PROCESS INTEGRATION APPROACH FOR ENERGY SAVING AND POLUTION PREVENTION IN INDUSTRIAL PLANTS

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ABSTRACT

*Process integration is a holistic approach to process design, retrofitting, and operation of industrial plants, which applications are focused on resource conservation, pollution prevention and energy management. Two key branches of process integration can be recognized as: Energy integration, that deals with the global allocation, generation, and exchange of energy throughout the process and Mass integration that provides a fundamental understanding of the global flow of mass within the process and optimizing the allocation, separation, and generation of streams and species. Specifically, in the past two decades process integration tools are developed for heat exchange networks (*HEN*), wastewater reduction and water conservation networks, mass exchange networks (*MEN*), waste interception networks (*WIN*)... This paper provides an overview of some of these developments, outlines the major methodology, ideas and objectives, and mark the process integration as an active research area which lead to significant contributions on the engineering principles of integrated systems.*

Key words*: System Engineering, Process Integration, Pinch Analysis, Energy Efficiency, Environmental Process Design.*

Introduction

Process Integration (PI) is a fairly new term that emerged in the 80's and has been extensively used in the 90's to describe certain systems oriented activities related primarily to process design. Process integration enables the process engineer to see “the big picture first, and the details later”. Based on this approach, it is not only possible to identify the optimal process development strategy for a given task but also to uniquely identify the most cost-effective way to accomplish that task. Generally speaking PI is concerned to the advanced management of material, energy and information flows in a production plant and the surrounding community (*Fig. 1.*) based on the multi criteria optimisation of the processing systems (*Fig. 2.*). PI can be used to:

- Minimize energy consumption (*energy efficiency*), improve *raw material utilization* (improved heat recovery will allow increased recycling in the process) and reduce equipment (*investments*), by identifying the optimal tradeoff between operating cost (raw materials and energy) and investment cost (equipment);

- Increase production volume (*plant capacity*) for plant debottlenecking;
- Reduce operating problems (*operability* ,start-up and shut-down);
- Increase plant *controllability* (which is an inherent feature of the design itself, not the control system) by selecting plant topology and equipment parameters in a way that makes the control easier, irrespective of the actual control system;
- Enabled the plant *flexibility* with respect to planned (new feedstock and/or products, adjusted production volume, etc.) and undesired (such as heat exchanger fouling and/or catalyst deactivation) changes in operating conditions;
- Minimize undesirable plant emissions, by reduced use of fossil fuels, switching to alternative energy sources, closing the processes,(*environment*);
- Add to the efforts in the process industries and society for a *sustainable development;*

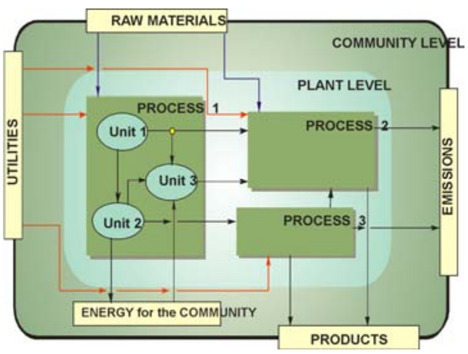


Fig. 1. Areas of PI

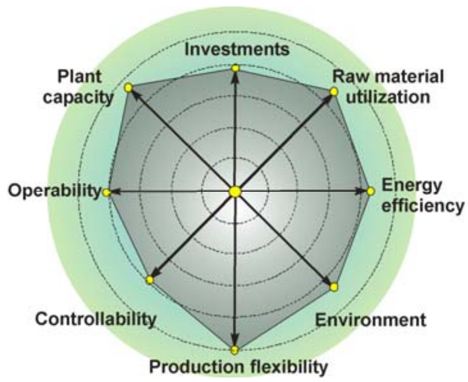


Fig. 1. Objectives of PI

The place of PI is in the science field of *Process Systems Engineering*, and can be described as systems approaches in *space* (the whole plant, the entire site, and sometimes even the whole community), in contrast with *Life Cycle Analysis* (a systems oriented methodology in *time)* and *Integrated Process Design* (a systems view across scientific *disciplines* and *software* systems).

Very often PI has incorrectly been interpreted as Heat Integration[1], disregarding its dynamic scientific potential, which is manifested in constant growing of the new methods and application areas. Due to that fact, a lot of

[1] Probably caused by the fact that Heat Recovery studies inspired by the Pinch Concept initiated the field and are still core elements of Process Integration.

proposals for definition of PI can be found in the literature, but the most complete is the one used by the IEA since 1993:

"*Systematic and General Methods for Designing Integrated Production Systems, ranging from Individual Processes to Total Sites, with special emphasis on the Efficient Use of Energy and reducing Environmental Effects*".[2]

Previous definition, points out that Process integration is a holistic approach to process design, retrofitting, and operation of industrial plants, which applications are focused on resource conservation, pollution prevention and energy management. In order to cover the areas of PI application some authors present the *Onion Diagram (Fig. 3)*, which indicates the hierarchy of most processes, represented symbolically by its layers. The design starts with the "core" of the process which is the reactor (*reactor task*). When reaction path and reactor have been selected, the designer can move outwards in the onion and make decisions on separation (separation task), heat recovery (*HENS*[3] *task*) and finally the utility system (*utility task*). The major drawback for this approach is its sequential nature, because there is no guarantee that a series of optimal local decisions leads to an optimal overall process. While there is a logical information flow from the core of the onion towards the outer layers (suggesting a sequential and decomposed approach), there are important interactions that require iteration towards the centre of the onion, alternatively a simultaneous approach is required.

