Recap

Objective: Cover the basic principles of Systems Modeling for a Renewable Energy Process and be able to model a simple system.

- Importance of Systems Modeling in Renewable Energy
- Modeling systems
  - Stream properties
  - Thermodynamic relationships
  - Unit models
- **Heat integration & Pinch Analysis**
  - Basic Principles
  - Composite Curves
  - The Heat Cascade and the Grand Composite Curve
- Life Cycle Assessment
  - Goal & Scope Definition
  - Life Cycle Inventory
  - Life Cycle Impact Assessment
- Uncertainty Analysis & The Monte Carlo Method

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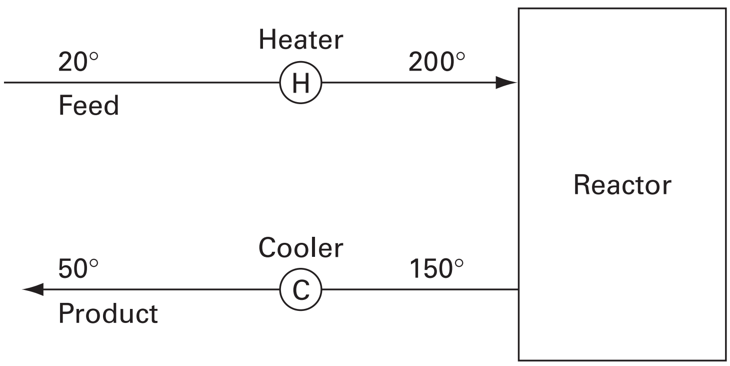
Pinch analysis

An example:



This could be more efficient...

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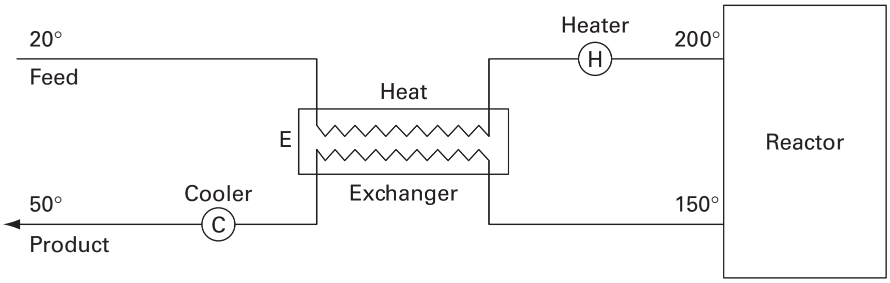
Pinch analysis

A slightly more efficient example:



By introducing a heat exchanger, we can recover some of the heat, but how much?

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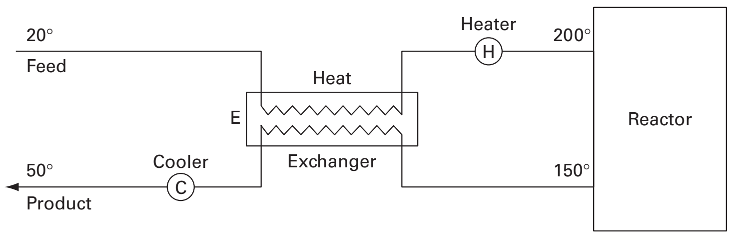
Pinch analysis



How much heat can we recover? We are limited by:

- Temperature difference = the driving force of heat exchange
  You cannot heat water from 90 to 100°C with water that needs to be cooled from 80°C to 60°C
- 1st law of thermodynamics: heat loads are conserved
  You cannot heat 1kg of water from 90 to 100°C with 1 g of water that needs to be cooled from 200°C to 190°C

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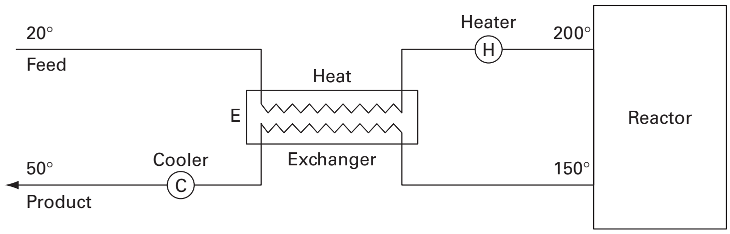
Pinch analysis



Heat load calculation:

$$Q = \Delta H = \int_{T_1}^{T_2} Cp\, dT = Cp\ (T_2 - T_1)$$

For a continuous process, we use enthalpy

Heat capacity

Assuming a constant Cp (or taking an average Cp)

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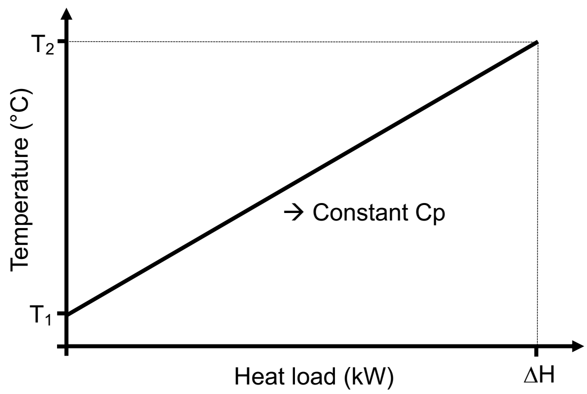
Pinch analysis

$$Q = \Delta H = Cp\ (T_2 - T_1) \quad \text{or} \quad T_2 = T_1 + \frac{1}{Cp}\Delta H$$



