3
Computer-aided Integration of Utility Systems

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3.1
Introduction

The integration of utility systems concerns the way energy entering a production plant will be transformed into useful energy for satisfying the needs of the production processes. In order to identify the best options for the utility systems, one has to consider the chemical industrial plant as a system (Fig. 3.1) that converts raw materials into valuable products and by-products. The production is realized by a list of interconnected physical unit operations that will together form the chemical process. These transformations are made possible by the use of energy and support media, like solvent, water, and catalysts. The transformations are not perfect and

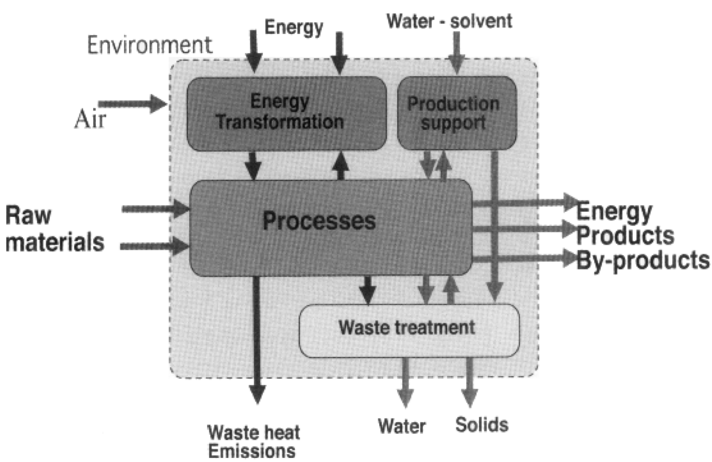

Figure 3.1 The process as a system that converts raw materials into products and by-products

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therefore the process results in the production of wastes. Wastes are emitted in several forms:

- waste heat in the cooling water or the air;
- emissions as combustion or other gases (e.g., humid air, steam vent, etc.);
- liquid streams as polluted water or solvent;
- solids.

Emissions are regulated or taxed, so the waste emissions should reach levels that meet waste processing strategies. When performed on site, waste treatment integration offers opportunities for reducing the treatment cost by material recycling, waste energy recovery or by using process waste heat to improve the treatment efficiency.

In this chapter, the utility system will be considered as being composed of different subsystems that serve the following production processes:

- energy conversion;
- compressed gases: air, O_2, N_2, H_2, etc.;
- cleaning in place;
- air conditioning and space heating;
- catalyst recovery;
- solvent recovery;
- water treatment;
- effluent treatment;
- etc.

We will, however, focus our presentation on energy conversion and water integration. Referring to Fig. 3.1, the goal of the engineer is to maximize the efficiency of the *horizontal* transformations from raw materials to products by minimizing the use of resources in the vertical transformations, leading by balance to the reduction of the emissions.

The process integration techniques based on the pinch analysis (e.g., [1]) have mainly focused on the definition of the minimum energy requirement (MER), expressed as the minimum (useful) heat requirement, and the definition of the optimal heat exchanger network (HEN) design that will realize the energy recovery between the hot and cold streams of the production processes at a minimum cost, achieving in this way the best tradeoff between the heat exchangers investment and the energy savings. In this approach, utilities are not really considered since they only appear as a way of supplying the minimum energy requirement. Using the analogy between temperature and concentration and between heat and flow rate, water usage may be tackled using a similar approach (e.g., [2]). We will therefore first present the methods for integrating the energy conversion and consider after the water usage aspects.

The role of the energy conversion subsystem is to supply the energy requirement of the process at a minimum cost or with a maximum efficiency. This means converting the available energy resources into useful energy (energy services) and distributing it to the process operations. From the process synthesis perspective, the problem has five aspects:

- the definition of the most appropriate energy resources;
- the selection of the conversion technologies;
- the definition of the most appropriate size of the equipment considered for the system (i.e., the investment);
- the definition of the most appropriate way of operating the conversion system;
- the definition of the utility-process heat exchanger network (energy distribution and interface between the utility system and the process).

In order to increase the efficiency of the energy conversion system, the rational use of the energy resources will be obtained by the combined production of different services (polygeneration), for example, combined heat and power, combined production of hydrogen, and steam or refrigeration.

In a process, the utilities are considered as a service provided to the production units. The control and the reliability issues are also part of the problem. For example, steam condensers are placed in such a way that these will control the target temperatures of the process streams. When the investment is made, the optimal management of the utility system will cover the aspects of exploiting market opportunities (e.g., electricity prices) and using at best the energy conversion equipment. The scheduling and the optimal management will then be an issue for the process.

The role of the utilities becomes even more important when considering multiprocess plants being served by one centralized utility system. In this case, the utility system will transfer heat between processes. Considering the variations of demand over time, the definition of the optimal system becomes a multimodal and multiperiod problem where the best sizes of the equipment will have to be defined considering annualized value on a yearly production basis. In this perspective, another dimension to consider is the influence of the ambient conditions that will influence both the process demands and the conversion process efficiency (e.g., the influence of the ambient temperature on the refrigeration cycle coefficient of performance (COP)).

3.1.1
Defining the Process Requirements Using the Utility System

In an ideal situation, the definition of the hot and cold streams of a process is obtained combining the use of data validation (for existing processes) or simulation tools (for new processes). The data of an existing process are, however, not always available for the engineers doing the process integration study. This is particularly the case when the chemical production site utility system is managed by an energy service company that is different from the production companies on the site. Furthermore, if utility systems are easy to instrument, instrumenting processes are not always so easy, particularly when dealing with processes in the food industry. Taking advantage of the utility system instrumentation, it is possible to deduce the definition of the hot and cold streams of the process from the data collected on the utility system. Data validation and reconciliation tools (see Chapter 2 in Section 5 of this book) will be used to combine online measurements with other information

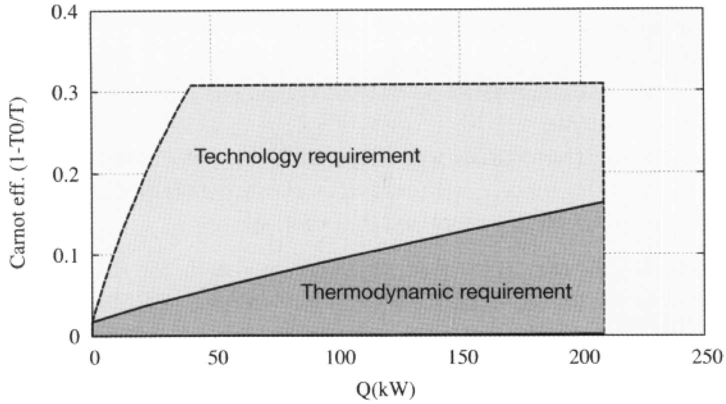

Figure 3.2 Dual representation of a heat requirement representing a stream heating by steam injection

from the specification sheets of the processes and obtain a coherent picture of the process.

Correctly defining the temperatures and the heat loads of the hot and cold streams is essential for a proper process integration study. For this reason, the first step of the analysis is defining the operations required to transform raw materials into the desired products. The heating or cooling requirements are inferred from the operating conditions. In this respect, the MER may be computed in two different ways. The first (thermodynamic requirement) consists of determining the temperature profiles of the process streams that maximize the exergy supplied by the hot streams and minimizes the exergy required by the cold streams. The second (technological requirement) is to consider the equipment used to convert utility streams into useful process heat. Those two approaches produce the same overall energy balance but with a different temperature profile. The shape of the composite curve may differ from one representation to another. An example of this dual representation is shown in Fig. 3.2 for the case of water preheating by steam injection. The thermodynamic requirement corresponds to water preheating from its initial to its target state, while the technological requirement corresponds to the production of the injected steam. When using the Carnot Factor (1−T0/T) as the Y axis, the area between the two exergy composite curves corresponds to the „thermal" exergy losses due to the technological implementation of the operation.

Following a systematic analysis [3], most of the process requirements may be defined from the knowledge of the process-utility interface.

3.2
Methodology for Designing Integrated Utility Systems

The process integration techniques aim at identifying the maximum energy recovery that could be obtained by counter-current heat exchange between the hot and cold

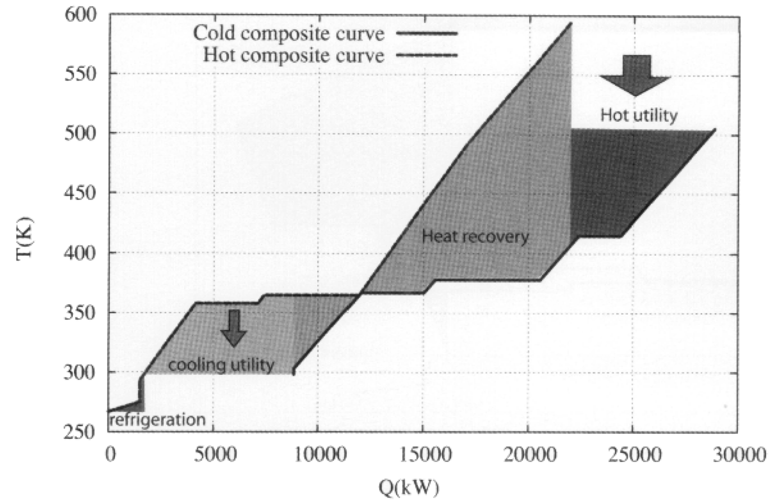

Figure 3.3 Hot and cold composite curves of the process

streams of the process. This technique, based on the assumption that a minimum temperature difference between the hot and the cold streams ($\Delta T_{\min}$), allows the calculation of the so-called MER target for the system. The identification of the pinch point, the point where the hot and cold composite curves of the process are the closest, is further used to design the heat recovery heat exchanger network structure. Using the concept of the hot and cold composite curves (Fig. 3.3), it is possible to compute the MER graphically. Mathematically, the minimum energy requirement is computed by solving the heat cascade model (3.1). This model is based on the definition of the corrected temperature list. The corrected temperatures are obtained by reducing the inlet and outlet temperature of the hot streams by $\frac{\Delta T_{\min}}{2}$ and increasing the temperature of the cold streams by $\frac{\Delta T_{\min}}{2}$. By assuming that the streams have constant cp, the fluid phase changing streams are divided into stream segments with constant cp. In a more detailed study, the value of $\frac{\Delta T_{\min}}{2}$ will be related to the heat film transfer coefficient, allowing for an account of a heat transfer resistance that depends on the fluid type considered. The heat cascade model (3.1) is a one-degree-of-freedom linear programming problem that computes the energy required to balance the needs of the cold streams when recovering the maximum energy from the hot streams by counter-current heat exchange and cascading heat from the higher temperatures. The energy balance is written for each temperature interval. The grand composite curve (Fig. 3.4) is the plot of the heat cascaded as a function of the temperature:

$$\min_{\substack{R_r \\ R_{nr+1}}} \tag{3.1}$$

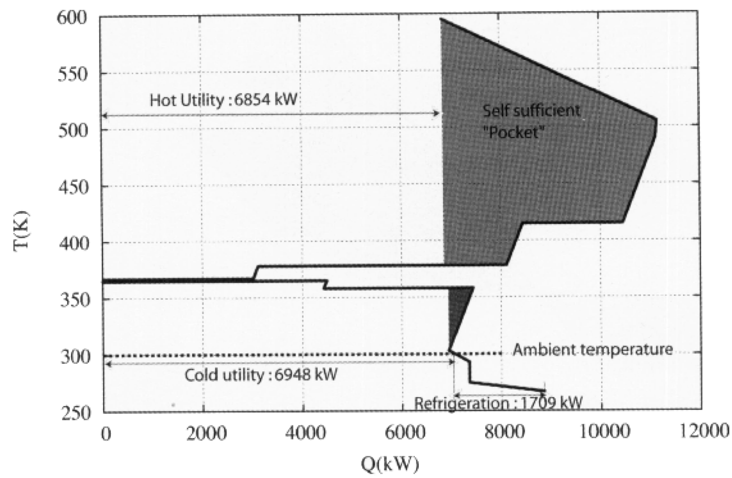

Figure 3.4 Grand composite curves of the process

subject to heat balance of the temperature intervals

$$\sum_{i=1}^{n} Q_{i,r} + R_{r+1} - R_r = 0 \quad \forall r = 1, \ldots, n_r \tag{3.2}$$

$$R_r \geq 0 \quad \forall r = 1, \ldots, n_r + 1 \tag{3.3}$$

where n is the number of specified process streams;
n_r is the number of temperature intervals;
R_r is the energy cascaded from the temperature interval r to the lower temperature intervals;
$Q_{i,r}$ is the heat load of the reference level of process stream i in the temperature interval r; $Q_{i,r} > 0$ for hot streams and ≤ 0 for cold streams.

The heat cascade constraints (3.2) is the equation system that is solved by the problem table method. An alternative set of equations (3.4) may be used to compute the heat cascade. This formulation has the advantage of involving only one R_r per equation, with each equation being related to one temperature in the temperature list. From the analysis of the pinch point location, it may be demonstrated that the list of temperatures (and therefore of equations) may be reduced in this case to the list of inlet temperature conditions of all the streams:

$$\sum_{k=r}^{n_r} \left(\sum_{i=1}^{n} Q_{i,k} \right) + R_{n_r+1} - R_r = 0 \quad \forall r = 1, \ldots, n_r \tag{3.4}$$

When considering the overall system (including the utility streams), it is necessary to define the complete list of streams to be considered in the system, including the hot and cold streams of the utility subsystem, prior to any heat exchanger network design. Compared to the conventional pinch analysis where hot and cold streams of the process have constant temperature and flow rates, the utility system integration has a much larger number of degrees of freedom since it requires the definition of the temperatures and flow rates of the utility streams that will minimize the cost of the energy conversion. This will be dealt with using modeling and optimization techniques.

The modeling of energy conversion units will be used to determine the operating temperatures and compositions allowing the definition of the hot and cold streams of the utility subsystem. The flow rates will be determined by optimization in order to minimize the cost of the energy delivered. The constraints of the heat cascade will be considered in the problem and the solution will be characterized by a list of pinch points, one of these being the process pinch point, representing the maximum energy recovery between the process streams, the others corresponding to the maximum use of the cheapest utility. If, in the simplest cases, the calculation of the utility streams may be done graphically, it is more convenient to use optimization techniques to solve the problem, especially when cycles like steam network or refrigeration system integration is considered.

There exist several ways of solving the optimal integration of the energy conversion system. All strategies are based on the definition of a utility system superstructure, which includes the possible conversion technologies that are envisaged. Although it is possible to set up a generic problem that would state and solve the problem in an automatic manner, it is more convenient to proceed by successive iterations, keeping in mind that learning from one step will result in new problem definitions and perhaps new ideas for the integration of alternative energy conversion technologies. This is particularly true because the problem definition is usually not known from the beginning and because the utility system integration may influence the process operating conditions.

The philosophy behind the computer aided utility system integration is to have a method that supports an engineer's creativity, helping him or her to identify the most promising options.

Three major aspects have to be considered:

- Technology data bases including thermoeconomic models of the different conversion technologies available. These models will be used to constitute the energy conversion system superstructure consistent with the technologies available on the market and the process requirement.
- An optimization framework for targeting the optimal integration of the utility system prior to any heat exchanger network design. The optimal utility system integration is by definition a mixed-integer nonlinear programming problem (MINLP), the integer variables being used to select in the superstructure the equipment to be used in the final configuration, while the continuous variables will be the operating conditions and the flow rates in the utility system.
- Graphical representations applying thermodynamic-based principles to assess, analyze, and understand the solutions obtained by optimization and to help in a

possibly new definition of the superstructure. Graphical representations are used to support the engineers when stating the problems and analyzing the results.

3.3
The Energy Conversion Technologies Database

When considering energy conversion technologies, we switch from the energy dimension to the thermoeconomic dimension, where cost of energy and the investments are considered simultaneously. It is therefore necessary to represent the market state by introducing market-related relationships between cost, sizes, and efficiencies. There is therefore a need to develop a technology database for the different conversion technologies. Today, Web-based techniques give access to the needed information [4]. The required data are as follows:

- Investment costs refer to the installed cost. It is computed by:

$$CI_e = CP_e + CC_e + CE_e + CG_e + CO_e \tag{3.5}$$

where $C\,I_e$ is the installed cost of the equipment e
$C\,P_e$ is the purchased cost of equipment e;
$C\,C_e$ is the cost of connections and piping;
$C\,E_e$ is the cost of engineering for equipment e;
$C\,G_e$ is the cost of civil engineering for equipment e;
$C\,O_e$ is the other costs like taxes, land, etc.

- maintenance cost required to operate the technology on a yearly basis;
- operating costs that refer to the manpower and the consumables related to the use of the technology;
- The fuel consumption and the type of fuel concerned. This usually refers to the thermal efficiency computed by $\eta_{\text{th}} = \frac{\text{useful heat (kJ)}}{LHV\,(kJ)}$. Ideally, efficiency should include partial load information.
- the electricity consumed or produced;
- the hot and cold streams that define the energy service delivery (process/utility heat exchange interface);
- the standard prescriptions for the technology specification;
- any information concerning the technology implementation;
- time to market information for emergent technologies;
- the list of suppliers.