Another frequently used representation, especially within *Pinch Analysis*, is the *Rubic Cube (Fig. 4.)*. It indicates the start of Pinch Analysis, focusing on HEN with minimum Energy consumption for *Grassroots Designs*. During the 80's and the 90's, Pinch Analysis has expanded in all three dimensions of the cube to cover almost complete process design.

Process integration can be broadly categorized into mass integration and energy integration. Energy integration deals with the global allocation, generation, and exchange of energy throughout the process. The development of the methodologies for energy conservation has been driven by the increasing demand for expensive utilities within industries. Mass integration provides a fundamental understanding of the global flow of mass within the process and optimizing the allocation, separation, and generation of streams and species. It has been developed and applied to identify global insights, synthesize strategies, and address the root causes of the environmental and mass processing problems at the heart of the process. A review of some of the process integration design tools for addressing energy conservation and waste reduction is provided in the **Appendix 1**.

[2] Later, this definition has been somewhat broadened and more explicitly stated in the description[2].

[3] HENS- heat exchanger network synthesis

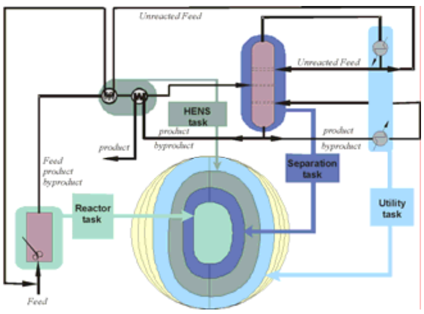


Fig. 3. Onion Diagram in PI

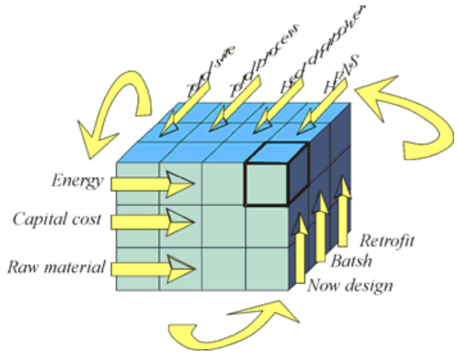


Fig. 4. Rubic Cube in PI

Pocess integration methods

Process integration includes a number of methods that allow engineers to evaluate entire processes or sites, rather than focusing on individual unit operations. These methods are particularly significant for large and complex industrial facilities, because the more complex the process becomes, the harder it is to identify the best design opportunities. Classification of PI methods can be expressed according to the following characteristics:

- *Algorithmic* (the use of mathematical models) vs. *Heuristic* (use design experience often in the form of rules of thumb);
- *Simultaneous* (address all design decisions at the same time) vs. *Sequential* (broke the design problem to a number of subproblems);
- *Quantitative* vs. *Qualitative*;
- *Automatic* vs. *Interactive* or *Manual*;
- *Analysis* (Targeting) vs. *Design* (Synthesis) vs. *Optimization*;
- Use of Graphical Diagrams and Representations;
- Use of *Thermodynamics* (First and Second Law) ;

The large number of structural alternatives can be significantly reduced by the three major features of Process Integration methods *heuristics*, *thermodynamics and* optimization. This features enabled a possible classification of PI methods, based on the two-dimensional diagram show in *Fig.5*.

Hierarchical Analysis is placed in the middle of the figure to indicate that all design methods are based on this idea in order to deal the problem by systematic methods. Optimization Methods can be deterministic (*Mathematical Programming*) or stochastic search (*Simulated Annealing, Genetic Algorithms*) methods but they provide a framework for developing automatic design tools.

Knowledge Based Systems are based on new computer paradigms and implementations are often called *Expert Systems*. *Heuristic Rules* are rules of thumb based on experience or intuition, rapid but with no guarantee of picking the best solution (the most important result is the dramatically reduce of the search space size). *Thermodynamic Methods* includes the *Pinch Analysis* and the *Exergy Analysis* which are based on the *First* and *Second Law* of Thermodynamics.

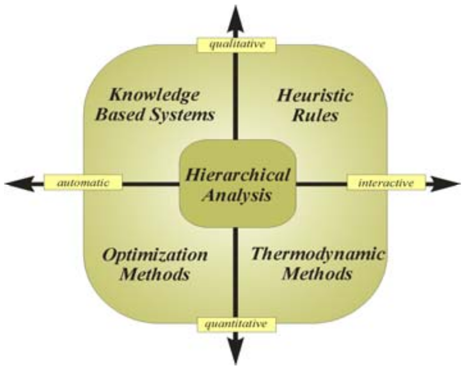


Fig. 5. Possible classification of PI methods.

Basic concept in process integration

From historical point of view the single most important concept and the one that originally gave birth to the field of Process Integration is the *Heat Recovery Pinch*[4], The concept has later been expanded into new areas, like *Mass Pinch*, *Water Pinch*, *Hydrogen pinch*, by using various analogies.[5]

As the name imply Heat Recovery Pinch is address to the problem of HENS which basic task can be expressed as follow:

For Given:

- *a set of hot process streams , each to be cooled from its supply temperature to its target temperature;*
- *a set of cold process streams, each to be heated from its supply temperature to its target temperature;*
- *the flow rates, heat capacities and film heat transfer coefficient of the hot and cold process streams;*
- *the utilities available and the temperature or temperature range and costs for these utilities,*

develop a heat exchanger network with the minimum annualized investment and operating costs.

[4] Discovered independently by *Hohmann* (1971.), *Umeda et al.* (1978-79) and *Linnhoff et al*. (1978-79).