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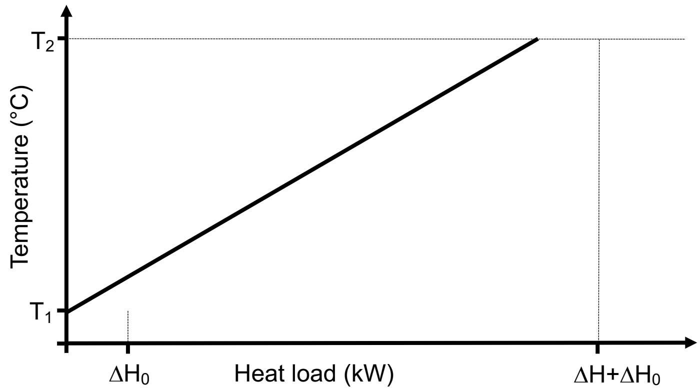
Pinch analysis

$$T_2 = T_1 + \frac{1}{Cp}(\Delta H_0 + \Delta H)$$



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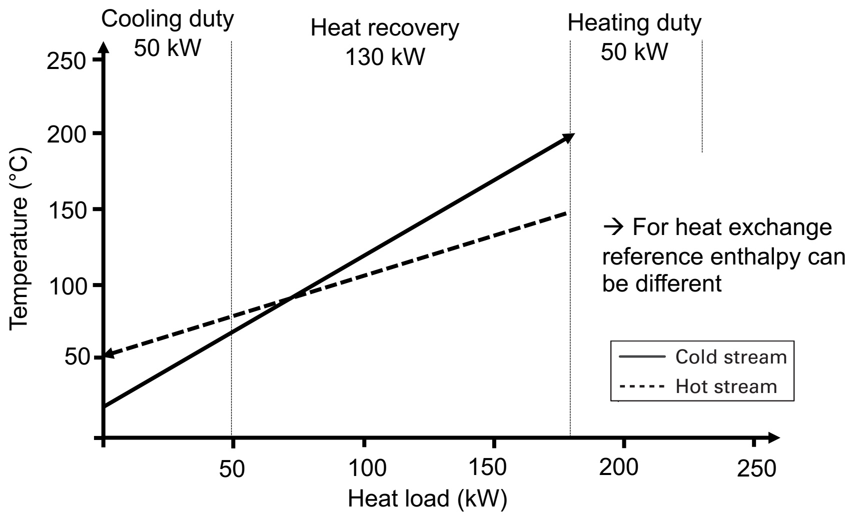
Pinch analysis



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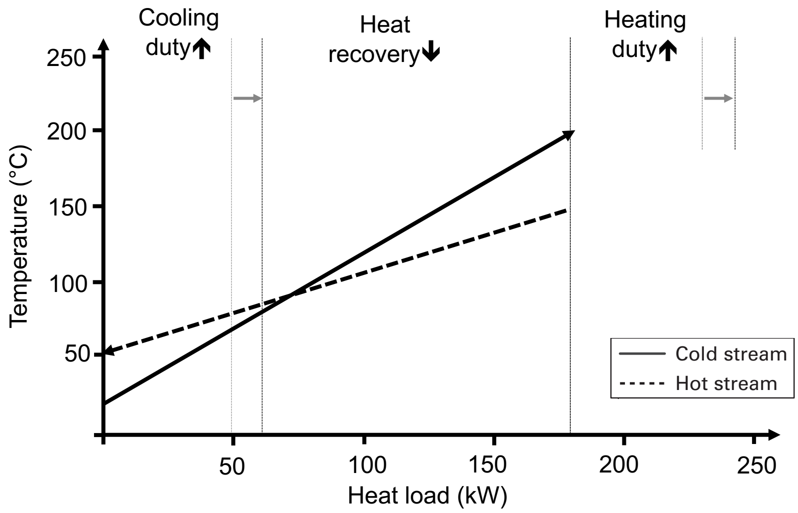
Pinch analysis



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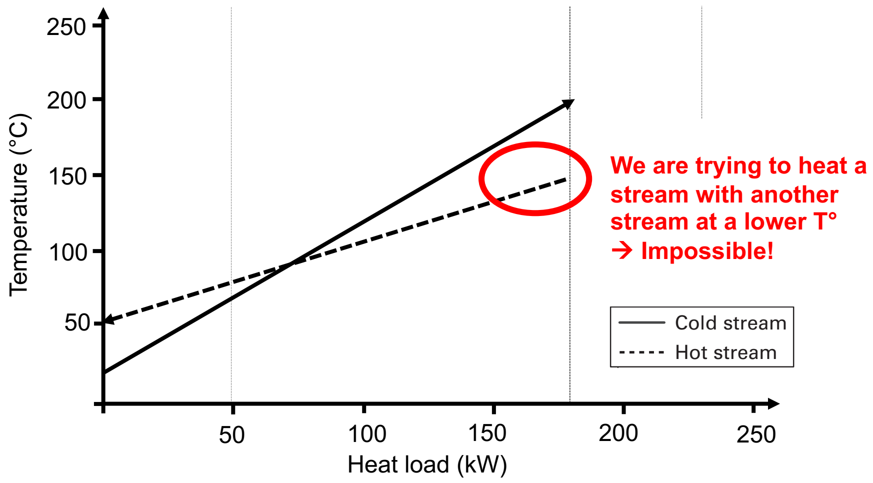
Pinch analysis



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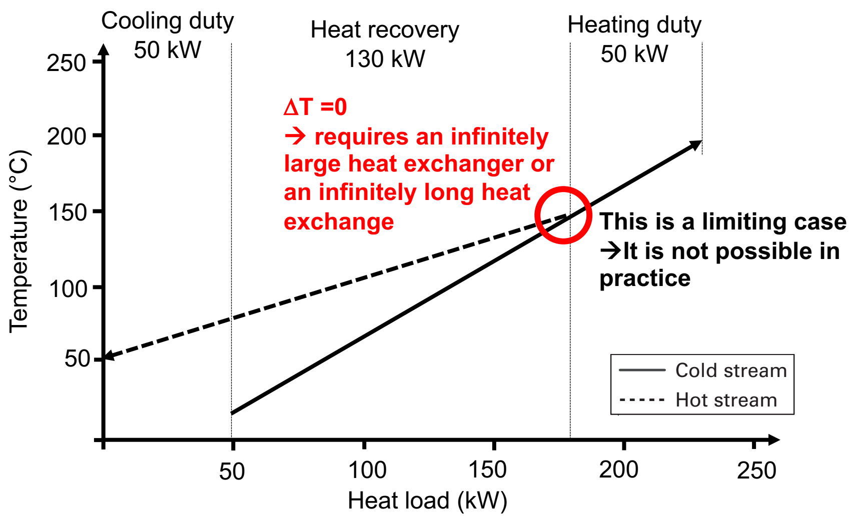
Pinch analysis