From data collection using a technology market study, correlation equations are obtained. These give, as a function of the size parameters, the required values for the optimal integration models. For the efficiency correlation, it is important to analyze the degrees of freedom in order to avoid developing a correlation that would be inconsistent with the rules of thermodynamics. For this reason it is usually preferred to use simulation models for the technologies in which the model parameters are defined as correlation functions, e.g., isentropic efficiency as a function of the turbine size. Two types of approach may be used. The first aims at representing the technology market by functions that correlate the model parameters with technology design parameters like temperature, pressure, or size. The model has the following generic form:

$$\begin{array}{lll} \text{Heat and mass balances} & B(X, S, P) = 0; & \\ \text{Efficiency equations} & F(X, S, P) = 0; & \\ \text{Cost correlations} & CI = CI(X, S, P); & (3.6) \\ \text{Correlations limits} & S_{\min} \leq S \leq S_{\max}; & \end{array}$$

where X is the list of state variables characterizing the streams of the technology;
S is the set of sizing variables of the technology;
P is the set of characterizing parameters of the technology identified from the market database correlations.

When detailed thermoeconomic models are available, the efficiency equations will become more complex. Examples of such relationships may be found in [5], [6] or [7]. With this approach, it is assumed that the technology may be custom designed. It applies well, therefore, to steam turbines, heat pumps, or heat exchangers.

The second approach considers that the technologies are available on the market with fixed sizes and operating design conditions. This is the case, for example, for the gas turbines market in which a limited number of models are available. In both situations, the database data are used to calibrate the thermoeconomic models by computing the model parameters in the standard conditions in which the reference

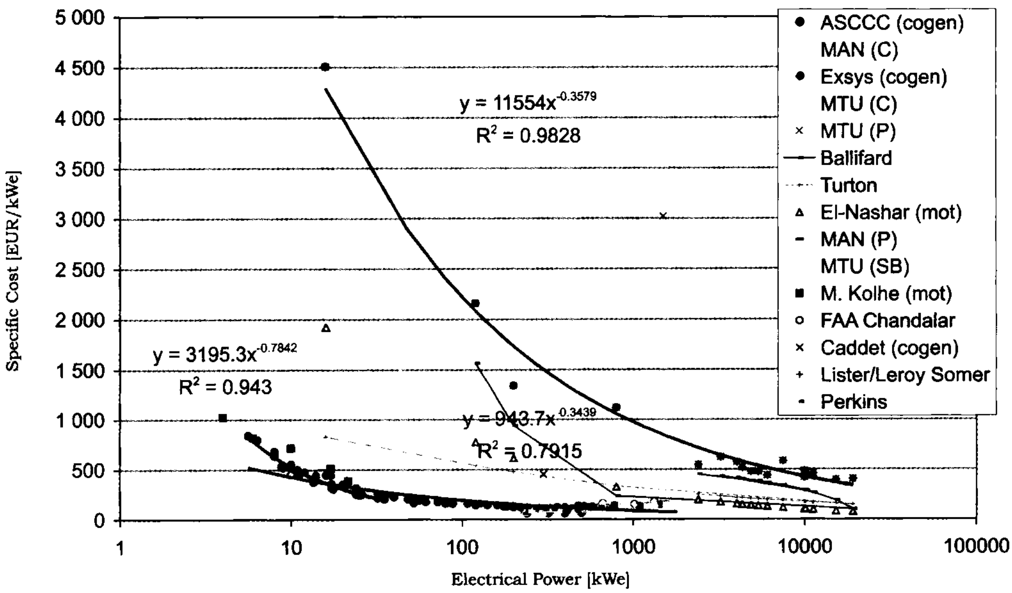

Figure 3.5 Comparison of different cost correlations for diesel engines in cogeneration applications

data have been collected. The parameters are then used to compute the system performances, including part load efficiencies, in the operating conditions of the plant under study.

Cost correlations have to be used with caution considering the conditions, the area, the date, and the ranges for which they have been established. Consider for example the results of Pelet [8] shown in Fig. 3.5. The different correlations obtained from the literature and other market surveys are compared and show big differences.

Tables 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7 give the values and correlation for the major energy conversion technologies. These data are representative of the European market in 2000. They have been gathered mainly by the partners of the European project EXSYS ([9], [4]). In order to update the cost given by the correlation, a plant or equipment index is used. The most important are the Marshall Swift index tables and the chemical engineering plant cost index (CEPCI), whose values are regularly updated in the *Chemical Engineering* journal. In the tables, all data are given with a CEPCI index of 382.

For other equipment, useful references like [10] may be used. When data are available from other sources, e.g., from quotations, the effect of size is represented by the relation (3.7), the exponent a_e may be obtained from different sources like [10] or [11]:

$$CI_e(S_e, y) = CI_{e_{\text{ref}}} \cdot \left(\frac{S_e}{S_{e_{\text{ref}}}}\right)^{a_e} \cdot \frac{CEPCI(y)}{CEPCI(y_{\text{ref}})} \tag{3.7}$$

where $C\,I_e\,(S_e,y)$ is the installed cost of the equipment e of size S_e in the year y.

S_e is the size of the equipment e. The size of the equipment is the relevant sizing parameter that mainly influences the cost of the technology. For this reason, when estimating the cost of a heat exchanger, the heat exchange area is preferred over its heat load.

$S_{e_{ref}}$ is the size of the known equipment similar to e.

$C\,I_{e_{ref}}$ is the cost of the known equipment.

$C\,E\,P\,C\,I\,(y)$ is the chemical engineering plant cost index for the year y.

y_{ref} the year of the reference cost $C\,I_{e_{ref}}$.

Table 3.4 Gas engine, lean burn configurations. $\dot{W}_e$: power in kW.

Gas engines, lean burn		
Generator eff.	[–]	$\eta_{gen} = 0.015 \cdot \ln(\dot{W}_e) + 0.8687,\ \dot{W}_e \leq 845$ [kW]
		$\eta_{gen} = 0.0013 \cdot \ln(\dot{W}_e) + 0.9611,\ \dot{W}_e > 845$ [kW]
Mechanical eff.	[–]	$\eta_{mec} = 0.2419 \cdot \dot{W}_e^{0.0653}$
Engine cooling eff. @ 90°C	[–]	$\eta_{th,refr} = 0.7875 \cdot \dot{W}_e^{-0.1682}$
Heat eff. from combustion gases	[–]	$\eta_{th,echap} = 0.1556 \cdot \dot{W}_e^{0.0513}$
NO_x emissions	[mg/m^3 N]	250
CO emissions	[mg/m^3 N]	650
Installed cost	[E]	$C_{inst} = 0.0266 \cdot \dot{W}_e^2 + 578.84 \cdot \dot{W}_e + 208174$
Catalyst cost	[E]	$85 \cdot \dot{W}_e^{0.8}$
Maintenance cost	[E/kWh]	$C_{maint} = 0.0407 \cdot \dot{W}_e^{-0.2058} + 0.0034$
Lifetime	[h]	48000

Table 3.5 Diesel engines. $\dot{W}_e$ electrical power in kW.

Diesel engines		
Generator eff.	[–]	$\eta_{gen} = 0.015 \cdot \ln(\dot{W}_e) + 0.8687,\ \dot{W}_e \leq 845$ [kW]
		$\eta_{gen} = 0.0013 \cdot \ln(\dot{W}_e) + 0.9611,\ \dot{W}_e > 845$ [kW]
Mechanical eff.	[–]	$\eta_{mec} = 0.0131 \cdot \ln(\dot{W}_e) + 0.3452$
Engine cooling @ 90°C	[–]	$\eta_{th,refr} = 0.2875 \cdot \dot{W}_e^{-0.0139}$
Heat eff. from combustion gases	[–]	$\eta_{th,echap} = 0.5433 \cdot \dot{W}_e^{-0.1026}$
NO_x	[mg/m^3 N]	100
CO	[mg/m^3 N]	400
Installed cost	[E]	$C_{inst} = -0.0266\ (3/4 \cdot \dot{W}_e)^2 + 578.84\ 3/4\ \dot{W}_e + 208174,\ \dot{W}_e > 1000$
		$C_{inst} = 1147.62 \cdot \dot{W}_e^{0.9009},\ \dot{W}_e > 1000$ [kW]
Catalyst	[E]	$136 \cdot \dot{W}_e$
Maintenance	[E/kWh]	$C_{maint} = 0.0407 \cdot \dot{W}_e^{-0.2058}$
Lifetime	[h]	48000

Table 3.6 Aeroderivative and heavy duty gas turbines.

Aeroderivative gas turbines: $\dot{W}_e$ electrical power in kW		
$\eta_{Generator\ eff.}$	[–]	$\eta_{gen} = 0.015 \cdot \ln(\dot{W}_e) + 0.8687,\ \dot{W}_e \leq 845$ [kW]
		$\eta_{gen} = 0.0013 \cdot \ln(\dot{W}_e) + 0.9611,\ \dot{W}_e > 845$ [kW]
$\eta_{Mechanical\ eff.}$	[–]	$\eta_{mec} = 0.0439 \cdot \ln(\dot{W}_e) - 0.0684$
$\eta_{Heat\ eff.}$	[–]	$\eta_{th,echap} = 0.838 \cdot \dot{W}_e^{-0.0587}$
NO_x	[mg/m^3 N]	80
CO_x	[mg/m^3 N]	50
Turbine cost	[E]	$C_{turbine} = 1564. \cdot \dot{W}_e^{0.8503},\ \dot{W}_e < 50\,000$ [kW]
		$C_{turbine} = 2977. \cdot \dot{W}_e^{0.7791},\ \dot{W}_e > 50\,000$ [kW]
Lifetime	[h]	48 000
Heavy duty gas turbines: $\dot{W}_e$ electrical power in kW		
$\eta_{Generator\ eff.}$	[–]	$\eta_{gen} = 0.015 \cdot \ln(\dot{W}_e) + 0.8687,\ \dot{W}_e \leq 845$ [kW]
		$\eta_{gen} = 0.0013 \cdot \ln(\dot{W}_e) + 0.9611,\ \dot{W}_e > 845$ [kW]
$\eta_{Mechanical\ eff.}$	[–]	$\eta_{mec} = 0.0187 \cdot \ln(\dot{W}_e) + 0.1317$
$\eta_{Heat\ eff.}$	[–]	$\eta_{th,echap} = 0.7058 \cdot \dot{W}_e^{-0.0315}$
NO_x	[mg/m^3 N]	50
CO_x	[mg/m^3 N]	50
Turbine cost	[E]	$C_{turbine} = 4786. \cdot \dot{W}_e^{0.7338},\ \dot{W}_e < 50\,000$ [kW]
		$C_{turbine} = 2977. \cdot \dot{W}_e^{0.7791},\ \dot{W}_e > 50\,000$ [kW]
Lifetime	[h]	55 000
Auxiliaries: $\dot{W}_e$ electrical power in kW, $\dot{Q}_{th}$ heat recovery boiler heat load in kW		
Reference cost	[E]	$C_{ref} = \dfrac{C_{turbine}}{(0.0503 \cdot \ln(\frac{\dot{W}_e}{1000}) + 0.3208)_+}$
Recovery boiler	[E]	$C_{boiler} = (125.5 - 0.4 \cdot (\frac{\dot{W}_e}{1000}) \cdot C_{ref}$
		$C_{boiler} = 0.2436 \cdot (\dot{Q}_{th}\ [\mathrm{kW}])^{0.8462}$

Table 3.6 (Continued)

Connection charges	[E]	$C_{conn} = (0.09318 - 0.00011 \cdot (\frac{\dot{W}_e}{1000}) \cdot C_{ref}$
Instrumentation	[E]	$C_{ins} = (0.0494 - 0.0047 \cdot \ln(\frac{\dot{W}_e}{1000})) \cdot C_{ref}$
Civil engineering	[E]	$C_{G.C} = (0.1232 - 0.0005 \cdot (\frac{\dot{W}_e}{1000}) \cdot C_{ref}$
Engineering	[E]	$C_{eng} = (0.1211 - 0.000735 \cdot (\frac{\dot{W}_e}{1000}) \cdot C_{ref}$
Others	[E]	$C_{div} = (0.1403 - 0.0142 \cdot \ln(\frac{\dot{W}_e}{1000})) \cdot C_{ref}$
Maintenance €cts	[kWh]	$C_{maint} = 8.15 \cdot \dot{W}_e^{-0.3081}$

Table 3.7 Thermoeconomic characteristics of industrial heat pump systems. The sizing parameter is the heat delivered Q_{th} in kW_{th}, the cost is expressed in €/kW_{th} computed by *Investment* = $a \cdot (Q_{th})^b$, source contribution of TNO in [9].

Type	ΔT_{lift} (°C)	Tc_{max} (°C)	Power (kW)	a (€/kW_{th})	b	eff.
Electric compression heat pump	45	110	10– 3000	814	−0.327	45% Carnot
Mechanical vapor recompression	30	200	250–50000	663.5	−0.3925	45% Carnot
Absorption heat pump NH_3/H_2O	50	150	5–60000	810.2	−0.3154	1.4 (COP)
Absorption heat pump $LiBr/H_2O$	50	150	5–60000	810.2	−03154	1.6 (COP)
Absorption heat transformer $LiBr/H_2O$	50	150	250– 4000	1164.8	−0.288	0.45 (COP)
Thermal vapor recompression	20	180	15–50000	268.56	−0.4832	

Table 3.8 Phosphoric acid fuel cells.

		PAFC	
η_{el}	[–]	0.35–0.4	[61]
η_{th}	[–]	0.25	
NO_x	[ppm]	0	[62]
CO	[ppm]	0	[62]
Installed cost	[€/kW]	4000	[61]
Maintenance	[€cts/kWh]	1	[61]
Lifetime	[h]	40000	[63]

Table 3.9 Solid oxide fuel cells.

		SOFC	
η_{el}	[–]	~ 0.5	[61]
η_{th}	[–]	0.35	
NO_x	[ppm]	< 0.2	[64]
CO	[ppm]	0	[64]
Installed cost	[€/kW]	450 (long term) – 1500	[65]
Maintenance	[€cts/kWh]	1	[61]
Lifetime	[h]	> 20000	[66]

Table 3.10 Proton exchange membranes.

PEMFC			
η_{el}	[-]	~ 0.3–0.4	[61]
η_{th}	[-]	0.5–0.45	
NO_x	[ppm]	–	
CO	[ppm]	–	
Installed cost	[€/kW]	~ 500 (long term) – 1000	[67], [61]
Maintenance	[€cts/kWh]	1	[61]
Lifetime	[h]	87 600	[67]

The total cost of the energy conversion system is given by (3.8):

$$\sum_{p=1}^{n_p} d(p)\left(\sum_{f=1}^{n_{\text{fuels}}} \left(\dot{m}_f(p)\cdot C_f(p)\right) + C_{\text{el}}(p)\dot{W}_{\text{el}}(p) - C_{\text{el}_s}(p)\dot{W}_{\text{el}_s}(p)\right) + \sum_{e=1}^{n_e} Cm_e + \sum_{e=1}^{n_e} CI_e\left(\frac{i(1+i)^{n_e}}{(1+i)^{n_e}-1}\right) \tag{3.8}$$

where $\dot{m}_f(p)$ is the flow rate of fuel f during the period p [kg/s];
$C_f(p)$ is the cost of fuel f during the period p [E/kg];
$\dot{W}el(p)$, $\dot{W}el_s(p)$ is the electrical power imported (exported) during period p [kW];
$C\,el(p)$, $C\,el_s(p)$ is the cost of electricity for import (export) during the period p [E/kJ];
$d(p)$ is the duration of period p [s/year];
$C\,m_e$ is the maintenance cost of equipment e [E/year];
n_e is the number of equipment pieces;
$C\,I_e$ is the installed cost of equipment e [E];
i is the interest rate for annualization;
n_p is the expected lifetime of the installed equipment e [year].

3.4
Graphical Representations

3.4.1
Hot and Cold Composite Curves

From the beginning, composite curves have been used to explain integration and identify energy savings opportunities. In most representations, temperature is a topological indicator in the sense that it allows one to pinpoint the process operations concerned with the pinch points or the pseudo-pinch points.

The hot and cold composite curves mainly concern the process streams. They are used to quantify the possible energy recovery by exchanging heat between the hot and cold process streams. Four zones are of importance in the hot and cold composite curves (Fig. 3.3). On the right, we visualize the hot utility requirement. The heat recovery zone represents the possible heat recovery by an exchange of the hot and cold streams of the process. The remaining heat of the hot stream has to be evacuated using a cold utility. The left part of the graph therefore defines the cold utility requirement. The latter is divided between cooling requirements above the ambient temperature and the refrigeration requirements below the ambient temperature.