[5] The most obvious analogy is between heat transfer and mass transfer. In heat transfer, heat is transferred with temperature difference as the driving force. Similarly, in mass transfer, mass (or certain components) is transferred with concentration difference as the driving force.

If each of the hot streams is coupled with only one cold stream in the heat exchanger (*He)*, and then both streams brought to their target temperatures using utilities, then the number of possible combinations[6] to couple the hot and cold streams in such *one-exchanger-per-stream* system is $p = N_{Hs} N_{Cs}$. For a simple case when $N_{Hs} = N_{Cs} = 2$, four possible configurations are shown in *Fig.6*.

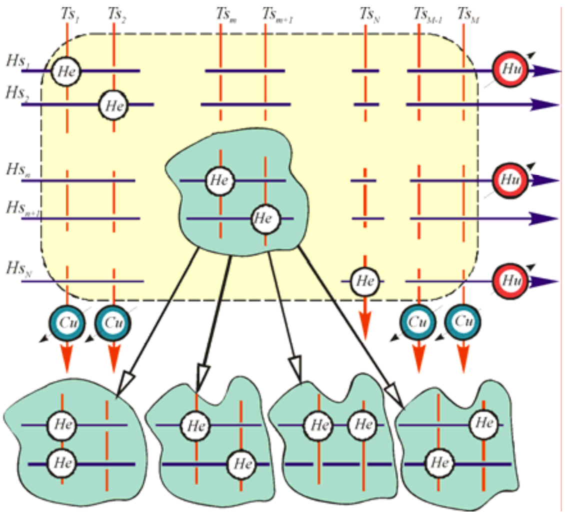


Fig. 6. Graphical presentation of HENS task

For any of these combinations there are $p-1$ possibilities to couple the next pair of hot and cold streams, so the number of two-exchanger configurations is $p(p-1)$, the number of three-exchanger will be is $p(p-1)(p-2)$, and the number of all possible configurations becomes $P = p!$. For a system consisting of 5 hot and 5 cold streams, the number of configurations could be approx. $P = 1.5 \circ 10^{25}$ The number of combinations is in realty smaller, some of them are thermodynamically impossible (for example, if the cold stream is hotter than the hot stream), and some are not desirable (those resulting in too small exchangers, gas-gas contact etc.). But still, even with these reductions, the problem is very complex.

One of the most important tool used in Pinch Analysis is the *Composite Curve*. The process streams are first divided into sources and sinks, corresponding to hot and cold streams. The hot streams are then plotted in terms of quality (temperature, *T*) against quantity (heat duty, enthalpy *H*). The resulting curve, hot composite curve, is a representation of the amount of heat in the process and the temperature range over which it is available. (*Fig. 7*). A similar plot for the cold streams shows the heat requirements of the process, again as a function of temperature.

By combining these curves on one diagram (*Fig. 8.*), the minimum hot and cold utility requirements (or targets) can be determined. Process heat recovery is

[6] Which is equal to the number of possible heat exchanger network configurations

possible where the hot and cold composite curves overlap. The remainder of the heat balance must be made up by external hot and cold utility, shown as the minimum, or target, value by the composite curves ($Q_{H,min}$ and $Q_{C,min}$). Comparing this target with the actual utility consumption quantifies the scope for saving. The "*pinch*" that gives its name to the technology is the point of closest approach between the two composite curves in the plot.

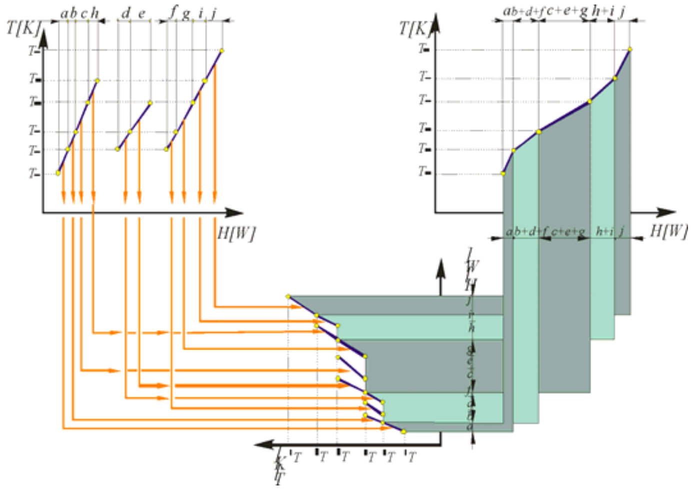


Fig. 7. Graphical design of composite curve

This point, sets the degree of possible heat recovery and divides the process into two energy subsystems; above the pinch and below the pinch, both of which are in enthalpy balance. Based on the composite curves a general strategy for *Process Modifications* can be established. In Pinch Analysis, this strategy has been referred as the *Plus/Minus* principle (*Linnhoff and Vredeveld, 1984*), which means to increase ("*plus*") heat available above Pinch and/or heat demand below Pinch, or to reduce ("*minus*") heat demand above Pinch and/or heat available below Pinch. In order to maximize heat recovery (and thus minimize external heating and cooling), the two composite curves can be moved horizontally towards each other, and the Pinch point is acting as a *bottleneck* where the driving forces for heat transfer, $\Delta T\ min$, become limiting.

The heat recovery Pinch also provides insight about the fundamentals of heat recovery systems that has been applied to develop so-called *Performance Targets* (*Fig. 9.*). This exercise of *pre-optimization*, by identifying a starting value for , $\Delta T\ min$ estimate of the total annual cost with respect to minimum energy consumption ($Q_{H,min}$ and $Q_{C,min}$), fewest number of heat exchangers (N_{min}) and the lowest total heat transfer area (A_{min}).