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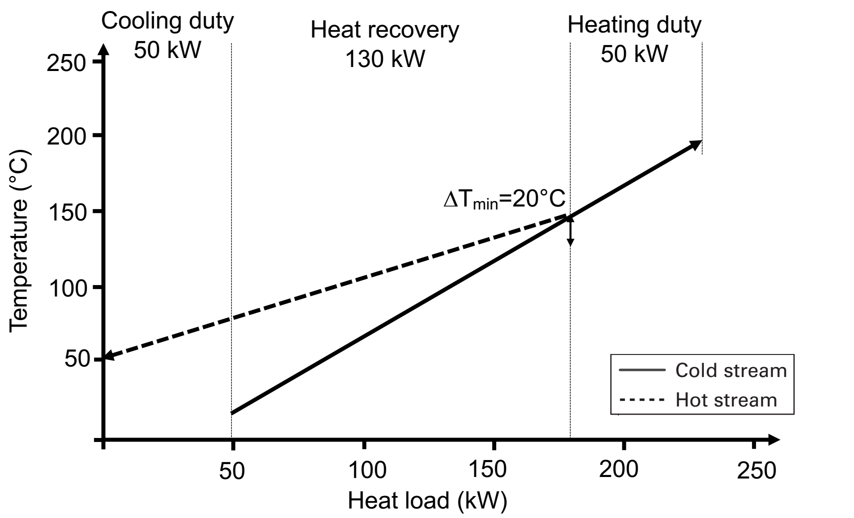
Pinch analysis



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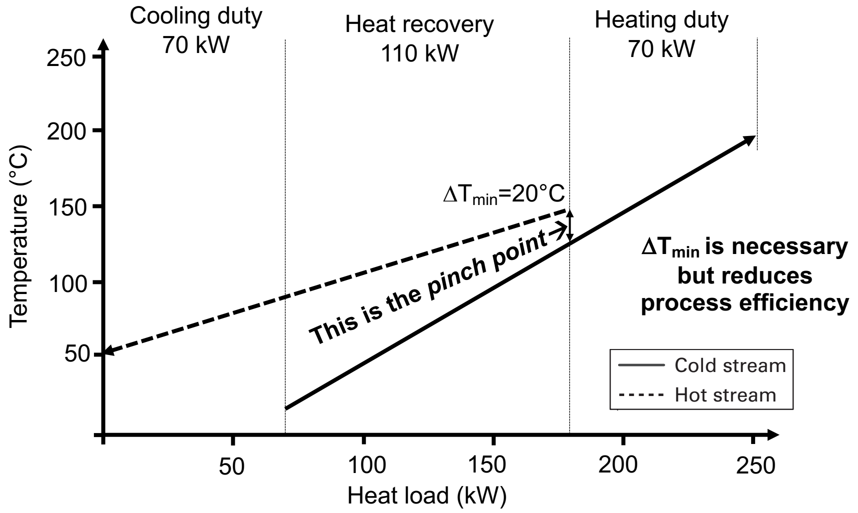
Pinch analysis



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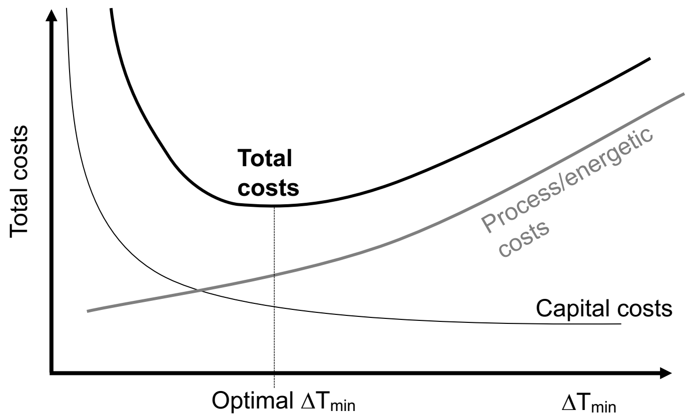
Pinch analysis

How is ΔT_{min} chosen?

Optimization:



Rule of thumb: ΔT_{min}= 8°C for gases, 4°C for liquids, 2°C for evaporating/condensing streams, and 25°C for reacting streams

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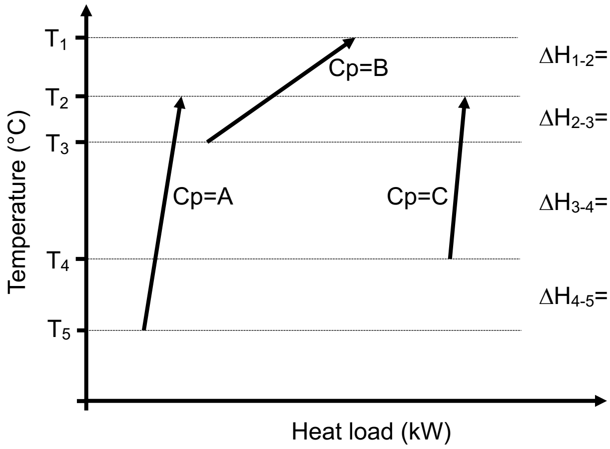
Pinch analysis: complex systems

How to handle more complex (multi-stream) systems?

Let's look at three cold streams:

What is Q for each T° interval?



$\Delta H_{1\text{-}2}$= B (T_1-T_2)

$\Delta H_{2\text{-}3}$= (A+B+C) (T_2-T_3)

$\Delta H_{3\text{-}4}$= (A+C) (T_3-T_4)

$\Delta H_{4\text{-}5}$= A (T_4-T_5)

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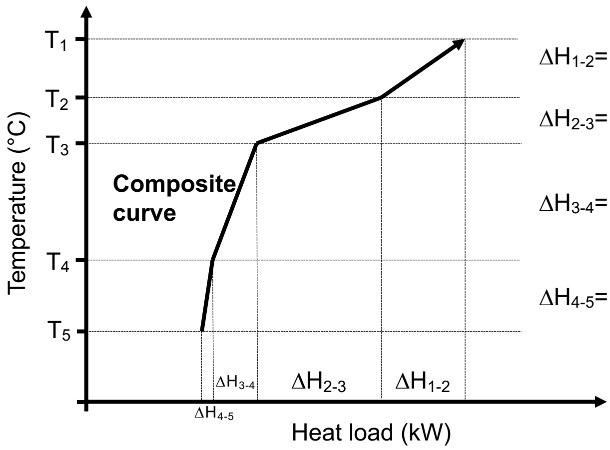
Pinch analysis: complex systems