3.4.2
Grand Composite Curve

For analyzing the energy conversion system integration, the grand composite curve (Fig. 3.4) will be used. It describes as a function of the temperature, the way energy has to be supplied to or removed from the system. The process grand composite curve is divided into three zones. Above the process pinch point, the system is a heat sink to be supplied by a hot utility. Below the process pinch point and above the ambient temperature, the process is a heat source. The heat has to be evacuated from the process by a cold utility or used in another energy consuming subsystem like another process or a district heating system. Below the ambient temperature, the process requires refrigeration. The feasibility rule of the utility integration is that the grand composite curve of the utility system should envelop the process grand composite curve. Resulting from the linear nature of the composite curve calculation, the optimal integration of the utilities will result in the definition of utility pinch points (the intersection between the utility composite and the process composite). Each of them will correspond to the optimal use (maximum feasible flow rate) of the cheapest utility stream. Above the pinch point, the grand composite curve represents, as a function of the temperature, the heat that has to be supplied to the process by the hot utility. When ignoring the pockets in this curve, the process appears as a cold stream to be heated up by the hot utility. Knowing the temperature–enthalpy profile of the

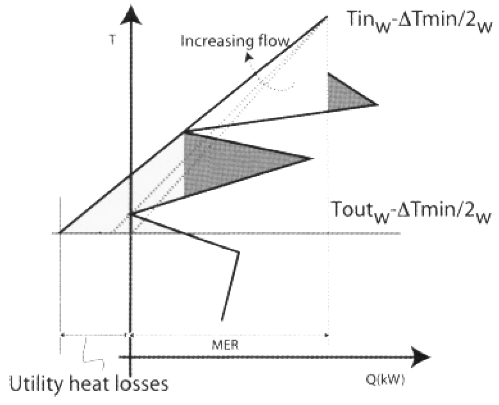

Figure 3.6 Computing the flow rate of the hot utility

utility, it is possible to determine the flow rate of the utility stream by activating the appropriate pinch point, as illustrated in Fig. 3.6, for one hot utility whose inlet temperature is higher than the maximum temperature of the process streams. In this situation, the flow rate of the utility stream is computed by:

$$f_w = \max_{k=1,n_k} \frac{R_{n_k+1} - R_k}{cp_w \cdot (T_{\mathrm{in}_w} - \max(T_{\mathrm{out}_w}, T_k + \Delta T_{\min}/2_w)} \tag{3.9}$$

where f_w is the flow rate of utility w [$kg\ s^{-1}$];
T_{in_w}, T_{out_w} are, respectively, the inlet and the outlet temperature of the utility stream w [°C];
cp_w is the specific heat of the utility w [kJ kg^{-1}/°C]
$\Delta T_{\min}/2_w$ is the contribution to the minimum approach temperature of the utility stream w;
R_k for $k = 1, n_k + 1$, are the values of the heat cascade, and R_{n_k+1} is the MER of the process.

It should be mentioned that in the example, the heat delivered by the hot utility is higher than the MER. The temperature T_k defining the intersection between the utility curve and the grand composite curve is called a utility pinch point. In the example, it differs from the process pinch point. Additional heat is therefore available from the hot utility and should be valorized. This situation often occurs in high temperature processes, like steam methane reforming processes, where the high temperature pinch point is activated by the integration of the combustion flue gases at the high temperature reforming reactor and where the heat excess available in the flue gases at lower temperatures is used to produce high-pressure steam that will be expanded in a condensing turbine to transform the excess heat into useful mechanical power by combined heat and power production. The same graphical representation applies for the cold utility and refrigeration requirements. The graphical definition of the utility flow rate has been widely used to define the flow rates in the steam system. The steam condensation defines a horizontal segment (constant temperature) whose length defines the steam flow rate.

This approach cannot, however, be applied when utility streams interact as it is the case when steam is produced in a boiler, then expanded to produce mechanical power before being condensed to heat up process streams. The utility system is made of more than one stream and the flow rate of the one (e.g., the steam flow rate) will define the flow rate of the other (e.g., the fuel consumption in the boiler). Furthermore, since the heat of the flue gases is available for the process, nothing restricts its use for temperatures above the steam condensation temperature. As will be demonstrated later on, the problem has to be solved by optimization in this case. Nevertheless, the grand composite curve representation will be of prime importance to define the possible utilities that may be envisaged for the process under study.

Another important aspect of the utility system integration is the combined production or consumption of mechanical power. Townsend and Linnhoff [12] have made a complete analysis on the use of the grand composite curves to analyze the optimal placement of the energy conversion systems and the combined heat and power production. Following the prescribed rules, the engineer is able to define a list of possible energy conversion technologies that may be envisaged for the process under study. The creativity of the trained engineers will unfortunately create a problem at this stage since they will usually be able to identify more than one technology per requirement.

3.4.3 Exergy Composite Curves

The exergy analysis is a thermodynamic-based useful concept that helps the understanding and analysis of efficiency in energy conversion systems. Exergy measures the thermodynamic value of energy. It defines the maximum work that could ideally be obtained from each thermal energy unit being transferred or stored using reversible cycles with the atmosphere being either the hot or cold energy source. The exergy approach (e.g., Kotas [13]) is used to represent in a coherent way both the quantity and the quality of the different forms of energy considered. The concept of exergy presents the major advantage of an efficiency definition compatible with all kinds of conversion of energy resources into useful energy services (heating and electricity, heating, cooling and electricity, refrigeration, heat pumping, etc.) and for all domains of energy use. While energy efficiencies are higher than 100% for heat pumping systems (because ambient energy is not accounted for), exergy efficiencies are lower than 100%. This gives an indication of how well the potential of an energy resource is exploited in the different technical concepts in competition.

In the context of process integration analysis, the exergy concept is combined with the pinch analysis for reducing the energy requirement of the process [14, 15] for optimizing the energy conversion system integration and for optimal combined heat and power production. The exergy composite curve concept has been introduced by Dhole [16] for this purpose. The exergy delivered ($\dot{E}$) by a stream exchanging heat ($\dot{Q}$) with a constant cp from T_{in} to T_{out} is computed by: $\dot{E} = \dot{Q}\,(1 - \frac{T_0}{T_{lm}})$, where T_{lm} is the logarithmic mean of temperatures computed by $T_{lm} = \frac{T_{\text{in}} - T_{\text{out}}}{ln\,(\frac{T_{\text{in}}}{T_{\text{out}}})}$ and T_0 is the ambient temperature (all temperatures are expressed in K). When representing the heat exchange in the temperature–enthalpy diagram, the exergy delivered may be represented by exchanging the temperature axis with the Carnot efficiency $(1 - \frac{T_0}{T})$. The exergy then corresponds to the area between the exchange curve and the enthalpy axis (Fig. 3.7).

When applied to the concept of the composite curves, the exergy composite curves (Fig. 3.8) represent the exergy lost in the heat exchange between the hot streams and

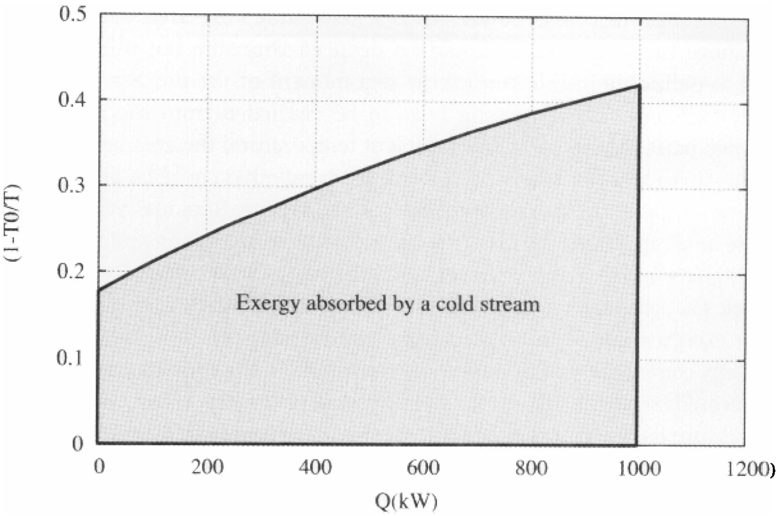

Figure 3.7 Exergy received by a cold stream heated from 350 to 500 K

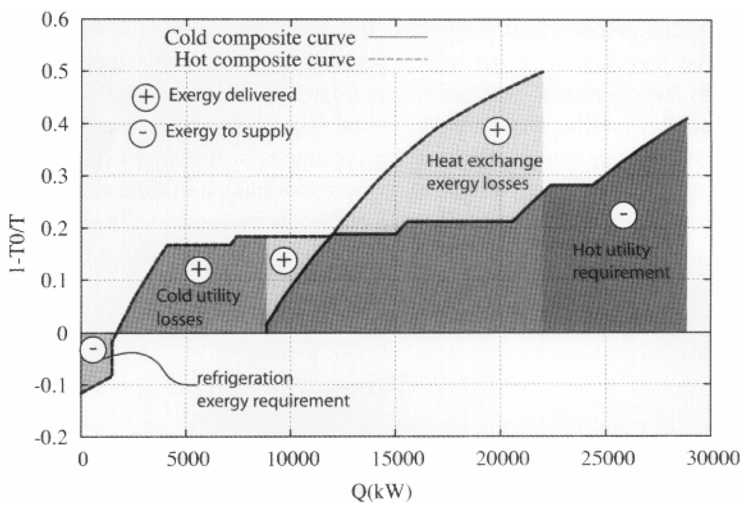

Figure 3.8 Exergy composite curves defining the process requirements

the cold streams of the system. The exergy delivered by the hot streams (shaded area between the hot composite curve and the X axis) is deduced from the exergy required by the cold streams (shaded area between the cold composite curve and the X axis). As for the hot and cold composite curves, there are four zones to be considered in the representation. The hot utility requirement is defined by an area (below the cold composite curve) representing the corresponding exergy requirement. The area between the two curves represents the amount of exergy that will be lost in the heat recovery heat exchange network. This exergy loss may be recovered partly by properly integrating combined heat and power devices. Therefore, the area between the curves and above the pinch point should be deduced from the hot utility exergy requirement to define the minimum exergy requirement of the process. After the heat recovery exchange, the remaining heat, to be evacuated from the system, is divided into two parts. Above the X axis (ambient temperature) the area between the hot composite curve and the X axis represents the exergy that could be obtained by integrating low temperature heat recovery devices like organic Rankine cycles. Below the X axis, the area represents the exergy required by the refrigeration system. Favrat and Staine [14] have added to this representation the exergy losses related to the compression work (as a function of the pressure drop) and the grey exergy. The grey exergy is the exergy required to construct the heat exchangers. It includes the raw materials exergy content as well as the exergy consumed in the construction process. This concept could be used to determine the threshold of the heat recovery effort; the exergy expenditure for the recovery equipment should not exceed the avoided exergy loss thanks to the heat recovery. This tradeoff is, of course, considered together with the economical tradeoff and should be used to define the appropriate value of the ΔT_{min}. The grey exergy may become important when the process and the heat recovery exchangers are operated only part-time.

When considering the exergy grand composite curve, the diagram represents the exergy required by the process. In this diagram, the special role of the self-sufficient pockets should be noted. This is the area representing the possible mechanical power recovery by the combined heat and power (Fig. 3.9). From this analysis, it is possible to identify the possible characteristics of the steam cycle as demonstrated by Marechal et al. [17]. This is done by integrating rectangles in the grand composite curve. The basis of any inserted rectangle being the vaporization and the condensation temperatures of the Rankine cycle. The use of the exergy concept allows one to

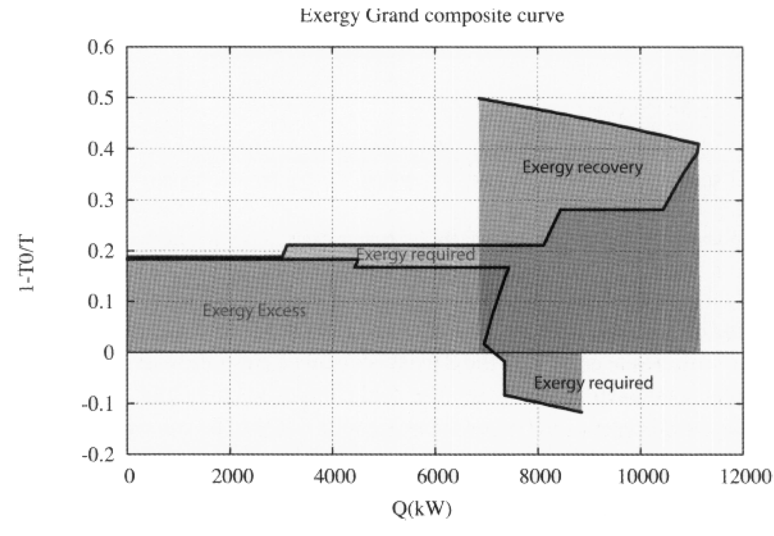

Figure 3.9 Exergy grand composite curves of the process requirements

quantify the exergy required and therefore allows one to set a target for the energy conversion system. Because the grand composite curve is computed in the corrected temperature domain, we consider that there will be an exergy loss that is a priori accepted for limiting the heat exchangers investment and that is related to the definition of the ΔT_{min}. The exergy analysis has been extended to account for the chemical reactions or the physical separations of the process operations [18]. In this representation, the temperature axes is replaced by $\frac{\Delta H - T_0 \Delta S}{\Delta H}$, which is an extension of the Carnot factor $(1 - \frac{T_0}{T})$.

One heuristic rule resulting from the exergy analysis is to try to minimize the area between the hot and cold composite curves of the integrated systems.

3.4.4
Balanced Composite Curves

The optimization models presented hereafter allow one to overcome such difficulties by computing the optimal flow rates in the utility system in order to minimize the cost of supplying the energy requirement. The composite curves of the process, together with the utility system, can then be represented. They are known as the balanced composite curves. An example of such curves is given in Fig. 3.10. This representation is characterized by a number of pinch points, one being the process pinch point, the others corresponding to the maximum use of the cheapest utilities to satisfy the process requirement. In particular, we have a pinch point at the lowest and highest temperatures of the system, indicating that the energy requirement of the process is satisfied by the utility subsystem. These curves are, however, difficult to analyze and do not really help in improving the system efficiency.

3.4.5
Integrated Composite Curves

The integrated composite curves [19] will help analyzing the results of the optimization or understanding the integration of subsystems. This representation is based on the decomposition of the system into subsystems: processes, boiler house, refrigeration cycle, steam network, heat pump, utility system, etc., even very detailed subsystems may be considered like one or several existing heat exchangers.

The integrated composite curves of a subsystem are obtained by subtracting from the grand composite curve of the overall system, the grand composite of the subsystem under study. The next step is to mirror the subsystem curve. The two curves intersect at the pinch points of the balanced composite curves. In order to locate the Y zero axis, it is convenient to consider the process pinch point location as a reference. From a mathematical point of view, the integrated composite curves are computed using the formulas below (Eqs. 3.10 and 3.11).

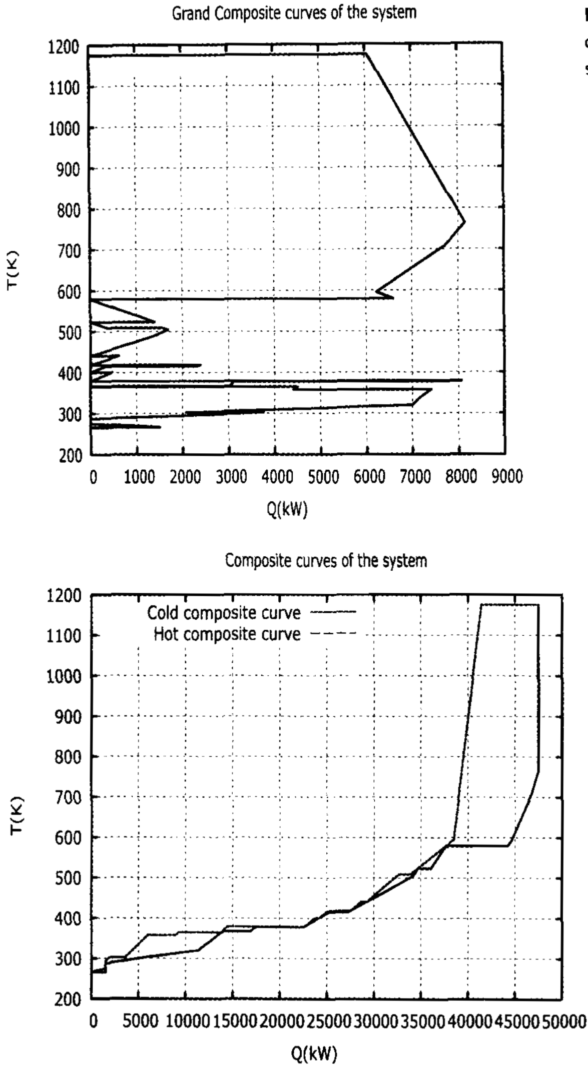

Figure 3.10 Balanced composite curves of the process with boiler, steam, and cooling system

The set of streams is divided into two subsets. The first (set A) defines the subsystem whose integration should be checked, the second (set B) is formed by all the other streams. Set B will be referred to as being the reference set and will be represented by a curve (RB_k,T_k), where T_k is the kth corrected temperature of the heat cascade and RB_k is computed by:

$$RB_k = R_r + \sum_{r=k}^{n_k} \sum_{s=1}^{N_B} Q_{sr} \quad \forall k = 1, \ldots, n_k \tag{3.10}$$

where N_B is the number of streams in subsystem B;
Q_{sr} is the heat load of stream s in the temperature interval r;
R_r is the enthalpy reference that defines the position of the temperature axis (see below).

