot Util. + 1 + 4)

→ Number of exchangers = 4 + 2 – 2 = 4



N. exchangers = (N. streams) + (N. utilities) + (N. loops) – (N. independent problems)

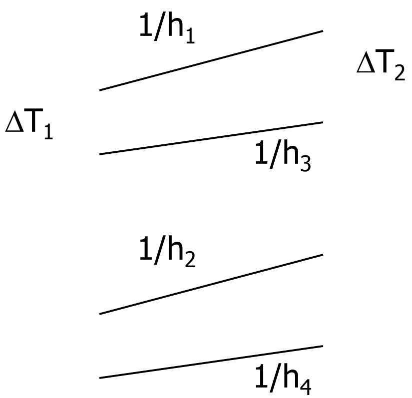
In this case there is only one independent problem (the whole problem).

We can see a loop: Hot Util. → 3 → 1 → 4 → Hot Util.

→ Number of exchangers = 4 + 2 + 1 – 1 = 6

Estimating areas

- Within each interval of the T-H diagram we consider the involved streams.
- An interval is identified by vertical lines in the T-H diagram where the stream lines are straight and characterized by a constant slope.
- In general: $1/U = 1/h_{hot} + 1/h_{cold} \rightarrow A = Q/(U\,\Delta T_{ML})$
- If there are multiple streams in any interval, we must consider the possible couplings.
- For instance, with two hot streams (1), (2) and two cold streams (3), (4) we have:

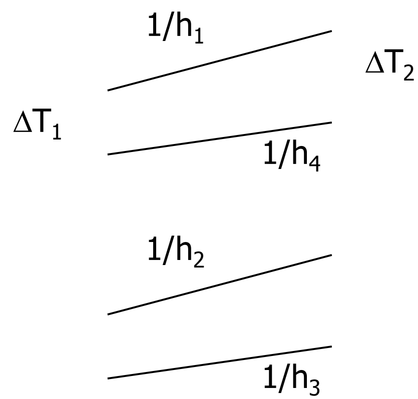


Case A

$$\frac{1}{U_{1A}} = \frac{1}{h_1} + \frac{1}{h_3} \quad \text{and} \quad \frac{1}{U_{2A}} = \frac{1}{h_2} + \frac{1}{h_4}$$

$$A_{TOTA} = A_{1A} + A_{2A} = \frac{Q}{\Delta T_{ML} U_{1A}} + \frac{Q}{\Delta T_{ML} U_{2A}}$$

$$\Rightarrow A_{TOTA} = \frac{Q}{\Delta T_{ML}}\left(\frac{1}{h_1} + \frac{1}{h_2} + \frac{1}{h_3} + \frac{1}{h_4}\right)$$



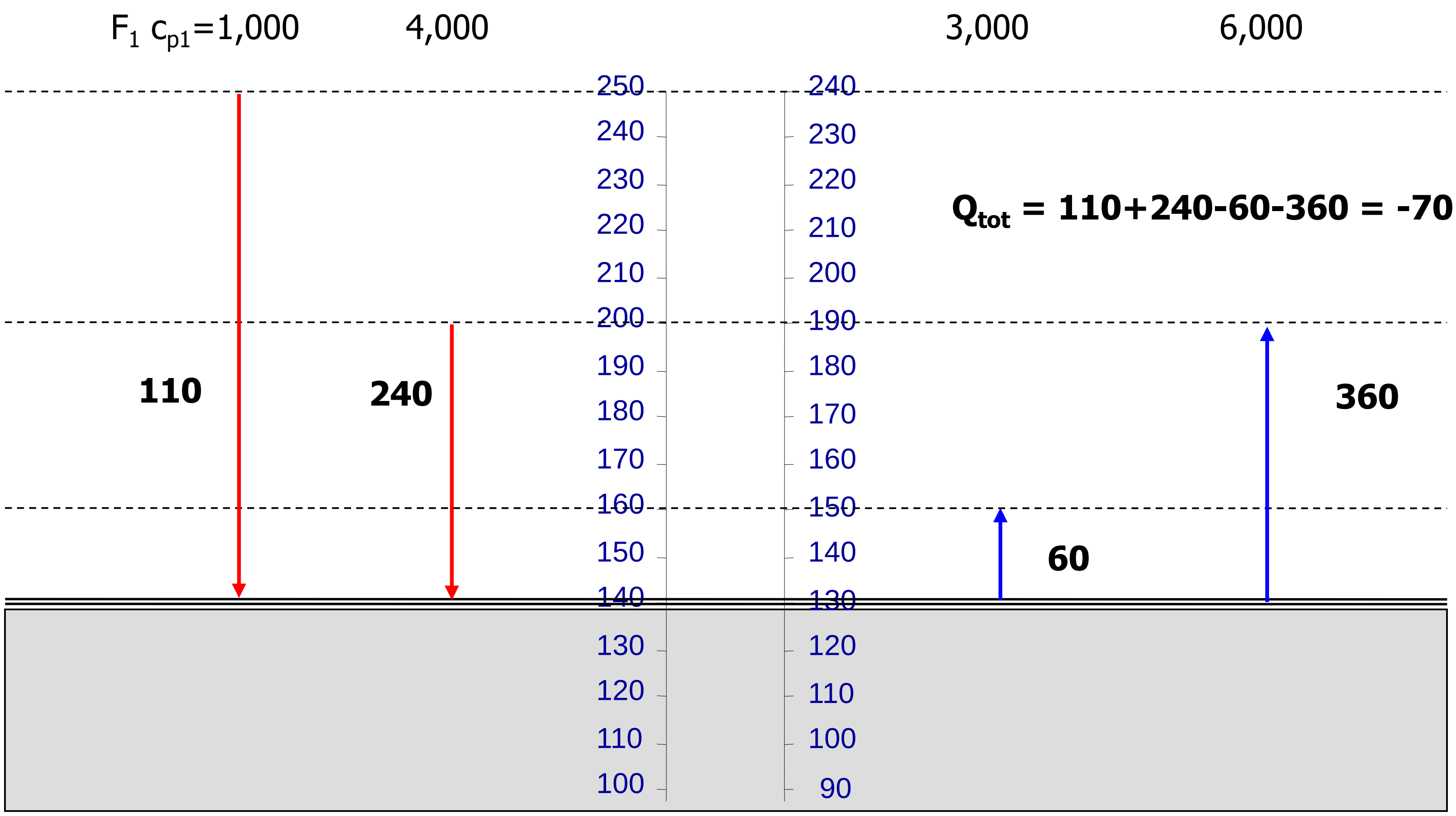
Case B

$$\frac{1}{U_{1B}} = \frac{1}{h_2} + \frac{1}{h_3} \quad \text{and} \quad \frac{1}{U_{2B}} = \frac{1}{h_1} + \frac{1}{h_4}$$

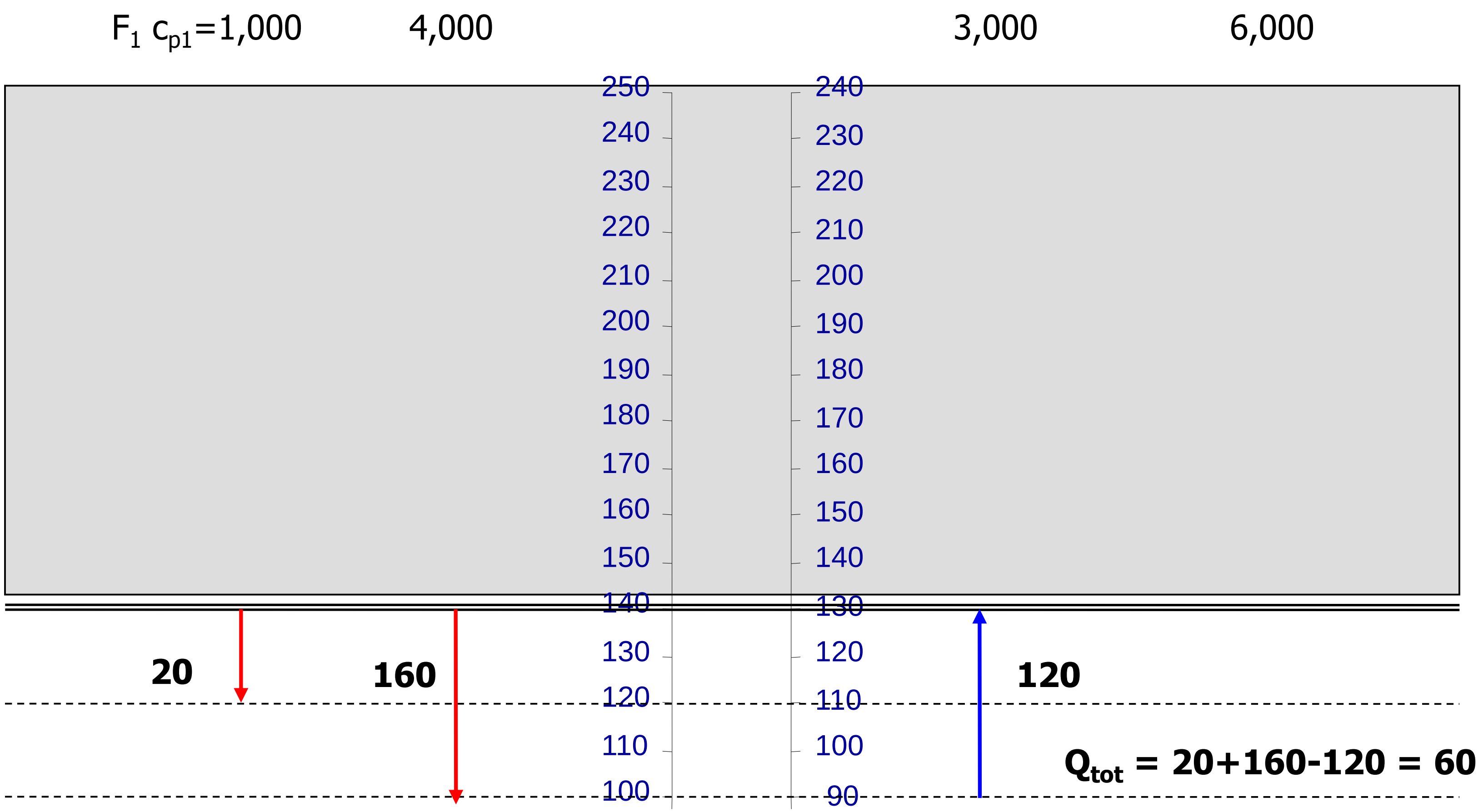
$$A_{TOTB} = A_{1B} + A_{2B} = \frac{Q}{\Delta T_{ML} U_{1B}} + \frac{Q}{\Delta T_{ML} U_{2B}}$$

$$\Rightarrow A_{TOTB} = \frac{Q}{\Delta T_{ML}}\left(\frac{1}{h_1} + \frac{1}{h_2} + \frac{1}{h_3} + \frac{1}{h_4}\right)$$

Above the PINCH

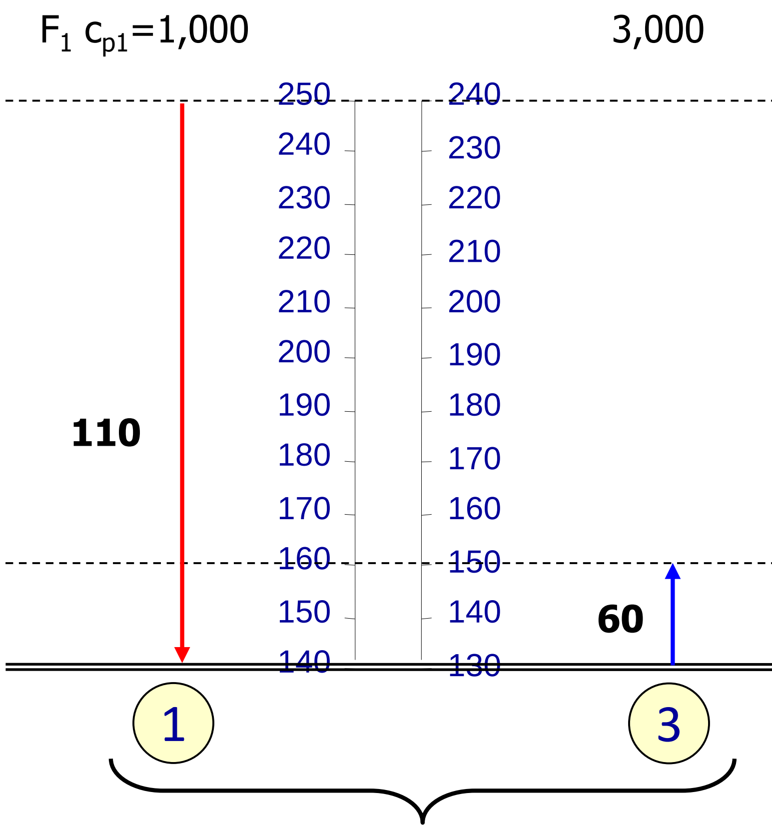


Below the PINCH



Matching the streams above the PINCH

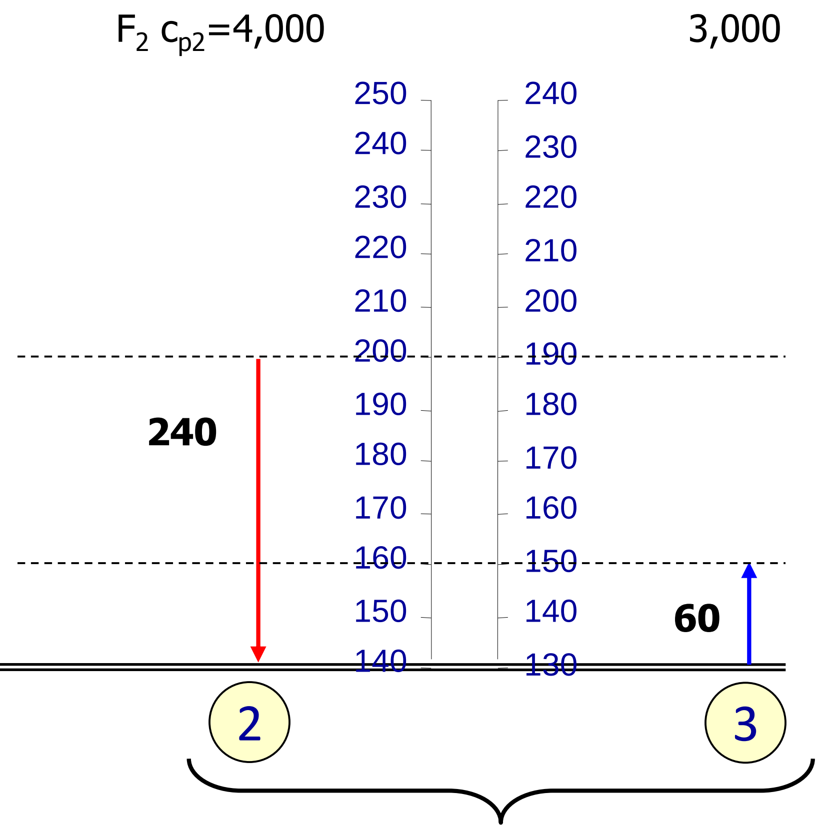
$$F_H\,C_{pH} \le F_C\,C_{pC}$$



$Q = 60{,}000 = 1{,}000(T_{1in}-140)$

$\rightarrow T_{1in} = 200 > T_{3out} + 10 = 150 + 10 = 160$

The pairing is **FEASIBLE**



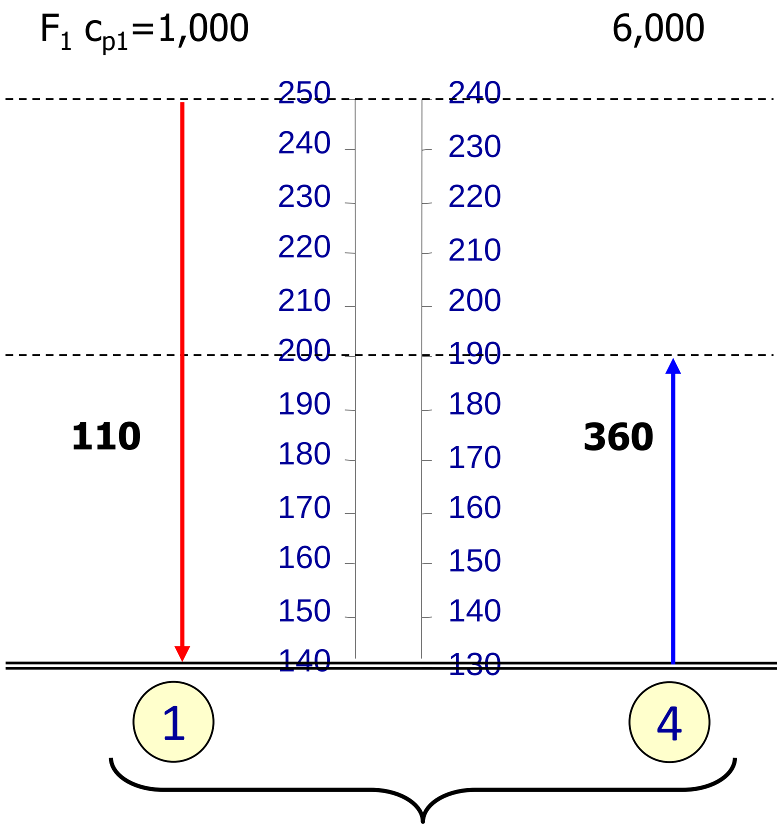
$Q = 60{,}000 = 4{,}000(T_{2in}-140)$

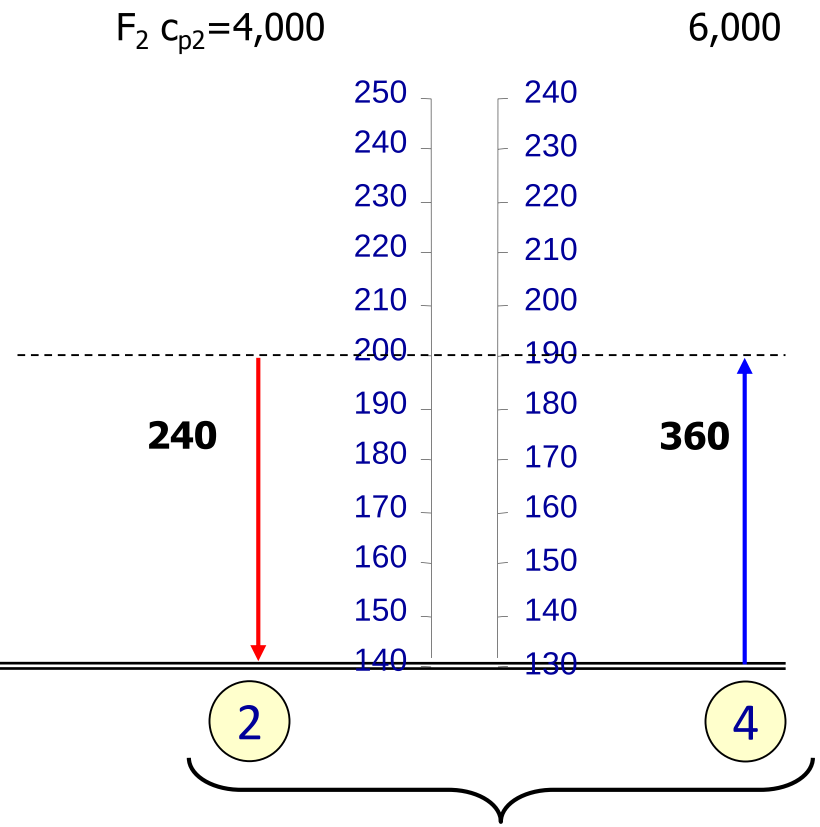
$\rightarrow T_{2in} = 155 < T_{3out} + 10 = 150 + 10 = 160$

