# Energétique avancée

# Process integration and exergy analysis

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# 4. Heat exchangers network synthesis

Goals

Short summary

# 4. Heat exchangers network synthesis

The previous steps define an energy target that is described by a list of streams with defined flow rates.

The goal of the synthesis will be to find out a heat exchangers network that will reach the target at minimum cost.

## 4.1. The methodology summary

The former sections define the targeting phase of the methodology for energy integration. Each step of it (figure 29) corresponds to a specific task.

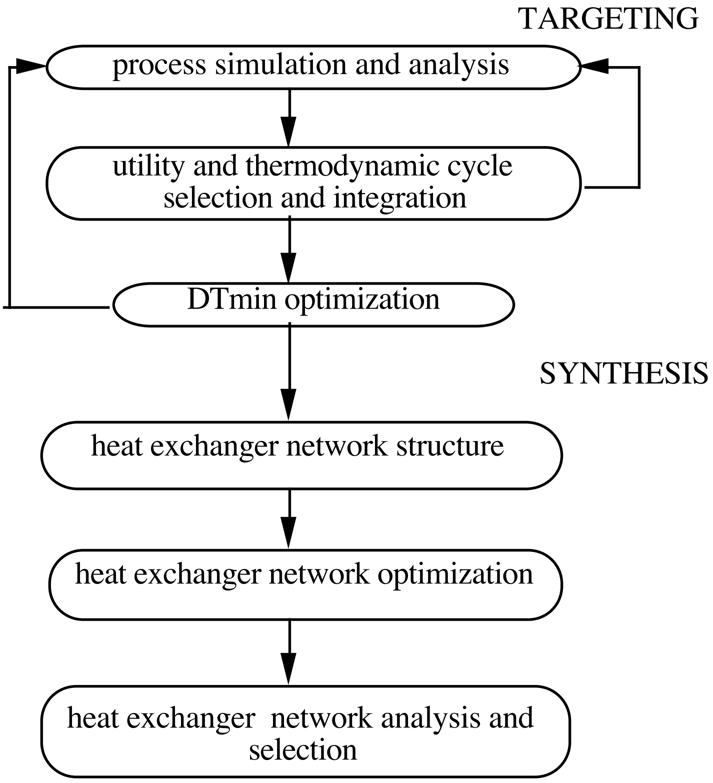


*Figure 29 : methodology for energy integration.*

Step 1: Process simulation and analysis.

The first step is the calculation of the composite curves from the process data and the determination of the minimum energy requirements (MER) according to a fixed DTmin/2 value for each stream. The analysis of the composite curves allows to propose process modifications and to identify the strategic streams of the process.

Step 2: Utility and thermodynamic cycles selection.

The choice of the adequate utility, refrigeration or Rankine cycle to be used is a capital step of a good energy integration. Intensive variables of different utilities and cycles are determined from composite curves analysis. A mixed integer linear programming (MILP) formulation based on a cost function defines the optimal integration of the utilities. This means the selection of the utilities to be used and the determination of their optimal flow rates. The integration implies usually both mechanical and thermal power integration.

Step 3: Optimization of the DTmin/2 contribution.

An estimation of the capital cost based on a global heat transfer coefficient value is used to analyse the influence of the DTmin/2 values. The DTmin/2 are linked to the film heat transfer coefficients. For this reason, their ratio does not change. The DTmin/2 influence will be analyzed by multiplying all the DTmin/2 by the same coefficient. The composite curves will be calculated for successive values of the coefficient. The purpose of these calculations is to identify pinch point switches. The experience shows indeed that better heat exchanger networks are obtained when starting the synthesis phase with DTmin/2 values rounding the optimal value. That is any value between the two pinch point switches framing the optimal value.

## 4.2. Definition of the problem

At this point, the synthesis of the heat exchanger network can begin.

The synthesis task can be completed by answering three questions:

"Which hot and cold streams should be paired for heat exchange?"

"What is the heat load corresponding to this exchange?"

"How is this exchange performed?"
(What are input and output temperatures? Is there a split? Etc...)

The heat exchanger network (HEN) obtained has to be optimal. This optimality is not only the minimum of the total cost, energy and investment. It has also to verify satisfactory a set of other criteria specific to the plant under study. These are the flexibility, the reliability, the safety, the layout, the starting, the operability, the technological constraints, the existing units,... Let us first define these notions:

The **flexibility** of an installation is its capacity to run under different regimes to satisfy market demands, production planning,... If these conditions must be accessible, one can not do these at any costs, the problem has to be taken into account during the synthesis task.

The **reliability** of an installation is defined as its capacity to run under intermediate regimes for short times: cleaning operation, safety running, etc... In this case the cost of these running conditions is out of the considerations.

The **safety**: problems of corrosion, leaks, explosivity, pressure levels must be taken into account during the synthesis task.

The **layout** or the topology of the installation must be considered in order to avoid exchanges between distant streams.

The **starting** of the installation must be realizable and if possible without specific exchanger investment.

The **operability** of the installation is very important. The set points of the physical operation units must be accessible and easily controllable. The coupling between regulation systems will be avoided if possible.

Technological constraints are taken into account in the cost of the heat exchangers when there are problems of corrosion or pressure. It is also very important during the conception to consider the fouling and the aging of the installation. **Cleaning** strategies will be studied during the synthesis task.

The **existing units** and their actual position have to be taken into account when performing retrofit or revamping studies so as to decrease the capital cost.