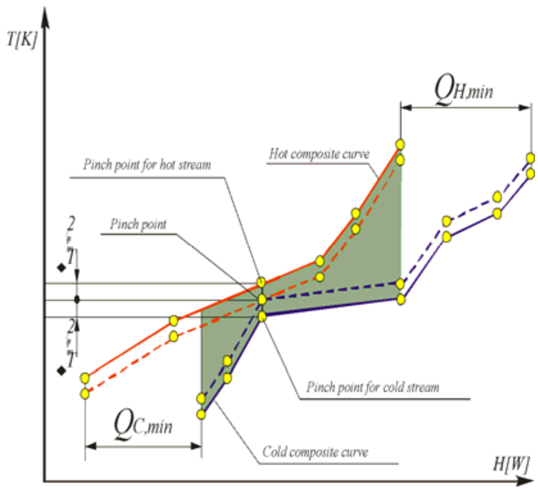
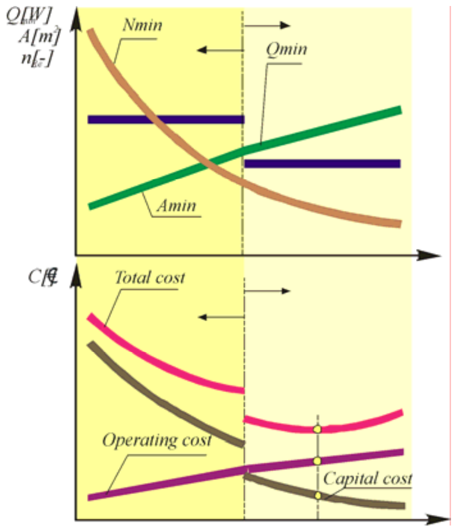


Fig. 8. Pinch diagram



F*ig. 9. Performanc*
Targets of design

In mass transfer processes, concentration difference (or more precisely: the difference in chemical potential) is the driving force in the same way as temperature difference is the driving force for heat transfer. Thus a complete methodology referred as *Mass Pinch* has been developed for designing *Mass Transfer Networks*, and it is very similar to the analysis and design methods for heat recovery systems. A special application of the analogy between heat transfer and mass transfer has been developed for the problem of wastewater management in the process industries. By optimal use, reuse, regeneration and possibly recycling of water streams, the amount of both, fresh water consumed and wastewater produced can be significantly reduced. The corresponding methodology, which has been referred as *Water Pinch*, has also been applied to the design of distributed effluent treatment systems, again with considerable savings in cost and/or improvements for the environment.

Composite curves provide the first and most widely recognized set of pinch tools. Other tools include *Heat Exchanger Grid Diagrams, Grand Composite Curves, Site Source/Sink Profiles, Column Profiles...* The complete design task can be divided on the four phases, for both new and existing processes:

- *Data Extraction*, which involves collecting data for the process and the utility system.
- *Targeting*, which establishes figures for best performance.
- *Initial design*, where an initial Heat Exchanger Network is established.
- *Optimization*, where the initial design is simplified and improved economically.

For the purpose of brief presentation Pinch Analysis is presented in **Appendix II**.

Benefit of Process Integration

Traditionally, capital spending on outright energy conservation projects has not been a priority in industries. The recent ratification of the Kyoto Protocol changed this focus. The PI approach, combined with conventional energy efficiency audit, and with monitoring & targeting techniques, is probably the best approach that can be used to obtain significant energy and water savings as well as pollution reductions (*Fig 10*).

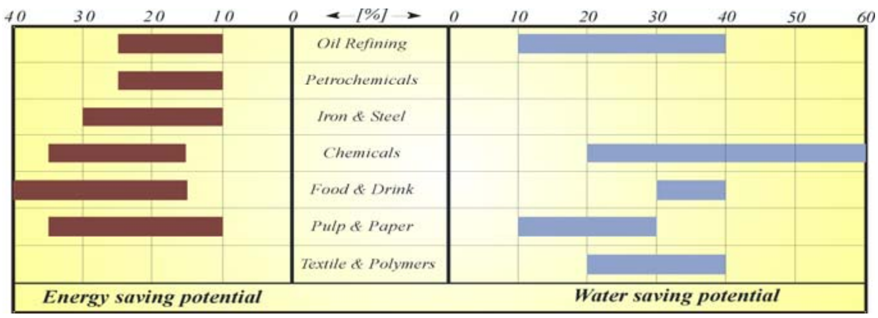


Fig. 10. Energy and water savings potential for different industries.

Economic projects identified during PI depend on the following: size and arrangement of the plant, required pipe distances and routes, space constraints, operating limitations, and level of engineering needed to overcome local hazards or influencing conditions. The paybacks may differ from plant to plant (*Fig. 11.*) but the most often can be classified as:

- Quick-win and short-payback projects save up to 5% of energy costs with a one-year payback;
- Medium-payback projects (the most attractive) produce a further 10%–15% energy saving within a one-to-three year payback;
- Long-payback (typically, utility infrastructure projects, such as a gas turbine with heat recovery steam generation system) projects can produce additional savings of up to 25% of the site energy bill with overall payback times of four to six years.

