PROCESS INTEGRATION AND IMPROVEMENT

François Marechal
Industrial Energy Systems Laboratory, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

Keywords: Process integration, Pinch Analysis, Rational Use of Energy, Heat Recovery, Heat Exchangers, Minimum approach temperature, Heat Exchanger Network, Minimum Energy Requirement, Heat load distribution.

Contents

1. Introduction
2. Pinch analysis and process improvement
3. Integration of heat pumps
3.1. Mechanical Compression Cycle Heat Pumps
3.2. Other Types of Heat Pumps
4. Utility integration
4.1. Using the Grand Composite Curve
4.2. Combining Pinch Analysis and Exergy Concepts
5. Methodology for designing integrated utility systems
6. Using the exergy depletion as the objective function
7. Representing the integration of the utility system
8. Final remarks concerning the process optimization and the utility system integration
Glossary
Bibliography
Biographical Sketch

Summary

The pinch analysis is a technique that has been developed to identify the possible energy recovery by counter-current heat exchange between the hot streams to be cooled down and the cold streams to be heated up in a system (see also: *Pinch Analysis*). The pinch analysis is based on the definition of the minimum approach temperature $(\Delta T_{\min})$ that represents the energy-capital trade-off between the energy savings obtained by heat exchange and the required heat exchangers investment. Pinch analysis results in the definition of the hot and cold composite curves and the pinch point location. Systematically analyzing the results of the pinch analysis allows on one hand to improve the energy performances of the process by modifying the operating conditions of the process units and integrating in an optimal manner the energy conversion technologies that will convert the purchased energy into process energy requirements. Based on the hierarchical representation of the unit operations of the process, the pinch point location allows one to draw recommendations on the value operating conditions (pressure, temperatures) of successively the reactors, the separation units and the waste treatment units. The analysis of the grand composite curve allows then to identify the possible energy conversion technologies to be used to supply the energy requirement of the system. The Carnot composite curves are used to analyze the integration of the polygeneration units that implement heat pumping and combined production of power

and heating-cooling requirements. Due to the high level of integration of the system, optimization based methods are used to compute the interactions between options in the integrated system and to select the best process configurations out of possible options. The analysis of the optimization results is made using integrated composite curves that represent the integration of a specified sub-system with the rest of the system.

1. Introduction

In a production site (Figure 1), industrial processes aim at converting raw materials into valuable products and by-products. To do so, raw materials are processed through a list of processing steps or interconnected process unit operations that are driven by energy. The purchased energy will be first converted and distributed to be supplied in the suitable form to the process unit operations. This is typically done by a succession of conversion and heat transfer steps. Conceptually speaking, improving the energy efficiency of the system means to maximize the horizontal streams (conversion of raw materials in to products and by-products) while minimizing the vertical ones (conversion of purchased energy into useful energy). By balance, this will result in the minimization of the waste streams and losses of the system.

