Module -01 : Introduction
Lecture-02: Process integration, methods and application

Key words: *Process Integration, Pinch Technology, Onion Diagram,*

Process integration(PI) , a part of Process Intensification, is a fairly new term that emerged in 80's and has been extensively used in the 90's to describe certain systems oriented activities related primarily to cover almost complete process design. Process integration is a holistic approach to process design, retrofitting, and operation of industrial plants, with applications focused on resource conservation, pollution prevention and energy management. Two main 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 optimizes the allocation, separation, and generation of streams and species.

PI is a smart framework for the holistic analysis of process performance and the generation of cost-effective and sustainable solution strategies. It is based on fundamental chemical engineering and systems principles and therefore provides a set of generally-applicable tools. It enables the process engineer to see "the big picture first, and the details later". With 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 based on the multi criteria optimization of the processing systems.

Process integration has already had a profound effect on the chemical process industries, in the form of pinch technology and heat-exchanger-network optimization. However, it has mistakenly been interpreted as Heat Integration by many people, probably due to the fact that heat recovery studies inspired by Pinch Concept initiated this field and still remains the central part of Process Integration. Process integration appears to be a rather dynamic field, with new method and application areas emerging constantly into new areas, like Mass Pinch, Water Pinch, Hydrogen pinch, by using various analogies. Another interesting example of process integration is a dividing-wall column, which essentially integrates two distillation columns into one, thereby eliminating two pieces of capital equipment — the condenser from the first column and the reboiler from the second one[18].

1.1 Process integration definitions

Over the years there have been several attempts to define process integration. A study of the most well-known definitions reveals that it has become difficult to describe the fundamental principle behind process integration [5]:

- **In 1993** the International Energy Agency **(IEA)** defined process integration as: 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 (Gundersen, 2002) [5]. By this definition, process integration is seen as a group of methods to optimize the use of energy, but with concerns for environmental aspects.
- **In 1997** the **IEA** broadened their definition of process integration to mean the application of methodologies developed for system-oriented and integrated approaches to industrial process plant design for both new and retrofit applications (Gundersen, 1997) [5]. Along with this the optimization of the system became a goal and a need for the method's applicability throughout the life cycle was recognized.
- Later, **Natural Resources Canada (2003) [26]** defined process integration as all improvements made to process systems, their constituent unit operations, and their interactions to maximize the effective use of energy, water and raw materials.
- In the **Finnish process integration technology program**, process integration was defined to mean: integrated and system-oriented planning, operation and the optimization and management of industrial processes (Timonen et al., 2006) [23]. The operation and management aspects are emphasized in the Finnish definition. The above definitions describe the objectivity of a process integration task rather than the principles through which the enhanced situation is achieved.
- **Rossiter and Kumana (1995) [24]** state that process integration methods includes, focus on ensuring that existing process technologies are selected and interconnected in the most effective ways rather than attempting to invent new

types of equipment or unit operations. This definition slightly touches the potential synergic effects which will be achieved by integration.

- **According to the definition by El-Halwagi (1997) [22],** integration emphasizes the unity of the process. According to him, “Process integration is a holistic approach to process design, retrofitting, and operation which emphasizes the unity of the process.”
- **According to Ferenc Friedler**, **2010[15],** Process integration is a family of methodologies for combining several processes to reduce consumption of resources or harmful emissions to the environment.

Many definitions of PI can be found in the literature, but the most complete is the one used by the IEA since 1993 which states that “*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]*”.

This definition brings Process Integration very close to Process Synthesis, which is another systems oriented technology. Process Integration and synthesis belongs to process systems engineering.

1.2 From History to the Future[4]

Process Design has evolved through distinct "generations". Originally (**first generation**), inventions that were based on *experiments* in the laboratory by the chemists, which were then tested in pilot plants before plant construction.

The **second generation** of Process Design was based on the concept of *Unit Operations*, which founded Chemical Engineering as a discipline. Unit Operations acted as building blocks for the engineer in the design process.

The **third generation** considered *integration* between these units; for example heat recovery between related processes streams to save energy.

A strong trend today (fourth generation) is to move away from Unit Operations and focus on *Phenomena*. Processes based on the Unit Operations concept tend to have many process units with significant and complex piping arrangements between the units. By allowing more than one phenomena (reaction, heat transfer, mass transfer, etc.) to take place within the same piece of equipment, significant savings have been observed both in investment cost and in operating cost (energy and raw materials). However, most of the industrial applications of this idea have been based on trial and error. In this area the research is making progress, with an aim to develop systematic methods to replace trial and error. No doubt, this will affect the discipline of Process Integration, since we no longer look at integration between units only, but also at integration within units and within a site.