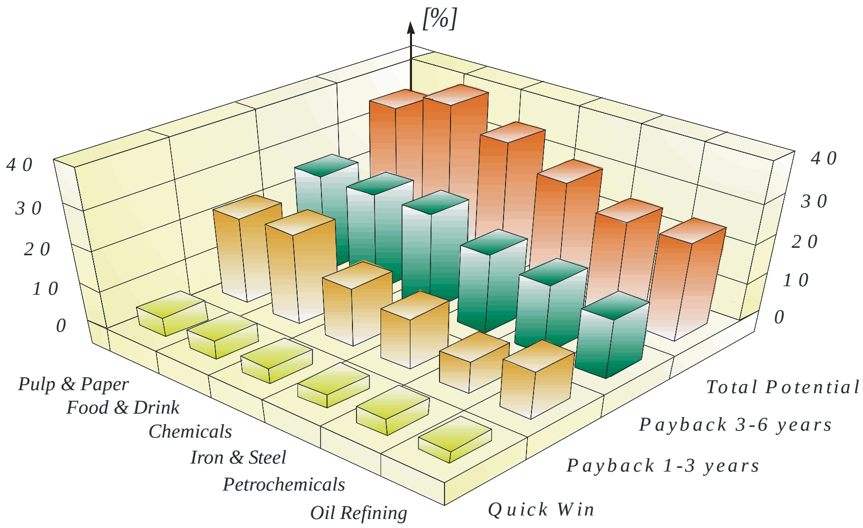


Fig. 10. The paybacks potential for different industries

Conclusion

A systematic approach to process development using process integration has been presented in this overview. Process integration is a very powerful and robust technique that identifies global performance targets ahead of any development activity, and at the same time, identifies the optimal strategy to reach it. Application of these methodologies often identifies process designs that are not intuitively obvious even by experienced engineers employing heuristics and brainstorming. Admittedly, process integration — especially the newer developments — has not been used as widely as it could be.[7].

One of the main conclusions from this paper is the need for education, training and dissemination. In all of the countries, except the UK, there is little knowledge of process integration tools and many respondents feel there is a need for a series of review articles in some of the process and chemical engineering journals to show where the methods can be, and have been, used to provide practical and efficient solutions. A brief review of Academic and Commercial Developers of PI are presented in **Appendix III and IV.**

[7] In this author's view, the major barrier has been simply a lack of knowledge. People will not want something if they do not know it exists.

References

[1] Rašković P. "Industrial energy system optimization based on heat exchanger network synthesis", Faculty of Mechanical Engineering, University of Nis, Serbia and Montenegro, 2002.

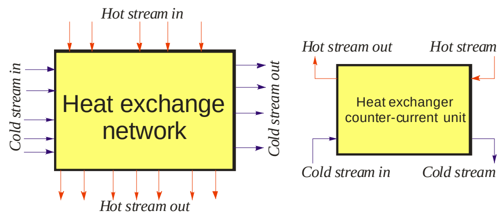
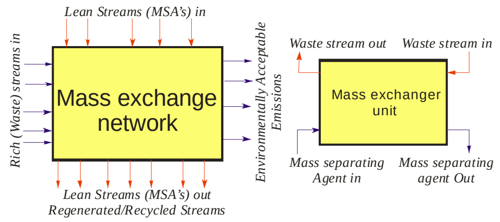
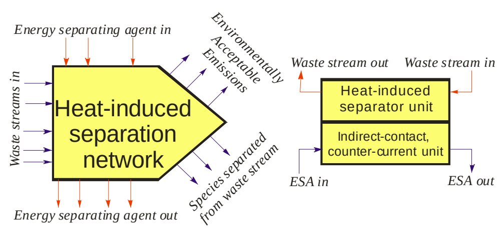
[2] Gundersen T., "Process Integration PRIMER", SINTEF Energy Research, May 2000.

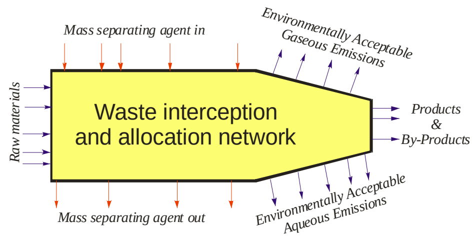
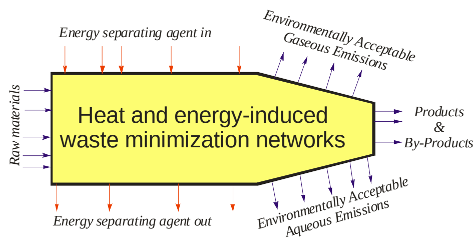
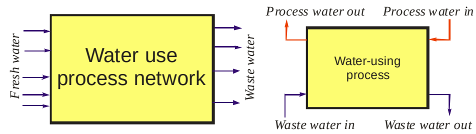
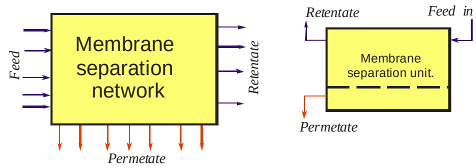
[3] Gundersen T., "A worldwide Catalogue on Process Integration", SINTEF , June 2001.

[4] El-Halwagi M. M, "Pollution Prevention Through Process Integration: Systematic Design Tools", Academic Press, San Diego (1997).