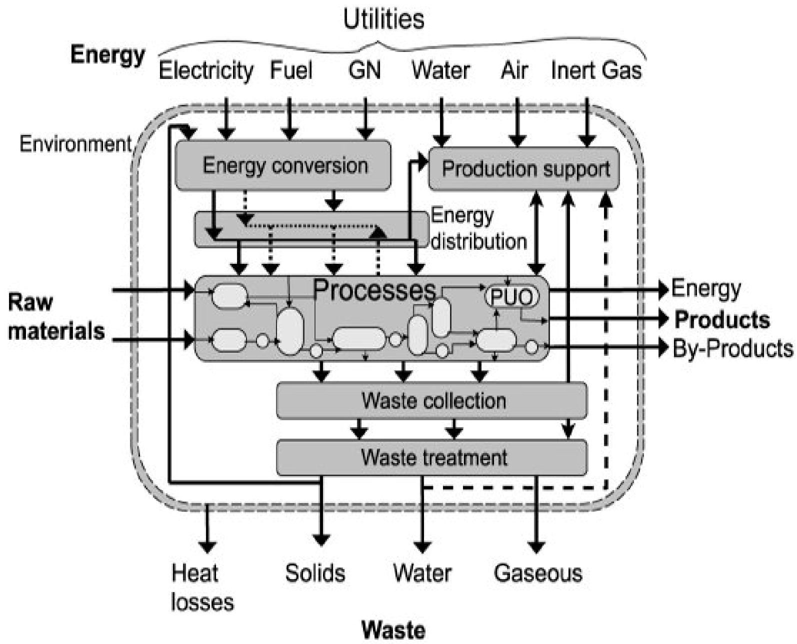

Figure 1. Production site: representation as an energy conversion system

In a generic manner, one may consider that each process in the system is typically made of three steps: a preparation step, a reaction or conversion step and a post treatment step. Both preparation and post treatment steps use typically separation units and produce unreacted or out of specification materials that will be either recycled, introducing processing loops, or processed in a waste management unit. Each process unit operation is realized at given temperature and pressure levels and often requires heat exchange to drive the operation. The heat transfer requirements are defined as hot streams to be cooled down and cold streams to be heated up. Pinch analysis has been developed to identify the possible heat recovery by heat exchange between these hot and cold streams and compute the minimum energy requirement of the system. In this chapter, we will analyze how pinch analysis will assist in defining the most appropriate process units operating conditions that will maximize the energy efficiency of the whole system. The analysis will not only concern process improvement where operating condition of one given process configuration or design are adapted to improve the energy efficiency of the system but also the conceptual process design of new processes where the unit operations have to be defined and arranged and for which the operating conditions have to be optimized. By extension, the method will also concern process retrofit where an existing process configuration will be improved by investing new equipment and optimizing the operating conditions of the process units integrated in the new configuration. Knowing the improved minimum energy requirement of the system, we will then present how pinch analysis will help to determine how heating and cooling requirements will be supplied by converting purchased energy into useful energy in well integrated energy conversion units.

2. Pinch Analysis and Process Improvement

In order to identify the way the process energy requirement can be reduced, a hierarchical approach can be used. The process can be seen as an onion with different layers (Figure 2). The heart of the process is the reaction layer. For improving the Minimum Energy Requirement (MER) of the process, we will first concentrate on the chemical reactions including catalysis aspects, their operating conditions and the type of reactor. The second layer will concern the separation units (distillations, stripping, absorptions, membranes,...) and the recycle streams. The third layer includes the support of production (like catalysts or solvent), then comes the waste treatment units.

The next layer defines the energy conversion and distribution known as being part of the utility system and that aims at satisfying the process energy requirements at a minimum cost using purchased energy.

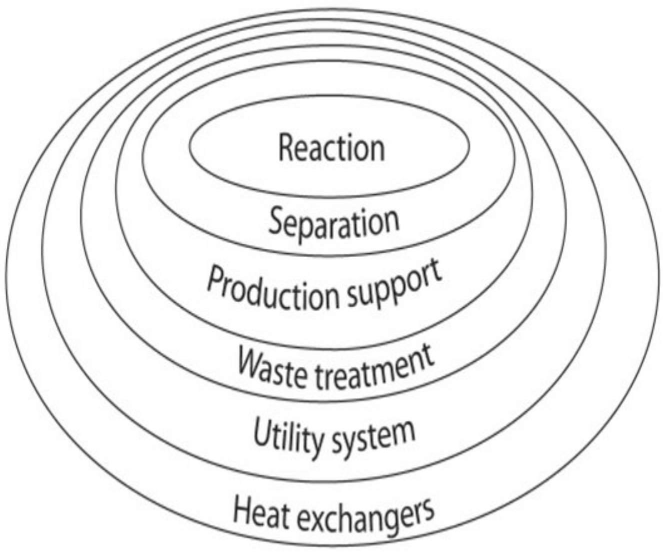

Figure 2. The onion representation of the process for energy efficiency improvement

Once all the previous layers are fixed, the complete list of streams for the heat recovery exchangers is fixed and the synthesis of the heat exchanger network can be realized.

Resulting from the calculation of the minimum energy requirement and the assumption of the $\Delta T_{\min}$, the pinch point temperature divides the heat transfer requirements in two groups: above the pinch point temperature, the heat transfer requirements define a heat sink and an additional amount of heat is needed to satisfy the requirements. Below the pinch point temperature, the heat transfer requirements define a heat source that requires heat to be transferred to the environment.

Being related to the fluid convective heat transfer coefficient, the pinch temperature is a stream dependent value corresponding to a single value in the corrected temperatures space (see chapter Pinch analysis for details). It will be the key driver for identifying profitable process modifications. Modifying process unit operations will aim at relocating the heat transfer requirement across the pinch temperature while delivering the same function in the process. This means to identify hot streams below the pinch point the conditions of which could change, in order to be relocated above the pinch point (i.e. moved from a heat source to a heat sink) and to identify cold streams above the pinch point the temperature of which could be modified to be relocated below the pinch point in order to profit from the excess of energy available.