If you assume that there are no restrictions in heat exchanger configurations, you can just use $Q_{interval}$:



$\Delta H_{1\text{-}2}$= B (T_1-T_2)

$\Delta H_{2\text{-}3}$= (A+B+C) (T_2-T_3)

$\Delta H_{3\text{-}4}$= (A+C) (T_3-T_4)

$\Delta H_{4\text{-}5}$= A (T_4-T_5)

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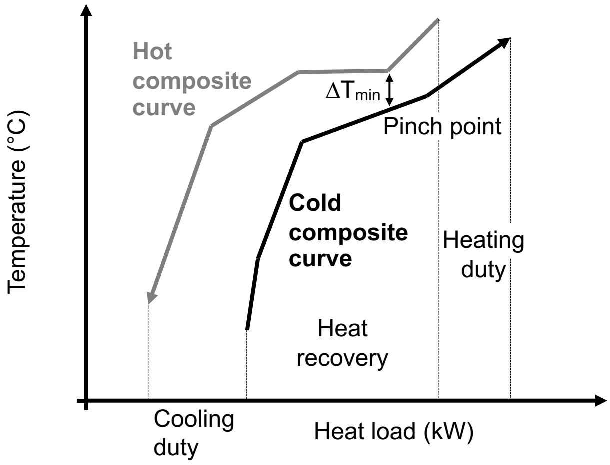
Pinch analysis: complex systems

We can construct a hot and cold composite curves for an entire multi-stream process:



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Pinch analysis: the heat cascade

How do you apply this graphical method with a computer?

Can an algorithm be developed for this graphical method?

→ This algorithm is referred to as *solving the heat cascade*

Starting point:

Inlet T° of unit *i* — Outlet T° of unit *i* — Heat exchanged in unit *i*

Thermal stream matrix: $\mathbf{Ts} = \begin{bmatrix} T_{i,in} & T_{i,out} & Q_i \\ T_{j,in} & T_{j,out} & Q_j \\ \ldots & \ldots & \ldots \end{bmatrix}$

→ For continuous processes it is computed with:

$Q_i = H_{i,out} - H_{i,in}$

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Pinch analysis: the heat cascade

From this matrix:

$$\mathbf{Ts} = \begin{bmatrix} T_{i,in} & T_{i,out} & Q_i \\ T_{j,in} & T_{j,out} & Q_j \\ \cdots & \cdots & \cdots \end{bmatrix}$$

→ This is extracted from your process model

We can determine the hot and cold streams:

$Q_i = H_{i,out} - H_{i,in} > 0$ Heat is received → It's a cold stream

$Q_i = H_{i,out} - H_{i,in} < 0$ Heat is removed → It's a hot stream

Use Q not T° to determine the type of stream (e.g. a positive ΔT≠ always a cold stream)

Once identified, it is useful to shift the temperatures of the hot and cold streams…

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Pinch analysis: the heat cascade

For cold streams:

$Q_i > 0 \quad T^*_i = T_i + \frac{\Delta T_{min}}{2}$

For hot streams:

$Q_i < 0 \quad T^*_i = T_i - \frac{\Delta T_{min}}{2}$

This results in a new matrix →

$$\begin{bmatrix} T^*_{i,in} & T^*_{i,out} & Q_i \\ T^*_{j,in} & T^*_{j,out} & Q_j \\ \cdots & \cdots & \cdots \end{bmatrix}$$

Again, for ΔT_{min}, we can use:

- ΔT_{min} = 8°C for gaseous streams
- ΔT_{min} = 4°C for liquid streams
- ΔT_{min} = 2°C for evaporating and condensing streams
- ΔT_{min} = 25°C for reacting streams

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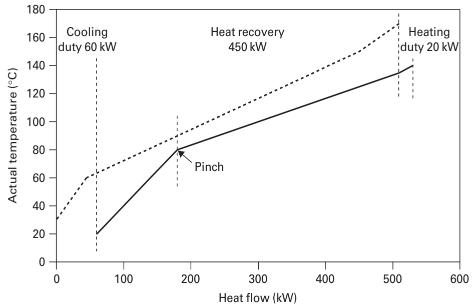
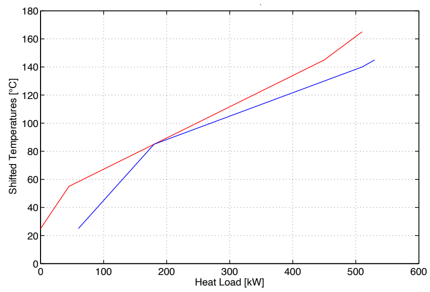
Pinch analysis: the heat cascade

This is what the change looks like:

Composite curve



T°-shifted composite curve



This shift make things easier because:

- With this shift, it is easier to identify the pinch…
- You can have stream-specific ΔT_{min} without knowing where the pinch is.

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Pinch analysis: the heat cascade

We also need a Cp for each heat exchange…

Cp is calculated from the heat exchanged in each unit (Q_i):

$$Cp_i = \frac{|Q_i|}{|T_{i,in} - T_{i,out}|}$$

This allows us to linearize Cp for each heat exchange (which is not necessarily the case for your process model).

A linearized Cp is not the same as using a constant Cp (i.e. independent of temperature).

Constant Cp → Cp ≠ f(T)
Linearized Cp → $\overline{Cp}\,(T_1-T_2)$ = [Cp(T_1)+Cp(T_2)]/2 * (T_1-T_2)

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Pinch analysis: the heat cascade

What about phase change?

$$Cp_i = \frac{|Q_i|}{|T_{i,in} - T_{i,out}|}$$

For a phase change: $T_{in}=T_{out}$

→ Phase changes have $Cp = \infty$

Two options:

- Identify and treat phase change separately
- Easier algorithm: $T^*_{i,out} = T^*_{i,out} + \Delta T_{\min} / 1000$ → $Cp_i = \frac{|Q_i|}{|\Delta T_{\min} / 1000|}$

$Cp_{\text{phase change}} >> Cp_{\text{other}}$ → A good approximation

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Pinch analysis: the heat cascade

At this point, we can define the following matrix:

Modified inlet Temperature — Modified outlet Temperature — Linearized Cp

$$\mathbf{Ts'} = \begin{bmatrix} T^*_{i,in} & T^*_{i,out} & Cp_i \\ T^*_{j,in} & T^*_{j,out} & Cp_j \\ \ldots & \ldots & \ldots \end{bmatrix}$$

Don't forget that:

- T_{in} or T_{out} are modified by $+\frac{\Delta T_{\min}}{2}$ for cold streams and $-\frac{\Delta T_{\min}}{2}$ for hot streams
- Linearized Cp values are calculated from Q and T_{in} and T_{out}

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Pinch analysis: the heat cascade

We now have to find the temperature intervals for our heat integration:

Starting point:

$$\mathbf{Ts'} = \begin{bmatrix} T^*_{i,in} & T^*_{i,out} & Cp_i \\ T^*_{j,in} & T^*_{j,out} & Cp_j \\ \ldots & \ldots & \ldots \end{bmatrix}$$

Find all unique temperatures (in and out) in **Ts'** and form $\mathbf{T_{int}}$:

We form a matrix of temperature intervals with the unique inlet and outlet temperatures:

$$\mathbf{T}_{\text{int}} = \begin{bmatrix} T^*_1 & T^*_2 \\ T^*_2 & T^*_3 \\ T^*_3 & T^*_4 \\ \ldots & \ldots \end{bmatrix}$$

Unique inlet and outlet temperatures

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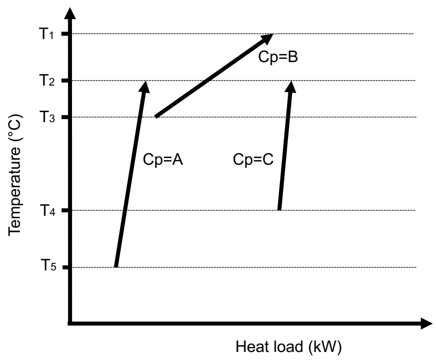
Pinch analysis: the heat cascade

Let's look at what we are trying to do graphically…

Let's look at the following example:



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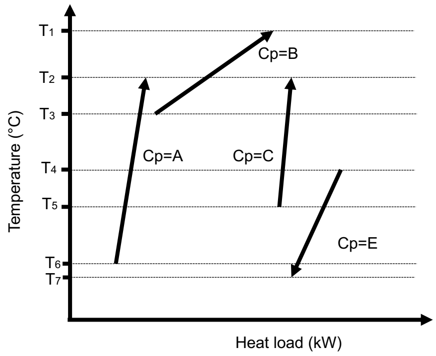
Pinch analysis: the heat cascade

Let's look at what we are trying to do graphically…

Let's look at the following example:

We can also add 1 (or more) hot streams…



We build a composite curve with both streams:

$\Delta H_{1\text{-}2}$= B (T_1-T_2)

$\Delta H_{2\text{-}3}$= (A+B+C) (T_2-T_3)

$\Delta H_{3\text{-}4}$= (A+C) (T_3-T_4)

$\Delta H_{4\text{-}5}$= (A+C-E) (T_4-T_5)

$\Delta H_{5\text{-}6}$= (A-E) (T_5-T_6)

$\Delta H_{6\text{-}7}$= (-E) (T_6-T_7)

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Pinch analysis: the heat cascade

Let's look at what we are trying to do graphically…

Let's look at the following example:

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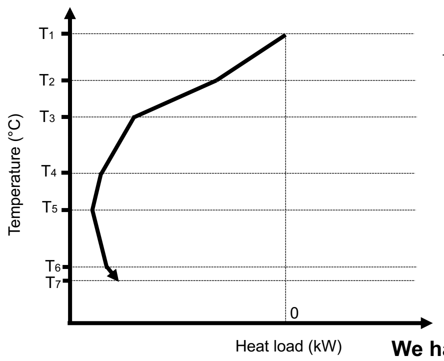

We build a composite curve with both streams:

$-\Delta H_{1\text{-}2}$= -B (T_1-T_2)

$-\Delta H_{2\text{-}3}$= -(A+B+C) (T_2-T_3)

$-\Delta H_{3\text{-}4}$= -(A+C) (T_3-T_4)

$-\Delta H_{4\text{-}5}$= -(A+C-E) (T_4-T_5)

$-\Delta H_{5\text{-}6}$= -(A-E) (T_5-T_6)

$-\Delta H_{6\text{-}7}$= -(-E) (T_6-T_7)

We have shifted the reference from the system to the user!
→ We add negative signs.
→ This builds one giant hot stream

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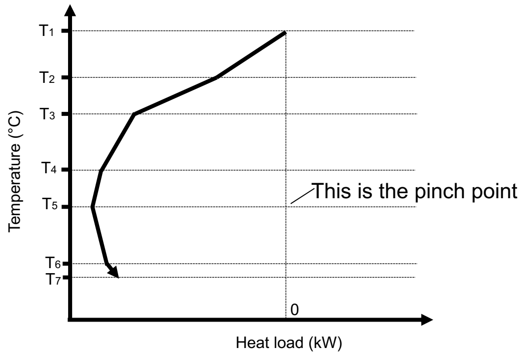
Pinch analysis: the heat cascade

Let's look at what we are trying to do graphically…

Let's look at the following example:

We can also add 1 (or more) hot streams…



Let's go back to trying to do this with a computer…

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Pinch analysis: the heat cascade

With these two matrices, we can truly start out heat cascade!

$$\mathbf{Ts'} = \begin{bmatrix} T^*_{i,in} & T^*_{i,out} & Cp_i \\ T^*_{j,in} & T^*_{j,out} & Cp_j \\ \ldots & \ldots & \ldots \end{bmatrix} \qquad \mathbf{T}_{\text{int}} = \begin{bmatrix} T^*_1 & T^*_2 \\ T^*_2 & T^*_3 \\ T^*_3 & T^*_4 \\ \ldots & \ldots \end{bmatrix}$$

We start with the highest T° interval and *cascade* down.