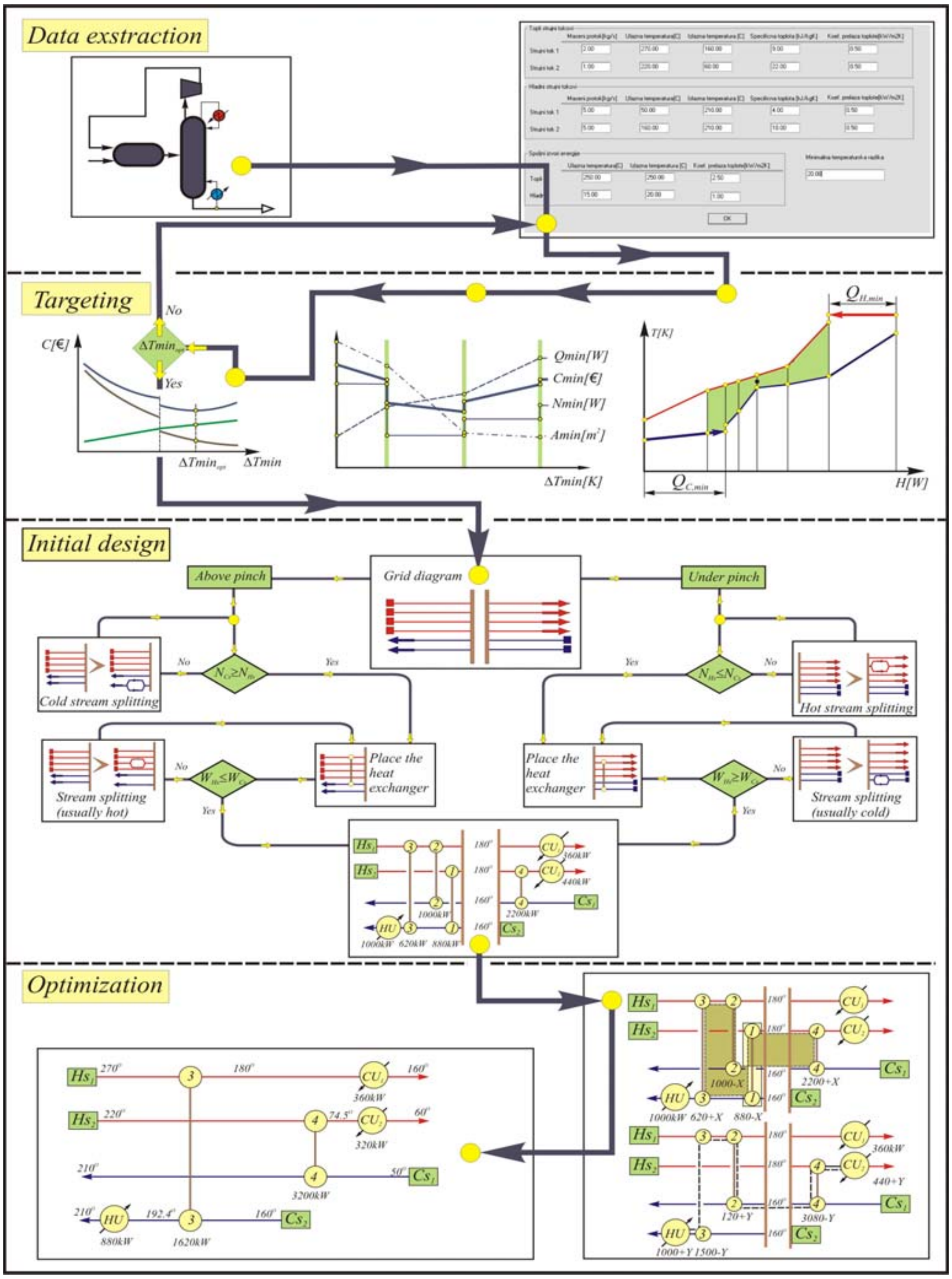
[5] Rašković P., "Proces integration-Case study sodiumtripolyphosphate manufacture". In Proceedings of ECOS 2005, Trondheim, Norway, Jun , 2005, Vol. 1, pp. 493-501.

Apendix I. Summary of process integration environment design tools

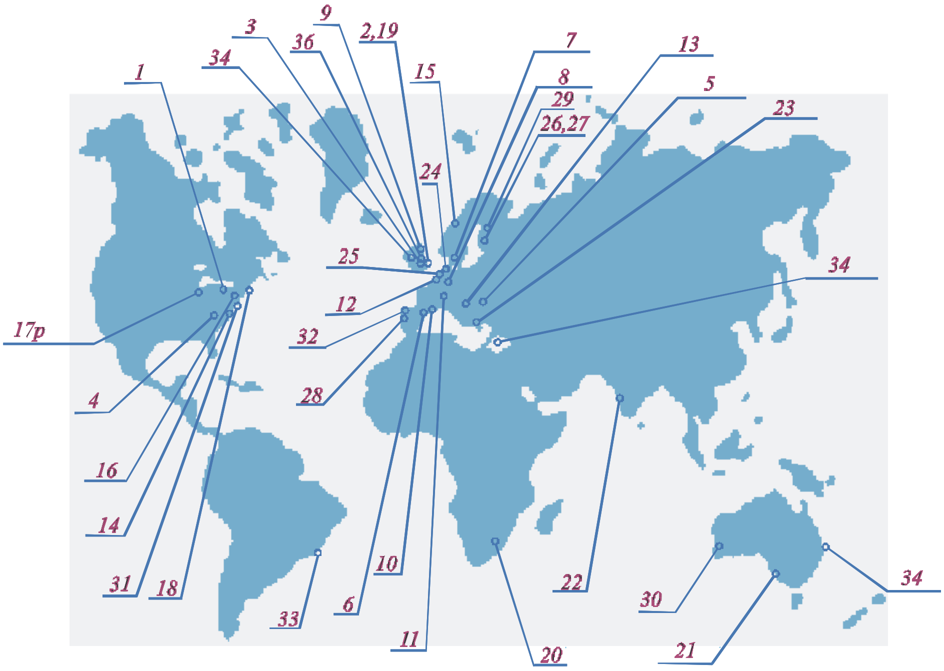
PI methodology	***Schematic representation***	***Short description***	***Technology targeted***
Heat integration systems or Heat Exchanger Networks (***HENS***)		The identification of heat recovery options, devices that minimize environmental emissions resulting from utility generation systems	• Heat exchangers • Heat pumps • Boilers/cooling towers
Mass exchange network (***MENS***) and reactive mass exchange network (***REAMENS***)		A network of process units that removes pollutant(s) from end-of-pipe streams via the use of physical or chemical, direct-contact, mass separating agents (MSAs).	• Adsorption • Absorption • Liquid–liquid extraction • Ion exchange
Heat-induced separation network (***HISENS***) and energy-induced separation network (***EISENS***)		A network of process units that removes pollutant(s) from end-of-pipe streams via the use of indirect-contact energy separating agents (ESAs), including stream pressurization and/or depressurization.	• Condensation • Evaporation • Drying • Crystallization • Compressors • Vacuum pumps