This is known as the "plus-minus" principle (Figure 3):

- Relocate hot streams from below to above the pinch point
- Relocate cold streams from above to below the pinch point

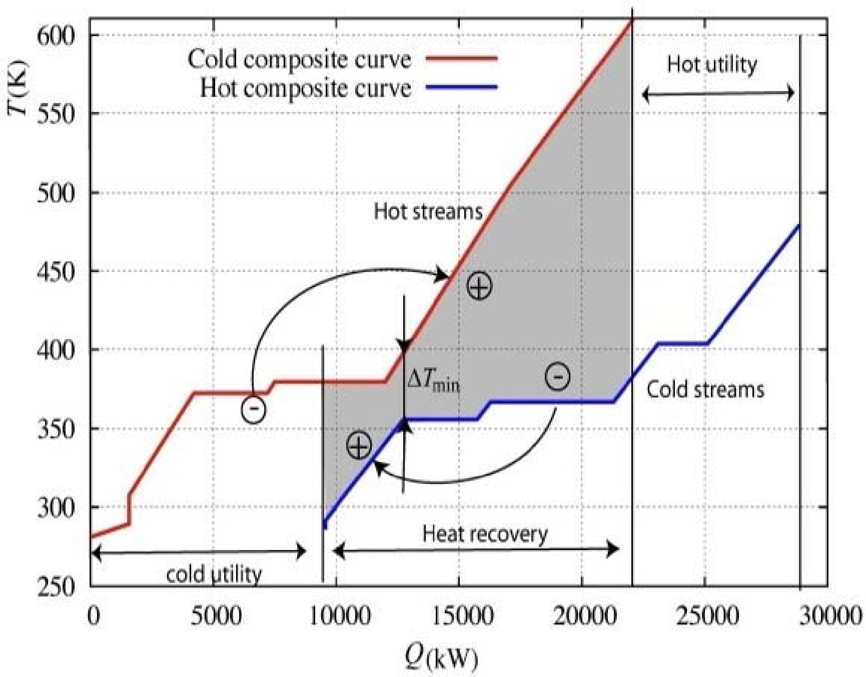

Figure 3. The composite curves for identifying key streams and process unit operations

In this analysis, the most important streams are obviously the streams that are near the pinch point since the temperature change will require fewer modifications in the operating conditions. At this stage, it is worth to note that the pinch point is always created by the inlet conditions of a stream. It can be the inlet of a stream or of the segments created if a fluid phase change occurs.

Referring to the onion diagram, changing the temperature level of a requirement is typically obtained by changing the operating conditions of the process unit operations while keeping as a general goal the efficiency of the conversion of raw materials to products and as constraints the final products to be delivered by the process. Among the important streams to be considered, the heat of reactions typically introduce near vertical lines in the composite curves, when an exothermic reaction occurs below the pinch temperature or an endothermic reaction occurs above the pinch temperature, one could imagine to modify the operating pressure or temperature or even change the reactor type, i.e. change from an adiabatic reactor to a heat transfer type reactor. Another option would be to realize the reaction in several steps in order to maintain the temperature as low as possible (if possible below the pinch point) for endothermic reactions and as high as possible (if possible above the pinch point) for exothermic reactions. This is for example what is realized when adding a pre-reformer in a steam methane reforming process for hydrogen production. In such process, the pinch temperature is the high temperature of the reforming reaction. By realizing the reformation in two steps, the heat of reaction of the pre-reformer becomes a cold stream below the pinch temperature while reducing in the same time the heat requirement of the remaining reforming reaction above the pinch temperature. This can be understood as a chemical heat pump that uses heat from the heat source to reduce the requirement in the heat sink above the pinch point temperature.

When fluid phase change occurs near the pinch point, changing the pressure of the phase change may be used to relocate a requirement around the pinch point. Decreasing the pressure of a fluid to be evaporated or increasing the pressure of a stream to be condensed will relocate respectively a cold stream from above to below the pinch temperature or a hot stream from below to above the pinch temperature. The changes (especially the pressures) obviously must remain compatible with the process unit operations in the flowsheet.