To do this, we have to identify all the units *i* (or heat streams) that operate within a given T° interval…

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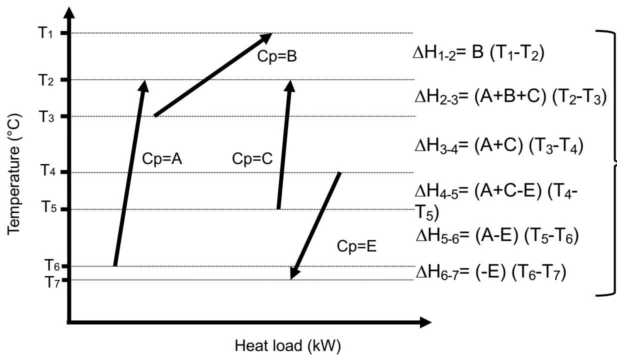
Pinch analysis: the heat cascade

With these two matrices, we can truly start out heat cascade!

$$\mathbf{Ts'} = \begin{bmatrix} T^*_{i,in} & T^*_{i,out} & Cp_i \\ T^*_{j,in} & T^*_{j,out} & Cp_j \\ \dots & \dots & \dots \end{bmatrix} \qquad \mathbf{T}_{\text{int}} = \begin{bmatrix} T^*_1 & T^*_2 \\ T^*_2 & T^*_3 \\ T^*_3 & T^*_4 \\ \dots & \dots \end{bmatrix}$$



In other words, we need to determine which Cp values to apply for each T interval….

→ This is less straightforward with a computer than graphically!

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Pinch analysis: the heat cascade

With these two matrices, we can truly start out heat cascade!

$$\mathbf{Ts'} = \begin{bmatrix} T^*_{i,in} & T^*_{i,out} & Cp_i \\ T^*_{j,in} & T^*_{j,out} & Cp_j \\ \dots & \dots & \dots \end{bmatrix} \qquad \mathbf{T}_{\text{int}} = \begin{bmatrix} T^*_1 & T^*_2 \\ T^*_2 & T^*_3 \\ T^*_3 & T^*_4 \\ \dots & \dots \end{bmatrix}$$

We start with the highest T° interval and *cascade* down.

To do this, we have to identify all the units *i* (or heat streams) that operate within a given T° interval…

→ We identify the relevant lines in **Ts'** for interval k, which we call $\mathbf{T_{rel,k}}$

$$\mathbf{T_{rel,k}} = \mathbf{Ts'} \text{ for which } \mathbf{Ts'}(i, high) > \mathbf{T}_{\text{int}}(k,2) \ \& \ \mathbf{Ts'}(i, low) < \mathbf{T}_{\text{int}}(k,1)$$

Matrix of relevant lines for interval *k* — High or low temperature of line *i* in ***Ts'***

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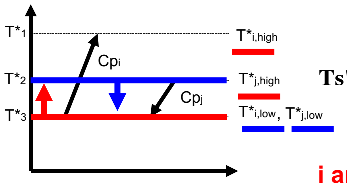
Pinch analysis: the heat cascade

For each line *k* of $\mathbf{T_{int}}$, we include lines from Ts' for which:

- We identify which lines in Ts' have a high temperature greater than the low temperature of interval k.
- We identify which lines in Ts' have a low temperature smaller than high temperature of interval k

$$\mathbf{T_{rel,k}} = \mathbf{Ts'} \text{ for which } \mathbf{Ts'}(i,high) > \mathbf{T}_{int}(k,2) \;\&\; \mathbf{Ts'}(i,low) < \mathbf{T}_{int}(k,1)$$



$$\mathbf{Ts'} = \begin{bmatrix} T^*_{i,in} & T^*_{i,out} & Cp_i \\ T^*_{j,in} & T^*_{j,out} & Cp_j \\ \dots & \dots & \dots \end{bmatrix} \qquad \mathbf{T}_{int} = \begin{bmatrix} T^*_1 & T^*_2 \\ T^*_2 & T^*_3 \\ T^*_3 & T^*_4 \\ \dots & \dots \end{bmatrix}$$

i and j satisfy condition 1   **i and j satisfy condition 2**

In this example, lines i and j are used for calculating the cascade of interval k

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Pinch analysis: the heat cascade

Now, the relevant lines for interval k are “stored” in $\mathbf{T_{rel,k}}$.

With this, we sum up the relevant Cps to calculate the heat in interval *k*:

$$Q_k = \sum[\pm Cp]\ (T_{high} - T_{low}) = \sum_i \left[\mathbf{T_{rel,k}(i,3)} \left(-\frac{Q_i}{|Q_i|} \right) \right] (\mathbf{T_{int}(1,k)} - \mathbf{T_{int}(2,k)})$$

We want a positive sign when there is a surplus and a negative sign when heat needs to be provided

What is needed is the reverse sign of what is calculated with the enthalpies, so we calculate that sign and then reverse it

Starting at 0 for the first interval, we now calculate the cumulative heat that is needed (we “cascade the heat”):

$$Q_{c,k} = \sum_k Q_k$$

Cumulative heat for interval *k*

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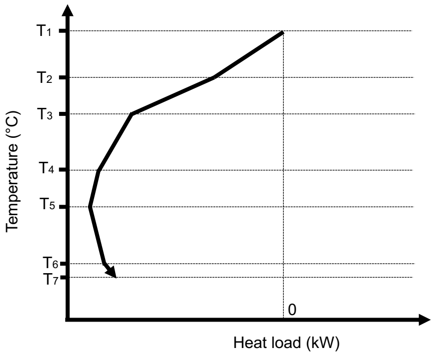
Pinch analysis: the heat cascade

Let's look back at what we were trying to do graphically…

We can also add 1 (or more) heat streams…



We build a composite curve with both streams:

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$\Delta H_{5\text{-}6}$= (A-E) (T_5-T_6)

$\Delta H_{6\text{-}7}$= (-E) (T_6-T_7)

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Pinch analysis: the heat cascade

The lowest value of $Q_{c,k}$ is the pinch point.

However, we want all the cascaded heat to be positive (because positive heat flows from a high T° to a low T°), so we set the pinch to zero:

$$Q'_{c,k} = Q_{c,k} + \left|\min\left(Q_{c,k}\right)\right|$$

By adding the absolute value of the minimum cumulative heat, we shift everything to positive values

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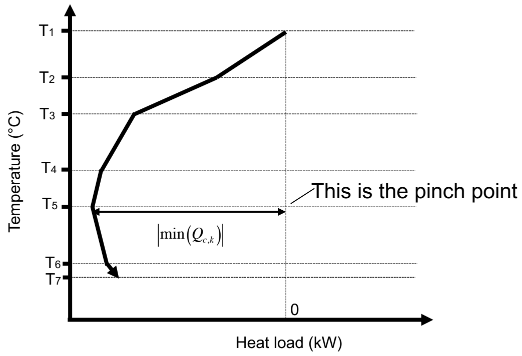
Pinch analysis: the heat cascade

Let's look back at what we are trying to do graphically…

Let's look at the following example:



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Pinch analysis: the heat cascade

The lowest value of $Q_{c,k}$ is the pinch point.