In-plant separation design via waste interception and allocation networks (***WINS***)		A network of process units that removes pollutant(s) from in-plant streams via the use of physical or reactive direct-contact mass separating agents (MSAs) and/or rerouting of in-plant process streams.	• Direct recycle opportunities • Adsorption • Absorption • Liquid–liquid extraction • Ion exchange
In-plant separation design via heat-induced waste minimization networks (***HIWAMINS***) and energy-induced waste minimization networks (EIWAMINs)		A network of process units that removes pollutant(s) from in-plant streams via the use of indirect-contact energy separating agents (ESAs) with stream pressurization and/or depressurization and/or rerouting of in-plant process streams. Full site heat integration is simultaneously addressed by this technique.	• Direct recycle opportunities • Heat exchange/heat integration • Condensation • Evaporation • Drying • Crystallization • Compressors • Vacuum pumps • Heat pumps
Wastewater minimisation systems		A design strategy for reuse, regeneration reuse, and regeneration recycling of wastewater streams that minimizes water usage and minimizes wastewater discharge.	• Direct recycle opportunities • Regeneration reuse and recycling opportunities
Membrane networks separation		A network of process units that removes pollutant(s) from end-of-pipe streams via the use of membranes and stream pressurization and/or depressurization.	• Reverse osmosis • Pervaporation

Appendix II. A brief presentation Pinch Analysis



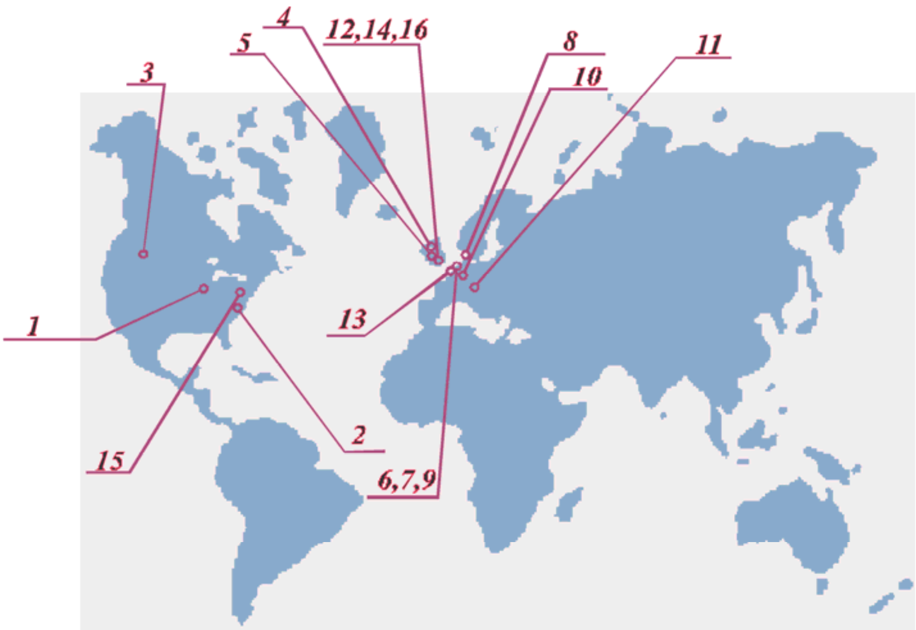
Appendix III. Academic Developers of Process Integration.



Academic Developers of Process Integration		Web
1.	*Carnegie Mellon University, Department of Chemical Engineering, Pittsburgh, USA*	http://www.cheme.cmu.edu/research/capd/
2.	*Imperial College, Centre for Process Systems Engineering, London, UK*	http://www.ps.ic.ac.uk/
3.	*UMIST, Department of Process Integration, Manchester, UK*	http://www.cpi.umist.ac.uk/
4.	*Auburn University, Chemical Engineering Department, Auburn, USA*	http://joy.eng.auburn.edu/department/che/
5.	*Technical Univ. of Budapest, Dept. of Chem. Unit Oper. and Proc. Engng, Hungary*	http://www.bme.hu/en/organization/faculties/chemical/
6.	*Universitat Politècnica de Catalunya, Chemical Engng. Department, Barcelona, Spain*	
7.	*Chalmers Univ. of Technol., Department of Heat and Power, Gothenburg, Sweden*	http://www.che.chalmers.se/inst/hpt/
8.	*Lehrstuhl für Technische Chemie A, University of Dortmund, Germany*	http://www.chemietechnik.uni-dortmund.de/tca/
9.	*University of Edinburgh, The ECOSSE Process Systems Group, Edinburgh, UK*	http://www.chemeng.ed.ac.uk/ecosse/
10.	*INPT-ENSIGC, Chemical Engng. Lab., Process Analysis Group, Toulouse, France*	http://excalibur.univ-inpt.fr/~lgc/elgcpa6.html
11.	*Swiss Federal Inst. of Technol., Lab. for Ind. Energy Systems, Lausanne, Switzerland*	http://leniwww.epfl.ch/
12.	*University of Liège, Department of Chemical Engineering, Liège, Belgium*	http://www.ulg.ac.be/lassc/
13.	*University of Maribor, Department of Chemical Engineering, Maribor, Slovenia*	http://www.uni-mb.si/
14.	*Massachusetts Institute of Technology, Dept. of Chemical Engng., Cambridge, USA*	http://web.mit.edu/cheme/www/Titlepage.html
15.	*Norw. Univ. of Sci. and Technol., NTNU, Dept. of Chem. Engng., Trondheim, Norway*	http://kikp.chembio.ntnu.no/research/PROST/
16.	*Princeton University, Department of Chemical Engineering, Princeton, USA*	http://titan.princeton.edu/
17.	*Purdue University, School of Chemical Engineering, West Lafayette, USA*	http://che.www.ecn.purdue.edu/
18.	*University of Massachusetts, UMass, Dept. of Chemical Engineering, Amherst, USA*	http://www.ecs.umass.edu/che/