The pairing is **NOT FEASIBLE**

Matching the streams above the PINCH

$F_H C_{pH} \leq F_C C_{pC}$





Actually: Q_{eff} = **110,000** = 1,000(T_{1in}-140)

T_{1in} = **250** > T_{4out} + 10 in fact T_{4out} :

110,000 = 6,000(T_{4out}-130) → T_{4out} = 148.333

The pairing is **FEASIBLE**

Actually: Q_{eff} = **240,000** = 4,000(T_{2in}-140)

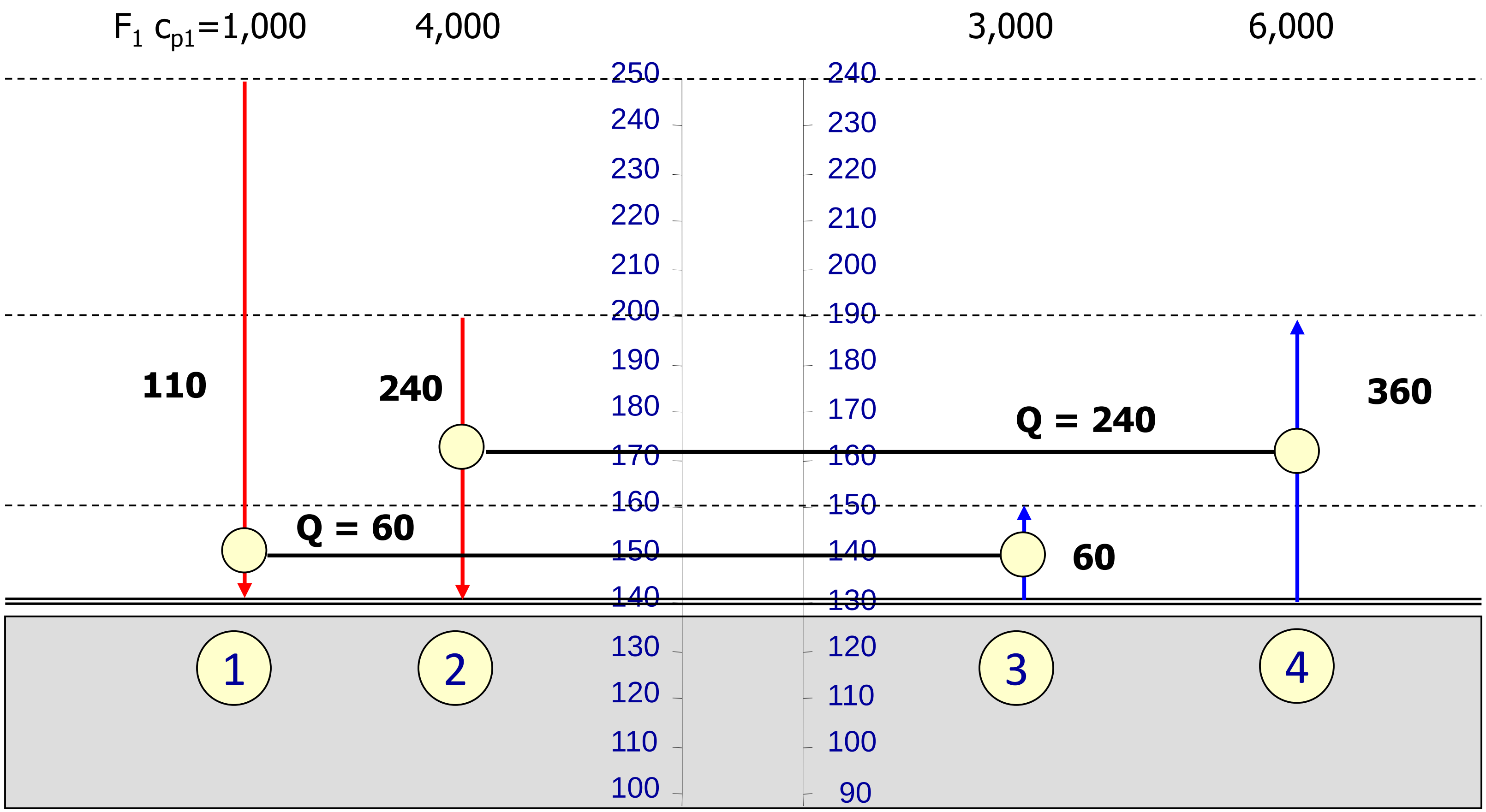
T_{2in} = **200** > T_{4out} + 10 in fact T_{4out} :

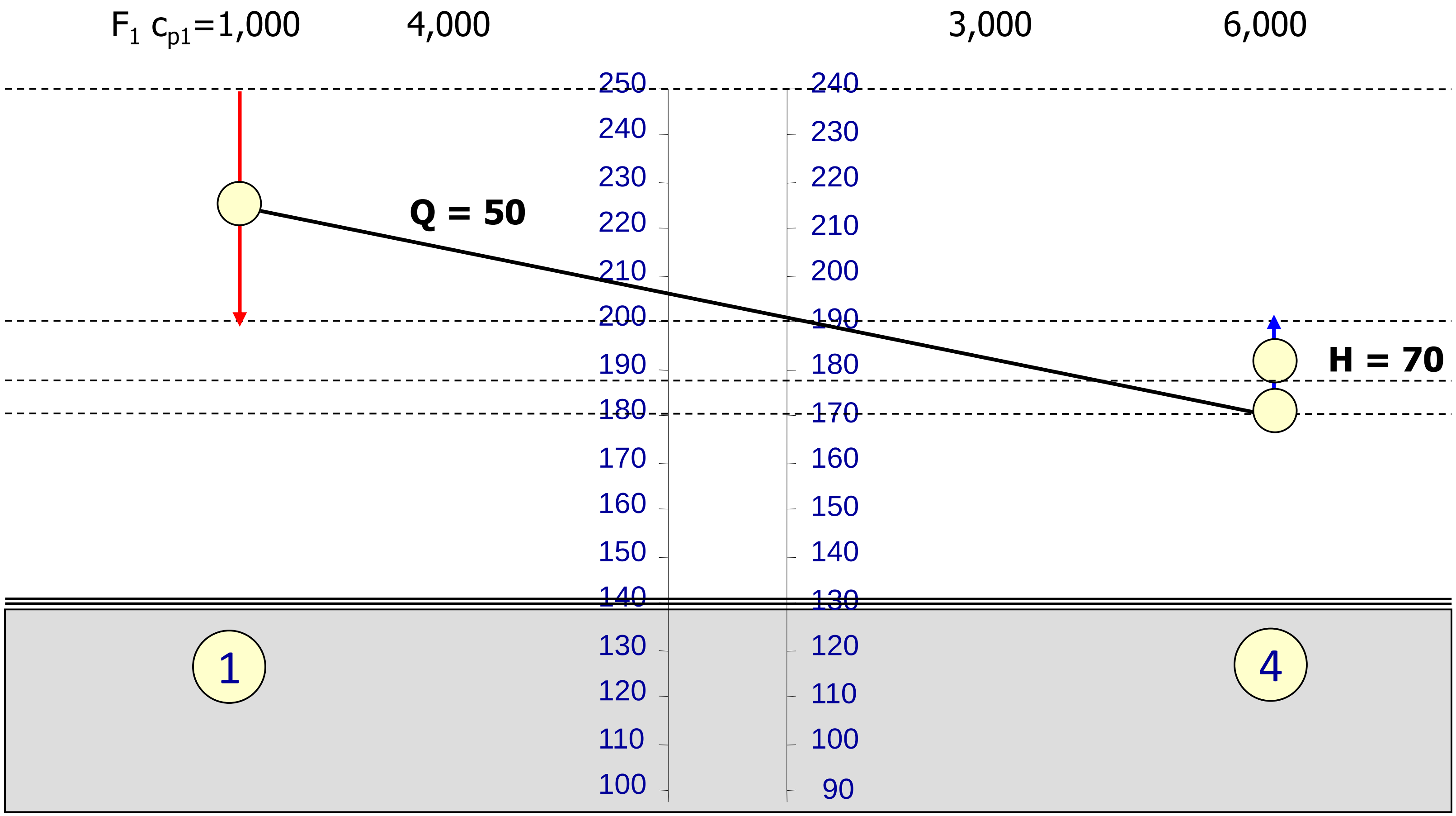
240,000 = 6,000(T_{4out}-130) → T_{4out} = 170

The pairing is **FEASIBLE**

Feasible pairings

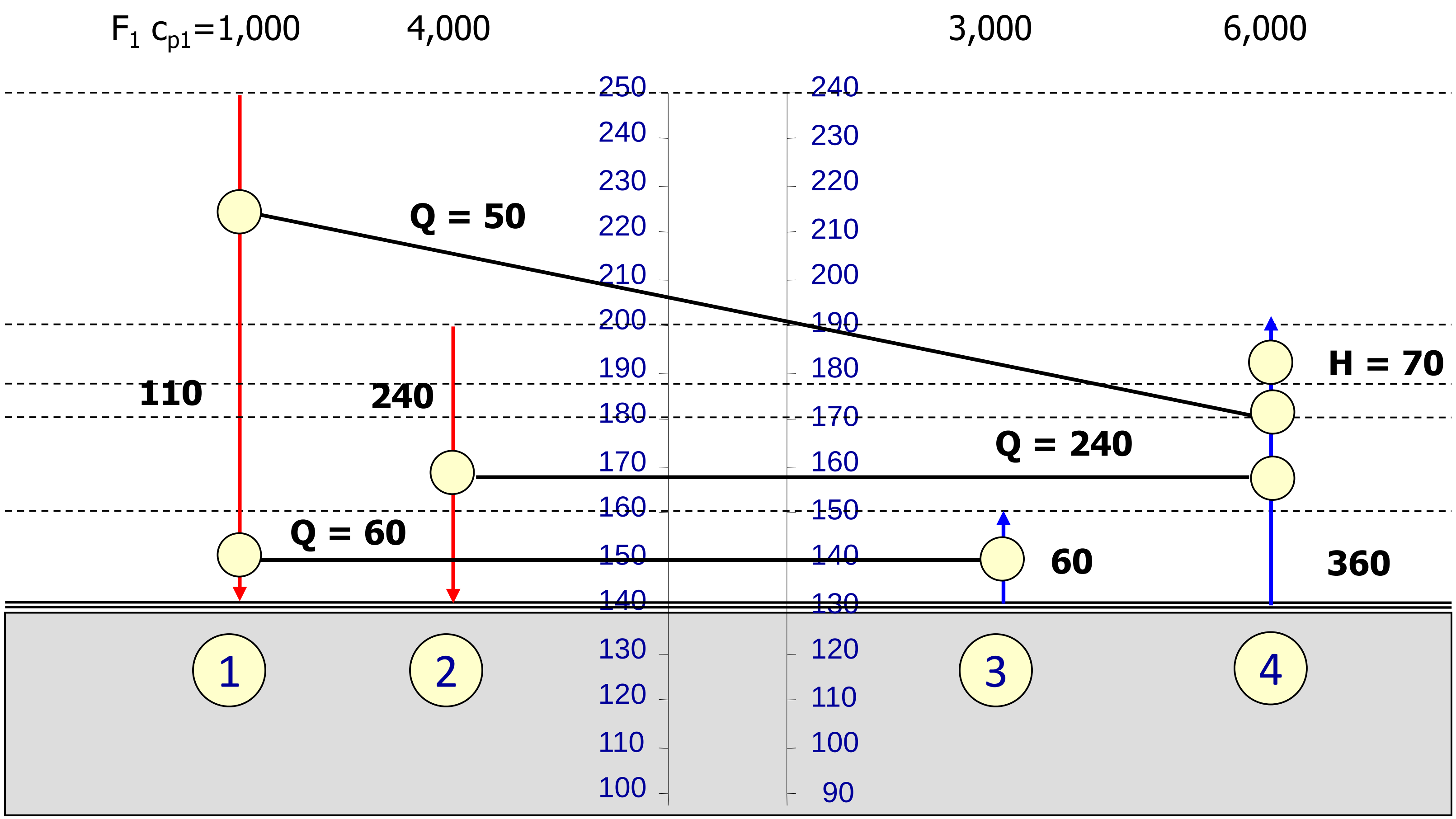
- 1 with 3
- 1 with 4
- 2 with 4





- 1 with 3: $Q = 60{,}000 = 1{,}000(T_{1in}-140)$ → $T_{1in}= 200$ (exchanger 1 with 3)
- 1 has still: 110 – 60 = 50 $Q = 50{,}000 = 1{,}000(T_{1in} - 200)$ → $T_{1in}= 250$ (exchanger 1 with 4)
- 4 with 2: $Q = 240{,}000 = 6{,}000(T_{4out}-130)$ → $T_{4in}= 170$ (exchanger 1 with 4)
- 4 with 1: $Q = 50{,}000 = 6{,}000(T_{4out}-170)$ → $T_{4out} = 178.333$ (exchanger 1 with 4)
- 4 still misses: 360 – 240 – 50 = 70 to be achieved by the hot utility

Above the PINCH we have:



Matching the streams below the PINCH

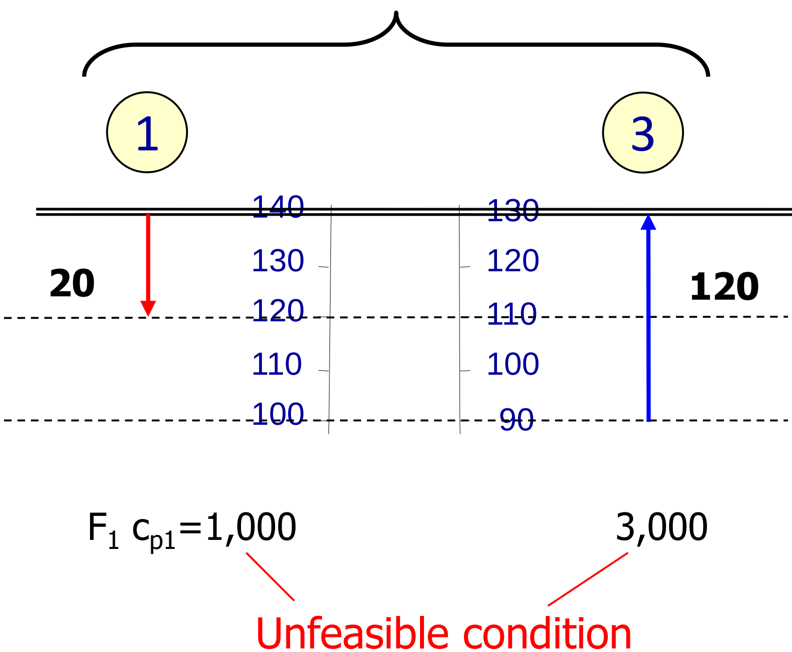
$F_H C_{pH} \geq F_C C_{pC}$

The maximum exchangeable heat is 20

$Q = 20{,}000 = 3{,}000(130 - T_{3\,in})$

$\rightarrow T_{3\,in} = 123.333$ whilst $T_{1\,out} = 120$

The pairing is **NOT FEASIBLE**

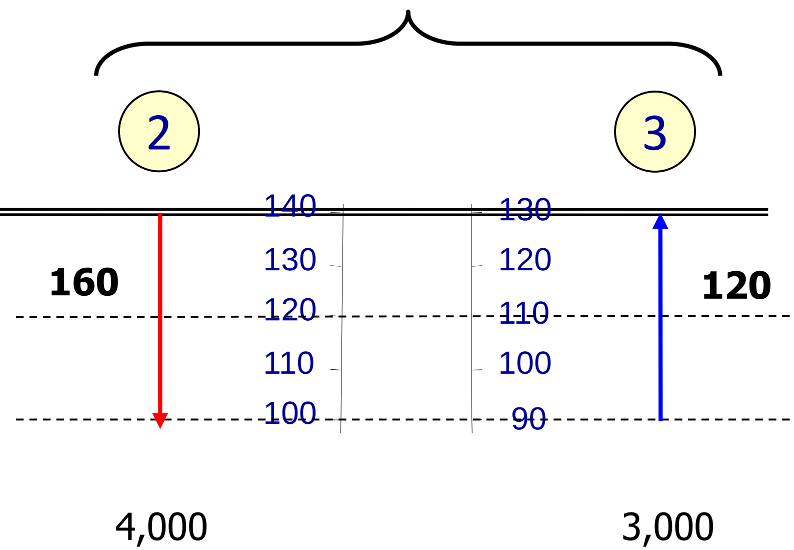


The maximum exchangeable heat is 120

$Q_3 = 120{,}000 = 3{,}000(130 - T_{3\,in}) \rightarrow T_{3\,in} = 90$

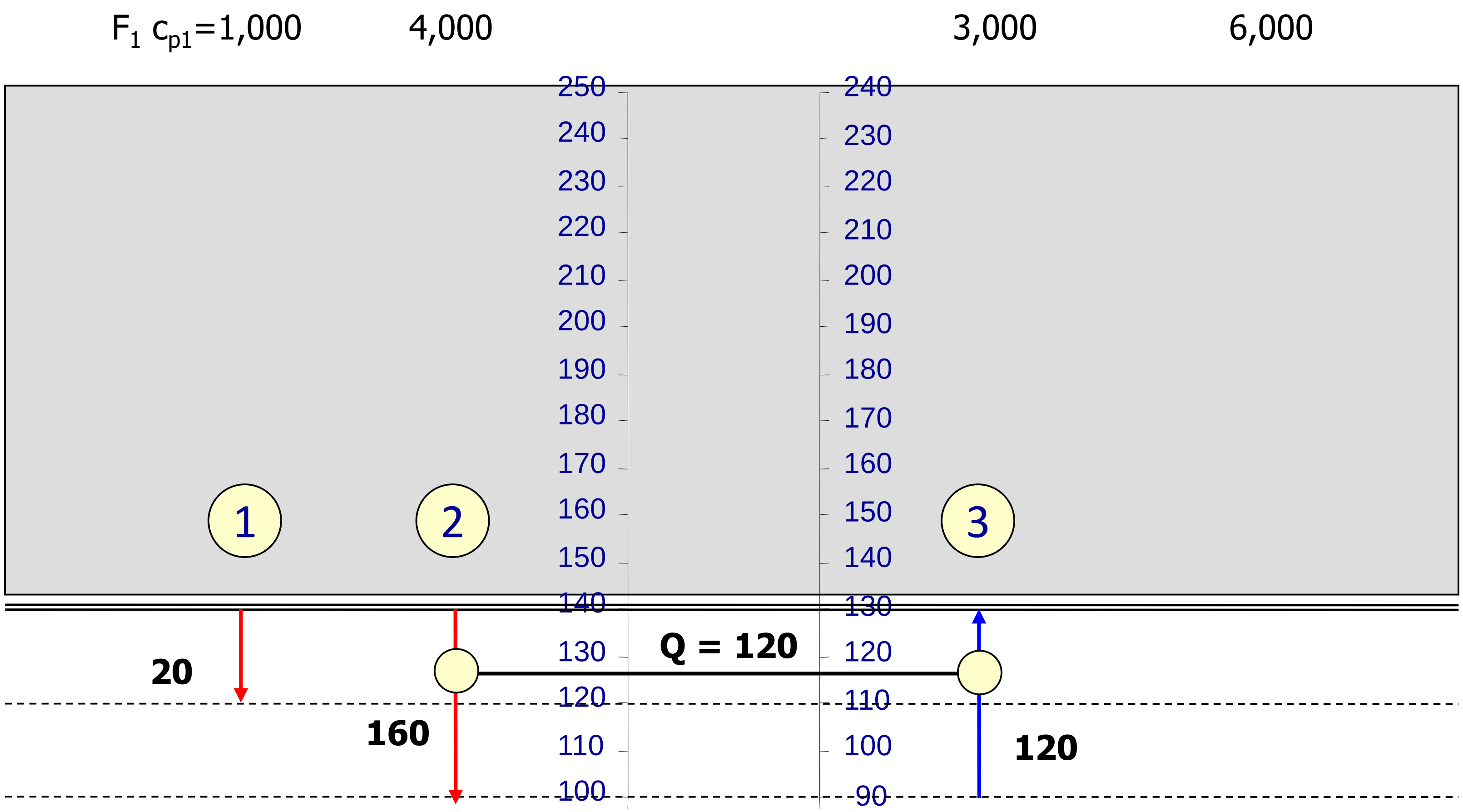
$Q_2 = 120{,}000 = 4{,}000(140 - T_{2\,out}) \rightarrow T_{2\,out} = 110$

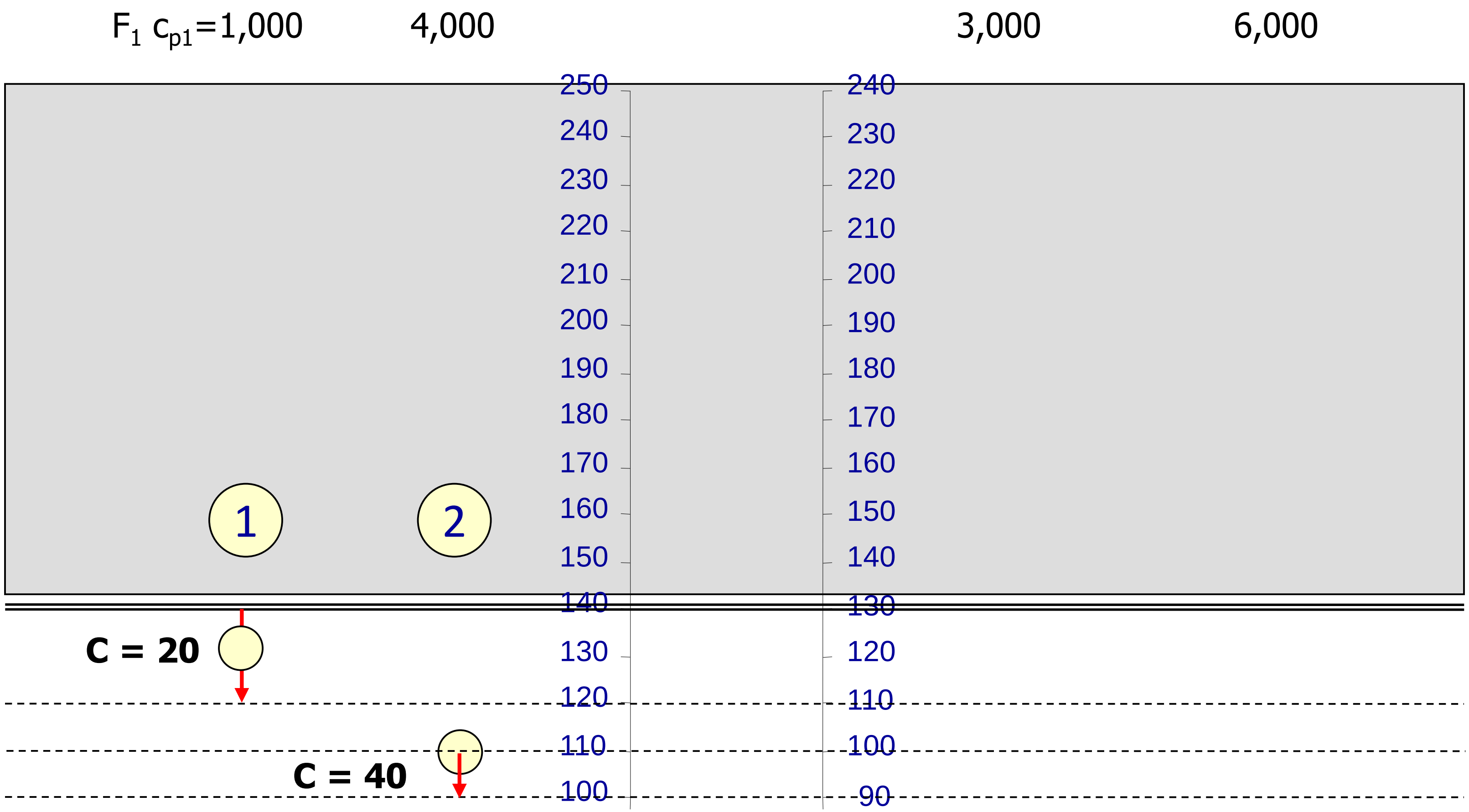
The pairing is **FEASIBLE**



Feasible pairings

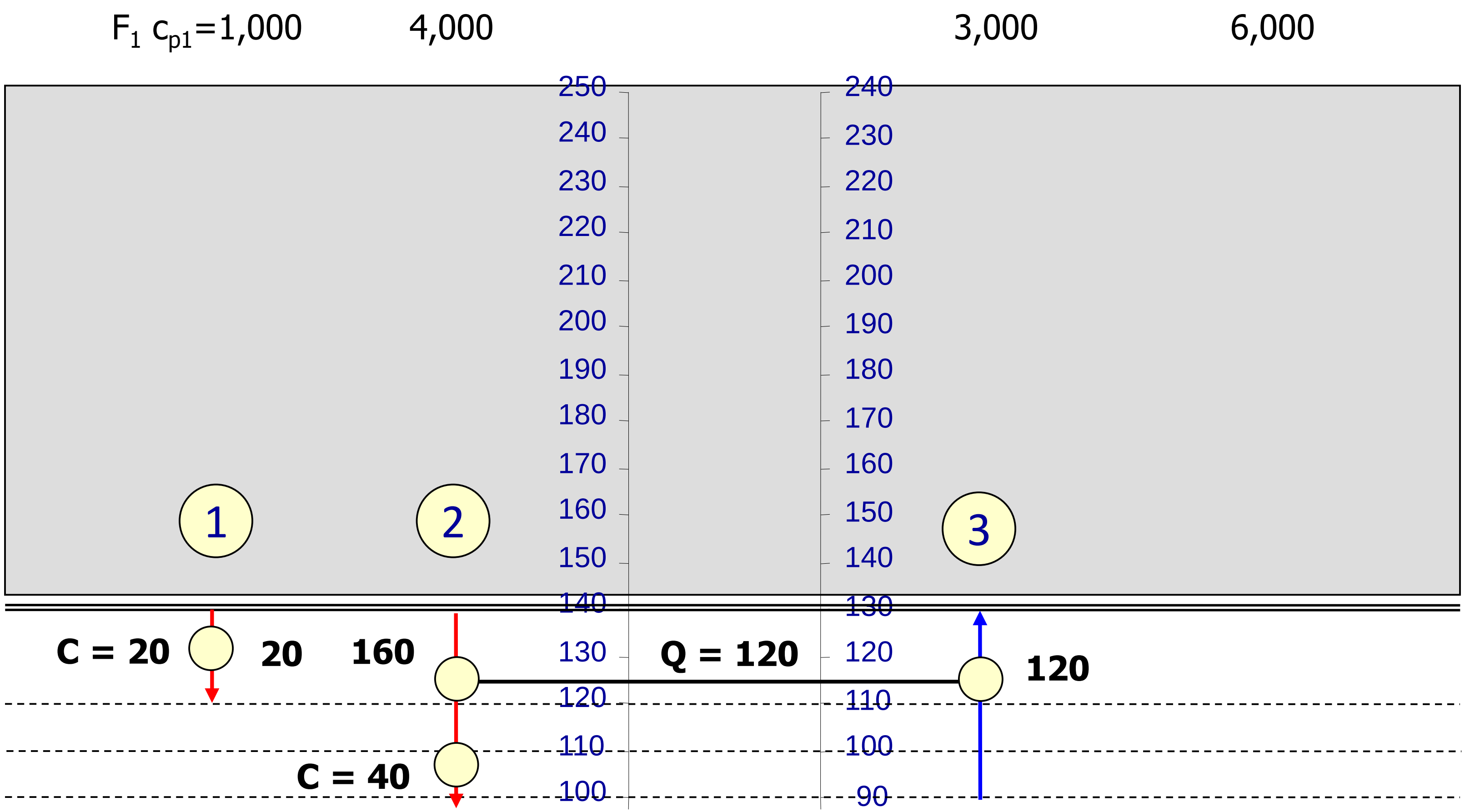
{ 2 with 3 }



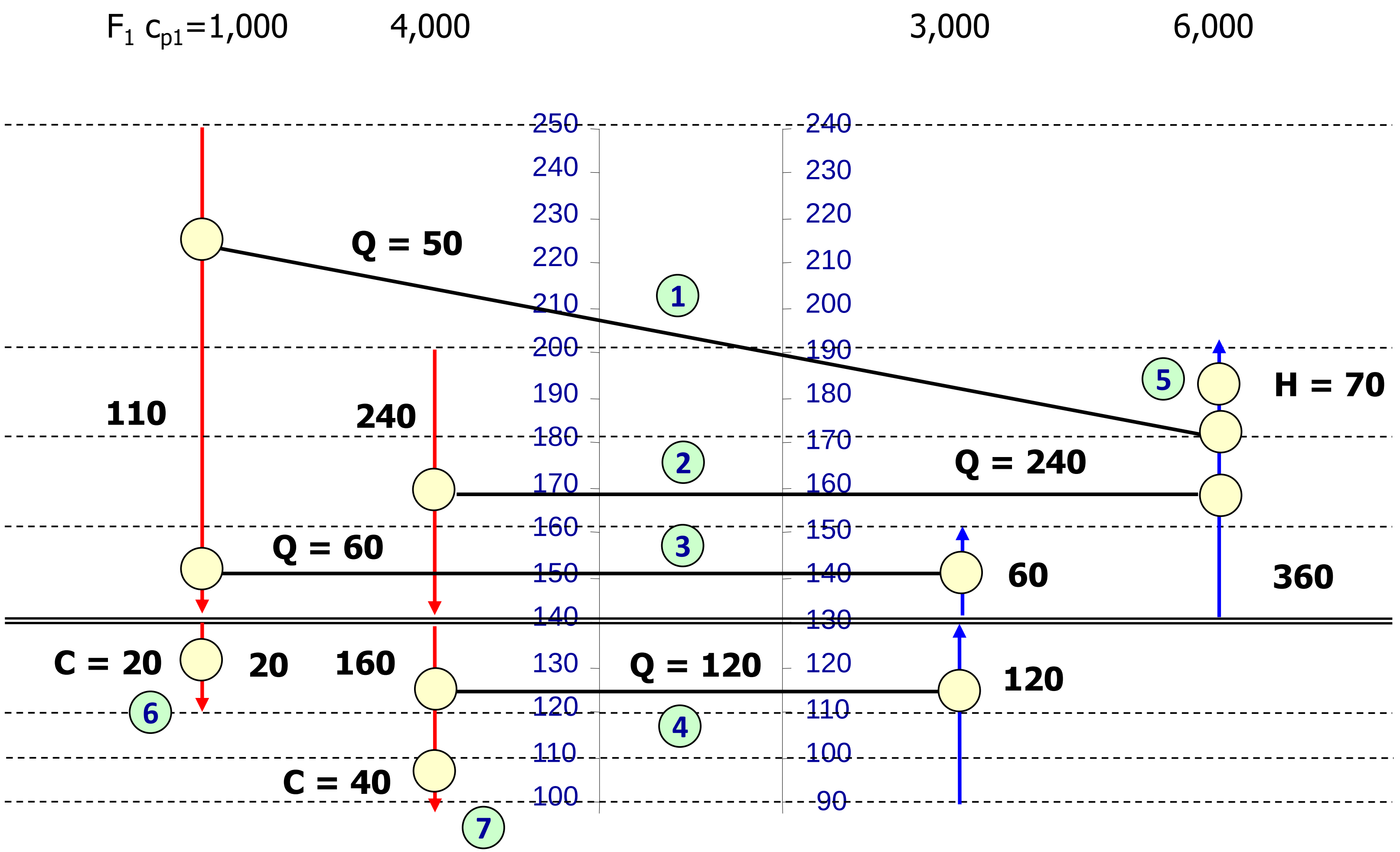


- 2 with 3: $Q = 120{,}000 = 4{,}000(140 - T_{2\ out})$ → $T_{2\ out} = 110$ (exchanger 2 with 3)
- 2 still has: 160 - 120 = 40 $Q = 40{,}000 = 4{,}000(110 - T_{2\ out})$ → $T_{2\ out} = 100$ (with cold utility)
- 1 is cooled with the cold utility

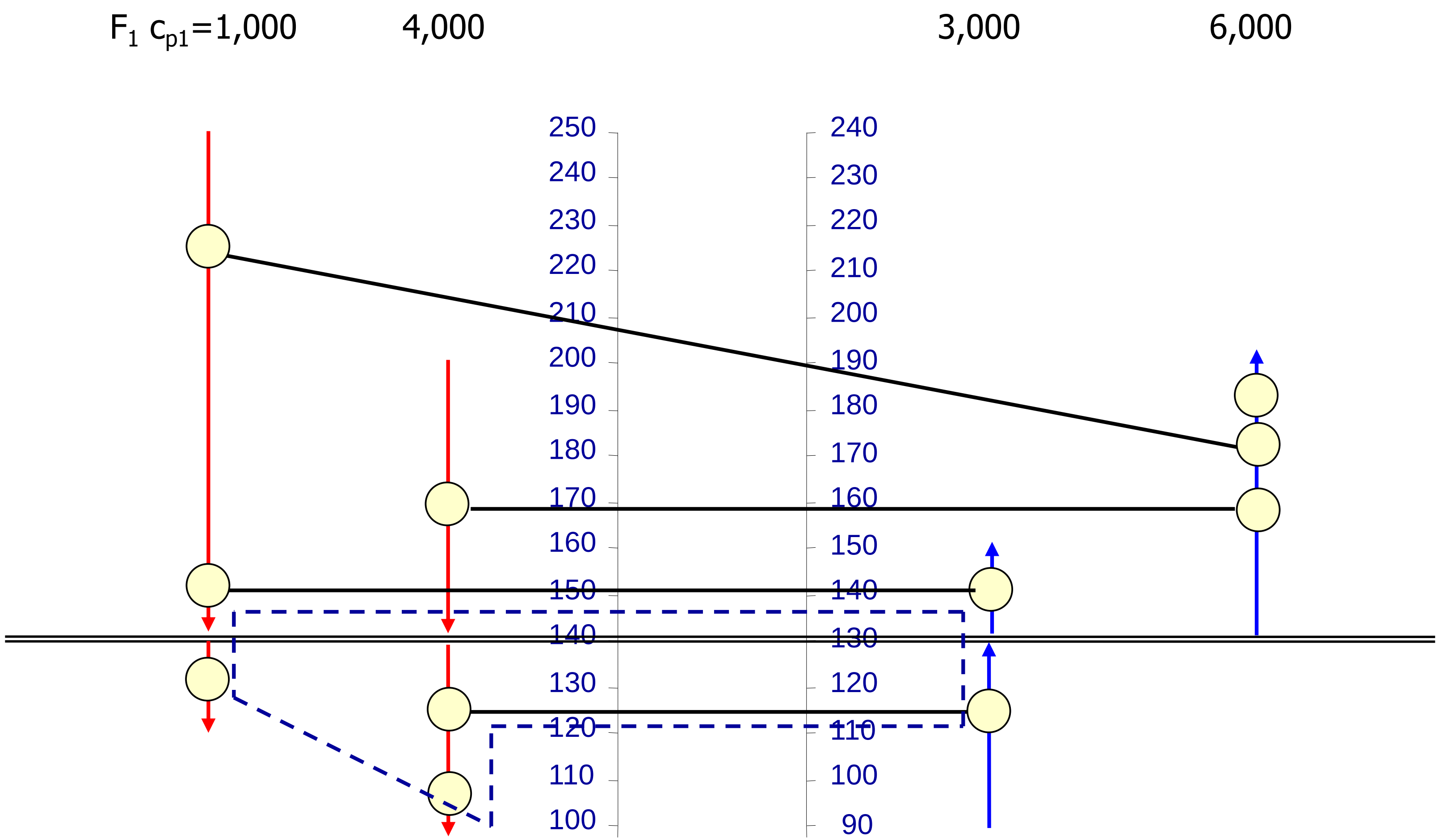
Below the PINCH we have:



The design with minimum energy requirement is…

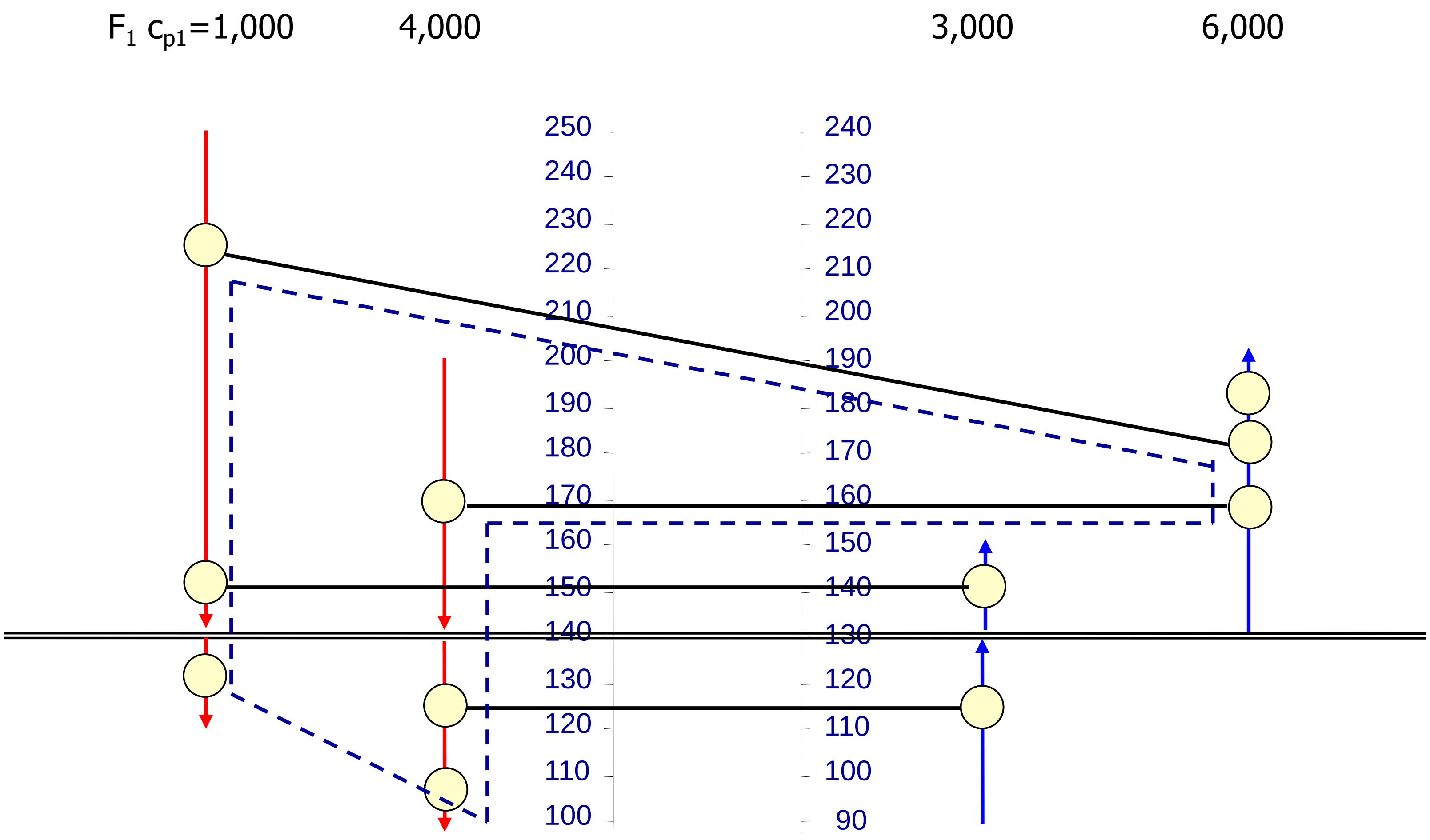


First loop



$F_1\ c_{p1}$=1,000
4,000
3,000
6,000
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90

Second loop



$F_1\ c_{p1}$=1,000
4,000
3,000
6,000
250
240
230
220
210
200
190
180
170
160
150
140
130
120
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100
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210
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160
150
140
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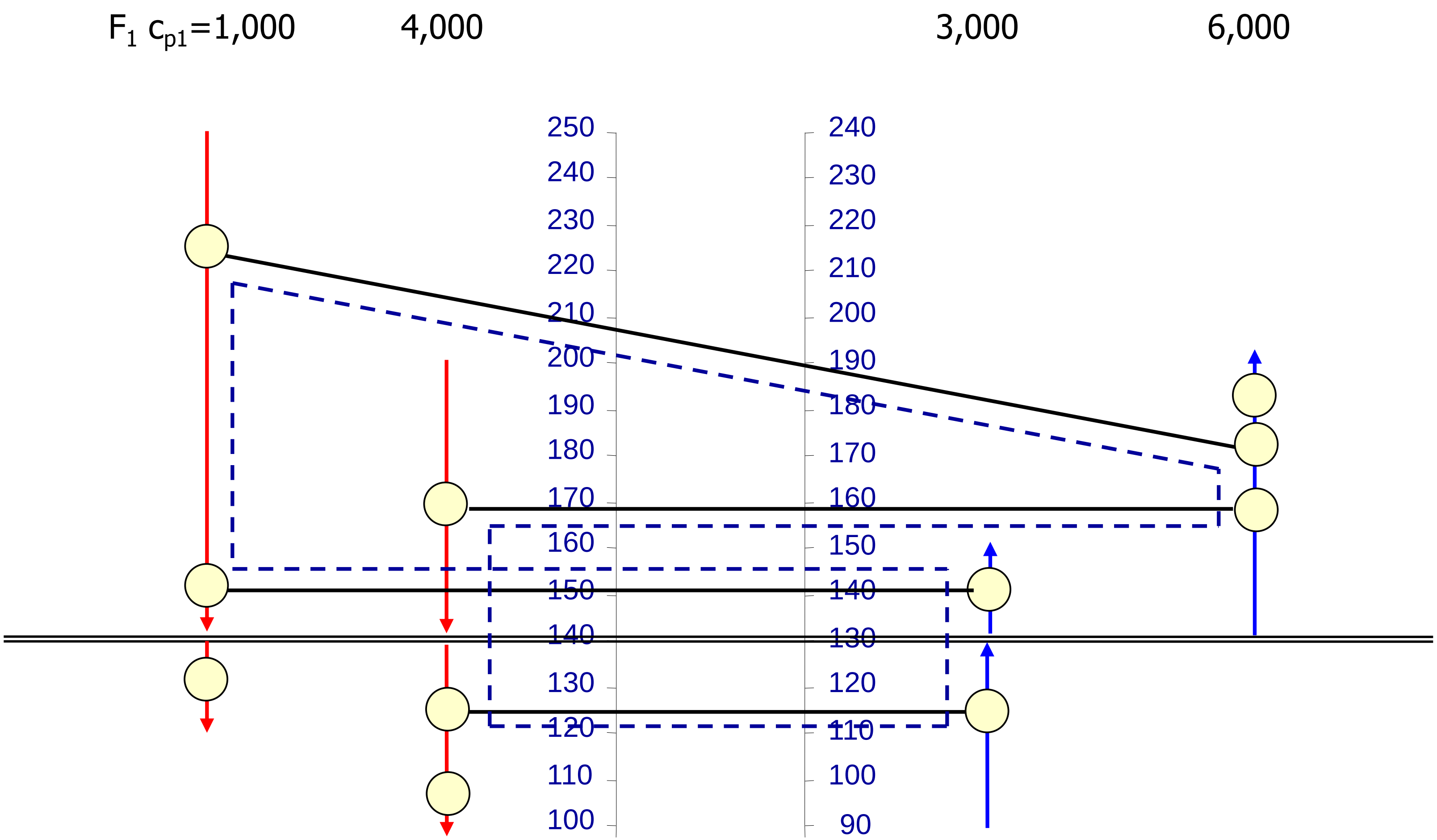
120
110
100
90

Third loop



$F_1\ c_{p1}$=1,000
4,000
3,000
6,000
250
240
230
220
210
200
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180
170
160
150
140
130
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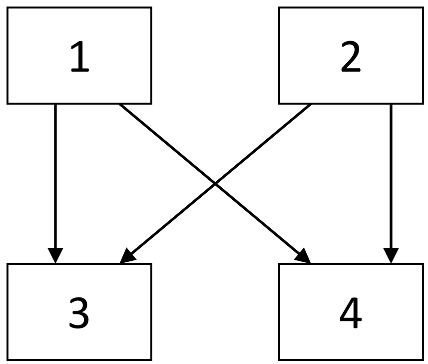
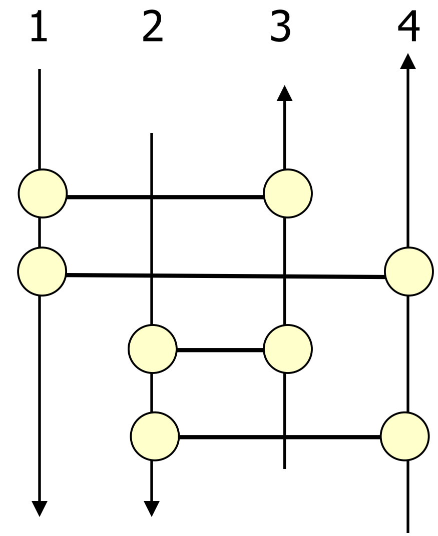
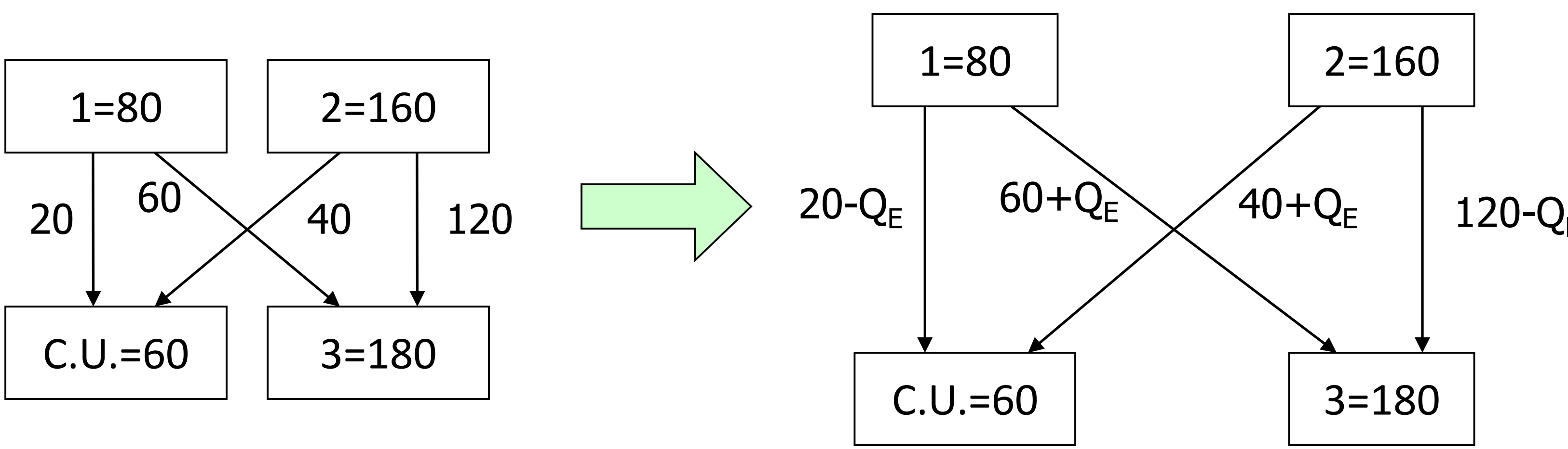
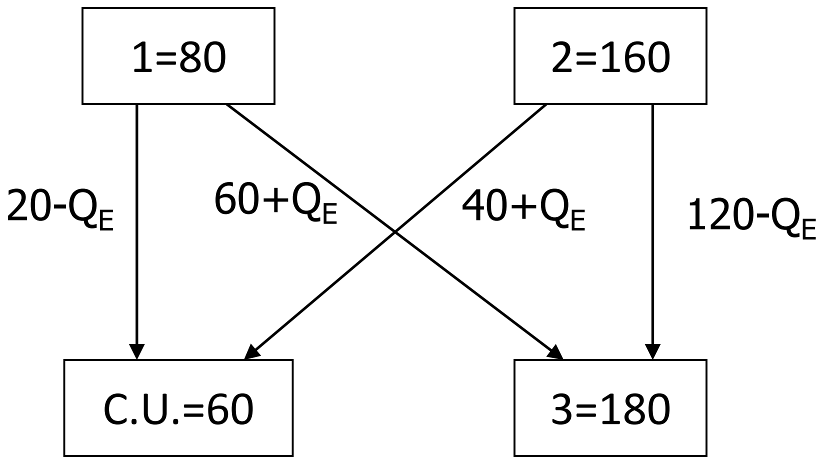