## 4.3. The heat exchangers network structure

The determination of the heat exchangers network (HEN) structure is the first step of the synthesis. It consists in finding a feasible structure which will be optimized in the next steps. The determination of the heat exchanger network structure is obtained by fixing the MER (Thus the utility flow rates). The pinch point divides the process into to independent parts that can be solved separately.

### 4.3.1. Heat exchanger network representation

The streams of the heat exchangers network are horizontal lines from lower to upper temperatures (figure 31). Hot streams go from right to left and the cold stream from left to right. The use of the corrected temperature instead of the real values makes the calculations easier. In this representation, a pinch point exchanger will feature one temperature difference DT=0.

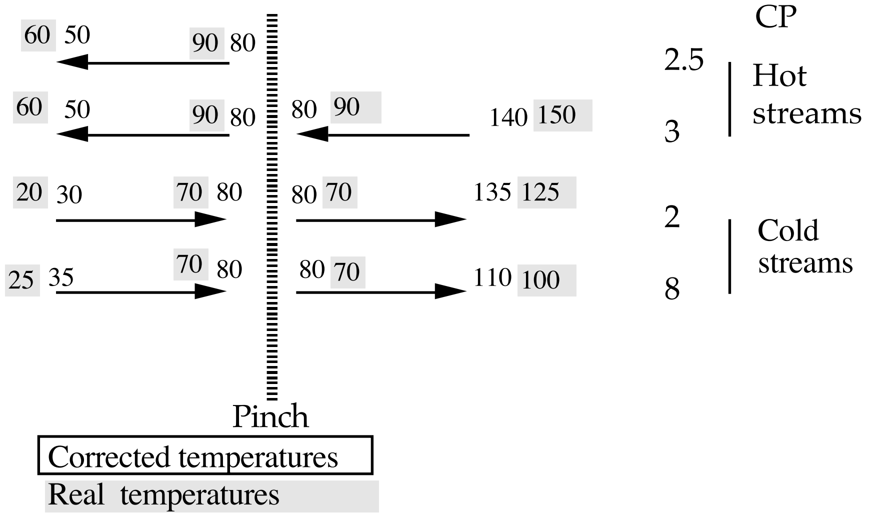


*Figure 31. HEN streams representation.*

In this representation, a heat exchanger is a vertical line linking to horizontal lines (streams) in figure 32. The counter courant heat exchanger is clearly identified and the DTlm is easy to calculate even by hand. Furthermore, the pinch point in an exchanger is easy to localize.

### 4.3.2. Feasibility rules

The pinch point is the bottleneck of the energy flow. In the preliminary step of the synthesis, we will consider the two systems defined by the pinch point as independent. The most important streams for the synthesis will be the one which are present at the pinch point; they will be called the "pinch point streams". The targeting indicates that no cold utility can be used above the pinch point. This implies that:

> Above the pinch point, the hot pinch point streams have to be cooled down to the pinch point temperature by the cold pinch point streams without cold utility.

The same reasoning is done below the pinch point where no hot utility can be used:

Below the pinch point, the cold pinch point stream has to be heated up to the pinch point temperature by the hot pinch point streams without hot utility.

During the synthesis task, the key streams are:

Above the pinch point: the hot streams at the pinch point.
Below the pinch point: the cold streams at the pinch point.

An exchanger involving two pinch point streams will be called a "pinch point heat exchanger". For example in figure 32, the exchanger 1 of the case (a) is a pinch point exchanger but not the exchanger 2. In the case (b), exchangers 1 and 2 are both pinch point heat exchangers and not the exchanger 3.

The pinch point heat exchangers have a temperature difference equal to the DTmin at one of the two extremities.

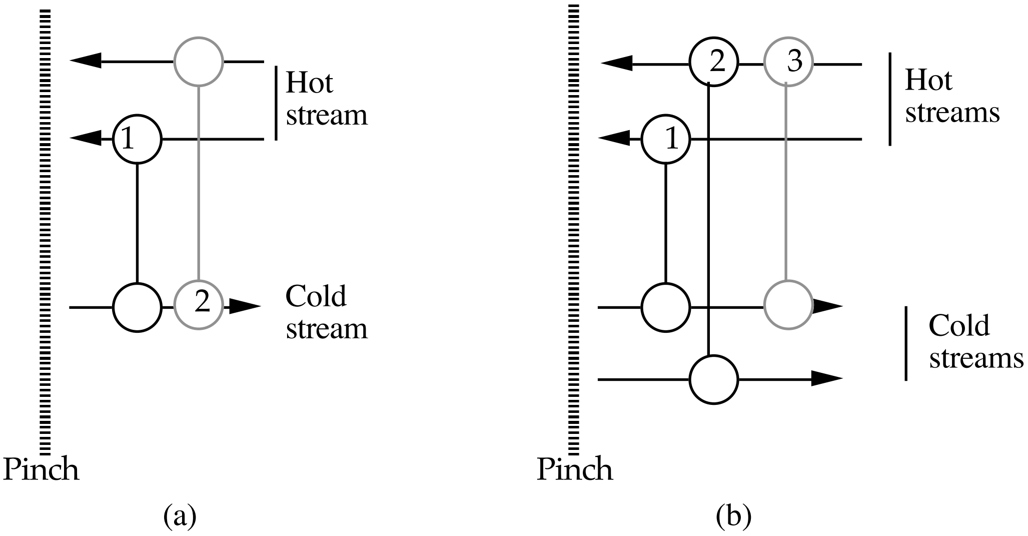


*Figure 32. Pinch point heat exchangers.*

The feasibility rules came directly from the proposition here above. The pinch point exchangers are the only exchangers concerned by these rules.