Not only the temperature level, but also the heat cascade has to be considered in this analysis. The grand composite curve of the process (Figure 4) gives useful insight in order to evaluate the interest of modifying the operating conditions. Each modification will be useful if it does not create a new pinch point, otherwise part of the expected energy savings will not be realized. Considering that the pinch point divides the system into two independent sub-systems, the application of the "plus-minus" principle will have the effect of adding heat to and subtracting heat from the corresponding sub-system. The grand composite curve is the plot of the heat cascaded as a function of the corrected temperatures defined by $((R_r, T_r^*), \forall r = 1, ..., n_r + 1)$. Since the heat cascade has still to be satisfied, the maximum heat ($\dot{Q}^{(+)}$) that can be subtracted from one temperature interval ($r^{(-)}$) and send back to another ($r^{(+)}$) will be obtained by solving Eq. (1). This equation is also valid for the transfer of the cold streams from above to below the pinch point. The mechanism that is explained here is illustrated graphically in the Figure 4.

$$\dot{Q}^{(+)}_{r^{(+)}} = \min((\min_r(R_r), \forall r = n_r + 1, \ldots, r^{(+)}), (\min_r(R_r), \forall r = r^{(-)}, \ldots, 1)) \qquad (1)$$

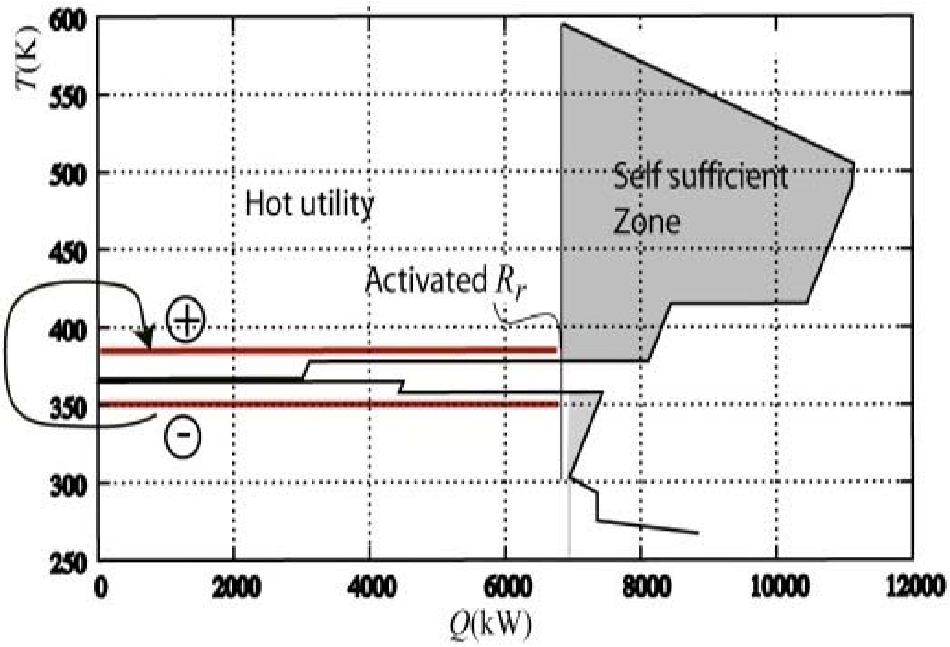

Figure 4. The Grand composite curves for computing the plus-minus heat load

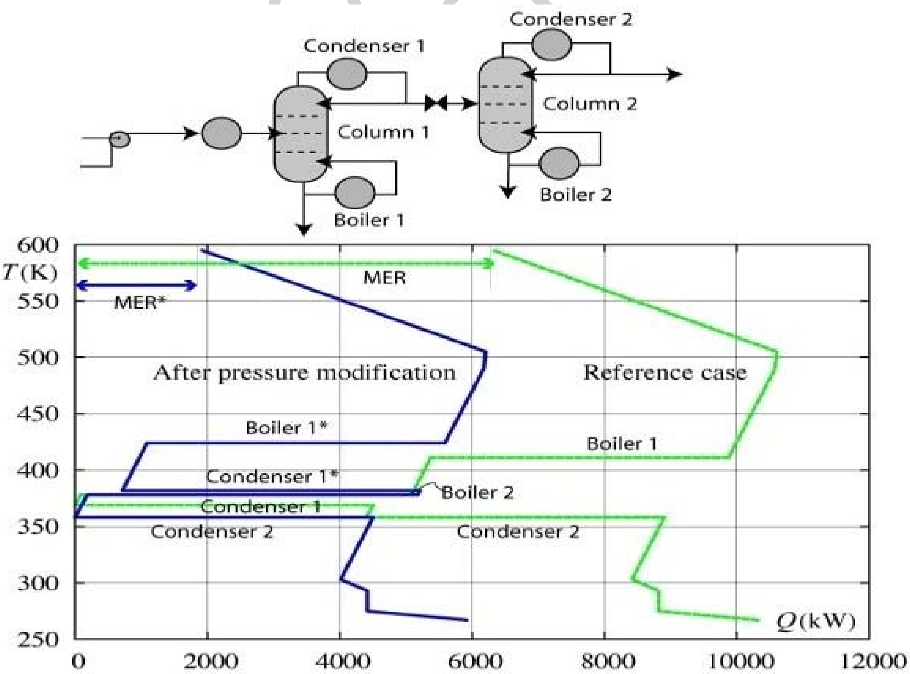

Figure 5. Modifying column pressure in a sequence of two distillation columns (the pressure of column 1 is increased)