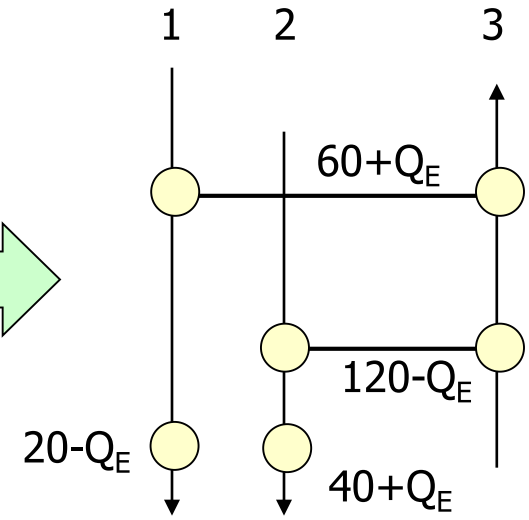
Example of loop



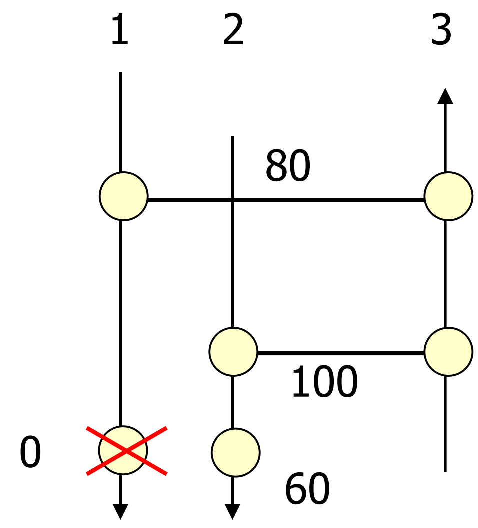


C.U. = **C**old **U**tility

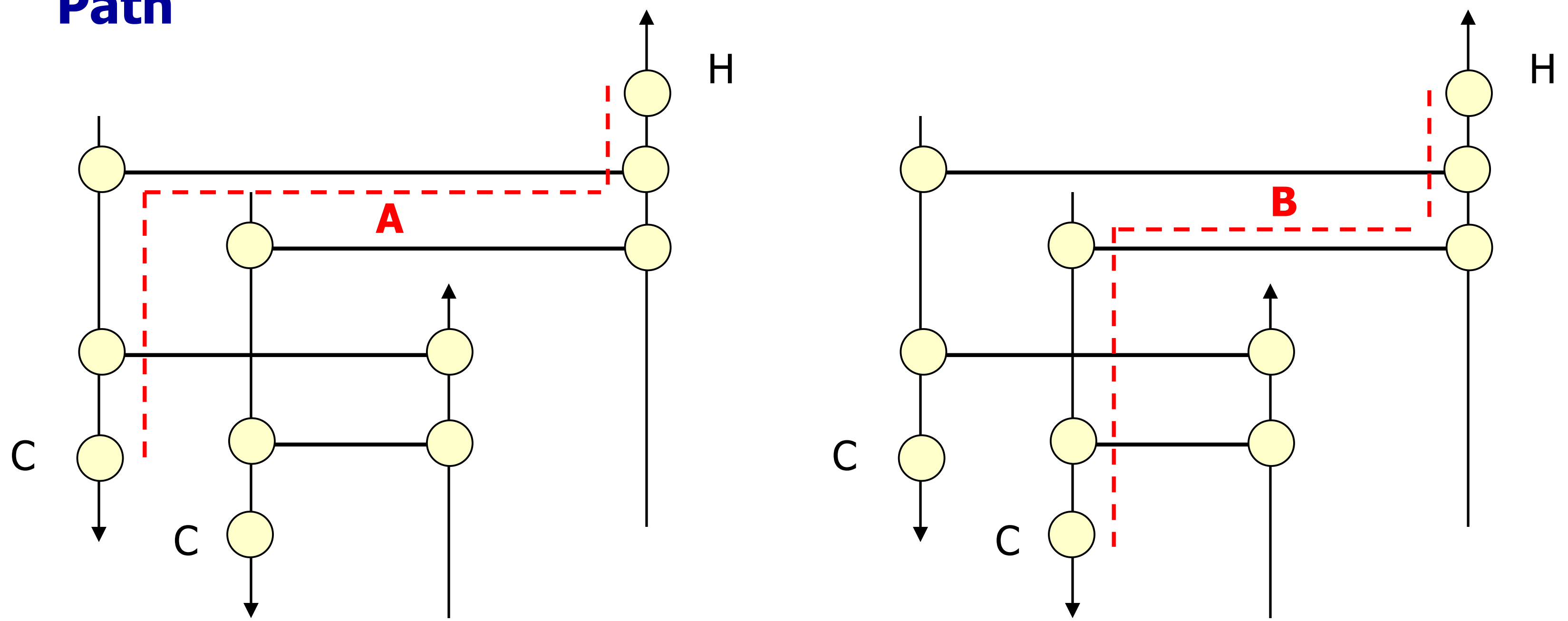


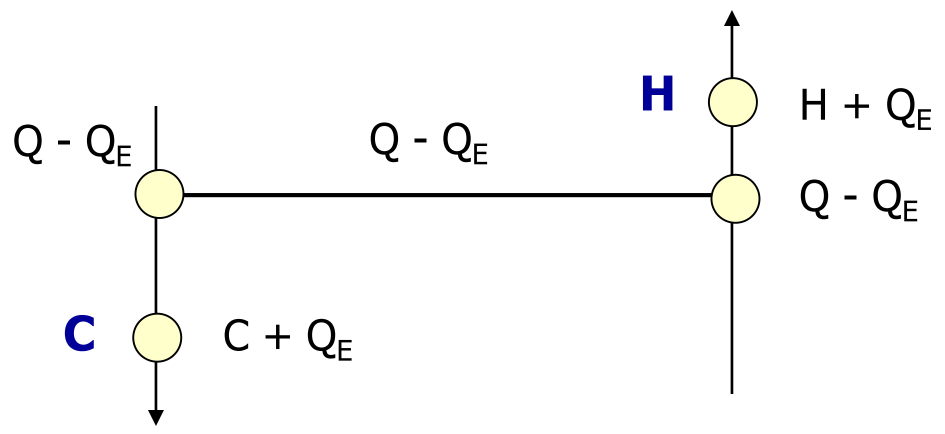


By setting Q_E equal to 20…

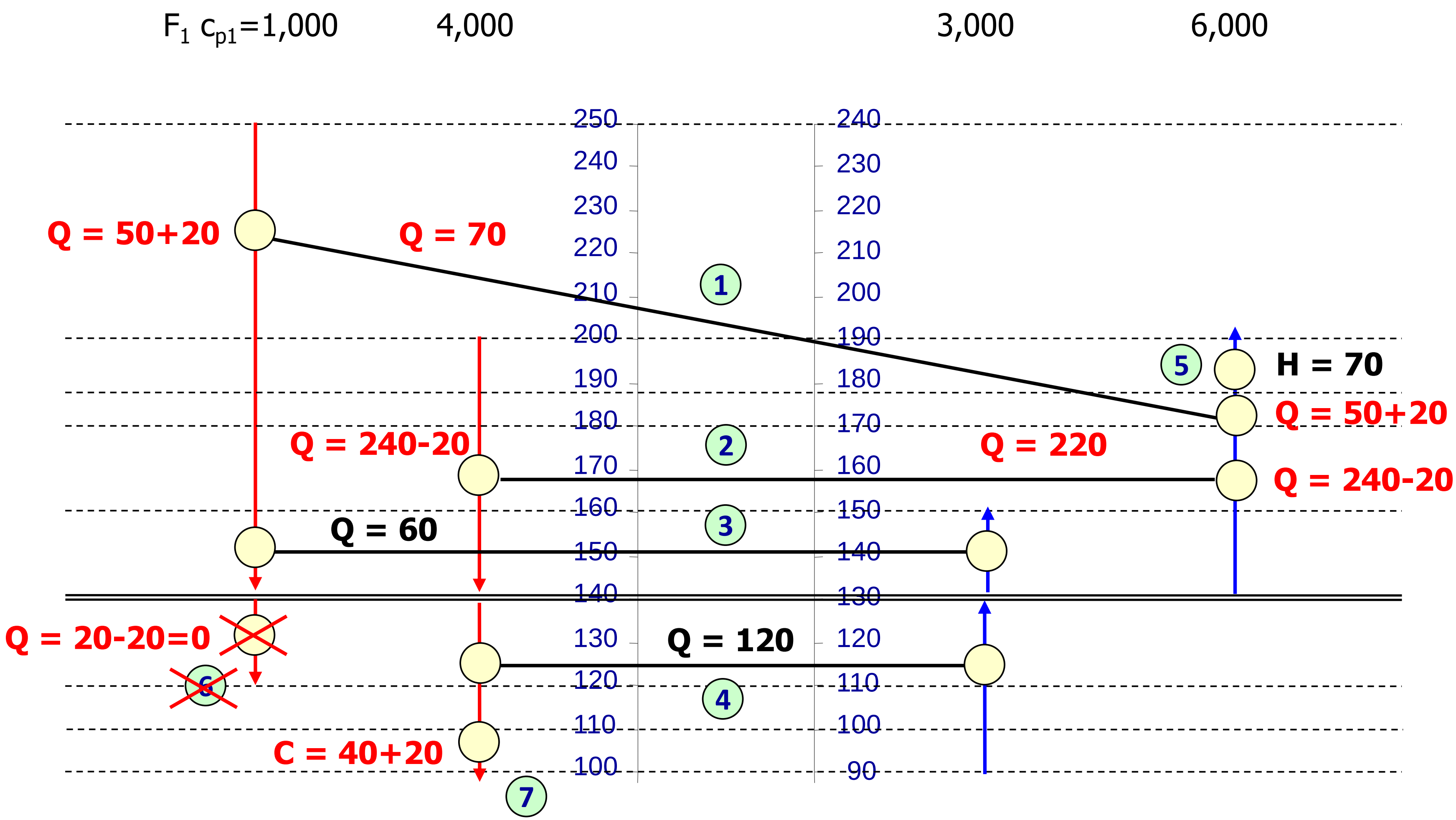


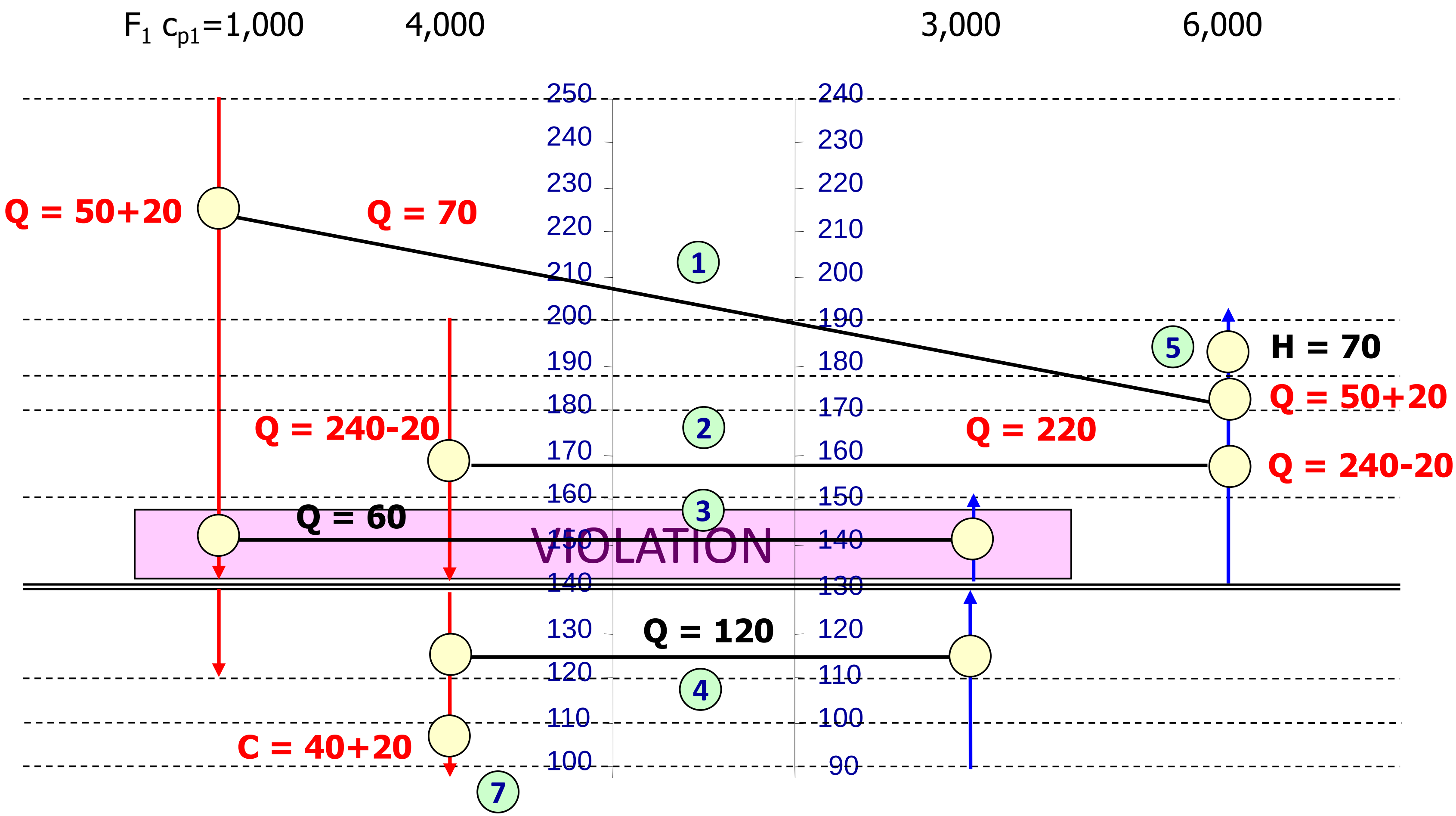
Path





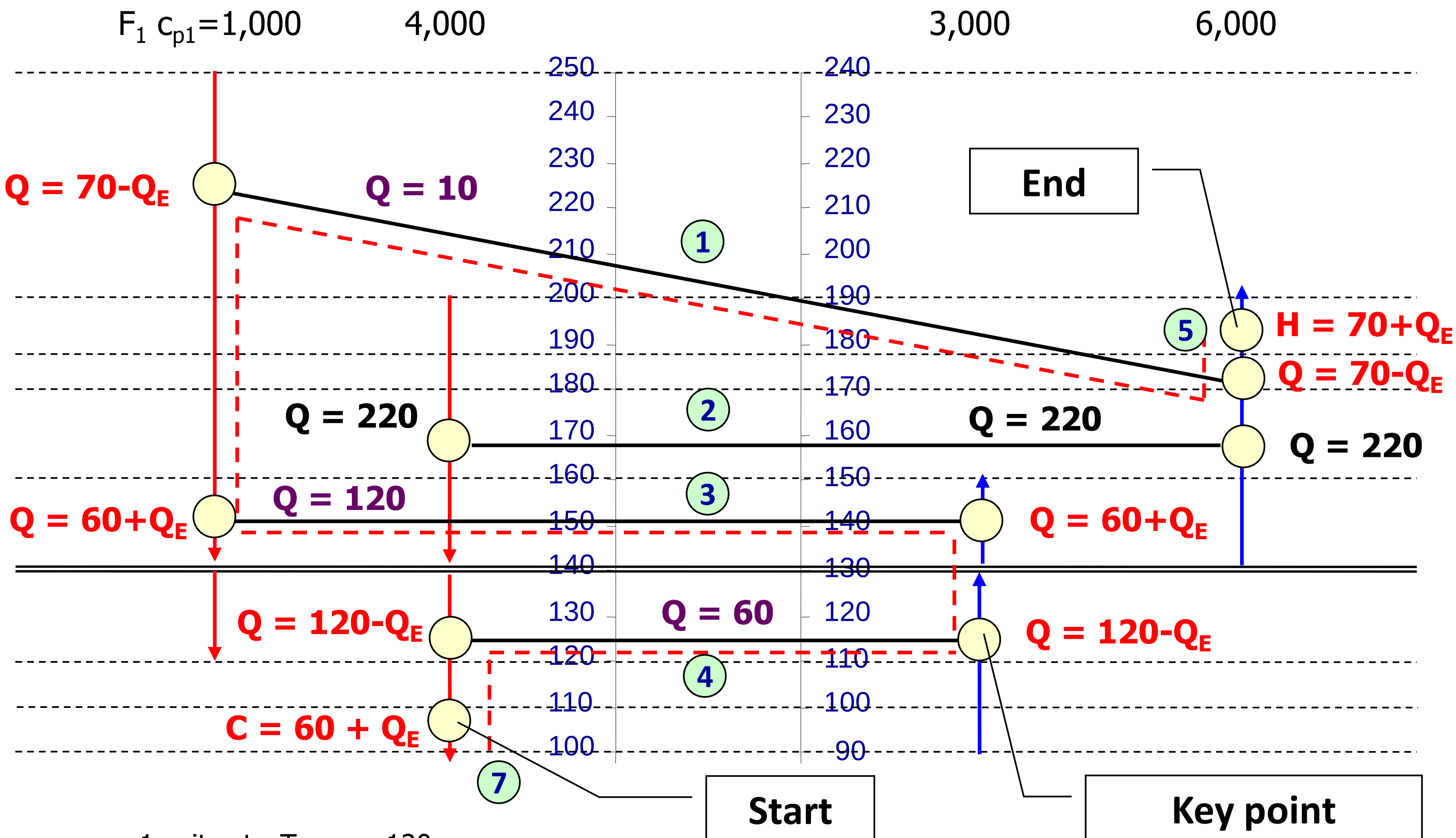
Reduction of the number of heat exchangers





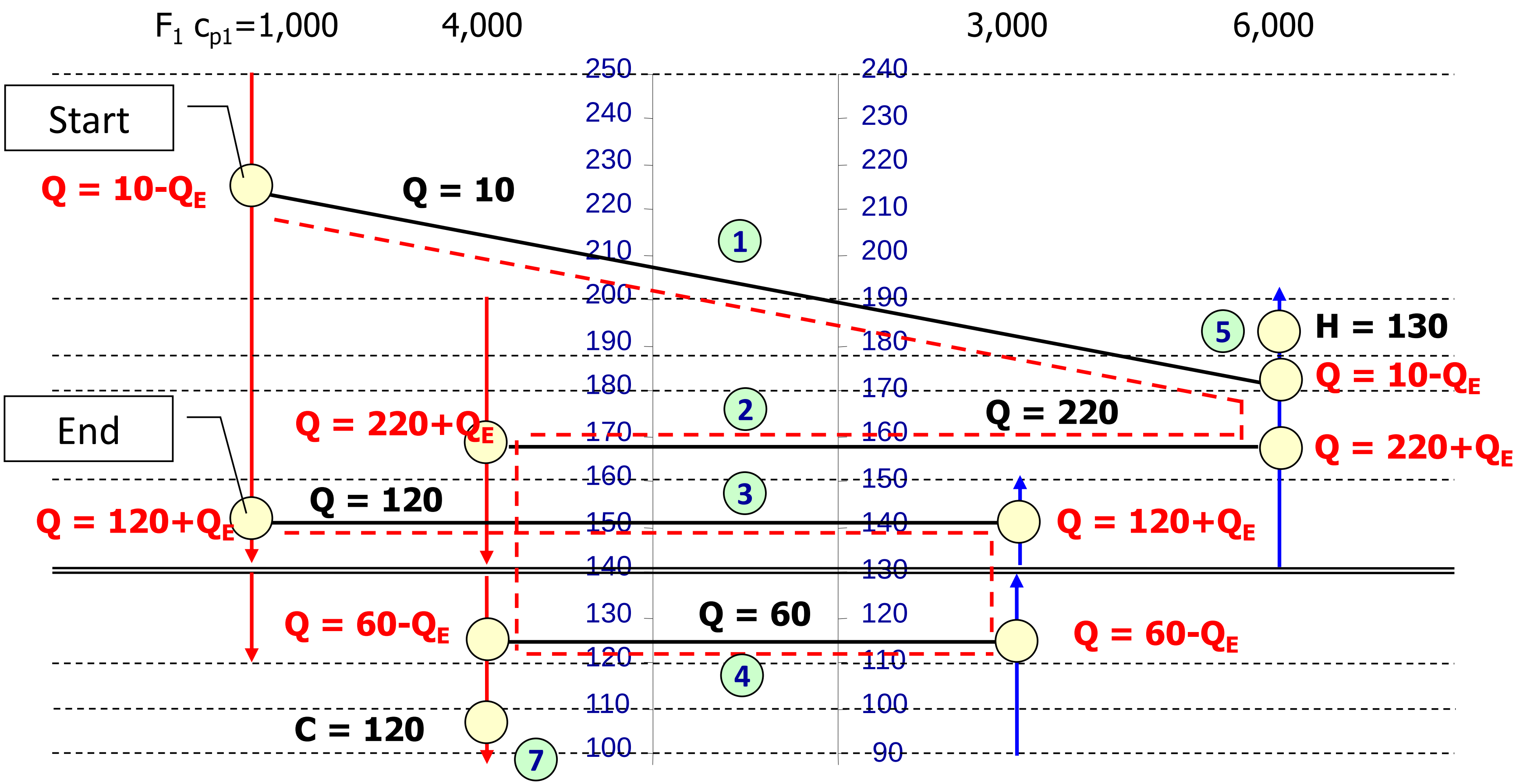
- 1 exits from heat exchanger (1) at: $70{,}000 = 1{,}000(250 - T_{1A\ out})$ → $T_{1A\ out} = 180$
- 1 exits from heat exchanger (3) at: $60{,}000 = 1{,}000(180 - T_{1B\ out})$ → $T_{1B\ out} = 120$
- 3 enters in heat exchanger (3) at: $T_{3\ in} = 130$
- Consequently, there is **VIOLATION**