The first rule concerns the number of streams at the pinch point. As no cold utility can be used above the pinch point, the number of cold streams above the pinch point must be greater or equal to the number of hot streams (figure 33). Similarly, below the pinch point, at the pinch the number of hot streams must be greater of equal to the number of cold streams.

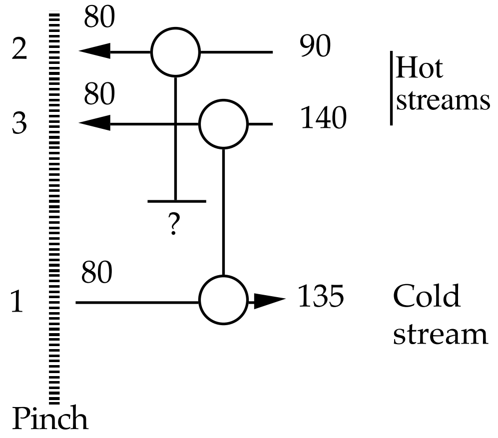


*Figure 33. The number of streams rule above the pinch point.*

| | |
|---|---|
| Number of streams rule: | Above the pinch point, Nh ≤ Nc |
| | Below the pinch point, Nc ≤ Nh |

For example, if the structure of figure 34 is used, there is no cold streams cold enough to bring the stream 3 to the pinch point. To satisfy the rule, the cold stream will be split into two sub streams as shown figure 34. There is different ways of choosing the splitting factor. One is to take the Cp ratio of the hot streams concerned. Another is to take the heat load ratio. Thermodynamics second law tends to encourage isothermal mixing after the exchange. The choice of the splitting factor will also be submitted to the other rule.

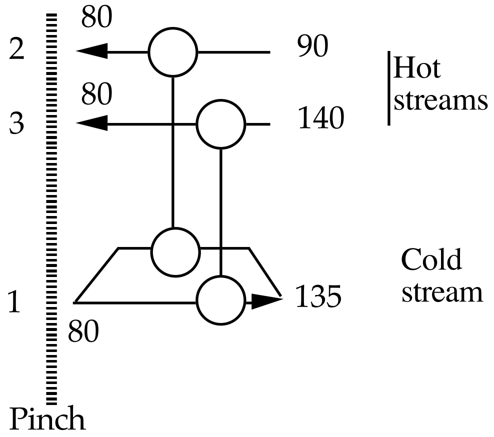


*Figure 34. Cold stream splitting to satisfy the number of streams rule.*

The second feasibility rule for the pinch point heat exchangers is the Cp rule. As above the pinch point, the DTmin is verified on the cold side of the exchange, the Cp of the cold stream must be greater than the hot stream Cp (figure 35). The temperature difference at the hot side of exchange will thus be greater or equal to the DTmin.

| |
|---|
| The Cp rule for the pinch point heat exchangers is |
| Above the pinch point: Cph ≤ Cpc<br>Below the pinch point: Cpc ≤ Cph |

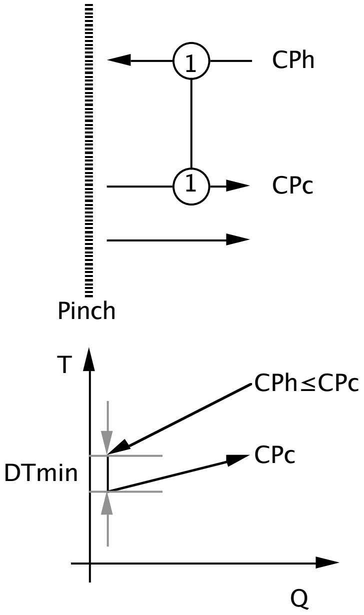


*Figure 35. The Cp rule at the pinch point.*

The Cp rule concerns only pinch point heat exchangers since it is based on the assumption that the DTmin is already verified at the pinch point. When no possible matching verifies the Cp rule, the hot stream featuring the too big Cp will be split. In this case, the number of stream rule has to be reexamined.

It is always possible to find a configuration which verifies the former rules because at the pinch point, the inequalities (26) are verified as shown figure 36.

$$\text{Above the pinch point: } \sum_{i=1}^{Nc} Cpc - \sum_{i=1}^{Nh} Cph \geq 0$$

$$\text{Below the pinch point: } \sum_{i=1}^{Nh} Cph - \sum_{i=1}^{Nc} Cpc \geq 0$$

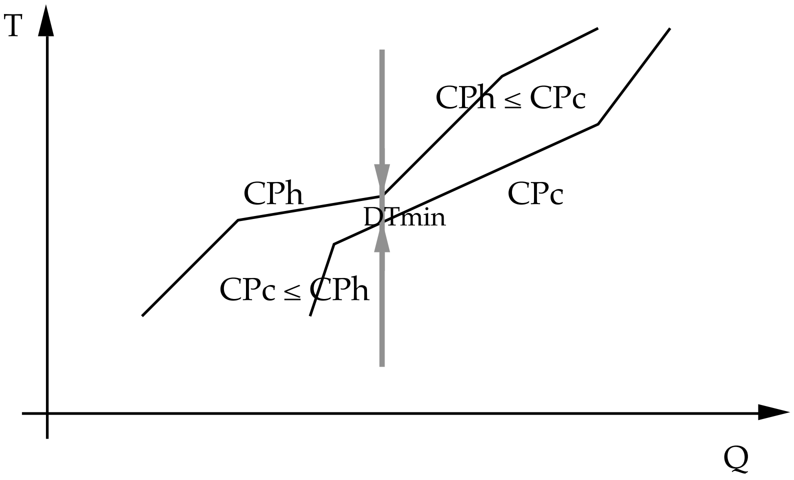


*Figure 36. Global Cp difference.*

Summary of the feasibility rules:

A pinch point heat exchanger is feasible if it satisfies the following rules:

1) Nk ≤ Nk-1

2) Cpk - Cpk-1 ≤ 0

The k indice denotes the key stream; k-1, the other one.
Above the pinch point, the key stream is the hot stream to cool down to the pinch point temperature.
Below the pinch point, the key stream is the cold stream to be heated up to the pinch point temperature.

### 4.3.3. Heuristic rules

The former rules allow to identify the streams which can exchange together. The second question is to identify the amount of heat which will be exchanged. Heuristic rule can be used to determine the heat load of the exchanger.

To verify the minimum number of units defined previously, in each connection, at least one of the two streams involved has to satisfy its total heat load.

This is known as the tick-off rule:

Try to satisfy the heat load of one of the two streams involved in a connection.

### 4.3.4. Remaining problem analysis

Each time an exchanger is chosen and calculated, the thermal cascade can be recalculated without the given heat exchanger. The new data for the streams involved in the exchange are the extreme temperatures of the heat exchanger shown in figure 37. The initial data are Tci and Tco for initial and objective temperatures of the cold stream and Thi and Tho for the hot stream. For the remaining problem analysis, each of the hot and cold streams gives two streams: the cold stream gives Tci-T1 and T3-Tco and the hot stream gives Thi-T4 and T2-Tho.

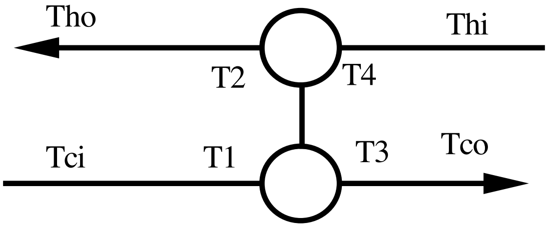


*Figure 37. The streams for the remaining problem analysis.*

This method is known as the "remaining problem analysis". If the new MER calculated is greater than the old one, the chosen connection implies an energy penalty for both hot and cold utility. The connection can either be accepted or suppressed and another connection will be calculated. If it is accepted, the new data for the synthesis are the remaining problem analysis one. They include new streams at the pinch point or even pinch point changes.

The remaining problem analysis allows to analyse the impact of a given connection. It can be used also for analysing the impact of actual exchangers on the energy recovery.

For each possible exchange, a lot of possibilities remain. The following heuristic allows to order the synthesis:

Try to connect together the cold and hot streams with the highest Cp.

Away from the pinch point, the exchanges are usually easier than at the pinch point. But the remaining problem analysis shows that while the exchangers are added during the synthesis calculation, new pinch points can be created.

An other feasibility rule concerns the utility placement. As they are usually at the end of the temperature range, the utilities will be placed at the key end of the zone under study. They will be used to control the target temperature of the associated process streams.

For reason of flexibility, the utility are usually split if they are matched with more than one process streams.

The heuristic rules for utility are:

Place the utility at the key end of the zone under study.
Split the utility if multiple connections are required.

## 4.3.5. A synthesis method.

Using the feasibility and the heuristic rules, a synthesis strategy can be proposed. It is only a way to approach the problem, not a systematic method to solve it. The know-how and the experience of the engineer will be very useful to complete the synthesis task.

To calculate a heat exchanger network structure (figure 38),

1) Analyze separately the sub systems defined by the pinch point(s).
The key idea is to bring the key {k} streams to the pinch point.
Above a pinch point, the key streams are the hot streams
Below a pinch point, the key streams are the cold streams.
{k} refers to the key streams, {k-1} to the other ones.

2) Identify the pinch point streams.
3) if the streams number rule is not verified split the {k-1} streams until the rule is verified.
4) find a connection verifying the Cp rule. If no connection is found and the problem is not terminated, split the {k} streams which do not verify the rule, until a connection is found, or suppress an already defined connection.
5) For the feasible connection, apply the tick-off rule and calculate the exchange.
6) Perform the remaining problem analysis and accept or not the connection
7) With the new data restart the procedure to find the next connection until all the streams heat loads are satisfied.