The opposite curve (RA_k,T_k), corresponding to the subset A, is computed to make the balance of the first one. It defines the integration of the streams of set A to the others (reference set B):

$$RA_k = R_r - R_{n_k+1} - \sum_{r=k}^{n_k} \sum_{s=1}^{N_A} Q_{sr} \quad \forall k = 1, \ldots, n_k \tag{3.11}$$

where N_A is the number of streams in subset A;
R_{n_k+1} is the additional energy that can not be provided by the proposed utility set.

The R_{n_k}+1 has been introduced to obtain a general definition. When the utilities are well integrated R_{n_k}+1 = 0. The value R_r that appears in the definition of the two curves defines the position of the temperature axis on the energy axis. The value of R_r is computed by considering that the curve of set B (the reference set) will intercept the temperature axis at the process pinch point temperature (T_{k_p}). The latter being identified by computing the heat cascade where only the process streams are considered. If k_p refers to the process pinch point, R_r is obtained by fixing $R\ B_{k_p} = 0$ in Eq. 3.10 giving:

$$R_r = \sum_{r=k_p}^{n_k} \sum_{s=1}^{N_B} Q_{sr} \tag{3.12}$$

Using this definition, the temperature axis divides the energy range into two parts: the positive values correspond to the energy concerned with the set B integration, while the negative values refer to the energy involved in the set A integration. The application of the integrated curves representation is described in more detail in Marechal and Kalitventzeff [19]. Some applications of the integrated composite curves are given in the example below. Such representation is really useful when analyzing the integration of cycles. In this case, the difference between the hot and cold streams corresponds to the mechanical power that closes the energy balance. The representation will therefore be used to verify the integration of steam networks or refrigeration cycles and to confirm the appropriate placement of the cycles in the process integration.

When the subsystem considered is a heat exchanger, the integrated composite curves of the heat exchanger are the graphical representation of the remaining problem analysis. When the two curves are separated by the temperature axis, no heat exchange is needed between the streams of the heat exchanger and the rest of the process, when this is not the case, the size of the heat exchange between the two curves will represent the energy penalty that would be associated to the heat exchanger under study. The graphical representation in this case also gives an indica-

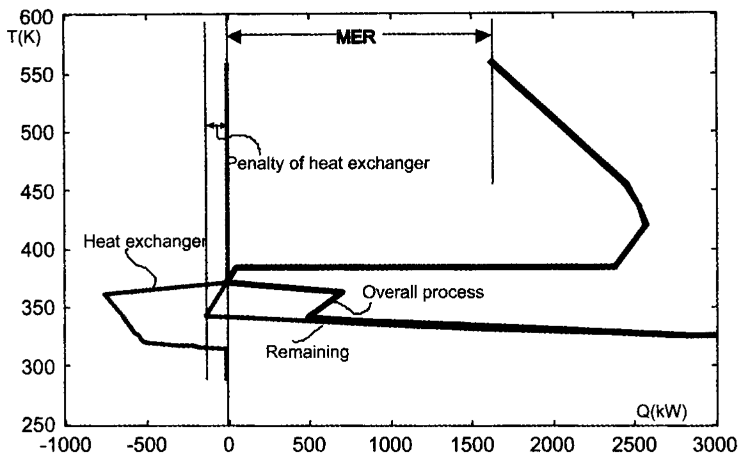

Figure 3.12 Integrated composite curves and remaining problem analysis

tion on the temperature profile of the heat exchange required to reduce the penalty. An example is given in Fig. 3.12.

3.5 Solving the Energy Conversion Problem Using Mathematical Programming

The analysis of the process requirement using the analysis of the grand composite curve and by applying the rules of optimal placement of Townsend et al. [12] and other rules for the optimal CHP schemes allows one to propose a list of energy conversion technologies able to supply the energy requirement of the process with a maximum of efficiency. The mathematical formulation of the targeting problem exploits the concept of effect modeling and optimization (EMO) [20], [21]. It will be used to select the equipment in a superstructure and determine their optimal operating flow rates in the integrated system. This approach assumes that the temperature and pressure levels are fixed, resulting from the analysis of the grand composite curve and the application of rules for the appropriate placement of utility streams [12]. The problem is then a mixed integer linear programming (MILP) formulation, where each technology in the utility system is defined for a nominal size and an unknown level of utilization to be determined in order to satisfy the heat cascade constraints, the mechanical power production balance, and additional modeling constraints. Two variables are associated with any utility technology w: the integer variables y_w represents the presence of the technology w in the optimal configuration and f_w its level of utilization. The objective function is the total cost including the operating costs and the annualized investment cost, both expressed in monetary units (MU) per year. Other objective functions like minimum operating cost or minimum of emissions may also be used. The annualizing factor is computed from the annualizing rate and the life time of the investment. In the equation system, we complete the model by an additional set of constraints (3.17) that are written in a generic form:

$$\min_{R_r, y_w, f_w} \left(\sum_{w=1}^{n_w} (C2_w f_w) + C_{\mathrm{el}_i} W_{\mathrm{el}_i} - C_{\mathrm{el}_s} W_{\mathrm{el}_s} \right) \cdot t \qquad (3.13)$$

$$+ \sum_{w=1}^{n_w} (C1_w y_w) + \frac{1}{\tau} \sum_{w=1}^{n_w} (ICF_w y_w + ICP_w f_w)$$

subject to: Heat balance of the temperature intervals

$$\sum_{w=1}^{n_w} f_w q_{w,r} + \sum_{i=1}^{n} Q_{i,r} + R_{r+1} - R_r = 0 \quad \forall r = 1, \ldots, n_r \qquad (3.14)$$

Electricity consumption

$$\sum_{w=1}^{n_w} f_w w_w + W_{\mathrm{el}_i} - Wc \geq 0 \qquad (3.15)$$

Electricity exportation

$$\sum_{w=1}^{n_w} f_w w_w + W_{\mathrm{el}_i} - W_{\mathrm{el}_s} - Wc = 0 \qquad (3.16)$$

Other additional constraints

$$\sum_{w=1}^{n_w} a_x^i f_w + c_w^i y_w + \sum_{k=1}^{n_x} d_k^i x_k - b_i \underset{\geq}{\overset{\leq}{=}} 0 \quad \forall i = 1, \ldots, n_e \qquad (3.17)$$

$$x_{\min_k} \leq x_k \leq x_{\max_k} \quad \forall k = 1, \ldots, n_x \qquad (3.18)$$

Existence of operation w during the time period p:

$$f_{\min_w} y_w \leq f_w \leq f_{\max_w} y_w \quad \forall w = 1, \ldots, n_w, \; y_w \in 0, 1 \qquad (3.19)$$

Thermodynamic feasibility of the heat recovery and utility systems

$$W_{\mathrm{el}} \geq 0, \quad W_{\mathrm{el}_s} \geq 0 \qquad (3.20)$$

$$R_1 = 0, R_{n_{r+1}} = 0, \quad R_r \geq 0 \quad \forall r = 1, \ldots, n_{r+1} \qquad (3.21)$$

where y_w is the integer variable associated with the use of the technology w;
$C1_w$ is the fixed cost of using the technology w [€ $year^{-1}$];
$C2_w$ is the proportional cost of using the technology w. This value is defined in [$€^{-1}$];
$I\,F_w$ is the fixed cost related to the investment of using technology w; $I\,F_w$ is expressed in monetary units [€] and refers to the investment cost of the combustion and cogeneration equip-

ments as defined above as well as to the other equipment considered in the utility system (turbines, heat pumps, refrigeration systems, etc.);

- IP_w — is the proportional investment cost of the technology w, $I\ P_w$ [€] allows one to account for size effect in the investment;
- τ — is the annualizing factor of the investment. This value is used to express the investment of the energy conversion units in MU per year. $\tau = \frac{(1+i)^{n_{years}}-1}{i\,(1+i)^{n_{years}}}$ is the annualization factor of the investment ($years^{-1}$) ment ($years^{-1}$) for a annualization interest i and an expected equipment life of n_{years};
- n_w — is the number of technologies proposed in the superconfiguration of the utility system;
- q_{wr} — is the heat load of the technology w in the temperature interval r for a given reference flow rate, $q_w r > 0$ *for a hot stream [k W]*;
- f_w — is the multiplication factor of the reference flow rate of the technology w in the optimal situation;
- w_w — is the mechanical power produced by the reference flow rate of technology w; $w_{w,t} < 0$ for a mechanical power consumer and > 0 for a producer [$k\ W$];
- C_{els} — is the selling price of electricity [Eper $k\ W$ € kJ^{-1}];
- W_{els} — is the net production of electricity [kW];
- C_{eli} — is the electricity cost at import [€ kJ^{-1}];
- W_{eli} — is the net import of electricity [kW];
- t — is the total annual operation time [$s\ year^{-1}$];
- Wc — is the overall mechanical power needs of the process; $Wc < 0$ if the overall balance corresponds to a mechanical power production [kW];
- x_k — is the (n_x) additional variables used in the additional equations of the technology models;
- a_w^i, c_w^i — are, respectively, the coefficients of the multiplication factor and the integer variables of technology w in the constraint i in the effect models;
- d_k^i, b_i — are, respectively, the coefficients of the additional variables and the independent term in the constraint i in the effect models;
- x_{min_r}, x_{max_r} — are, respectively, the minimum and maximum bounds of x_r;
- f_{min_w}, f_{max_w} — is the minimum and maximum values accepted for f_w.

The method presented may be applied to any kind of energy conversion technologies. It is based on the assumption that the operating conditions have been defined for each piece of equipment concerned and that only the flow rates are unknown. This is a limiting assumption but it allows one to solve most of the problems of energy conversion integration mainly because nonlinearities may usually be solved by discretizing the search space. The method has been further adapted to compute the optimal integration of steam networks [22], to incorporate restricted matches constraints [23], to integrate refrigeration cycles [24] [25] and organic Rankine cycles[26] as well as heat pumps [27]. It has been applied to integrate new technologies like the partial oxidation gas turbine [28], or to design new types of power plants by introducing the concept of isothermal gas turbines [29].

3.5.1 Gas Turbine and Combustion System

In order to demonstrate the ability of the formulation to tackle complex problems, the model for computing the integration of gas turbines and combustion will be given in more detail. The purpose is to explain how to formulate the problem as a linear problem even if the models appear to be nonlinear. The model represents the integration of the gas turbine including its partial load operation, the possible post-combustion of the gas turbine flue gas, the use of different fuels in the gas turbine and in the post combustion, and of course the integration of conventional combustion in a radiative furnace with possible air enrichment or air preheating. The post combustion and the partial load models are required because there is no possibility of identifying a gas turbine model whose heat load will perfectly match the heat requirement of the process. The principle of the integration is illustrated in Fig. 3.21. The following integration constraints are added to the aforementioned problem. Hot stream corresponding to the flue gas of a gas turbine g is defined by:

$$Q_g^{gt} = f_g \cdot \dot{m}_g \cdot cpf_g \cdot \left(TOT_g - T_{\text{stack}_g}\right) \quad \forall g = 1, n_g \tag{3.22}$$

where

- $\dot{m}_g$ is the flue gas flow rate at the outlet of the gas turbine g in nominal conditions. These values result from the simulation of the gas turbine g;
- Q_g^{gt} is the total heat load of the flue gas from the gas turbine g;
- cpf_g is the mean cp of the flue gas at the outlet of the gas turbine g;
- TOT_g is the temperature of the flue gas at the gas turbine g;
- T_{stack_g} is the stack target temperature accepted for the outlet of the gas turbine g after heat recovery;
- f_g is the level of utilization of gas turbine g with $f_g^{min} \cdot y_g \leq f_g \leq y_g \cdot f_g^{max}$;
- y_g is the integer variable representing the use or not (1,0) of the gas turbine g;
- $f_g^{min(max)}$ is the minimum (maximum) level of utilization of the gas turbine g;
- n_g is the number of gas turbines proposed in the utility system super configuration.

Hot stream corresponding to the post combustion (heat available for convective heat exchange) is given by:

$$Q_g^{pc} = f_g^{pc} \cdot \dot{m}_g \cdot cpf_g \cdot (T_{\mathrm{rad}} - TOT_g) \quad \forall g = 1, n_g \tag{3.23}$$

where $Trad$ is an arbitrary temperature used in the combustion model and representing the limit of the radiative exchange;
f_g^{pc} is the fraction of the nominal gas turbine flue gas flow rate used for postcombustion;
Q_g^{pc} is the heat load supplied by the flow rate fraction of the flue gas flow rate of gas turbine g used in the post combustion device.

Fuel consumption in the gas turbine g is as follows:

$$\sum_{c=1}^{n_{cgt}} f_c^g \cdot LHV_c - (y_g \cdot FCI_g + f_g \cdot FCP_g) = 0 \quad \forall g = 1, n_g \tag{3.24}$$

where n_{cgt} is the number of fuels available for combustion in the gas turbines;
LHV_c the lower heating value of the fuel c;
f_c^g the flow rate of the fuel c in the gas turbine g;
$y_g \cdot FCI_g + f_g \cdot FCP_g$ is the linearized fuel consumption of gas turbine g as a function of its level of utilization.

Electricity production with the gas turbines W_{gt} is given by:

$$W_{gt} - \sum_{g=1}^{n_g} (y_g \cdot WI_g + f_g \cdot WP_g) = 0 \tag{3.25}$$

where $y_g \cdot WI_g + f_g \cdot WP_g$ is the linearized mechanical power production of the gas turbine g as a function of its level of utilization.

The parameters for the linearization are computed by simulation considering the partial load operation of the gas turbine. For each gas turbine g, the unknowns are f_g, y_g, and f_g^{pc}, while the other parameters are obtained from the thermoeconomic models. The quality of the linearization will mainly depend on the range in which the partial load operation is expected to happen in the optimal situation.

The operating costs OC_{gt} and the investment costs IC_{gt} of the selected gas turbines are computed by:

$$\sum_{g=1}^{n_g} (y_g \cdot OCI_g + f_g \cdot OCP_g) - OC_{gt} = 0 \tag{3.26}$$

$$\sum_{g=1}^{n_g} y_g \cdot ICI_g - IC_{gt} = 0 \tag{3.27}$$

where $y_g \cdot OCI_g + f_g \cdot OCP_g$ is the linearized maintenance cost of gas turbine g as a function of its level of utilization;
$y_g \cdot ICI_g$ is the investment cost of gas turbine g from the data base catalog.

The fraction of the flue gas of the gas turbine used in the post combustion is limited to the level of utilization of the gas turbine g.

$$f_g^{pc} \leq f_g \quad \forall g = 1, n_g \tag{3.28}$$

The combustion model is made up of different equations: (3.29) includes different terms representing the oxygen balance required by the combustion of the fuels and the oxygen supplied by air and post combustion flue gas.

$$\sum_{g=1}^{n_g} f_g^{pc} \cdot \dot{m}_g \cdot x_g^{O_2} + f_{\text{air}} \cdot x_{\text{air}}^{O_2} + \sum_{a=1}^{n_a} f_a \cdot \dot{m}_a \cdot x_a^{O_2} - \sum_{c=1}^{n_c} f_c^c \cdot \kappa_c^{O_2} \geq 0 \tag{3.29}$$

where $x_g^{O_2}$ is the oxygen content of the flue gas at the outlet of the gas turbine g;
- $x_{air}{}^{O_2}$ is the oxygen content of the ambient air;
- f_{air} is the amount of air used by the combustion in the system;
- $f^c{}_c$ is the flow rate of fuel c used in the combustion ($f^c{}_c \leq f_c^{max}$); its specific cost is C_c;
- $\dot{m}_c^f$ is the fumes flow rate resulting from the combustion of one unit of fuel c;
- cp_c^f is the mean specific heat of the fumes resulting from combustion. This cp is considered between $T\ rad$ and $T\ stack$;
- n_c is the number of fuels that can be used in the system including those for firing the gas turbine (n_{cgt});
- $\kappa_c^{O_2}$ is the oxygen requirement per unit of fuel c. For practical reasons, the oxygen requirement includes the minimum oxygen excess for this fuel;
- $x_a^{O_2}$ is the oxygen content of the enriched air stream leaving the air separation unit a;
- $\dot{m}_a$ is the flow rate of enriched air leaving the air separation unit a under nominal conditions;
- f_a is the level of utilization of the air separation unit a, with $f_a^{min} \cdot y_a \leq f_a \leq f_a^{max} \cdot y_a$;
- y_a is the integer variable representing the use or not (1,0) of the air separation unit a
- $f_a^{min(max)}$ is the minimum (maximum) level of utilization of the air separation unit a;
- n_a is the number of air separation units considered in the system.

The fuel consumption balance of any fuel c that might be used either in a gas turbine or in standard combustion follows:

$$f_c^c + \sum_{g=1}^{n_g} f_c^g - f_c = 0 \tag{3.30}$$

where f_c is the overall consumption of fuel c.