In the onion diagram, the operating pressure in the separation units will be of major importance. Distillation column typically introduces two streams with nearly constant temperature: the reboiler defines a cold stream with a higher temperature, while the condenser defines a hot stream at a lower temperature. Changing the operating pressure of one distillation column will allow one to change the temperature of the requirement around the pinch point. Decreasing the column pressure will allow one to shift the reboiler from above to below the pinch point, while increasing the pressure will transfer the condenser from below to above the pinch point. This would be easy to do when the column is fed with a liquid. Considering that most of the separation systems proceed with more than one column, changing the pressure of one column with respect to the other will allow us to save energy by heat integration. An example of such a modification is given in Figure 5 where the pressure of the first column is increased to relocate its condenser above the pinch point. This modification assumes that the hydrodynamics of column 1 has been verified with the new conditions. The modification leads as well to a modification of the pinch point location.

3. Integration of Heat Pumps

3.1. Mechanical Compression Cycle Heat Pumps

The most common heat pump is the mechanical compression cycle illustrated in Figure 6. A fluid (typically a refrigerant) is evaporated by cooling a process stream ($\dot{Q}^{(-)}$), using the mechanical power ($\dot{W}^{+}$), the pressure is changed and the heat is sent back by condensing the evaporated fluid at a higher pressure and temperature. Considering the temperature of evaporation ($T^{(-)}$) and of condensation ($T^{(+)}$), the mechanical power may be approximated by applying an efficiency (η_{Carnot}) to the reversible work of heat pumping (2).

$$\dot{W}^{+} = \dot{Q}^{(-)} \frac{(T^{(+)} - T^{(-)})}{T^{(-)} \eta_{\text{Carnot}}} \qquad 2)$$

The heat load of the condensation ($\dot{Q}^{(+)}$) is equal to $\dot{W}^{+} + \dot{Q}^{(-)}$. The advantage of a heat pump is the fact that is modifies the temperature level of a heat source to make it available at a higher more useful temperature. A heat pump will therefore be attractive when the heat source is a free source (e.g. the environment or waste heat) and when the heat can be delivered to satisfy an energy requirement of the process.

Pinch analysis identifies the possible heat recovery between the hot and the cold streams. It also defines the enthalpy-temperature profile of the process heat source and the process heat sink. The heat source will become the cold source of the heat pump (i.e. the hot stream of the evaporation) and the heat sink profile defines the energy requirements of the process that defines the hot source (cold stream of the condenser). From the definition of the "plus-minus" principle, it can be seen that the only feasible possibility for appropriately integrating a heat pump in the system with a heat exchanger network is to introduce a new cold stream below the pinch temperature. This stream will receive heat from a hot stream of the heat source sub-system and send the heat back after compression in the heat sink sub-system by introducing a new hot stream above the pinch point. The optimal integration of the heat pump system will try to maximize the heat load ($\dot{Q}^{(-)}$), while minimizing the mechanical power ($\dot{W}^{+}$). The temperature lift has therefore to be minimized.

The mechanical power of the heat pump can be estimated using the Carnot factor computed from the temperatures of $\dot{Q}^{(-)}$ and $\dot{Q}^{(+)}$, therefore the integration of the heat pump may be calculated by Eq. (3).

When pumping heat from below to above the pinch point the energy saving is equal to $\dot{Q}^{(+)}$ at the expense of $\dot{W}^{+}$ of mechanical power. The integration of the heat pump if explained on Figure 7.

It has to be noted that when the heat pump is not located to pump heat from below to above the pinch point, the benefit of the heat pump (that may be apparently profitable at its location) is cancelled by the heat integration of the system.

This means also that a heat pump may be profitable in one process configuration and not when the same process is considered as integrated in the production site.