ΔT_{min} can be restored by moving heat (Q_E) along a path…



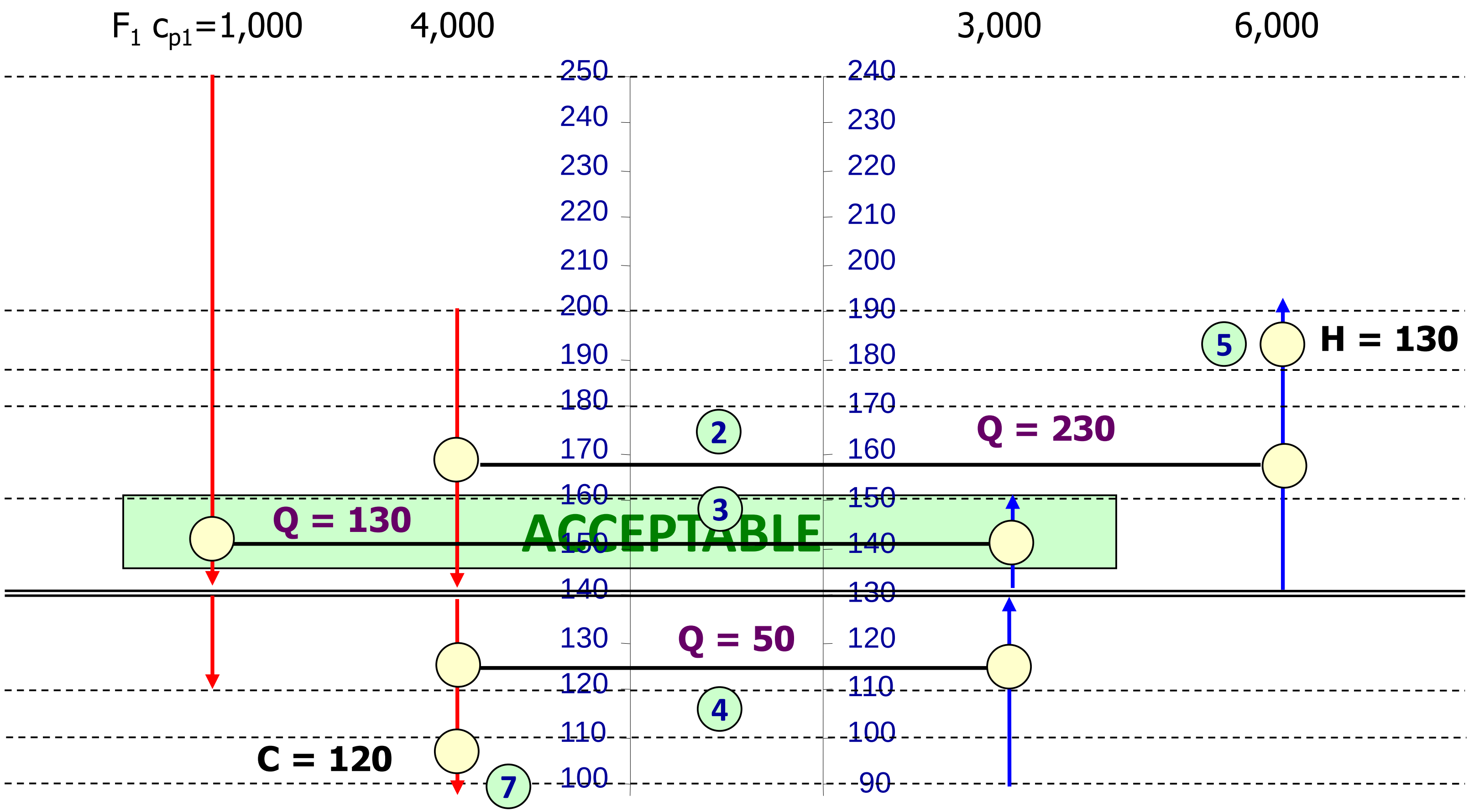
- 1 exits at: $T_{1B\ out}$ = 120
- 3 MUST enter in exchanger (3) at: $T_{3B\ in}$ = 110
- Consequently, in exchanger (4) we must have $T_{3A\ out}$ = 110
- It follows that: 120,000 – Q_E = 3,000($T_{3A\ out}$ – $T_{3A\ in}$) = 3,000(110-90) → **Q_E = 60,000**

It remains to remove only the third loop…



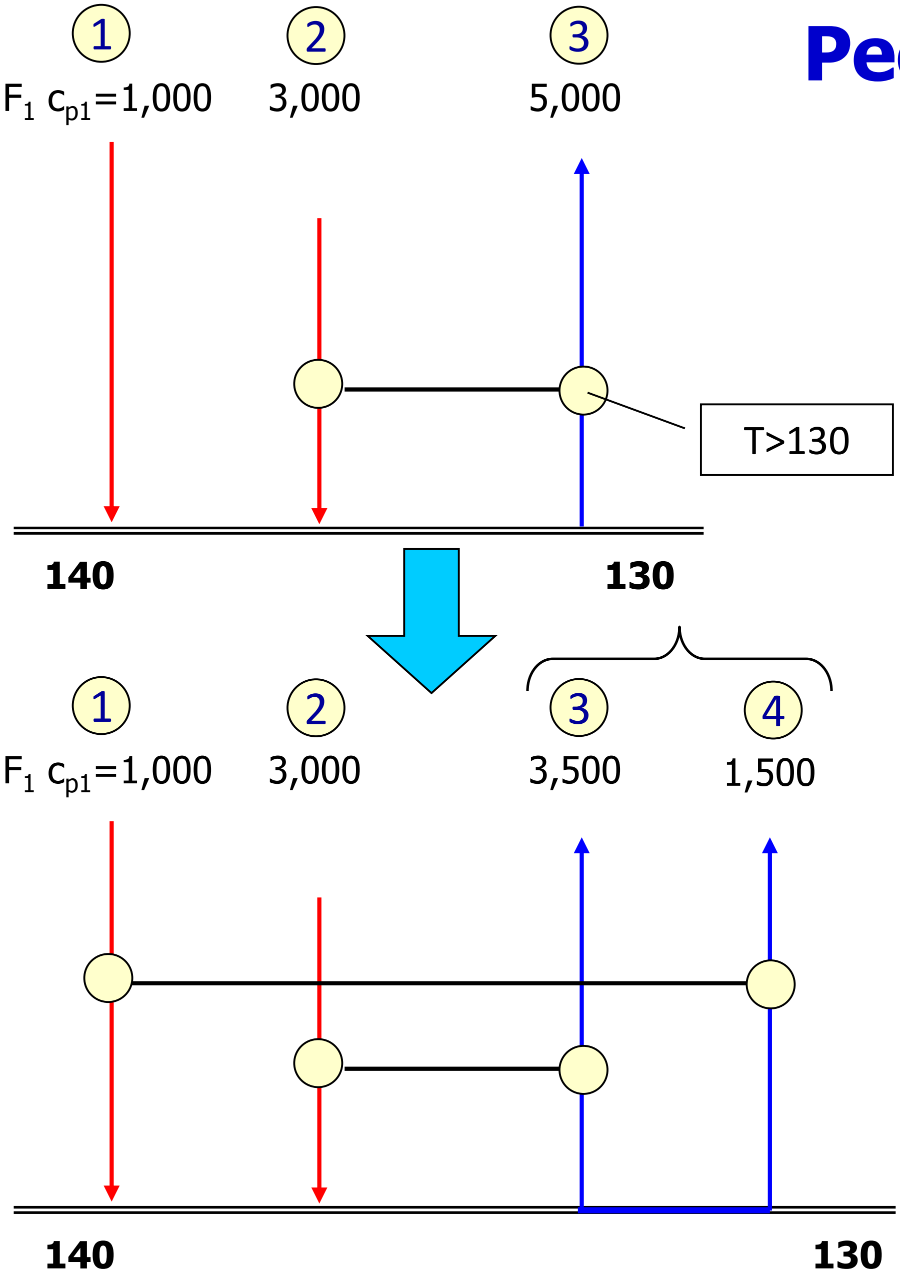
- The minimum request for heat to be subtracted is: $Q_E = 10$ (let us focus the attention on the loop)
- Let us check that ΔT_{min} is not violated. Also in this case we are across the PINCH
- As far as exchanger (3) is concerned, $T_{1out} = 120$ whilst $Q_3 = 120 + Q_E = 120 + 10 = 130$
- $130{,}000 = 3{,}000(150 - T_{3B\,in}) \rightarrow$ $T_{3B\,in} = 106.666$ The $\Delta T = 120 - 106.666 > 10$ **THERE IS NOT ANY VIOLATION**

Finally, the minimum number of heat exchangers is…



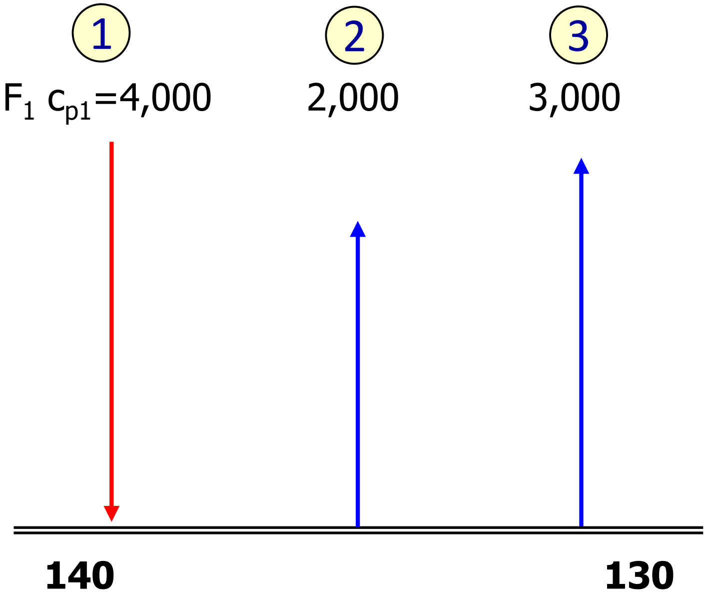
- ΔT = 120 – 106.666 > 10 can be further reduced by moving the heat through the path
- Only 5 heat exchangers remain: (2), (3), (4), (5) and (7)
- The heat to be exchanged with hot and cold utilities has increased significantly. At the same time, the overall difference between **C** and **H** is still equal to: 120 – 130 = **-10**

Peculiar situations…

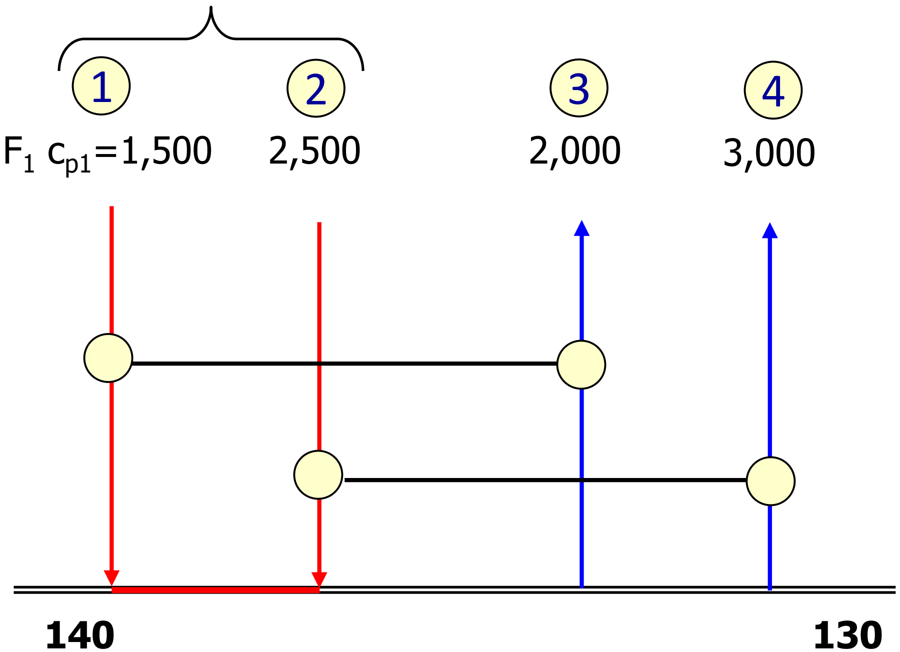


- $F_H\ C_{p\,H} < F_C\ C_{p\,C}$ for every stream but stream (3) is heated at T > 130 (when it interacts with stream (2)).
- The introduction of a heat exchanger between streams (1) and (3) does not satisfy any longer the ΔT = 10 condition as $T_{1\ out}$ = 140
- We still have $F_H\ C_{p\,H} < F_C\ C_{p\,C}$ for every stream, but now stream (4) with $T_{4\ in}$ = 130 satisfies the ΔT = 10 condition respect to $T_{1\ out}$ = 140

Other counter examples…

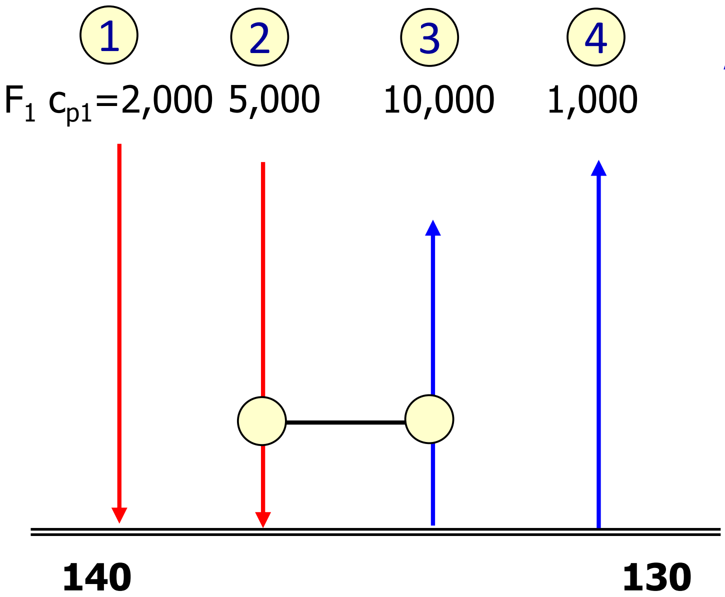


- The condition $F_H C_{p\,H} < F_C C_{p\,C}$ is **NOT** respected.

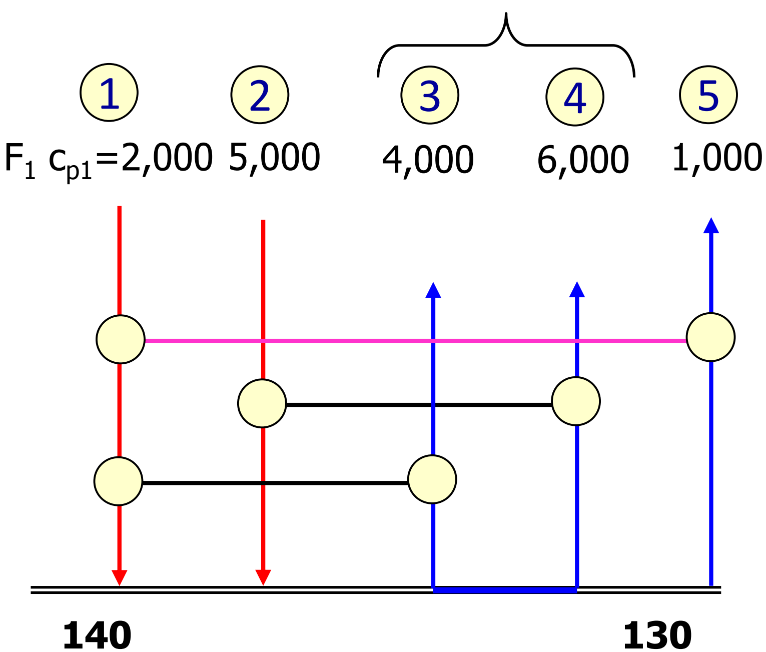


- We can split stream (1) into two streams, so condition $F_H C_{p\,H} < F_C C_{p\,C}$ is fulfilled.
- We then pair stream (1) with stream (3) and stream (2) with stream (4).