High-temperature balance: radiative exchange model above $T\ rad$:

$$\sum_{c=1}^{n_c}\left(f_c \cdot (LHV_c + \left(cp_{\text{air}} \cdot \frac{\kappa_c^{O_2}}{x_{\text{air}}^{O_2}} \cdot (T_{\text{rad}} - T_0)\right)\right) - f_{\text{air}} \cdot cp_{\text{air}} \cdot (T_{\text{rad}} - T_0)$$
$$- \sum_{a=1}^{n_a} f_a \cdot \dot{m}_a \cdot cp_a \cdot (T_{\text{rad}} - T_a^O) + Q_{\text{prh}} - Q_{\text{rad}} = 0 \tag{3.31}$$

Low-temperature balance: convective exchange below $T\ rad$:

$$f_{air} \cdot cp_{air} \cdot (T_{\text{rad}} - T_{\text{stack}}) + \sum_{c=1}^{n_c}\left(f_c \cdot \left(\dot{m}_c^f \cdot cpf_c - cp_{\text{air}} \cdot \frac{\kappa_c^{O_2}}{x_{\text{air}}^{O_2}}\right) \cdot (T_{\text{rad}} - T_{\text{stack}})\right)$$
$$+ \sum_{a=1}^{n_a} f_a \cdot \dot{m}_a \cdot cp_a \cdot (T_{\text{rad}} - T_{\text{stack}}) - Q_{\text{cnv}} = 0 \tag{3.32}$$

where Q_{rad} is the total amount of heat available above $T\ rad$;
Q_{cnv} is the total amount of heat available from $T\ rad$ to $T\ stack$;
$L\ H\ V_c$ is the lower heating value of the fuel c. This value is the value computed by simulation of the combustion using the minimum accepted value of the oxygen content in the fumes;
T_0 is the reference temperature used for computing the LHV;
Q_{prh} is the heat load of air preheating, the existence of the air preheating equipment is defined by an integer variable y_{prh} and the following equation: $y_{prh}Q_{ph}{}^{min} \leq Q_{prh} \leq y_{prh}Q_{ph}{}^{max}$. The investment cost of the air preheating device is computed by linearizing the air preheater cost by $I\ C_{prh} = I\ C\ F_{prhyprh} + I\ C\ P_{prh}Q_{prh}$;
cp_a is the mean specific heat of the enriched air leaving unit a at a temperature of T_a^O.

Table 3.11 gives the values needed to compute the integration of some typical fuels used in the industry including some renewable fuels (wood and biogas).

Table 3.11 Values for some typical fuels.

	LHV (kJ/kg)	T_{ad} (K)	T_{stack} (K)	Air (kg_{air}/kg)	Cost (€/GJ_{LHV})	CO_2 (kg_{CO_2}/GJ)
CH_4	50 000	2646.5	374	17.1	–	55
Natural gas	39 680	2270	374	13.9	7.67	55
Light fuel oil	45 316	2425	440	14.4	6.9	70
Heavy fuel oil	44 500	2423	441	14.3	4.67	71
Coal (lignite)	25 450	2111	438	7.29	2.53	81
Wood	18 900	2185.43	374	7.9	5	0
Biogas	13 358	2077	374	4.63	–	0

Natural gas composition: 87% Methane, 13% N_2
Light fuel oil: C-86.2% mass, H 12.4% mass, S 1.4% mass
Heavy fuel oil: C-86.1% mass, H-11.8% mass, S-2.1% mass
Lignite: C-56.52%, H-5.72%, O-31.89%, N-0.81%, S-0.81%, Ash-4.25%
Wood (wt) composition: C-49.5%, H-6%, O-44.6% → $C_1H_{1.4}O_{0.7}$, CO_2 neutral 50% CO_2 and 50% CH_4, CO_2 neutral
Cost 2004, European market

Air Preheating: Outlet Temperature Calculation

When combustion is considered, air preheating plays the role of a chemical heat pump. It is used to pump waste heat available below the pinch point and make it available above the pinch point (by an increase of the adiabatic temperature of combustion). The effect of air preheating is, however, limited to the preheating of the stoichiometric air flow. When the flow rate is higher, the adiabatic temperature of combustion decreases and the benefit of air preheating is lost for the part corresponding to the excess air. When combined heat and power are considered using the steam network, the process pinch point no longer defines the maximum preheating temperature. In this case, the combustion air may be preheated up to the temperature corresponding to the highest condensation pressure of steam because this steam will produce mechanical power before being used as a preheating stream. The preheating heat load will become available at a higher temperature to produce an additional amount of steam at the highest pressure or to increase the superheating temperature. The air preheating temperature is therefore unknown and its optimal value has to be computed. When a heat cascade is considered, computing the optimal preheating temperature is a nontrivial task, mainly because the temperature is used to generate the list of the heat cascade constraints. This makes the problem nonlinear and discontinuous (i.e., according to the temperature, the stream will appear or not in a given heat cascade constraint). Some techniques have been proposed to solve this problem as a nonlinear programming (in our case mixed-integer) problem using smooth approximation techniques (e.g., [30]). This approach is explained in more detail in another chapter. A further approach consists of keeping the linear programming formulation by discretizing the temperature range in which the air preheating will take place in n_i intervals of ΔT. The air preheating stream is therefore defined by a list of cold streams from T_i^{air} to $T^{air}{}_{i+1} = T_i^{air} + \Delta T$ and by adding the following constraints:

$$f_{\text{air}} \geq fa_i \quad \forall i = 1, \ldots, n_i; \tag{3.33a}$$

$$Q_{\text{prh}} = \sum_{i=1}^{n_i} fa_i cp_{\text{air,i}}(T_{i+1} - T_i) \tag{3.33b}$$

where fa_i is the flow rate of air preheated from T_i to T_{i+1};
$cp_{air,i}$ the specific heat capacity of the air flow rate from T_i to T_{i+1}.

In the combustion model, the optimal temperature calculation model is also used to compute the outlet temperature of the air and enriched air preheating, fuel preheating as well as to compute the outlet temperature at the stack. This calculation is done in two steps:

1. Solve the model and compute the optimal flow rates in each interval (fa_i).
2. Compute the resulting temperature To_{n_i} by solving from $i = 1$ to n_i:

$$To_i = \frac{(fa_{i-1} - fa_i)\ To_{i-1} + fa_i \cdot T_{i+1}}{fa_{i-1}}$$

with $To_0 = Ta_{\text{in}}$, which is the inlet temperature of the stream a.

The precision of the model is related to the size of the discretizing temperature intervals. A compromise between the precision required for the equipment sizing and the number of variables is therefore required. A similar formulation is also used to compute the optimal temperature of the gas turbine flue gas after heat recovery.

This systematic choice has been made to keep the robustness advantage of the MILP formulation.

3.5.2 Steam Network

The steam networks play a very important role in most industrial process plants. They are the major interface between the utilities and the process streams while allowing the combined production of heat and power. Furthermore, by transferring heat from one process stream to another, the steam network will be used to reduce the energy penalty resulting from restricted matches. The importance of steam networks is also present for site scale process integration since the steam network will be the method of transferring heat from one process to another.

Targeting the integration of the steam network is an important part of the integration of the energy conversion technologies. In the first attempt to study the integration of energy conversion technologies, the idea was to consider steam as being a constant temperature stream that supplies or extracts heat from the process. This provided an easy way of understanding the multiple utilities integration from the grand composite curve analysis. When designing the site scale steam networks, Dhole and Linnhoff [16] introduced the total site integration concept. They defined the total site composite curves to represent the integration of chemical plants that are composed of several processes and may be integrated. The purpose of these curves is to identify the way energy has to be transferred from one plant section to another using the steam network. This method assumes that heat recovery inside the process has already been performed before allowing for exchanges between processes. The construction of the total site composite curve is explained in Fig. 3.15 (top) for the integration of two processes whose grand composite curves are given on the left. After eliminating the pockets (self sufficient zones), the hot utility and cold utility profiles are composed to build the hot and cold site profiles. The exchange between the processes is then realized using the steam network as a heat transfer medium. If this approach is convenient from the graphical point of view, it can not be applied when considering the integration of steam networks in practice. Two major defaults should be removed. First, the pockets can not be ignored because these may hide heat exchange potentials. This is demonstrated in the center of the figure, where the integrated composite curves of process 1 versus process 2 shows the energy saving that could be obtained when exchanging heat between the two processes. In this example, the energy saving mainly results from the integration inside the pockets. In reality, the hot and cold composite curves of the whole system should be considered. The second drawback of that total site approach is that it ignores the combined production of mechanical power in the steam network. This is shown in the bottom of

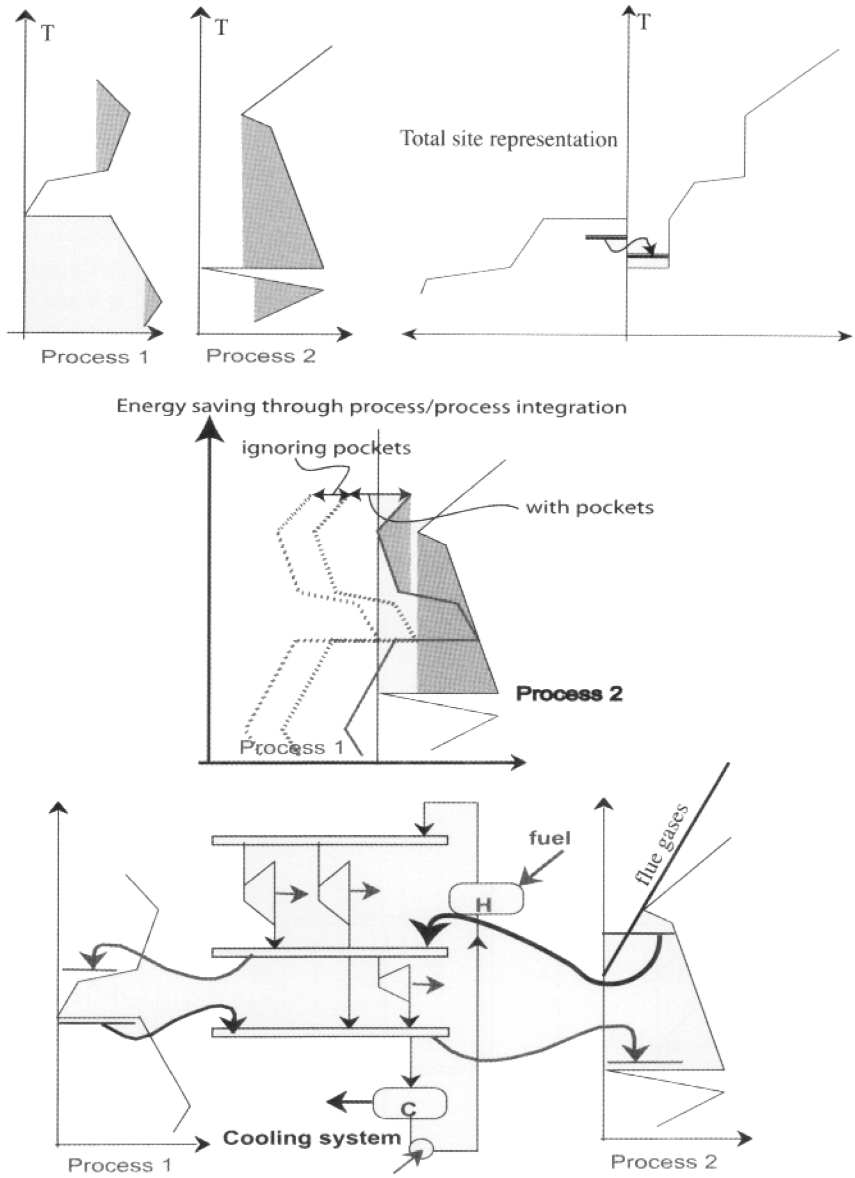

Figure 3.15 Total site integration and steam network

the figure where steam is produced at high pressure in process 2 to be used at high pressure in process 1 and low pressure steam produced in process 1 is used at a lower pressure in process 2. In between, the steam is expanded in a back pressure turbine to produce mechanical power. From the exergy analysis, the potential for combined production of mechanical power is proportional to the size of the pockets in the exergy grand composite curve. These can not therefore be ignored from the heat integration and CHP perspective. In real steam networks, the steam production and condensation cannot be considered at a constant temperature. One should consider the preheating and the superheating for the steam production and the de-superheating, condensation, and liquid undercooling for the steam condensation. Furthermore, the maximization of the mechanical power production will be obtained by optimizing the heat exchanges within the steam network, e.g., by condensing low-pressure steam to preheat high-pressure water of the steam network.

The MILP formulation presented above may be extended to define a more precise model of the steam network. The formulation has been given in [22]. It is based on the definition of a steam network superstructure (Fig. 3.13). This superstructure was first proposed by Papoulias and Grossmann [31]. It has been adapted to account for the temperature–enthalpy profiles of the steam production (i.e., preheating, vaporization, and superheating) and consumption (de-superheating, condensation, and undercooling). One of the difficulties of this formulation has been to guarantee a coherency between the heat and the mass balances while using linear equations. This has been obtained by a special formulation of the mass balances of the steam network headers. Hot and cold streams of the steam network are considered in the heat cascade model and the contributions of the steam expansion in turbines are added in the mechanical power balances. It should be mentioned that using this

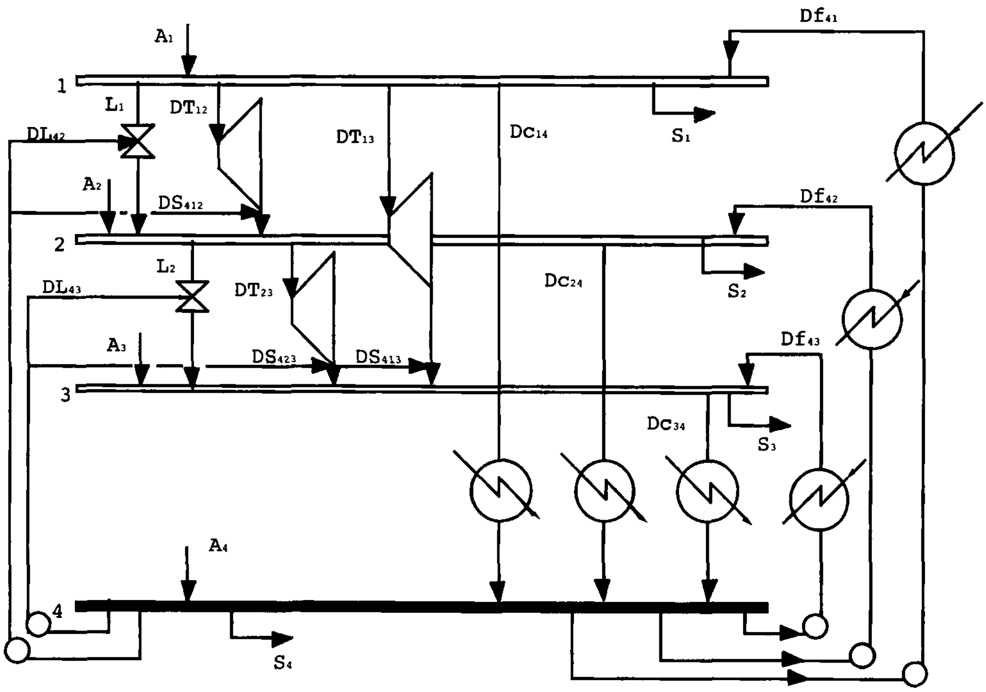

Figure 3.13 Superstructure of a steam network including three production/usage levels and one condensing level (deaerator)

model, the optimal flow rate in the steam network will be determined also by considering the possibility of exchanging heat between the streams of the steam network. This leads to an optimized steam network configuration where steam draw offs are used to preheat the high pressure water. The model may therefore be used as a tool for a rapid prototyping of complex steam cycles in conventional power plants [29].

The integrated composite curves of the steam network (e.g., in Fig. 3.20) is used to represent the results of its integration. In the figure, the overall mechanical power production corresponds to the balance between the hot and cold streams of the system. It is made of the contribution of the expansions between the different pressure levels in the superstructure. A post processing analysis will be required in order to decide the best configuration of the steam turbine(s): single turbine with multiple draw off or multiple back-pressure turbines. The use of the process pinch point as a reference to locate the zero heat (temperature axis) is used to verify the appropriate placement of the steam headers and the combined production of mechanical power. Combined heat and power is well located when it takes heat above the pinch point and sends it above or when it takes heat below and sends it to the cold utility [12]. When the combined heat and power production satisfies the rules for appropriate placement above the pinch point, the part of the integrated composite curve of the steam network that will appear in the left side of the temperature axis should correspond to the mechanical power production. This would indicate that the additional energy required by the system is equal to the mechanical power produced. If not, the rules for appropriate placement are not satisfied and the reason for this penalty should be investigated.