More specifically, when a heat pump is placed above the pinch point temperature, it is indeed equivalent to an electric heater since both $\dot{Q}^{(+)}$ and $\dot{Q}^{(-)}$ concern the same sub-system, the difference $\dot{W}^{+}$ being the only energy input in the sub-system. Moreover, when $\dot{Q}^{(+)}$ is delivered below the pinch point temperature, the electric power of the heat pump is added to the exothermic sub-system, therefore it will just increase the cooling requirement of the system.

$$\begin{aligned}&\dot{Q}^{(+)}_{r^{(+)},r^{(-)}} = \min((\min_r(R_r), \forall r = n_r + 1, \ldots, r^{(+)}),\\ &((1+\frac{(T^{(+)}-T^{(-)})}{T^{(-)}\eta_{\text{Carnot}}})(\min_r R_r, \forall r = r^{(-)}, \ldots, 1)))\end{aligned} \qquad (3)$$

with

η_{Carnot} the efficiency of the heat pump with respect to the reversible heat pump

$T^{(+)}$ the temperature of the hot stream of the heat pump that supplies heat to the process at the temperature $T_{r^{(+)}}$ of the heat cascade

$T^{(-)}$ the temperature of the cold stream of the heat pump that takes heat from the process at the temperature $T_{r^{(-)}}$ in the heat cascade

In reality, the hot and cold streams in the condenser and the evaporator do not have a constant enthalpy-temperature profile. The equation 3 will therefore be adapted to account for such heat transfer profiles. In such situation, more detailed models applying linear programming methods (e.g. Eq. (6)) will be used.

-
-
-

Bibliography

[1] B. Linnhoff. Pinch analysis - a state-of-the-art overview. *Chemical Engineering Research and Design*, 71(A5):503–522, 1993. [Gives an overview of the different applications of pinch technology.]

[2] Robin Smith. *Chemical Process design and integration*. ISBN 0471486809. John Wiley & Sons, 2005. [This book presents the principles of process synthesis of process integration.]

[3] L.T Biegler, I.E. Grossmann, and A.W. Westerberg. *Systematic Methods of Chemical Process Design*. Number ISBN 01334924223. Prentice Hall PTR, Marsh 1997. [This book presents computer aided process modeling and design methods focusing on the application of mathematical programming techniques for the optimization of process system design.]

[4] M.M. El-Halwagi. *Process integration*. Number ISBN0123705320 in Process system engineering. Academic Press, 2006. [In addition to the pinch analysis, this book presents other applications of process integration techniques for materials integration.]

[5] B. Linnhoff, D.W. Townsend, P. Boland, G.F. Hewitt, B.E.A. Thomas, A.R. Guy, and R.H. Marsland. *A User Guide on Process Integration for the Efficient Use of Energy*. Number ISBN 0852953437. The Institution of Chemical Engineers, IChemE, Revised edition, 1994. [Pioneering user guide on process integration based on the application of pinch technology and pinch design method.]

[6] R. Turton, W. Whiting, and J. Shaeiwitz. *Analysis, Synthesis and Design of chemical processes*. Number ISBN:130647926. Prentice Hall, NJ, 1998. [This book presents methods for process system analysis and design as well as cost estimation methods for process system design and optimization.]

[7] Warren D. Seider, J. D. Seader, and Daniel R. Lewin. *Product and process design principles, Synthesis, Analysis and Evaluation*. Number ISBN 04712116631. Wiley, 2nd Edition, July 2003. [This book presents product and process design principles for reducing the environmental impact of the process design and including the application of new techniques: artificial intelligence, optimization and computer modeling.]

[8] Luis Puigjaner, Georges Heyen (eds.) *Computer Aided Process and Product Engineering*, Number ISBN-10: 3-527-30804-0, Wiley-VCH, 1rst Edition, September 2006. [This book in 2 volumes presents the state of the art in the field of computer aided process and product engineering methods.]

Biographical Sketch

François M. A. Marechal is a chemical engineer (1986) from the University of Liège (B) and got his PhD degree in 1995 in the field of the energy analysis and synthesis of industrial processes. From 1986 to 2001, he worked as a researcher in the Prof. B. Kalitventzeff's group in the University of Liège. He joined the Industrial Energy Systems Laboratory (Prof D. Favrat) in Ecole Polytechnique Fédérale de Lausanne (EPFL) in 2001 where he is leading the computer aided energy systems analysis and design group. He teaches process integration, process modeling and optimization in the School of Mechanical Engineering. He authored more than 50 scientific papers in the field of computer aided process system engineering and process integration. His major research interests are rational use of energy in the industry, large scale process integration and thermo-economic design of energy conversion systems using multi-objective optimization techniques.