Apparent violation of ΔT_{min}



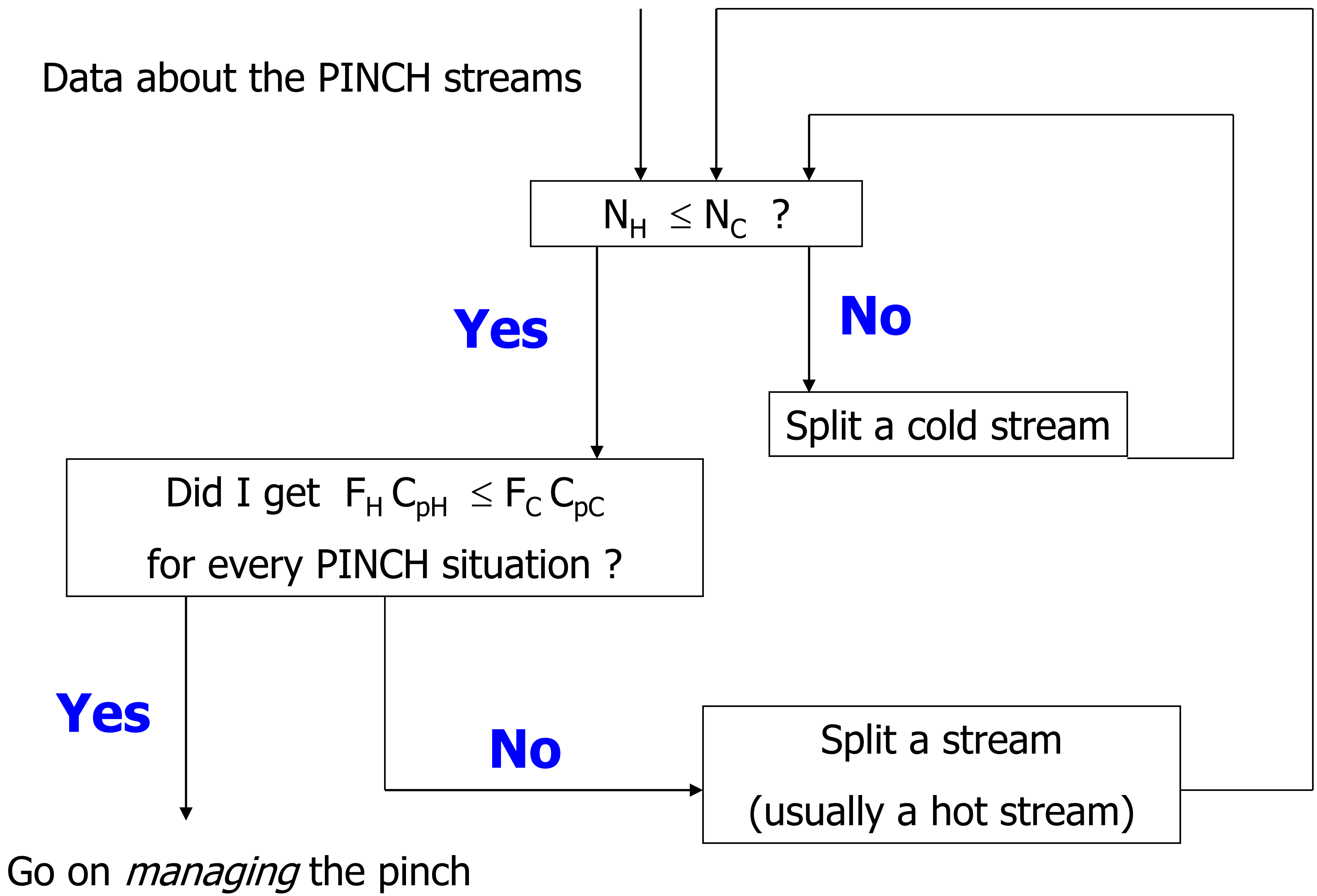
- Condition $F_H\, C_{p\,H} < F_C\, C_{p\,C}$ is **NOT** respected between stream (1) and stream (4)
- we can split stream (3)



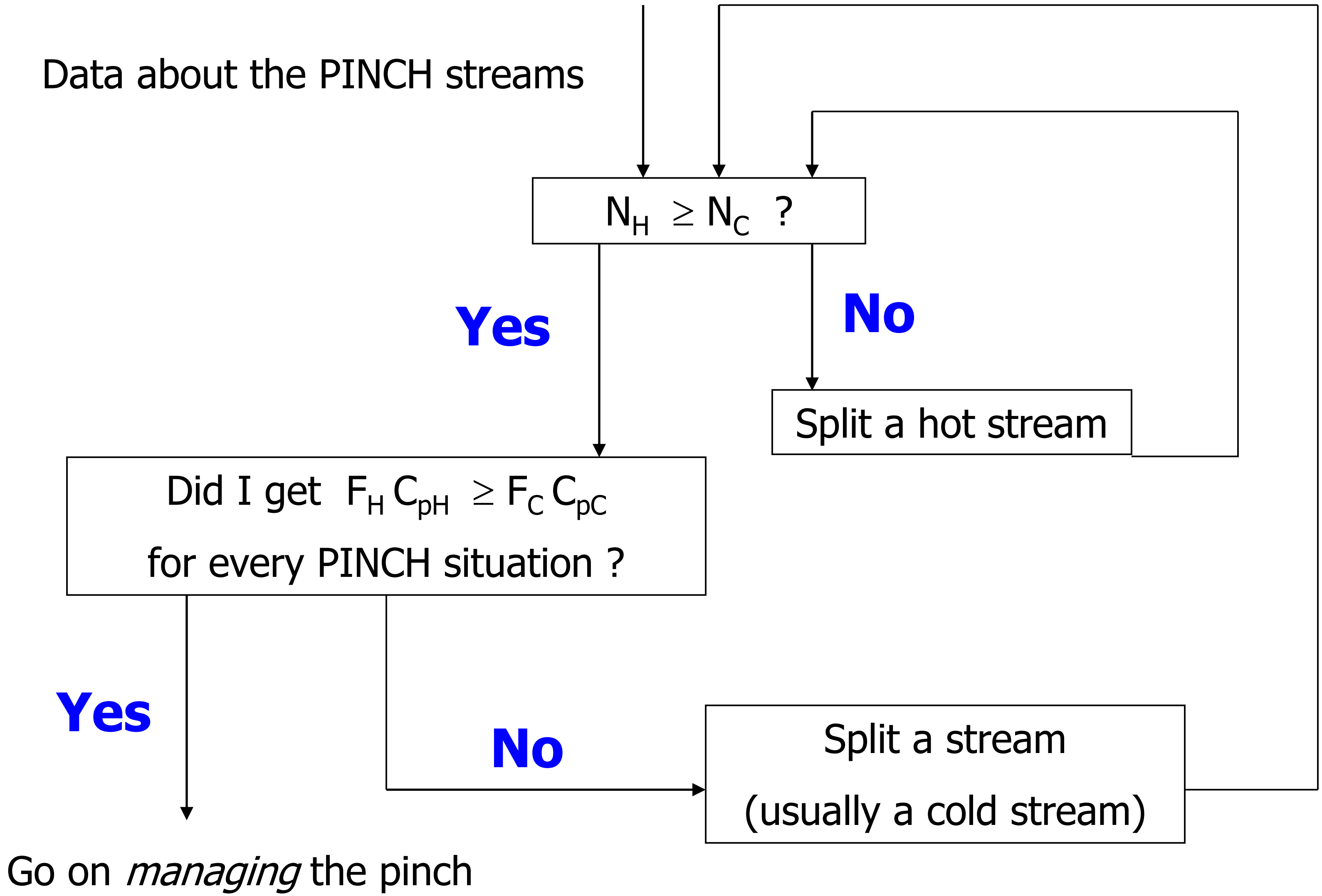
- Now pairings (2) – (4) and (1) – (3) are consistent with condition: $F_H\, C_{p\,H} < F_C\, C_{p\,C}$

- On the other hand, the pairing (1) – (5) seems not to meet the condition: $F_H\, C_{p\,H} < F_C\, C_{p\,C}$. Conversely, since the exchanger between streams (1) – (3) allowed moving away from the PINCH, there aren't any more problems raised by the apparent violation produced by: $F_H\, C_{p\,H} > F_C\, C_{p\,C}$

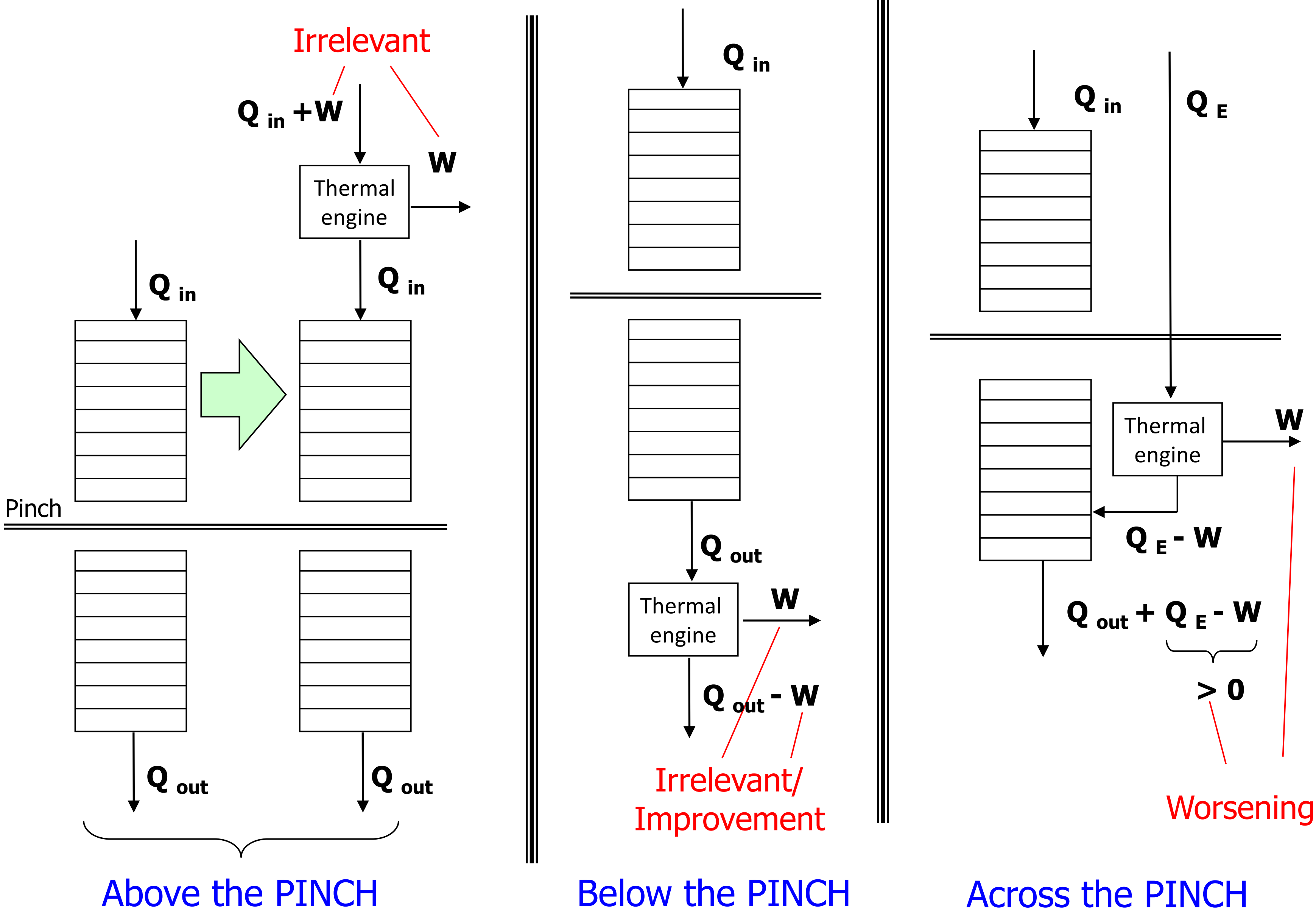
Above the PINCH



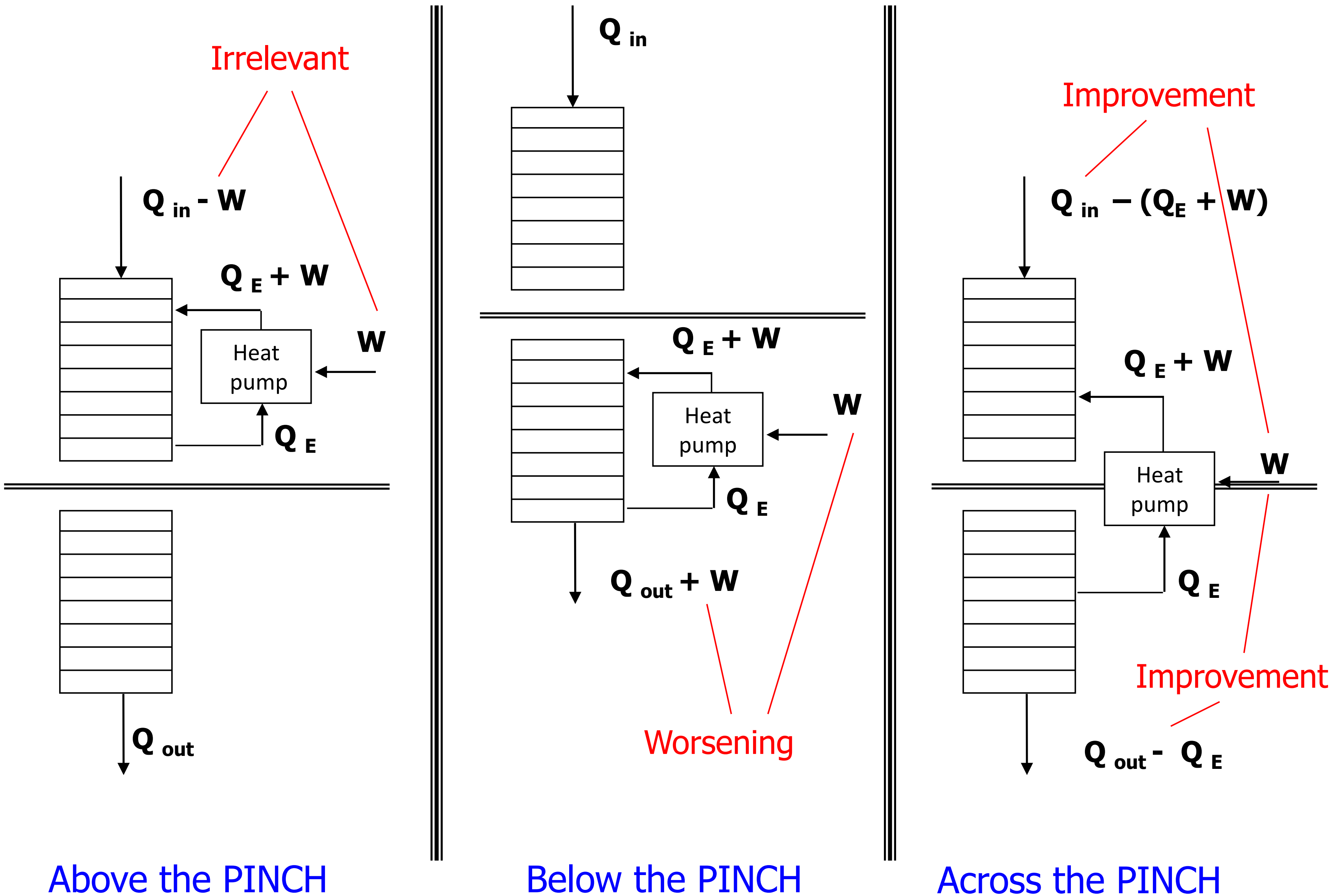
Below the PINCH



Thermal engines

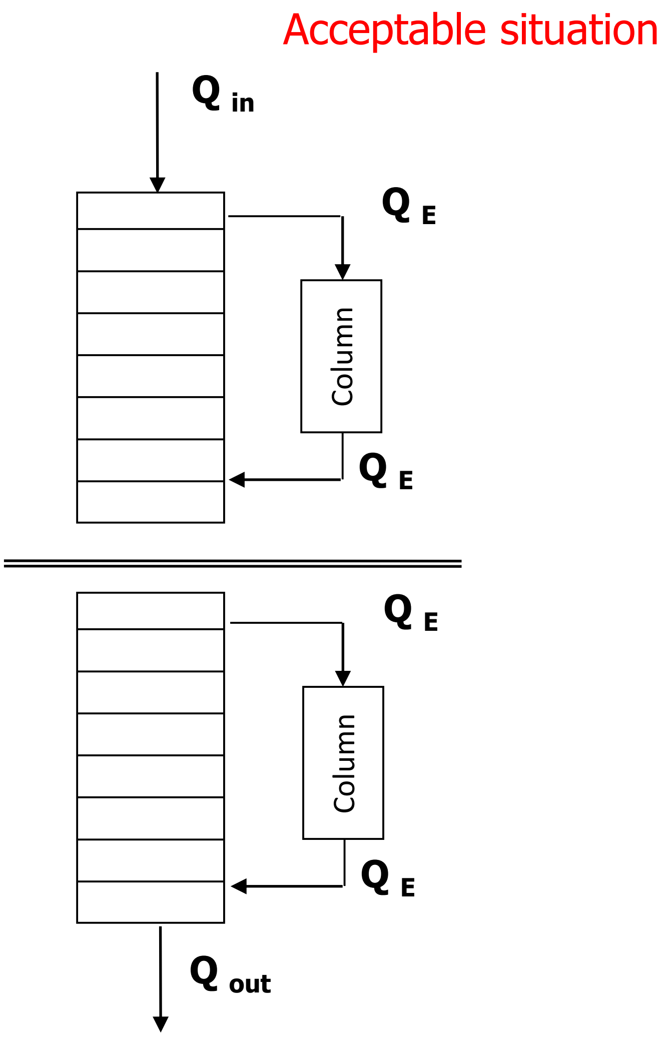


Heat pumps

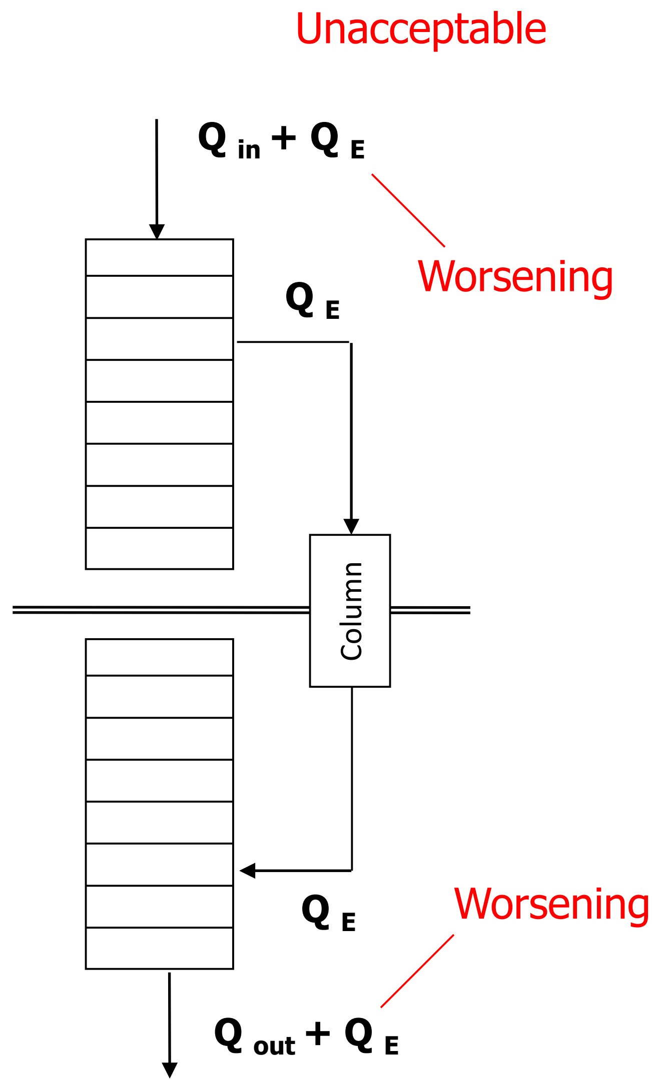


Irrelevant
Q in - W
Q E + W
Heat pump
W
Q E
Q out
Above the PINCH
Q in
Q E + W
Heat pump
W
Q E
Q out + W
Worsening
Below the PINCH
Improvement
Q in – (QE + W)
Q E + W
Heat pump
W
Q E
Improvement
Q out - Q E
Across the PINCH