3.5.3 Refrigeration Cycles

Refrigeration cycles are used as a cold utility below the ambient temperature. The major principle of the refrigeration cycle is to use the compression power to change the temperature level of the streams. A simple refrigeration cycle is presented in Fig. 3.14, it is composed of one compressor, one evaporator (at low temperature), one condenser (at higher temperature) and a valve. From the process integration point of view, the refrigeration cycle is defined by one hot and one cold stream and by the corresponding mechanical power consumption. The optimal flow rate will be determined by the MILP formulation presented above. The temperature levels obtained from the grand composite curve analysis will usually define the type of fluid to be used but other considerations have to be taken into account like the environmental aspects (CFC refrigerants) or safety (flammability). The use of fluids already in use in the process plant is also an important criterion. The efficiency of the integration of one refrigeration cycle depends on its compression ratio and on the flow rate. It will depend also on the structure of the cycle and on the possibility of combining cycles with different refrigerants or with different pressure levels. The problem is therefore highly combinatorial since refrigerants, structures, pressure levels and flow rates have to be optimized. A graphical approach based on the exergy analysis has been

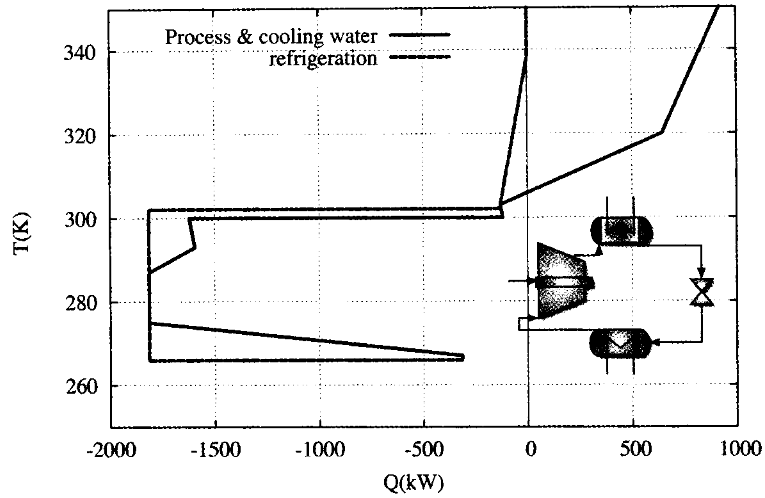

Figure 3.14 Integrated composite curve of a single stage refrigeration cycle

proposed in [32]. This approach illustrates the methodology of the integration of complex refrigeration systems. A nonlinear programming model has been proposed in [33]. The method presented by Marechal and Kalitventzeff [24] shows the extension of the MILP formulation to tackle this complex problem. The method first identifies the most important temperature levels in the grand composite curve using an MILP formulation. The systematic integration of the cycles with the possible refrigerants is made by applying heuristic rules. From this first selection, the remaining cycles for which the refrigerants, the configuration, the temperature levels, and the mechanical power are known are added in the energy conversion system superstructure and the best configurations are sorted out by solving the MILP problem. When several cycles compete, integer cut constraints are added to the problem to systematically generate an ordered set of solutions. The integer cut constraint is used to avoid the generation of an already known solution when solving the MILP problem. The restriction of the k^{th} solution is obtained by adding the following constraint:

$$\sum_{w=1}^{n_w} (2 \cdot y_w^k - 1) \cdot y_w \leq \left(\sum_{w=1}^{n_w} y_w^k \right) - 1 \quad \forall k = 1, \ldots, n_{\mathrm{sol}} \tag{3.34}$$

where y_w^k is the value of y_w in the solution k
n_{sol} is the number of solutions so far.

The use of an integer cut constraint is an important tool when solving utility system integration. The systematic generation of multiple solutions allows the comparison of the proposed utility system configurations using different criteria (not accounted in the definition of objective function) and to perform a sensitivity analysis to uncertain problem parameters like the cost of energy or the investment.

3.5.4 Heat Pumps

When appropriately placed heat pumping systems should drive heat from below to above the pinch point. Several types of heat pumping systems may be considered (mechanical vapor recompression, mechanically driven heat pumps, or absorption heat pumps). Table 3.7 gives some useful thermoeconomical values for the evaluation of the industrial heat pumping systems. The optimal integration is determined by first identifying the streams or the temperature levels for which heat pumping is envisaged. The simulation of the heat pump system using process modeling tools defines the hot and cold streams characteristics that are added to the system integration model and the optimal flow rate for each of the levels will be computed by solving the MILP problem. When mechanical vapor recompression (MVR) is used, a hot stream at lower temperature (mvr_{low}) is replaced by another hot stream ($mvvr_{high}$) with a higher temperature and a mechanical power consumption W_{mvr}. From the grand composite curve analysis, it may happen that only part of the stream will be recompressed. This situation will be represented by considering as variable the fraction used in the two streams (resp. $fmvr_{low}$ and $fmvr_{high}$) and by adding the following constraints (3.35):

$$fmvr_{\text{high}} + fmvr_{\text{low}} \leq 1 \tag{3.35}$$

The inequality represents the situation presented in Fig. 3.17 where the stream is partly recompressed and the remaining part is cooled to lower temperature. It should be noted that the heat load of the high temperature stream is higher than the one of the colder stream because it includes the mechanical power of compression. All the streams have the same target temperature. The adiabatic valve being considered after liquid subcooling. The useful heat of the recompressed stream is therefore lower than the total heat load since part of the heat remains available below the pinch point temperature. When the recompressed stream may be vented (e.g., in the case of evaporation stream), the constraint becomes an inequality. In this case, there are in fact three options: (1) venting the stream and the heat is lost to the atmosphere, (2) condensing the stream and use it because the heat is needed below the pinch point, and (3) recompressing it and using the recompressed stream as a hot utility. The optimal flow rate in each of the options will be obtained from the optimization and will take into account the constraints of the heat cascade. As for the refrigeration cycles, multiple options corresponding to different technologies with different levels of pressure and temperature may be considered and will be handled by the optimization. The results of the heat pump integration correspond to the activation of multiple pinch points. The integrated composite curve of the heat pumping system (Fig. 3.23) is a useful tool to verify the appropriate integration of the system.

3.5.5 Handling Nonlinear Cost Functions

In the problem formulation, linear costs are needed. When the whole range of sizes is covered by the model, a piecewise linearization technique may be used to re-

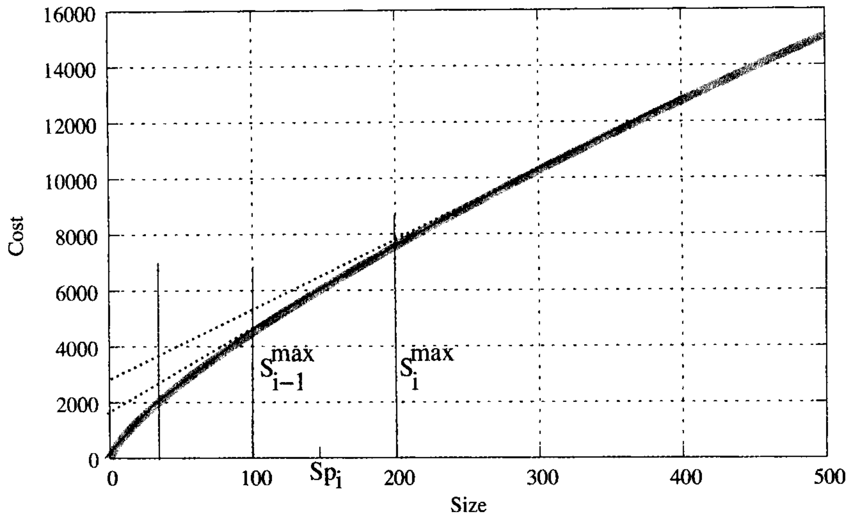

Figure 3.16 Piece-wise linearization of the cost function (exponent 0.75)

present a nonlinear cost function. The generic investment cost function $C\,(S) = C_{ref} \cdot (\frac{S}{S_{ref}})^b$ will be approximated by a set of segments (Fig. 3.16) defined by the following set of constraints (3.36) in the linear optimization problem definition:

$$
\begin{aligned}
C &= \sum_{i=1}^{n_{\text{segments}}} \left\{ \left(C(S_{i-1}^{\max}) - \frac{C(S_{i-1}^{\max}) - C(S_{i}^{\max})}{S_{i-1}^{\max} - S_{i}^{\max}} \cdot S_{i-1}^{\max} \right) \cdot y_i \right. \\
&\quad \left. + \frac{C(S_{i-1}^{\max}) - C(S_{i}^{\max})}{S_{i-1}^{\max} - S_{i}^{\max}} \cdot Sp_i \right\} \\
S &= \sum_{i=1}^{n_{\text{segments}}} Sp_i \\
& y_i \cdot S_{i-1}^{\max} \leq Sp_i \leq y_i \cdot S_{i}^{\max} \quad \forall i = 1, \ldots, n_{\text{segments}} \\
& y_i \in \{0, 1\}
\end{aligned}
\tag{3.36}
$$

where $C\,(S)$ is the installed cost of the equipment of size S;
$S_i^{\max}$ is the maximum size in segment i;
Sp_i is the size of the equipment in segment i;
y_i is the integer variable used to select the segment i.

The linearization by segments is also applicable for performances indicators of technologies like power and efficiency of a gas turbine. The linear formulation may in this case be extended to account for piecewise linearizations of nonlinear functions.

3.5.6 Using the Exergy Losses as an Objective Function

Due to the linear nature of the problem, the use of the energy cost as an objective function may reveal some difficulties [27]. When the cost of fuel and electricity is such that the electrical efficiency of a cogeneration unit is attractive without the use of heat (i.e., when the electrical efficiency of the unit $\eta_{el} = \frac{\dot{W}_{el}}{L\dot{H}V}$ is greater than $\frac{C_{LHV}\ (€\ \mathrm{kJ}^{-1})}{C_{el}\ (€\ \mathrm{kJ}^{-1})}$ there is an economical interest to produce electricity even without cogeneration). In this case, the linear programming procedure leads to a situation where the cogeneration unit is used at its maximum. This situation usually does not occur when the investment costs are properly considered or when the costs of the different forms of energy are coherent with respect to the electrical efficiency. Nevertheless, the relative price of the different forms of energy will influence the technology selection and their level of usage in the integrated solution. When the target is the maximization of the system efficiency, alternative formulations that take into account the value of energy in the objective functions have to be considered. The minimization of the exergy losses (3.37) is an attractive way of formulating the problem:

$$\operatorname*{Min}_{R_k, y_w, f_w} \sum_{w=1}^{n_w} \left(f_w \cdot \left(\Delta Ex_w \pm \sum_{k=1}^{n_k} \Delta ex_{wk} \right) \right) + EL_i - EL_c \tag{3.37}$$

where ΔEx_w is the exergy consumed to produce the hot and cold streams and the electricity of equipment w;

Δex_{wk} is the exergy supplied by the conversion unit w in the temperature interval k,

$$\Delta ex_{wk} = \sum_{s=1}^{ns_w} q_{sk} \cdot \left(1 - \frac{T_0 \cdot \ln\left(\frac{T_{k+1} + \Delta T_{\min}/2_s}{T_k + \Delta T_{\min}/2_s} \right)}{T_{k+1} - T_k} \right); \tag{3.38}$$

$\Delta T_{\min}/2_s$ is the contribution to the $\Delta T_{\min}$ of the stream s; $\Delta T_{\min}/2_s \geq 0$ for hot streams and ≤ 0 for cold streams;

q_{sk} is the heat load of the stream s in the temperature interval k computed for the nominal conditions of the related equipment;

ns_w is the number of streams of conversion unit w.

Using this formulation it is possible to define the set of energy conversion technologies that minimize the exergy losses of the system. It is even possible to introduce the aspects related to the investment by adding the grey exergy into the exergy consumption of the conversion technologies.

3.5.7 Handling Restricted Matches

The use of mixed-integer linear programming in process integration was first proposed to solve the problem of the heat exchanger network design [34]. The design problem is presented as a transportation problem by Cerda et al. [35] or as a transshipment problem [36] with a significant reduction of the number of variables. Such methods can easily be extended to account for restricted matches by adding constraints to the MILP formulation. The draw back of such approaches is that they are designed to find a feasible heat load distribution that satisfies the MER target. In this case, the restricted matches are an advantage because they reduce the search space of the possible connections. When there is no feasible solution, these methods give the energy penalty of the restricted matches. Unfortunately, none of these methods search for ways of reducing the penalty. The integration of energy conversion technologies allows one to go one step further in the analysis because the utility can be used as an intermediate heat transfer fluid to reduce the restricted matches penalty. Steam or hot water may be produced in one section and condensed or cooled down in another section of the plant. Another fluid (e.g., Dowtherm) can be used as a „heat belt". The computer aided design methodology will help in defining the characteristics of the streams to be considered as an intermediate heat transfer fluid to indirectly exchange heat between the streams of the penalizing restricted matches. The formulation proposed by Marechal and Kalitventzeff [23] uses a MILP formulation of the restricted matches to target the energy penalty of the restricted matches. The penalty is divided into two parts according to the position of the process pinch point. From the optimization results, hot and cold restricted matches penalty composite curves are computed (Fig. 3.22). The hot curve represents as a function of the temperature the heat that can not be removed from hot streams involved in restricted matches by the allowed process streams. This heat has to be received by the cold streams of the heat transfer fluid system. The cold composite represents the temperature enthalpy profile of the heat that has to be sent back to the process by the heat transfer fluid in order to avoid the restricted matches energy penalty. The two composite curves have a pinch point temperature that is identical to the one from the MER calculation since no heat can be exchanged through the pinch point in the MER situation. Any combination of hot and cold streams of the utility system that is framed by the two curves will allow one to eliminate the penalty, provided that the temperature difference will be sufficient. The use of intermediate streams imposes the use of two heat exchangers instead of one, thus doubling the $\Delta T\, min$ value. One should note that the restricted matches composite curves are designed in order to preserve the possible combined heat and power production (i.e., producing high-pressure steam by the hot streams and sending it back to the process at a lower pressure after expansion in a turbine). Once the utility streams characteristics are identified, restricted matches constraints are added to the optimal energy conversion system integration problem. The constraint formulation is an extension of the heat load distribution formulation [37] that complements the MILP problem definition. As a result, the complete list of hot and cold streams to be considered for the heat exchanger network design will be obtained and we know that there exists at least one feasible heat exchanger network configuration that satisfies the restricted matches constraints and the minimum cost of the energy target.

3.5.8 Nonlinear Optimization Strategies

The analysis of the integrated composite curve helps in interpreting the results of the optimization and verifying (or optimizing) the choice of the utility system operating conditions (temperature or pressure levels) that were supposed to be "well chosen" when stating the MILP problem.

In order to solve the nonlinear problems with a linear programming formulation, three strategies may be used: (1) the appropriate formulation of the problem constraints as it is explained for the gas turbine integration, (2) the piecewise linearization, and (3) the continuous search space discretization. The latter consists of defining different operating conditions of a given technology as an option among which the optimization will select, using integer variables. The method presented here has tackled the problem of nonlinearities by discretization of the continuous variables search space.

Other authors have directly tackled the MINLP problem. These formulations use the alternative heat cascade formulation (3.4) because in this formulation each constraint is associated with one key temperature (stream inlet temperature) of the system. In this case, when the inlet temperature changes, the definition of the equation is not changed, but it may happen that some of the streams that were above the key temperature will now be below. This creates a discontinuity that is usually not acceptable for most nonlinear programming solvers. In order to smooth the discontinuities, Duran and Grossmann [30] have defined a temperature enthalpy diagram of the streams that is continuous for the whole temperature range. For a cold stream, the enthalpy profile (Fig. 3.11) of a stream is defined by (3.39).

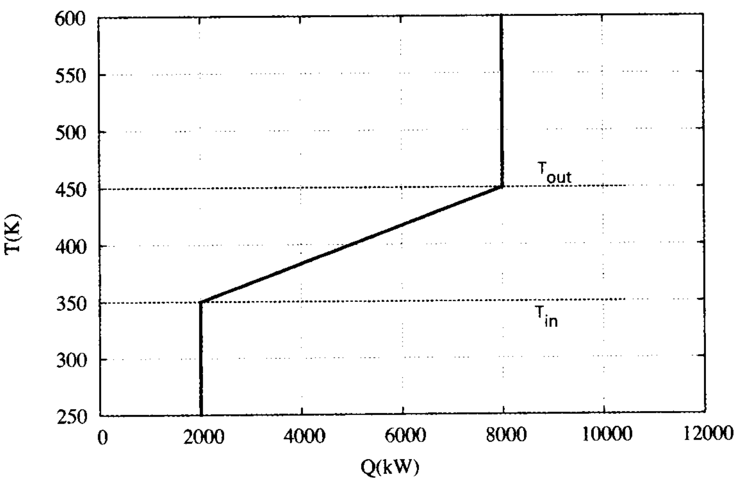

Figure 3.11 Temperature–enthalpy profile of a stream in the process integration

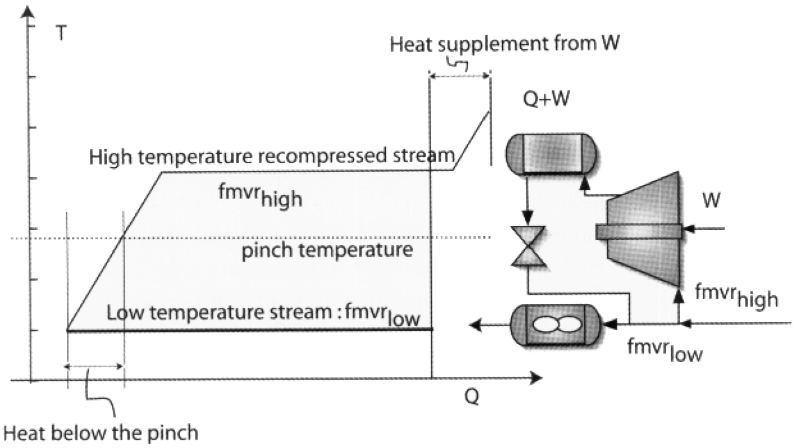

Figure 3.17 Mechanical vapor recompression

$$h(T) = 0 \qquad \text{if} \quad T < T_{\text{in}} \tag{3.39a}$$
$$= \dot{m}cp(T - T_{\text{in}}) \qquad \text{if} \quad T_{\text{in}} \leq T \leq T_{\text{out}} \tag{3.39b}$$
$$= \dot{m}cp(T_{\text{out}} - T_{\text{in}}) \qquad \text{if} \quad T > T_{\text{out}} \tag{3.39c}$$

A smoothing technique is then used to round the corners of the enthalpy profile. The difficulty being to tune the smoothing parameters to be compatible with the nonlinear solver criteria without introducing infeasibilities in the heat integration results. This technique was first proposed by Duran and Grossmann. It has been used and extended by other authors [38], [39] for simultaneously optimizing process performances and heat integration problems.