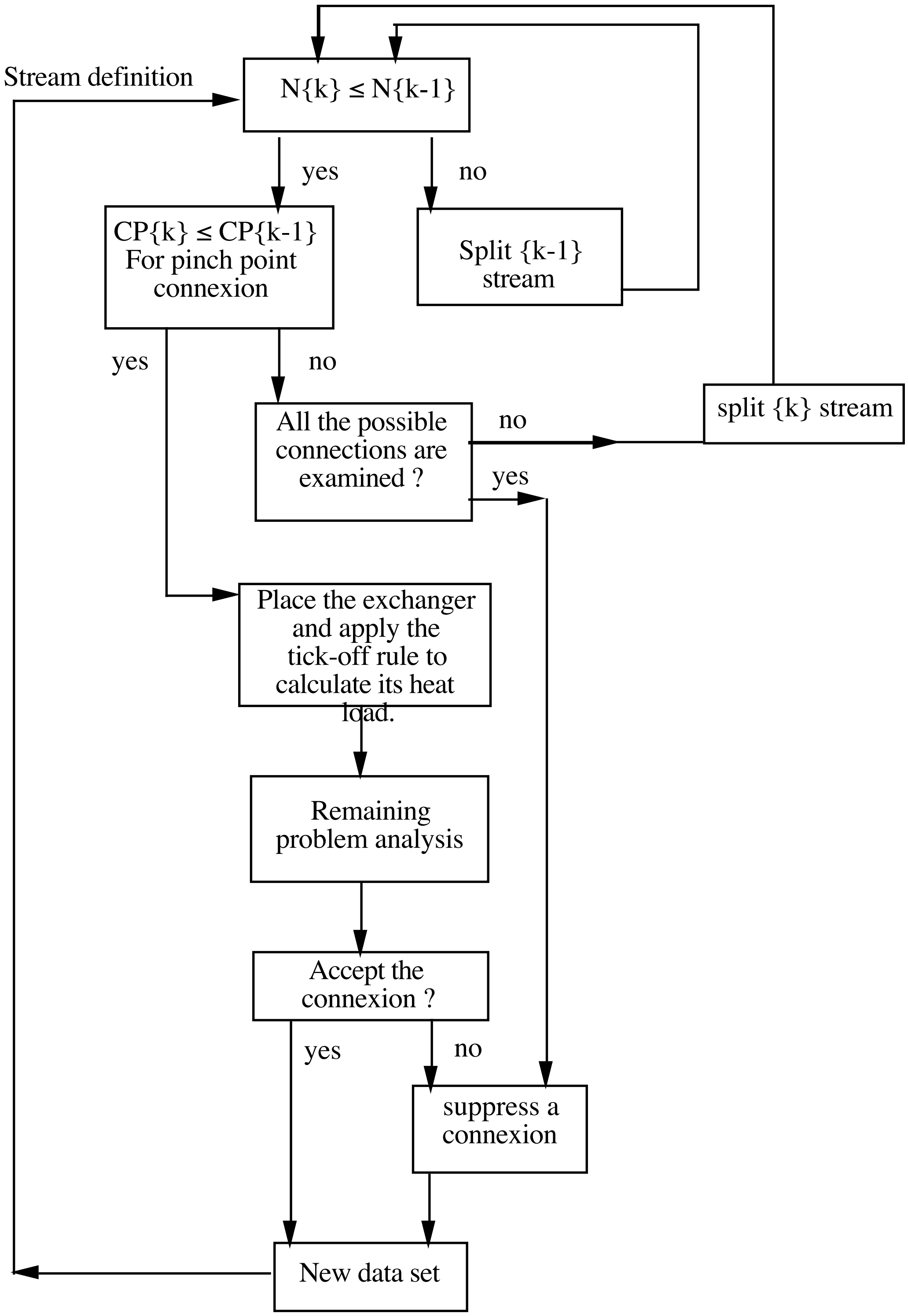


*Figure 38. The synthesis method: a simple approach.*

## 4.3.6. Loops

The method proposed is only a way to approach the problem. A lot of HEN can be found which verify all the rules described here above and it is not possible to calculate all the possibilities. Furthermore, no guaranty of finding optimal networks is given during the synthesis.

On the other hand, feasible networks that do not respect the tick-off rule can be found. In this case the number of units is greater than the expected minimum number calculated by the Euler graph theory. The number of units is

$$U = U_{min,mer} + L \tag{17}$$

Where $U_{min,mer}$ is the minimum number of units
$L$ is the number of loops.

A loop is defined as a path through the exchangers and the streams linking a heat exchanger to it self. To identify a loop in the HEN, we will follow verticals and horizontals to return back to the starting exchanger. In this determination the utilities and the split streams will be taken into account. In the figure 39, two loops can be identified. The first links the connections (or exchangers) 1 and 4. The second links the connections 2,4,3 and 5.

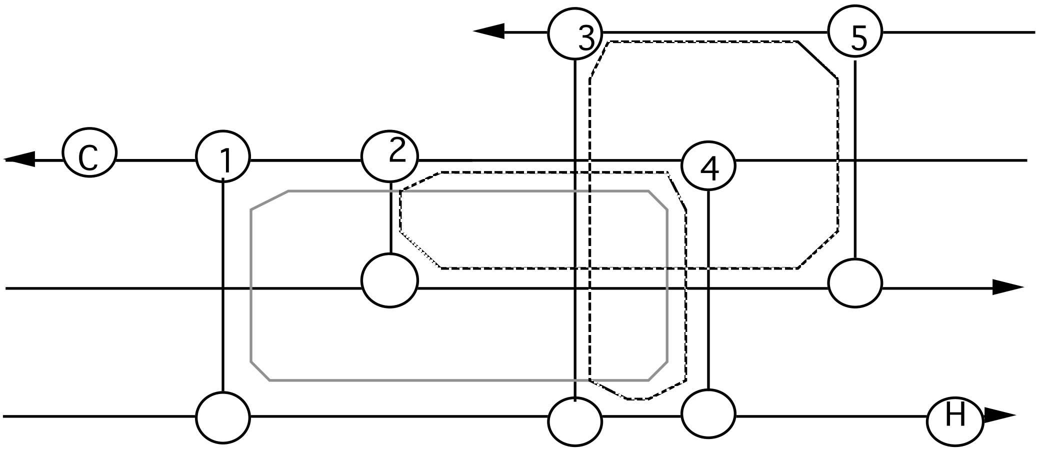


*Figure 39. Loops in a heat exchanger network.*

The decrease of the total number of units is obtained if the loop is broken. In a loop, the heat flows from one exchanger to the other following the stream. For example, if the heat load of the heat exchanger 2 (figure 40) is deceased of X2, X2 will be added to the exchanger 5. By thermal balance, it has to be suppressed from the heat exchanger 3. That implies the X2 heat load to be added to the heat exchanger 4 satisfying the thermal balance of the stream. The method used to suppress an exchanger in a loop is to distribute its heat load along the loop. In the example, it is obtained if X2=Q2. The exchanger to be suppressed is always the one which feature the smallest heat load in the identified loop.