However, we want all the cascaded heat to be positive (because positive heat flows from a high T° to a low T°), so we set the pinch to zero:

$$Q'_{c,k} = Q_{c,k} + \left|\min\left(Q_{c,k}\right)\right|$$

By adding the absolute value of the minimum cumulative heat, we shift everything to positive values

We are now respecting the golden rule of pinch analysis:
Don't transfer heat through the pinch!
Otherwise, you would be heating the part of the process that needs to be cooled!

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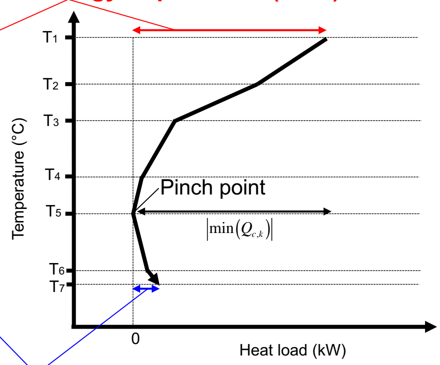
Pinch analysis: the heat cascade

We now have everything we need to build the *Grand Composite Curve*:

This is the minimum energy requirement (MER)

$$\text{GCC} = \begin{bmatrix} \mathbf{T_{int}(1,1)} & |\min(Q_{c,k})| \\ \mathbf{T_{int}(1,2)} & Q'_{c,1} \\ \mathbf{T_{int}(2,2)} & Q'_{c,2} \\ \dots & \dots \\ \mathbf{T_{int}(n,2)} & Q'_{c,n} \end{bmatrix}$$



This is the minimum cooling requirement (MCR)

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Pinch analysis: the heat cascade

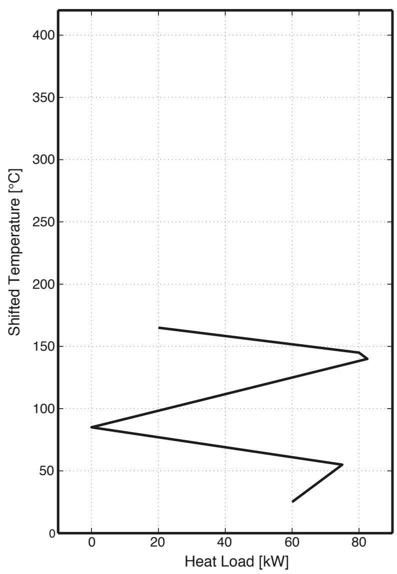
How do we fulfill the hot and cold utilities?

We have to fit **all hot utilities above the curve**

and **all cold utilities below the curve**

For example:

- Hot utility: **gas stream coming out at 400°C that needs to be cooled to 60°C**



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Pinch analysis: the heat cascade

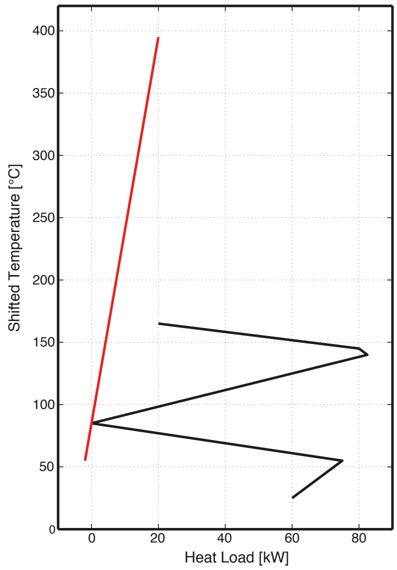
How do we fulfill the hot and cold utilities?

We have to fit **all hot utilities above the curve**

and **all cold utilities below the curve**

For example:

- Hot utility: **gas stream coming out at 400°C that needs to be cooled to 60°C**
- Cold utility: **River water that comes in at 15°C and must be released no hotter than 25°C**



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Pinch analysis: the heat cascade

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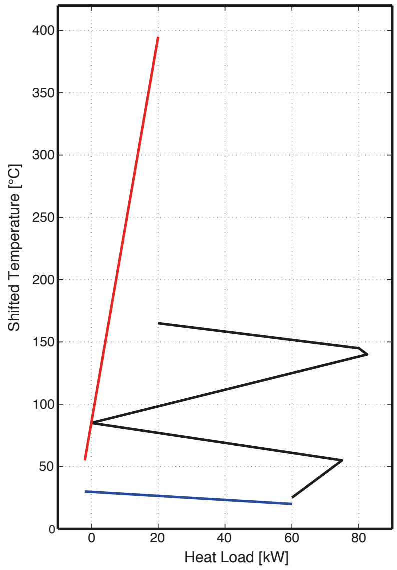
For example:

- Hot utility: **gas stream coming out at 400°C that needs to be cooled to 60°C**
- Cold utility: **River water that comes in at 15°C and must be released no hotter than 25°C**



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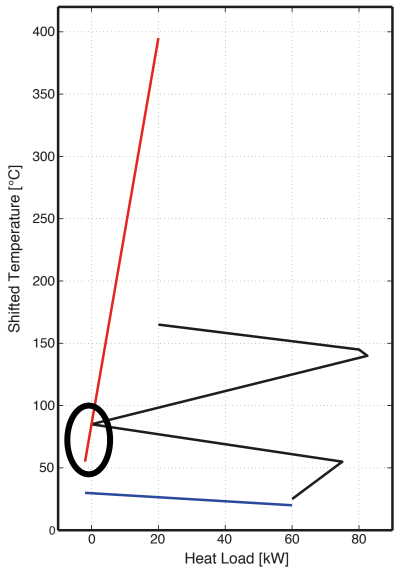
Pinch analysis: the heat cascade

How do we fulfill the hot and cold utilities?