When isothermal streams are considered in the problem, the smoothing technique to smooth the discontinuities is not valid anymore from the mathematical (numerical) point of view. In this case, it is necessary to use integer variables that will represent the contribution of the isothermal stream i in the heat balance above the temperature j constraint. The expressions $y_{i,j} = 0$ if $T_j < T_i$ and $y_{i,j} = 1$ if $T_j \geq T_i$ are represented by the following equations:

$$T_j - y_{i,j}T_i \geq 0 \tag{3.40a}$$
$$(1 - y_{i,j})T_j - T_i \leq 0 \tag{3.40b}$$

This formulation is generic and may be used to represent all situations even the situations solved by the smoothing approximation technique. The resulting MINLP problem will have a huge number of integer variables and will be solved using an outer-approximation algorithm or using disjunctive optimization techniques.

3.6 Solving Multiperiod Problems

Even when the processes may be considered as being stationary, it is often necessary to consider multiperiod operations where the requirements of the processes are considered to be constant during a given period. The utility system serves the different processes of the plant. It therefore has to answer the varying demands of the different processes. Two different problems have to be addressed in this case: the optimal design of the system and the optimal operating strategy.

3.6.1 Optimal Design

In multiperiod problems, the goal of the optimal design task is to determine the best investment to be made in terms of energy conversion equipment considering the varying demands of the processes. This implies taking into account the partial load efficiencies of the equipment, but also to determine in each period the best way to operate the system. The use of MI(N)LP methods for solving multiperiod process synthesis problems has been reviewed by Grossmann et al. [40] and [41]. Multiperiod optimization is a well known problem that has been considered mainly in heat exchanger network design: e.g., [42], [43],[37]. The generic problem is formulated as follows (3.41):

$$\min_{y_t, x_t, y, s} \sum_{t=1}^{n_t} t_t \cdot c(x_t, s) + I(y, s) \tag{3.41}$$

subject to:

$$h_t(x_t, s) = 0 \qquad \forall t = 1, \ldots, n_t \tag{3.42a}$$
$$g_t(x_t, s) \geq 0 \qquad \forall t = 1, \ldots, n_t \tag{3.42b}$$
$$y_t \leq y \qquad \forall t = 1, \ldots, n_t \tag{3.42c}$$
$$y_t, y \epsilon \{0, 1\} \qquad \forall t = 1, \ldots, n_t \tag{3.42d}$$

where $h_t(x_t, s)$ is the set of modeling constraints during the period t;
$g_t(x_t, s)$ is the set of inequality constraints during the period t;
x_t is an array representing the operating conditions of the equipments
during time period t;
y_t is an integer variable representing the use or not of an equipment during time period t;
s is the array of the sizing parameters of the equipment sets, once an equipment is selected (see the value of y), it is used throughout all operating periods;
y is the array of the integer variables representing the global selection of the equipment sets (i.e., the decision to invest or not);

$c(x_t, s)$ is the operating cost during the operating period i;
$I(y, s)$ is the total annualized cost of the equipments of size s;
t_t is the operation time of period t.

In the general formulation, the set of constraints may be linear or nonlinear and it is assumed that the operating scenari in each period are independent and without heat exchange between periods. If this is not the case, the problem becomes an even more complex batch process synthesis problem. By generating the heat cascade constraints in each period, the model for integrating the energy conversion units presented above may be adapted for solving multiperiod problems [27]. The partial load operation of some of the units has been introduced in the model. Shang et al. [44] have demonstrated that a transshipment model can account for part-load efficiency of expansion turbines and boilers. When using heat cascade constraints, it is assumed that it will be possible to make the heat exchanges required by the heat cascade representation in each time period. If this appears to be a restriction with respect to the heat exchange network structure, its impact may be limited by considering the utility system that will offer a greater flexibility in terms of process utility interface.

The multiperiod design formulation implicitly accounts for the optimal operating scenario. Iyers and Grossmann [45] proposed a MILP formulation for multiperiod problems where the design problem includes operational planning of the system in which the limited availability of the units is accounted for. To overcome the difficulties related to the size of the problem, the authors propose a bilevel decomposition of the problem that reduces the size of the MILP problems and considerably reduces the computing time required.

3.6.2 Optimal Operating Strategy

Once the utility system structure is defined, an optimal operating strategy has to be established. Some authors ([46], [47]) propose a linear programming approach to solve this multiperiod problem in order to calculate the optimal scheduling of the system, considering the start up and shut down time as well as the unavailability of the equipment during the maintenance period.

The optimization of the operating conditions of a utility system has been solved by Kalitventzeff et al. [48], [49] as a mixed integer nonlinear programming problem. The nonlinear models allow one to account for effects of pressure, temperature, and flow rates, and to consider the available heat exchanger areas. To solve the MINLP problem, the outer-approximation algorithm was applied [50]. Combined with data reconciliation techniques for process performance follow-up, this method has been applied with success for the optimal operation of complex industrial utility systems. The MINLP problem formulation assumed that each operating scenario may be optimized independently of the history. It has been demonstrated [49] that this MINLP formulation may be used to make the simultaneous optimization of heat exchanger network integrated with a complex utility system. The method has also been applied to solve utility system retrofit problems where available equipment (e.g., an exchanger) is attributed to a specific operation (e.g., a heat exchange). Papalexandri et al. [51] proposed a MINLP strategy that solves the multiperiod optimization problem and accounts for uncertainties in certain parameters.

3.7 Example

Let us consider the system requirements defined in Fig. 3.4 that result from the hot and cold composite curves of Fig. 3.3. For the calculations, we assumed that all possible process improvements were already implemented before analyzing the grand composite curve for the energy conversion technologies integration. In terms of energy, the requirements are given in Table 3.12. From the grand composite curve, several utilities may be proposed. The simplest solution is to integrate a boiler house using natural gas (with a LHV of 44495 kJ kg^{-1}) and to cool the process with cooling water. The refrigeration needs will be supplied with a refrigeration cycle using ammonia (R717). The operating conditions of the refrigeration cycle (Table 3.13) have been obtained by simulation considering the temperature levels in the composite curve and the $\Delta T\,min$ to be reached in the heat exchangers.

The results are presented on table 3.5 and the integrated composite curves presenting the results of the optimization are presented in Fig. 3.18. The refrigeration cycle consumption is 314 kW. It should be noted that the energy consumption is higher than the MER due to the losses at the boiler house stack (398 K). The solution accounts for the possibility of air preheating to valorize the energy excess available in the process. The heat load of air preheating is 131 kW.

Table 3.12 Minimum energy requirements for the process.

Heating requirement	6854 kW	Above 365 K
Cooling requirement	6948 kW	Between 365 and 298 K
Refrigeration requirement	1709 kW	Below 298 K (lowest T = 267 K)

Table 3.13 Refrigeration cycle characteristics.

Refrigerant			R717	Ammonia	
Reference flow rate			0.1	kmol/s	
Mechanical power			394	kW	
	P (bar)	T_{in} (K)	T_{out} (K)	Q (kW)	$\Delta T\,min/2$ (K)
Hot stream	12	340	304	2274	2
Cold stream	3	264	264	1880	2

Table 3.14 Steam cycle characteristics.

P	*T* *(bar)*	*Comment* *(K)*	
HP2	92	793	superheated
HP1	39	707	superheated
HPU	32	510	condensation
MPU	7.66	442	condensation
LPU	4.28	419	condensation
LPU2	2.59	402	condensation
LPU3	1.29	380	condensation
DEA	1.15	377	deaeration

Table 3.15 Results of the energy conversion system integration for different options.

Option	**Fuel** **(kW_{LHV})**	**GT** **(kWe)**	**CHP** **(kWe)**	**Cooling** **(kW)**	**Heat pump** **(kWe)**
Boiler	7071	–	–	8979	–
Boiler + steam	10086		2957	9006	–
GT + steam	16961	5427	2262	9160	–
Boiler + heat pump	–	–	–	2800	485
Boiler + steam + heat pump	666	–	738	2713	496

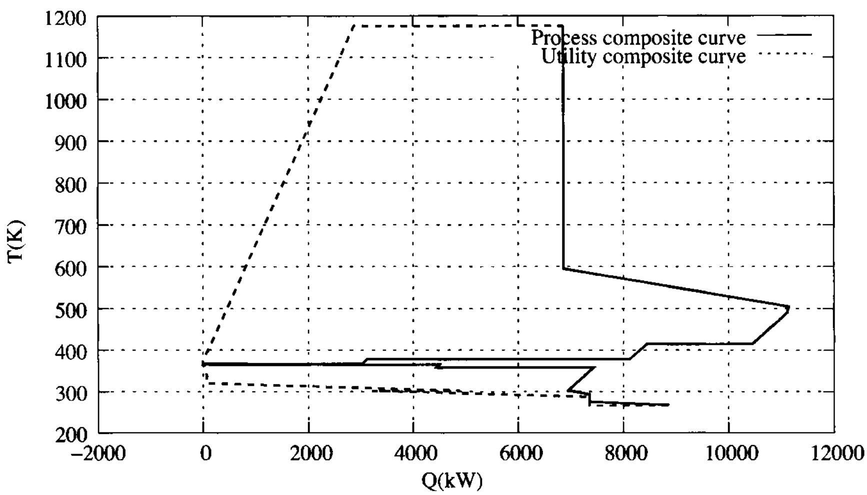

Figure 3.18 Integrated composite curves of the utility system with fuel, cooling water, and refrigeration

In order to valorize the exergy potential (Fig. 3.8), a steam network has been integrated. The steam network characteristics are given in Table 3.14. The grand composite curve obtained by the integration of the steam network is given in Fig. 3.10. This figure is not readable and even the integrated composite curves of the system

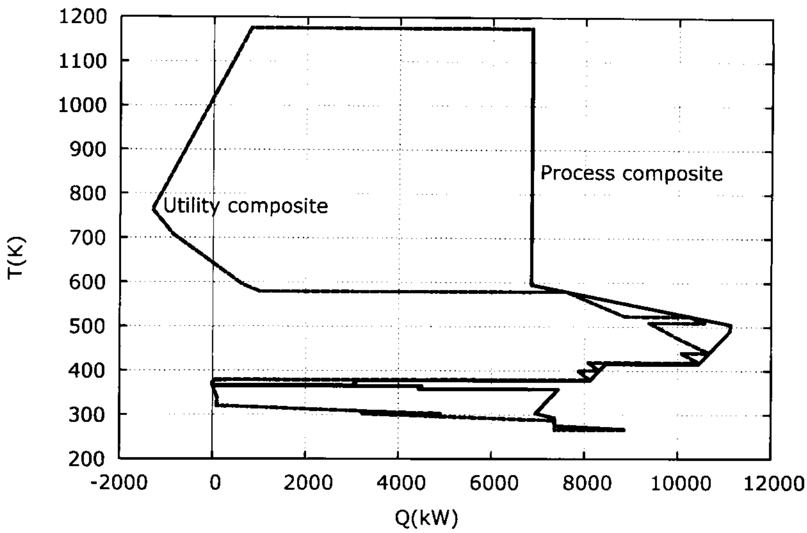

Figure 3.19 Integrated composite curve of the utility system: boiler, steam, refrigeration, and cooling water

(Fig. 3.19) becomes difficult to read. Based on the same results. The integrated composite curves of the steam network (Fig. 3.20) offer a better visualization of the steam network integration. It should be mentioned that the choice of the process pinch point location as a reference for locating the temperature axis allows one to verify the

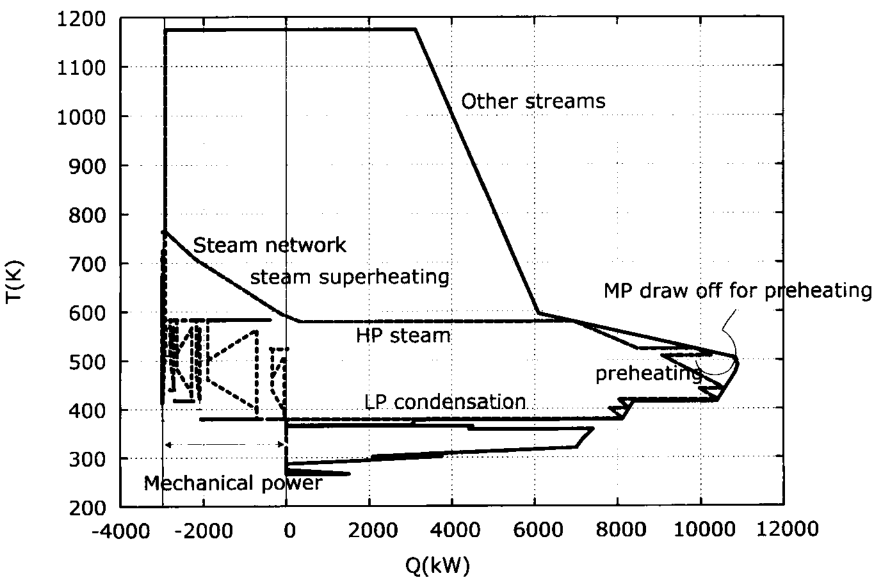

Figure 3.20 Integrated composite curve of the steam network: boiler, steam network, refrigeration, and cooling system

appropriate choice of the steam pressure levels. The energy balance of the hot and cold streams of the steam network is the net mechanical power production. When the steam levels are appropriately placed, the mechanical power production corresponds to a supplement of energy to be supplied to the process. The fact that the mechanical power production appears on the left of the temperature axis proves that the steam network characteristics are appropriate for the optimal production of mechanical power. The area between the two curves gives an indication of the quality of the exergy valorization.

Applying the rules of the appropriate placement of heat pumping devices, three heat pumping cycles have been proposed and simulated (Table 3.17). The high values of the coefficient of performance (COP) are explained by the very small temperature raise to be obtained from the heat pump when considering small $\Delta T_{min}/2$ values for the heat exchangers. Using the optimization tool, the optimal flow rates in the three cycles have been computed together with the new value of the fuel in the boiler house. In the example considered, this leads to a situation where the whole heat requirement may be provided by the heat pumps. The integrated curves of the heat pump system integration are given in Fig. 3.23. When the steam network is considered the results are slightly different since in this case, an additional amount of energy is supplied to the system to produce mechanical power by expansion in the steam network.

The solution of heat pumping is then compared with a combined heat power production using a gas turbine.

The summary of the energy conversion integration target is given in Table 3.16. It is shown that a MER of 6854 kW for the heating requirement and of 1709 kW for the refrigeration requirement is finally supplied with an equivalent of 893 kW of fuel when considering the possibility of heat pumping and when valorizing the exergy content of the process streams. Compared to the boiler house solution, the new situ-

Table 3.16 Overall energy consumption of the different options based on 55% fuel equivalent for electricity.

Option	Fuel (kW_{LHV})	Net electricity (kWe)	Total consumption (kW_{LHV})
Boiler	7071	371	7746
Boiler + steam	10 086	−2481	5575
GT + steam	16 961	−7195	3879
Boiler + heat pump	–	832	1513
Boiler + steam + heat pump	666	125	893

Table 3.17 Characteristics of the heat pump system, based on R123 as working fluid.

Option	P_{low} (bar)	T_{low} (I K)	P_{high} (bar)	T_{high} (K)	COP –	kWe
Cycle 3	5	354	7.5	371	15	130
Cycle 2	6	361	10	384	12	323
Cycle 0	6	361	7.5	371	28	34

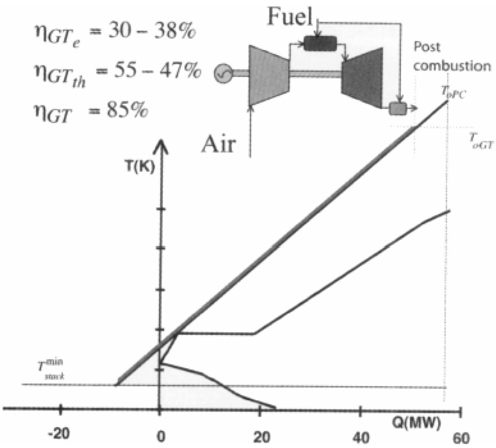

Figure 3.21 Integration of a gas turbine with postcombustion process.

ation corresponds to a fuel consumption reduction by a factor of eight. These data have been computed by considering a fuel equivalence of 55% for electricity production.