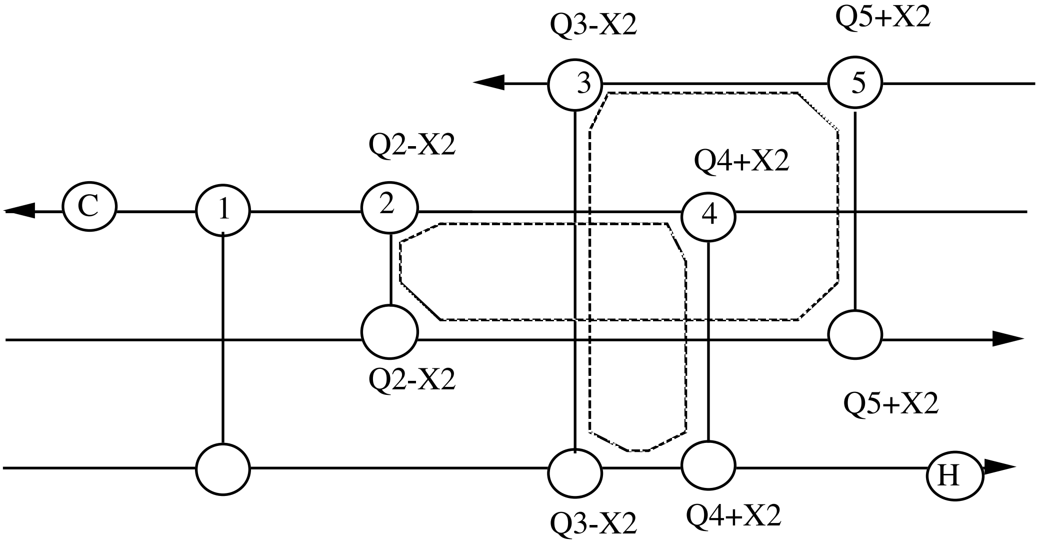


*Figure40. Loop breaking.*

## 4.3.7. Energy relaxation

When calculating the loop breaking, one has to verify that the exchanger can be suppressed. That means that the DTmin constraint is verified in the new heat exchanger network. It is never the case when the loop crosses the pinch point. In this case, to make the heat exchanger network feasible, utility have to be increased, transferring heat across the pinch through the loop. In order to restore the DTmin in the heat exchanger, one has to identify a "downstream path" linking a hot to a cold utility and passing through the exchanger featuring the DTmin violation. In figure 41, the downstream path used to restore the DTmin in exchanger 1 is marked in doted line. If the hot utility is increased of X, the heat load of 1 can be reduced of X but the cold utility will be increased of the same amount. Since the temperatures are modified all along the downstream path, the DTmin can be restored by increasing X.

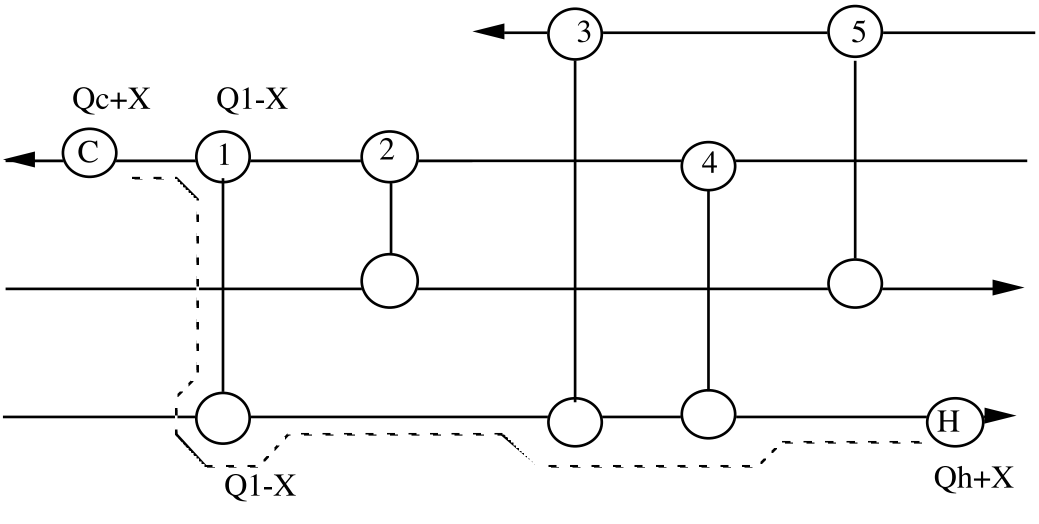


*Figure 41. The "downstream path"*

The energy penalty X to restore the DTmin is calculated by (18)

$$X = (DTmin - DTviol)\ Cpj \tag{18}$$

Where DTmin defines the MER. When working with the corrected temperature, this value is zero. Otherwise, DTmin is the sum the DTmin/2 of the streams involved in the connection.