Distillation columns



Above and below the PINCH



Across the PINCH

Heat Exchanger Networks

- Rather than approaching the heat exchange problem considering one device at a time, it is useful to consider the ENERGY INTEGRATION of the whole process.
- The goal of this global approach is to calculate the MINIMUM supply of energy (heating or cooling) for the heat exchangers network.
- It will thus be possible to determine the minimum number of heat exchangers needed to meet the design specifications.
- With reference to the HDA process, we have to:
  - Heat the inlet streams to the reactor section (fresh toluene and hydrogen, recycles) and the streams in the reboiler
  - Quench the output stream from the reactor, cool the products (down to T_{amb} for safe storage) and the streams in the condensers

Heat Exchanger Networks

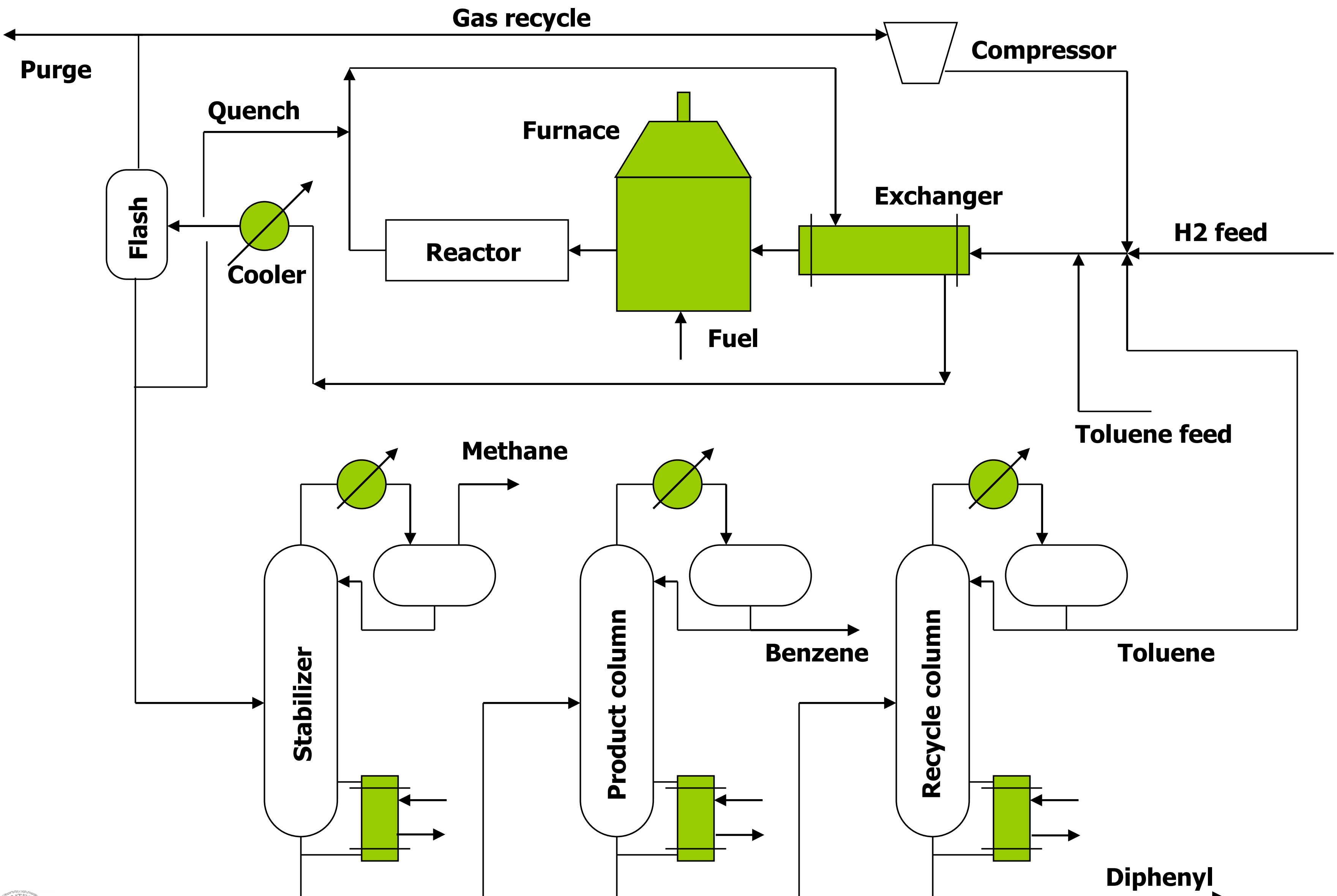
First law of Thermodynamics

Given *n* hot streams and *n* cold streams, it is possible to evaluate for each stream the heat either released (positive) or absorbed (negative) and algebraically add these values. If the resulting amount is positive then the heat must be removed, otherwise, the streams must be heated.

The problem is that it is NOT sufficient to know how much heat must be exchanged, but also whether or not such exchange complies with the Second Law of Thermodynamics: it is necessary that the T of the hot stream is higher than the T of the cold stream.

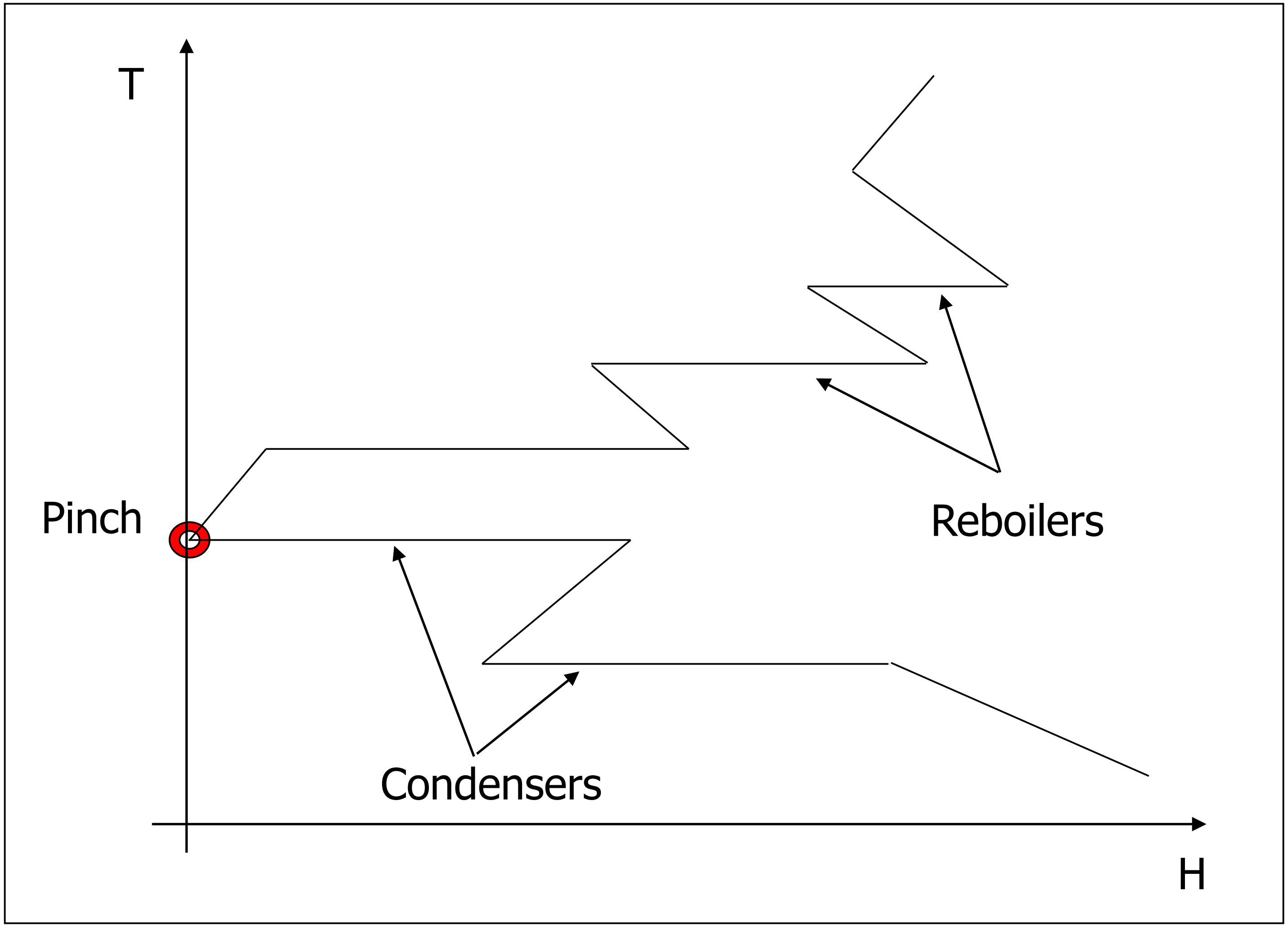
Moreover, the condition $T_{hot} > T_{cold}$ is not sufficient to make heat exchangers that are acceptable in terms of physical dimensions. Indeed, it is also necessary to assign a ΔT_{min} to have a suitable DRIVING FORCE to design an EFFICIENT heat exchanger.

Heat exchange in the HDA process



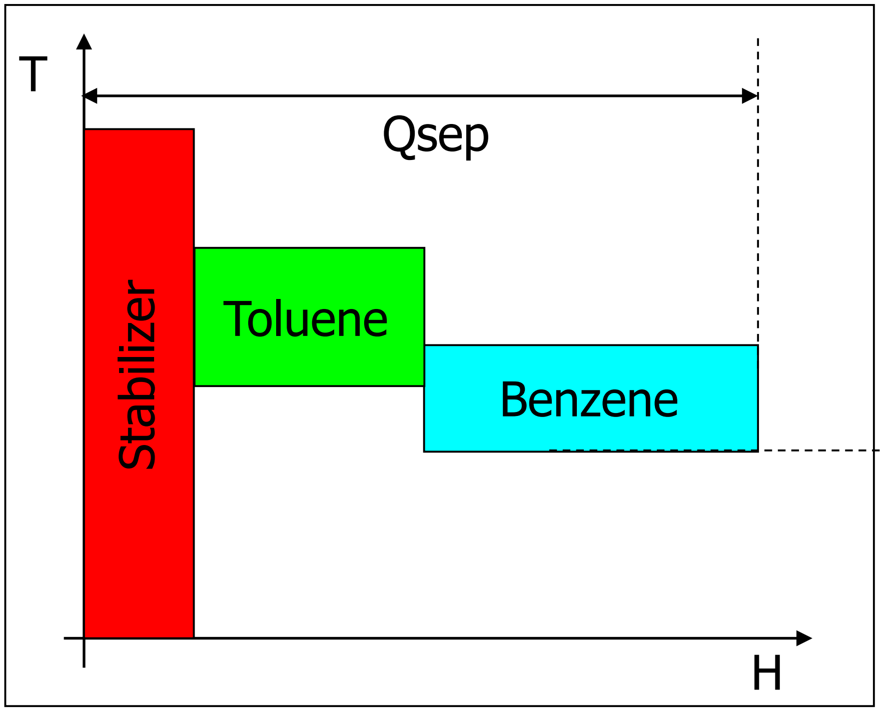
Applied case study

The grand composite curve of the HDA process for the liquid separation section has the following qualitative behavior:

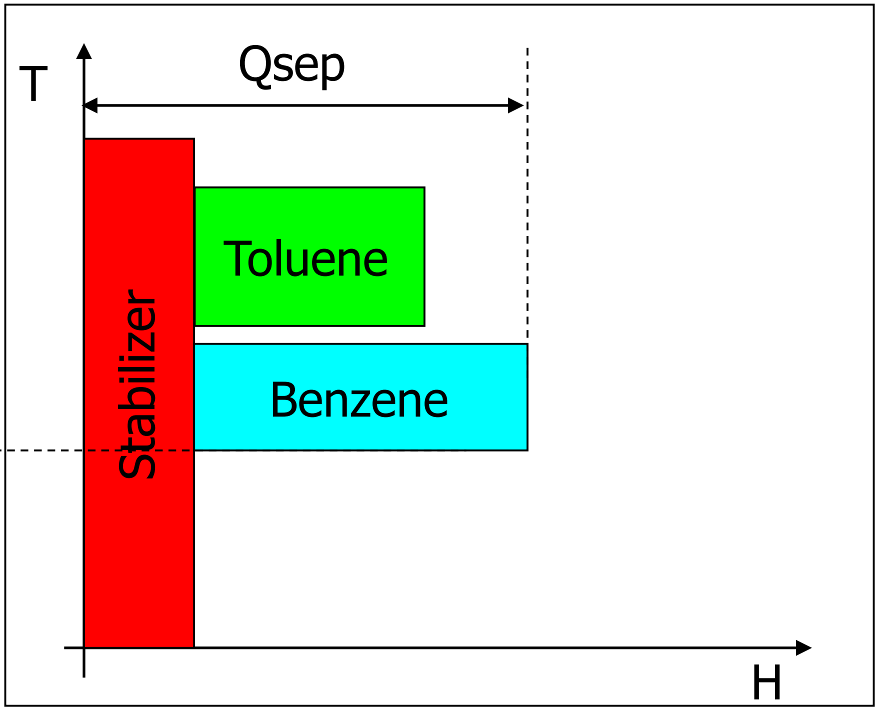


Applied case study

In the HDA process, **reboilers** and **condensers** are respectively above and below the pinch. The situation is undesirable. Therefore, to solve the problem it is possible to modify appropriately the operating pressure of the column(s) (*i.e.* pressure-swing) to *move* the column above the pinch.

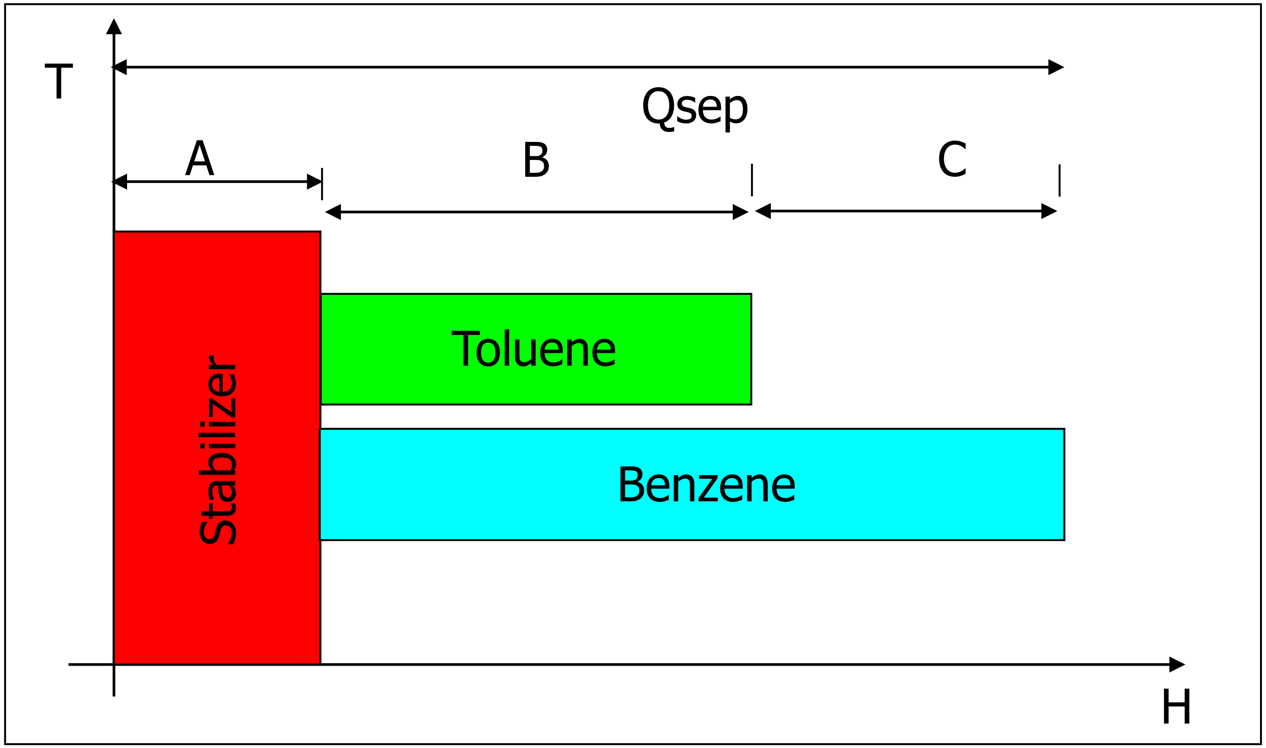


Conventional operating conditions



Operating conditions after introducing *pressure-swing*

Applied case study



By implementing the pressure-swing, the benzene column *moves* under the toluene one, which has been keeping the same energy demand. It is worth underlining that only the temperature at which the enthalpy exchange takes place has changed, as a consequence of the pressure-swing. The enthalpy request of the benzene column can then shift to the left because a portion B of the total heat that is required (B+C) is supplied by the toluene column. Now, the benzene column requires only a reduced quantity C from some utility.

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