The method applied here allows one to quickly evaluate energy conversion alternatives and to quickly assess the impact of process modifications on the processes. Using the targeting method based on optimization, the major advantage of the approach stands in the accounting of the energy savings in terms of cost of energy or in terms of exergy losses rather than in terms of energy. The method allows one to make a first selection of energy conversion options to be further analyzed in more detail using thermoeconomic optimization tools. In this analysis, the cost of the energy conversion system should then be considered together with the cost of the heat exchanger network in order to assess the profitability of the solutions.

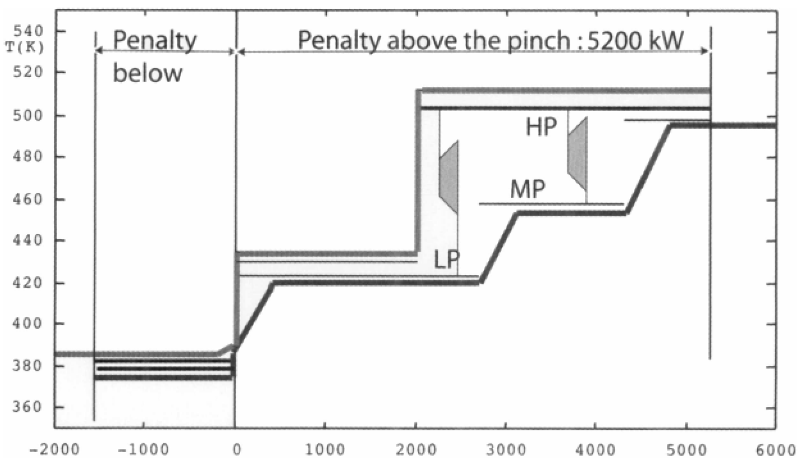

Figure 3.22 Restricted matches penalty composite curves.

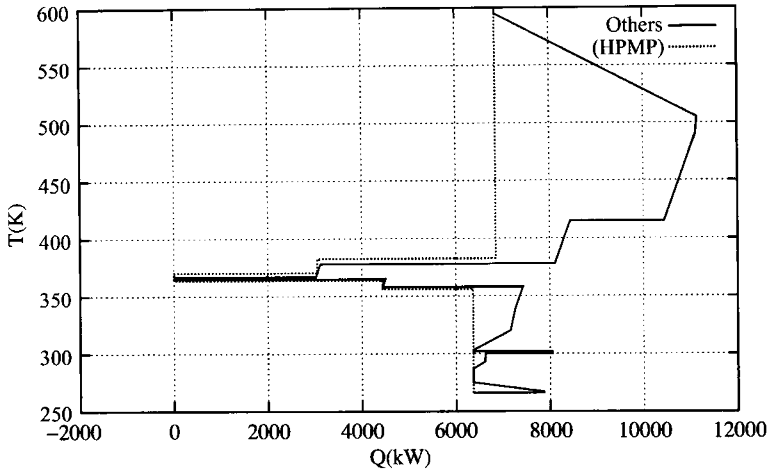

Figure 3.23 Integrated composite curve of the heat pump system: boiler, refrigeration, and cooling system

3.7.1 Rational Use of Water in Industry

In chemical process systems, water is often used as processing support. The optimization of the water usage concerns two aspects: water savings (i.e., resource usage minimization) and the emissions (i.e., the level of contaminant in the waste water). Resulting from the mass balance and the process requirements, both objectives are

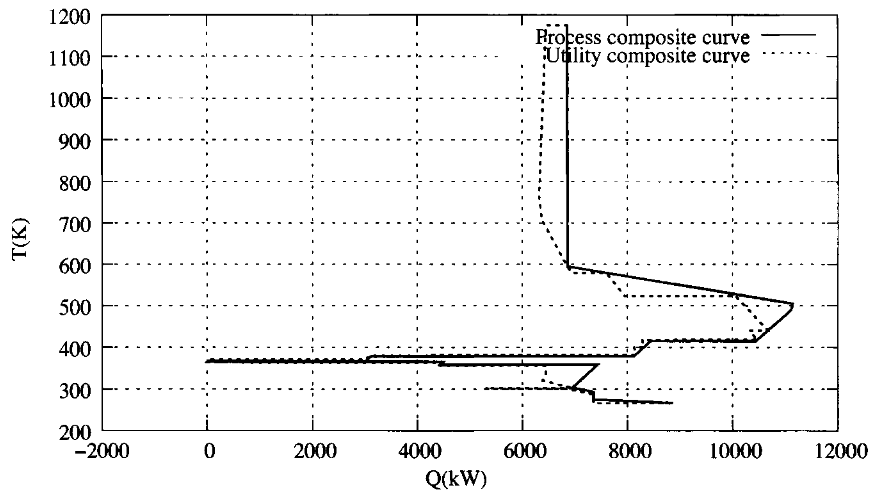

Figure 3.24 Integrated composite curve of the utility system: boiler, steam network, refrigeration, and cooling system

antagonistic since the mass of contaminant to be extracted from the process is constant: if the flow rate decreases, the concentration should increase. El-halwagi and Manousiouthakis [52] presented the analogy between the energy pinch analysis and the mass exchange networks: the concentration replaces the temperature and the water flow replaces the heat load. The method uses mathematical programming techniques where a constraints set defines the water cascade.

Wang and Smith [2] proposed a graphical method based on the same analogy. In their approach, each unit utilizing water is represented by a limiting water profile defined as a concentration/mass of contaminant profile (Fig. 3.25). This profile represents the worst conditions (in terms of flow rate and concentration) that should have the support water entering and leaving the unit in order to realize the mass transfer required. This allows one to draw a composite curve that may be assimilated to the utility profile in the energy domain and to which the fresh water curve (utility) will be integrated. The utility curve starts with a mass of contaminant of zero. Its slope corresponds to the fresh water flow rate required for the system. The minimum flow rate is computed by activating the pinch point between the utility curve and the limiting profile. By balance, the maximum concentration of water is determined. From this targeting procedure, it is then possible to design a water exchange network using a procedure similar to the pinch design method for the heat exchangers. The proposed method suffers however from the drawbacks of being based on the limiting profiles of the mass transfer that does not allow for generic representation of the water usage in the chemical industry and on the difficulty of handling multiple contaminants even if the authors have proposed an adaptation of the method [53] [54]. Dhole et al. [55] proposed another representation of the water cascade considering the water units as being source and demand of water with a given level of purity (Fig. 3.26). The advantage of this representation is the generalization of the approach to represent all types of water usage units and not only the one based on the mass transfer profiles. This allows one to draw the hot (source) and cold (demand) composite

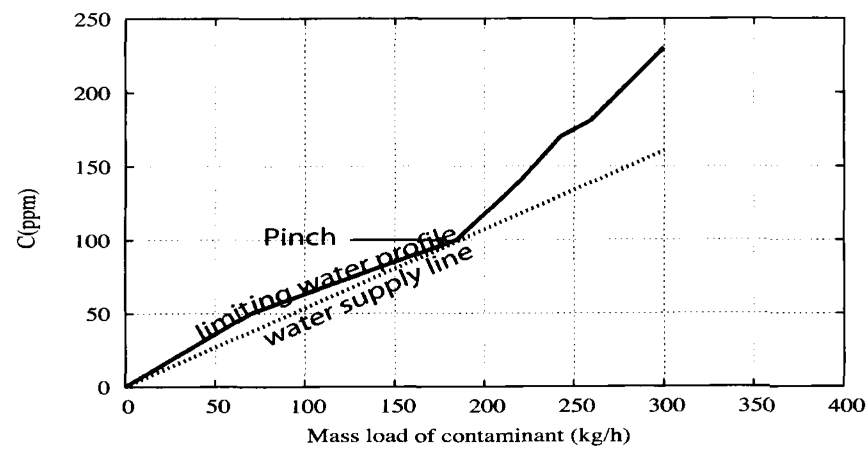

Figure 3.25 Water limiting composite curve

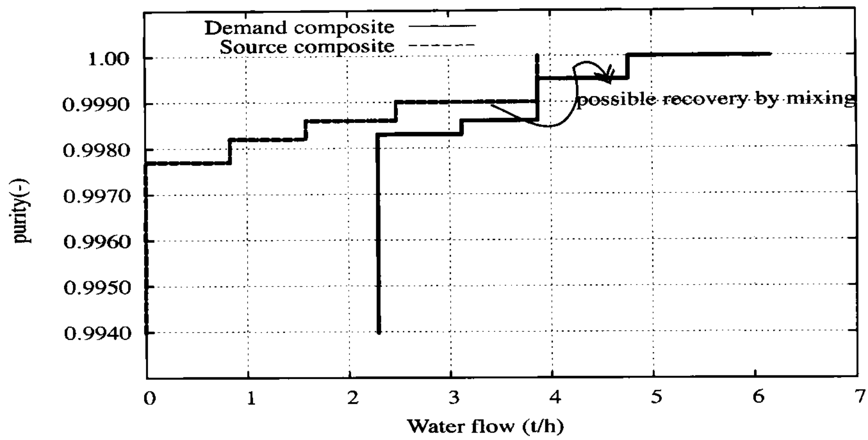

Figure 3.26 Water source–demand profiles

curves, and the corresponding grand composite curve, and to identify the pinch of the system. This approach, however, suffers from the problem of not being able to identify the purity changes that will result from the mixing of a high purity stream (above the pinch point) with a low purity stream (below the pinch point) to produce water with a medium purity above the pinch point. This has some energy analogy with heat pumping by absorption heat pumps. Based on this representation, Hallale [56] proposed an algorithm that computes the possible recovery by mixing and that is based on the water surplus profiles (Fig. 3.27). By analogy with the process integration techniques, the methods based on the graphical representations help to identify the possible integration of water regeneration equipment. The rules are similar to the one of the heat pumps integration.

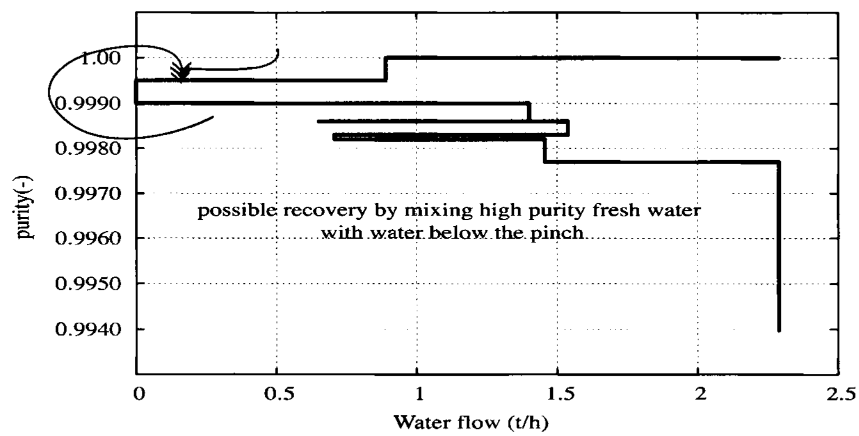

Figure 3.27 Water surplus composite

The graphical representations are attractive to solve and explain water usage targeting. These methods become difficult to apply, however, when multiple contaminants are concerned. In this case, the use of mathematical programming appears to be more convenient. Several formulations have been used: following the formulation of El-halwagi [52], Alva-Argaez et al. [57] proposed a transshipment formulation of the problem that allows one to introduce multi contaminants constraints and balances in the system. Such methods simultaneously solve the water target and the mass exchange network.

Like in the case of energy conversion integration, the water usage minimization will not only concern the minimization of the water usage but also the integration of water treatment or purification units that will concentrate the effluent and perhaps transfer the contaminant to another phase (e.g., solid). In this case there is an interest to consider the combined integration of the water usage and the energy. This would become especially true in situations where waste water will be treated by concentration (cold stream) followed by biomethanation to produce biogas (fuel) or in the case of thermal water desalting systems.

Furthermore, when analyzing the grand composite curve of the water requirement profile (water surplus composite), one may suggest introducing water regeneration units (e.g., filtration) that will change the shape of the water profile and will allow one to further reduce water consumption. This approach will therefore be similar to the one used in the energy conversion technology integration. The mathematical programming approach [58] presented below is based on a multiple contaminants transshipment model. It may be combined with heat integration by summing up MILP problems. The link between the two models will be the value of the level of utilization f_w, which is related to water usage and to energy effects:

$$\min_{\dot{m}_{s,d}, f_w, y_w} \sum_{w=1}^{n_w} (C2_w \cdot f_w + C1_w \cdot y_w) + C_{s,d} \cdot \dot{m}_{s,d} \tag{3.43}$$

subject to:

$$\begin{aligned}
&\sum_{s=1}^{n_s} \dot{m}_{s,d} - \dot{m}_d \cdot f_w(d) = 0 \quad \forall d = 1, \ldots, n_d \\
&\dot{m}_s \cdot f_w(s) - \sum_{d=1}^{n_d} \dot{m}_{s,d} \geqslant 0 \quad \forall s = 1, \ldots, n_s \\
&\sum_{s=1}^{n_s} \frac{\dot{m}_{s,d}}{X_s} \cdot x_{s,j} \leqslant \frac{\dot{m}_d}{X_d} \cdot f_w(d) \cdot x_{d,j}^{\max} \quad \forall j = 1, \ldots, n_j \quad \forall d = 1, \ldots, n_d \\
&\sum_{s=1}^{n_s} \frac{\dot{m}_{s,d}}{X_s} \cdot (1 - X_s) \leqslant \frac{\dot{m}_d}{X_d} \cdot f_w(d) \cdot (1 - X_d) \quad \forall d = 1, \ldots, n_d \\
&X_d = 1 - \sum_{j=1}^{n_j} x_{i,j} \\
&f_w = 1 \quad \forall w = 1, \ldots, n_{up} \\
&f_w^{\min} \cdot y_w \leqslant f_w \leqslant f_w^{\max} \cdot y_w \quad \forall w = 1, \ldots, n_w \\
&y_w \in \{0, 1\}
\end{aligned} \tag{3.44}$$

where $\dot{m}_{s,d}$ is the flow rate exchanged from source s to demand d;
X_d^{max} is the purity required by demand d;
X_s is the purity of source s;
$f_w(d)$ ($f_w(s)$) is the level of usage of unit w corresponding to demand d (respectfully, source s);
$\dot{m}_d$ is the flow rate in the nominal conditions of demand d;
$x_{s,j}$ is the fraction of impurity j in source s;
$x_{d,j}{}^{max}$ is the maximum allowable fraction of impurity j in demand d;
$C1_w$, $C2_w$ are, respectfully, the fixed and the proportional cost of the unit w expressed as a function of its nominal flow rate;
$C_{s,d}$ is the cost of exchanging one unit of flow rate from source s to demand
n_w is the number of utility units in the system;
n_{up} is the number of process units in the system;
n_d (n_s) is the number of demands (sources);
n_j is the total number of impurities to be considered in the problem.

By analogy with the energy integration technique, the use of graphical representations allows a representation of the quality of the integration and suggests further process modifications.

It should be mentioned that the approach suggested for water usage may be implemented by analogy to design and retrofit of the hydrogen networks in refineries. Both graphical techniques [59] and mathematical programming techniques [60] are transposed from water minimization to the refinery hydrogen management domain. In this context, it will be important to consider simultaneously the energy conversion integration techniques, since hydrogen recovery from the hydrogen network will have to be accounted for by its energy content value. The energy consumption used to produce pure hydrogen and the possible combined production of mechanical power must be considered, with the latter being used to drive the recycling hydrogen compressors.

3.8 Conclusions

In process design, the optimal integration of the utility system allows one to transform energy minimization problems into energy cost or exergy loss minimization. It offers a way of considering the energetic problem as a whole, adopting a system vision for the use of energy in the process. The optimal integration of the utility system defines the complete list of streams to be considered in the heat exchanger network design. It is therefore an important step in any process integration study.

The computer-aided methodology for integrating the energy conversion system (utility) in chemical production sites combines the use of graphical techniques and mixed integer linear optimization. Considering that the problem formulation is not always known from the beginning, it is important to use methods that support an engineer's creativity rather than a push-button method. The MILP technique is a robust problem formulation and solving method for process engineers. Many complex problems in process design and operation can be formulated and efficient solutions may be identified. Obviously, the utility integration study, as presented in this chapter, represents only one step of the problem, but it allows one to capture, in a quick and easy way, the major aspects of the integration and to identify the most important options while eliminating the less attractive ones.

An important aspect of the methodology presented is the fact that it does not need the definition of the utility system structure. That will be done only when the best options are identified and together with the heat exchanger network design and optimization.

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