DTviol is the actual temperature difference

Cpj is the Cp of the stream which outlet temperature defines DTviol (figure 42).

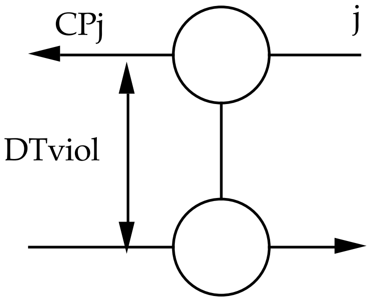
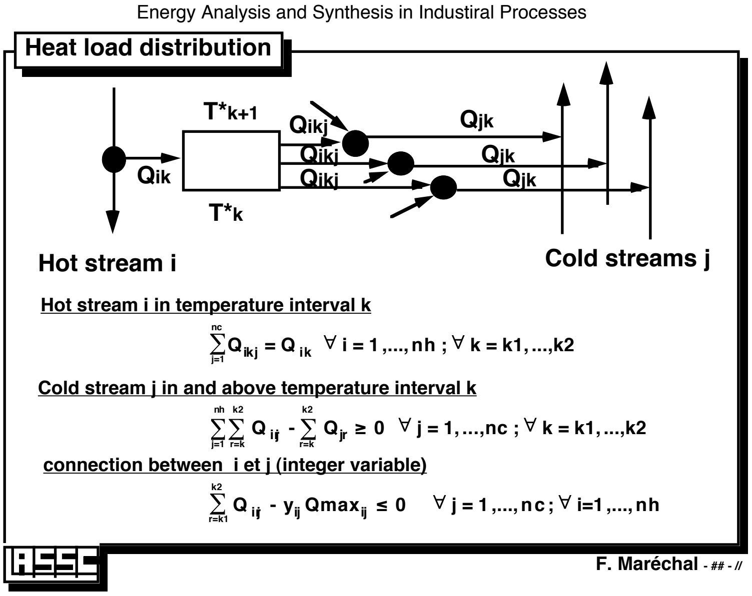


*Figure 42.*

## 4.4. Heat Load Distribution

The synthesis method described here above is mainly based on the pinch design method of Linnhoff (1983). It tends to answer the three questions of the HEN synthesis problem by applying a set of simple rules. This approach is very didactic and helps the engineer to understand the problematic of the synthesis task. But when applied by the non-expert engineer, it can lead to configurations that are far from optimum, because the great number of solutions which satisfy the given rules. On the other hand, mathematical optimization with MILP and non linear programming (NLP) formulations can be found in the literature (Floudas and Grossman (1986), Saboo (1986) and others (Gundersen 1987)). They give a unique solution according to the definition of a well suited cost function formulation, and appropriate problem decomposition. This latter approach is very attractive from ease of use point of view but suffers the disadvantage of being a black box, with no possible interaction of the engineer. The unique cost criterion, and the objective function definition, particularly in the sub problems, are not always of real cost sense for the engineer. How to tell a priori what will be the cost of a particular connection with respect to an other? If you know it: you can apply the method, if not: you will not be sure to find the good solution.

## 4.4.1. The MILP formulation of the Heat Load Distribution



Energy Analysis and Synthesis in Industiral Processes

**Heat load distribution**

**Hot stream i in temperature interval k**

$$\sum_{j=1}^{nc} Q_{ikj} = Q_{ik} \quad \forall\, i = 1,\ldots,nh\ ;\ \forall\, k = k1,\ldots,k2$$

**Cold stream j in and above temperature interval k**

$$\sum_{j=1}^{nh}\sum_{r=k}^{k2} Q_{irj} - \sum_{r=k}^{k2} Q_{jr} \geq 0 \quad \forall\, j = 1,\ldots,nc\ ;\ \forall\, k = k1,\ldots,k2$$

**connection between i et j (integer variable)**

$$\sum_{r=k1}^{k2} Q_{irj} - y_{ij}\, Qmax_{ij} \leq 0 \quad \forall\, j = 1,\ldots,nc\ ;\ \forall\, i=1,\ldots,nh$$

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The synthesis methodology proposed here below takes the advantages of these two approaches and proceeds by decomposing the synthesis task into several steps. The first of these steps is the heat load distribution calculation. It answers the first two questions: determination of the streams involved in a connection and the corresponding heat load.

To do this, we use a MILP formulation explained here below.

We consider the temperature interval k of figure 43. Let us define the variables: Qikj is the heat load exchanged between the hot stream i in the temperature interval k and the cold stream j in the temperature interval k and lower. yij is an integer variable representing the connection between hot stream i and cold stream j, if it exists yij = 1, if not yij = 0. In our method, we divide the temperature range into several zones according to each pinch point location. It is obvious that the formulation can be extended to the global system. But for reasons explained further, we don't want to work with the global system. Let kp1 and kp2 be the lower and upper interval of the calculated zone. The solution of the MILP problem (19) gives us the load of Qij exchanged between hot stream i and cold stream j, satisfying the minimum number of connections, the DTmin constraint, and the global thermal balance.