19.	***University College, Dept. of Chemical and Biochemical Engineering, London, UK***	http://www.chemeng.ucl.ac.uk/
20.	***University of the Witwatersrand, Process & Materials Eng., Johannesburg, South Africa***	http://www.wits.ac.za/fac/engineering/procmat/homepage.html
21.	***University of Adelaide, Dept. of Chemical Engineering, Adelaide, Australia***	http://www.chemeng.adelaide.edu.au/
22.	***Indian Institute of Technology, Dept. of Chemical Engineering, Bombay, INDIA***	http://www.che.iitb.ernet.in/
23.	***CPERI, Chemical Process Engineering Research Institute, Thessaloniki, Greece***	http://www.cperi.forth.gr
24.	***Technical University of Denmark, Dept. of Energy Engineering, Lyngby, Denmark***	http://www.et.dtu.dk/
25.	***TU of Hamburg-Harburg, Dept. of Process and Plant Engineering, Hamburg, Germany***	http://www.tu-harburg.de/vt3/
26.	***Helsinki University of Technology, Dept. of Mechanical Engineering, Helsinki, Finland***	http://www.hut.fi/Units/Mechanic/
27.	***Helsinki University of Technology, Dept. of Chemical Engineering, Helsinki, Finland***	http://www.hut.fi/Units/ChemEng/
28.	***Instituto Superior Técnico, Dept. of Chemical Engineering, Lisbon, Portugal***	http://dequim.ist.utl.pt/english/
29.	***Lappeenranta University of Technol., Dept. of Chem. Technol., Lappeenranta, Finland***	http://www.lut.fi/kete/laboratories/Process_Engineering/mainpage.htm
30.	***Murdoch University, School of Engineering, Murdoch, WA, Australia***	http://wwweng.murdoch.edu.au/engindex.html
31.	***University of Pennsylvania, Department of Chemical Engineering, Philadelphia, USA***	http://www.seas.upenn.edu/cheme/chehome.html
32.	***University of Porto, Dept. of Chemical Engineering, Porto, Portugal***	http://www.up.pt/
33.	***Universidade Federal do Rio de Janeiro, Escola de Química, Rio de Janeiro, Brazil***	http://www.ufrj.br/home.php
34.	***University of Queensland, Computer Aided Process Engng. Centre, Brisbane, Australia***	http://www.cheque.uq.edu.au/
35.	***Technion, Department of Chemical Engineering, Haifa, Israel***	http://www.technion.ac.il/technion/chem-eng/index_explorer.htm
36.	***University of Ulster, Energy Research Centre, Coleraine, UK***	http://www.ulst.ac.uk/faculty/science/energy/index.html

Appendix IV. Commercial Developers of Process Integration



	Comercial Developers of Process Integration	Web
1.	***Advanced Process Combinatorics (APC), West Lafayette, USA***	http://www.combination.com
2.	***Aspen Technology Inc. (AspenTech), Cambridge, USA***	http://www.aspentech.com
3.	***Hyprotech Ltd., Calgary, Canada***	http://www.hyprotech.com
4.	***National Engineering Laboratory (NEL), Glasgow, UK***	http://www.ipa-scotland.org.uk/members/nel.htm
5.	***QuantiSci Limited, Henley-on-Thames, UK***	http://www.quantisci.co.uk/
6.	***COWI, Consulting Engineers and Planners AS, Copenhagen, Denmark***	http://www.cowi.dk
7.	***Danish Energy Analysis, Copenhagen, Denmark***	http://www.dea.dk/
8.	***CIT-ETA, Gothenburg, Sweden***	http://www.cit.chalmers.se
9.	***dk-TEKNIK Energy and Environment, Copenhagen, Denmark***	http://www.dk-teknik.com/
10.	***GHN (Gesellschaft für Heur.-Numerische Beratungssysteme mbH, Dortmund, Germany***	http://www.ghn.de/
11.	***Helbling Engineering, Zürich, Switzerland***	http://www.helbling.ch/
12.	***HRC Consultants Ltd., Disley, Cheshire, UK***	http://www.ioi.co.uk/cica/cica1/cripps.htm
13.	***Keuken & de Koning, Delft, The Netherlands***	http://www.keuken-and-de-koning.com/index.htm
14.	***Linnhoff March Ltd., Northwich, Cheshire, UK***	http://www.linnhoffmarch.com/
15.	***Matrix Process Integration, Leesburg, Virginia, USA***	
16.	***Protea Limited, Crewe, Cheshire, UK***	http://www.protea.ltd.uk/