For example:

- Hot utility: **gas stream coming out at 400°C that needs to be cooled to 60°C**
- Cold utility: **River water that comes in at 15°C and must be released no hotter than 25°C**

In this example, the hot utility goes below the pinch and contributes to increasing the cold utility… This is common.



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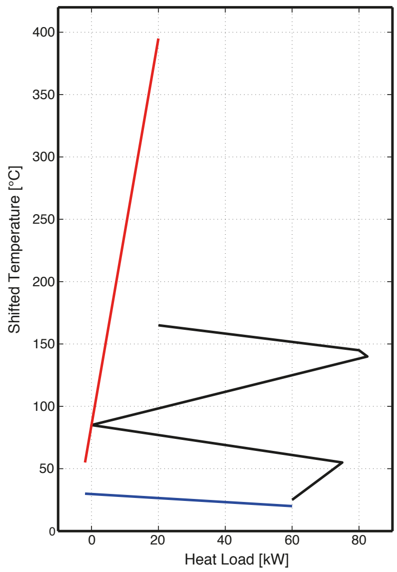
Pinch analysis: the heat cascade

Another way of representing this process is to integrate the hot and cold utilities into the total process and the Grand Composite Curve.



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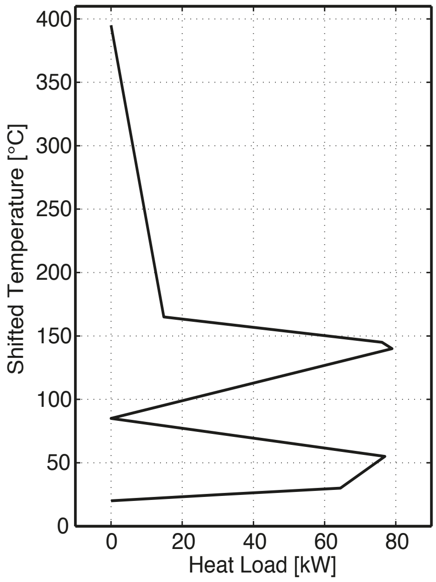
Pinch analysis: the heat cascade

Another way of representing this process is to integrate the hot and cold utilities into the total process and the Grand Composite Curve.

Not surprisingly, the heat and cold utility requirements disappear and the process becomes self sufficient.

We can also represent this as a hot and cold composite curve.



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Pinch analysis: the heat cascade

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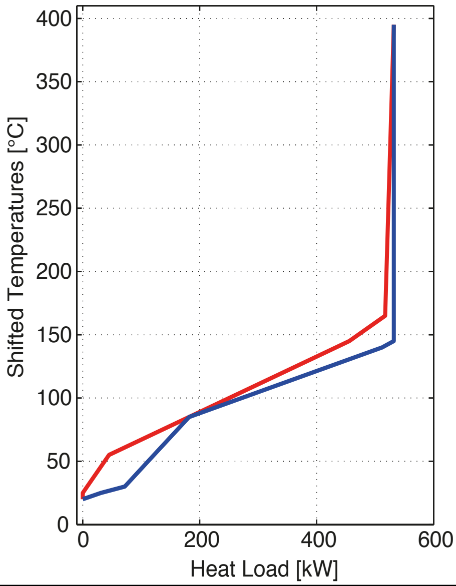

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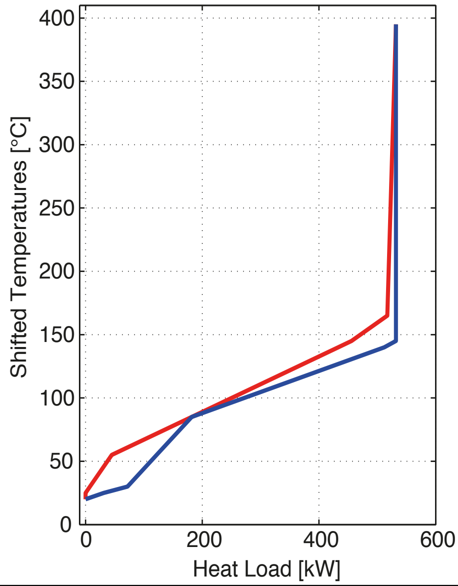
Pinch analysis: the heat cascade

<u>Minimum heat exchanger area</u>

Using the two composite curves, we can calculate a minimum heat exchanger area.

We can assume that these two curves are two long streams between which you can perform heat exchange.

To start, you break up the curves into segments of constant Cp_i



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Pinch analysis: the heat cascade

<u>Minimum heat exchanger area</u>

To start, you break up the curves into segments of constant Cp_i

$$A_{\min} = \sum_i^{n_{seg.}} A_i = \sum_i^{n_{seg.}} \frac{Q_i}{U_i \Delta T_{lm,i}}$$

Minimum total area — $A_{\min}$

Heat exchanger area for a constant-Cp segment — A_i

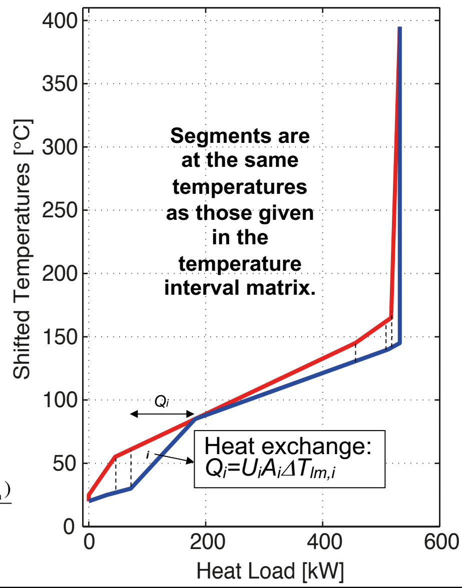
Heat exchanged for segment *i* — Q_i

Heat transfer coefficient for segment *i* — U_i

Logarithmic mean temperature for segment *i* — $\Delta T_{lm,i}$

<u>Logarithmic mean temperature for segment *i*:</u>

$$\Delta T_{lm,i} = \frac{(T_{in,hot} - T_{out,cold} + \Delta T_{\min}) - (T_{out,hot} - T_{in,cold} + \Delta T_{\min})}{\ln\left(\dfrac{T_{in,hot} - T_{out,cold} + \Delta T_{\min}}{T_{out,hot} - T_{in,cold} + \Delta T_{\min}}\right)}$$



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