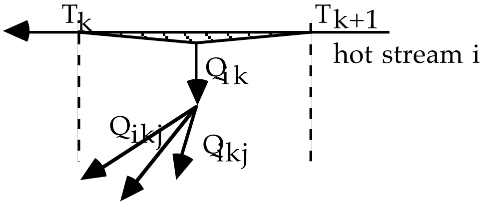


*Figure 43. MILP for heat load distribution.*

$$\underset{yij\ Qikj}{\text{Min}} \quad CT = \sum_{j=1}^{nftc}\{\sum_{i=1}^{nfth} yij\} \qquad (19)$$

subject to

Thermal balance of hot stream i in temperature interval k.

$$\sum_{j=1}^{nftc} Qikj = Qik \qquad \begin{matrix}\text{"i=1...nfth} \\ \text{"k=kp1...kp2}\end{matrix} \qquad (19.1)$$

Thermal balance of the cold stream j.

$$\sum_{i=1}^{nfth}\{\sum_{k=kp1}^{kp2} Qikj\} = Qj \ \square \quad j=1...nftc \qquad (19.2)$$

Existence of the connection ij.

$$\sum_{k=kp1}^{kp2} Qikj - yij\ Qmax \le 0 \qquad \begin{matrix}\text{"j=1...nftc} \\ \text{"i=1...nfth}\end{matrix} \qquad (19.3)$$

Feasibility of the connection: the heat load demand of the cold stream j in the intervals k and above, Qjkcum, must at least be satisfied by the hot streams in the intervals from kp2 to k.

$$\sum_{r=k}^{kp2}\{\sum_{i=1}^{nfth} Qirj\} - Qjkcum \ge 0 \qquad \begin{matrix}\text{"j=1...nftc} \\ \text{"k=kp1...kp2}\end{matrix} \qquad (19.4)$$

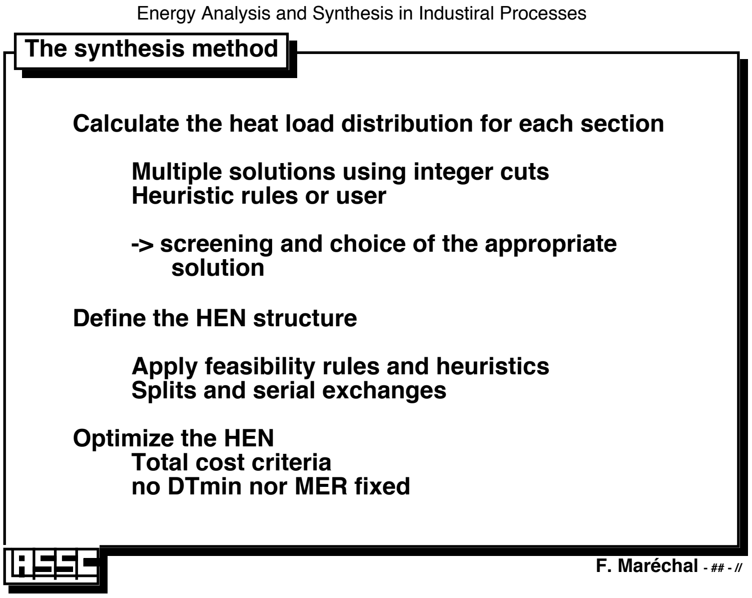
Each heat load must be positive.

$$Qikj \ge 0 \qquad \begin{matrix}\square\ k=kp1...kp2 \\ \square\ j=1...nftc \\ \square\ i=1...nfth\end{matrix}$$

$$yij \ \square\ \{0,1\}$$

Where
- Qik is the heat load of the hot stream i in interval k.
- Qi, Qj are respectively the load of hot stream i and cold stream j between kp1 and kp2 temperature intervals.
- Qmax is a bound on the heat exchanged = $\max_{i\ j}$ (Qi, Qj)
- nftc, nfth are respectively the total number of cold and hot streams between temperature interval kp1 and kp2, including all active utilities, considered as process streams with fixed flow rates.

## 4.4.2. The synthesis method



Energy Analysis and Synthesis in Industiral Processes

**The synthesis method**

**Calculate the heat load distribution for each section**

**Multiple solutions using integer cuts**
**Heuristic rules or user**

**-> screening and choice of the appropriate solution**

**Define the HEN structure**

**Apply feasibility rules and heuristics**
**Splits and serial exchanges**

**Optimize the HEN**
**Total cost criteria**
**no DTmin nor MER fixed**

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When using this formulation, our goal is not to find a unique solution by associating a cost to each connection. We just want to calculate all feasible solutions satisfying the Nmer and DTmin criteria. We give thus the same cost to each allowed connection; mandatory connections are assigned null cost and forbidden ones at very high cost. The solution set answering the two questions (Which connection and its corresponding load), includes the solution we had found using particular pricing for connection, unless cases where some connections will have an unusually lower cost. But it also includes the better solutions we can find by applying the "pinch design method" (Linnhoff 1983), without all the bad ones. The criteria applied to choose from this set a good solution and the way to answer the third question to obtain good networks are described in the next steps.

### 4.4.2.1. Initial structure of networks.

We have a set of solutions corresponding to a collection of connections with their respective loads verifying the Nmer and MER criteria. The only question we have to answer at this point is: "What is the network structure corresponding to the given connections?”

The pinch design method will present at this stage a very attractive feature: the number of solutions is reduced because it remains only one question to answer: "how do we perform the given connection?” The engineer can thus apply the method described previously to build an initial structure. He can also apply other criteria such as layout: if a connection involves two close streams, we will choose the solutions which include this connection. Flexibility, retrofit or safety can also be considered to select potentially good structures to be optimized in the next step.