1.3 Different Schools of Thoughts in Process Integration[3]

The three major features of Process Integration methods are the use *heuristics* (insight), about design and economy, the use of *thermodynamics* and the use of *optimization* techniques. There is significant overlap between the various methods and the trend today is strongly towards methods using all three features mentioned above. The large number of structural alternatives in Process Design (and Integration) is significantly reduced by the use of insight, heuristics and thermodynamics, and it then becomes feasible to address the remaining problem and its multiple economic trade-offs with optimization techniques.

Despite the merging trend mentioned above, it is still valid to say that *Pinch Analysis* and *Exergy Analysis* are methods with a particular focus on Thermodynamics. *Hierarchical Analysis* and *Knowledge Based Systems* are rule-based approaches with the ability to handle qualitative (or fuzzy) knowledge. Finally, *Optimization* techniques can be divided into deterministic (Mathematical Programming) and non-deterministic methods (stochastic search methods such as Simulated Annealing and Genetic Algorithms). One possible *classification* of Process Integration methods is to use the two-dimensional (automatic vs. interactive and quantitative vs. qualitative) representation in Fig. 1.11.

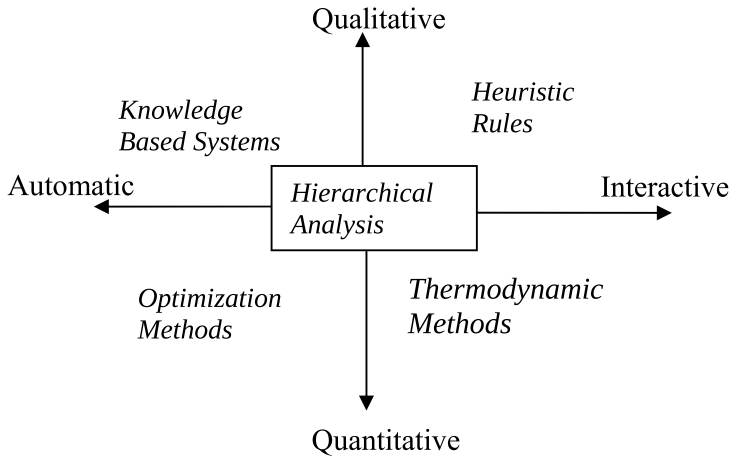

Fig. 1.11 One possible Classification of Process Integration

1.4 Application of Process Integration [6]

Process Integration concepts can be applied in various fields such as:

1. Heat integration – heat exchange network
2. Distillation column targeting
3. Cogeneration and total site targeting
4. Batch process targeting and optimization
5. Emission targeting(GHG emission reduction)
6. Mass exchange network (water and waste water management & recovery of valuable materials)
7. Hydrogen management in refineries
8. Debottlenecking of critical areas in process industries.
9. Pollution prevention [8]
10. E- Education system [9]
11. Co-production system[14]
12. Low temperature process[19]
13. supply-chain management [16]
14. Financial management[17]
15. Carbon-constrained energy-sector planning[7]

1.5 Techniques Available for Process Integration

1. Pinch Technology Approach [13]

2. MILP/MINLP Approach [11]
3. State-Space Approach [10]
4. Genetic Algorithm Approach [12]
5. Process Graph Theory Approach [20]

1.6 Current Status of Process Integration

Process Integration is a strongly growing field of Process Engineering. It is now a standard curriculum for process engineers in both Chemical and Mechanical Engineering at most universities around the world, either as a separate topic or as part of a Process Design or Synthesis course. Research at UMIST in this area has for last 27 years been supported by a large number of industrial companies through a Consortium that was established in 1984. As part of the International Energy Agency (IEA) project on Process Integration, 35 other universities around the world are involved in this research field.

Process Integration has evolved from a Heat Recovery methodology in the 80's to become what a number of leading industrial companies in the 90's regarded as a *Major Strategic Design and Planning Technology*. Process integration, combined with other tools such as process simulation, is a powerful approach that allows engineers to systematically analyze an industrial process and the interactions between its various parts. Process integration design tools have been developed over the past two decades to achieve process improvement, productivity enhancement, conservation in mass and energy resources, and reductions in the operating and capital costs of chemical processes. The primary applications of these integrated tools have focused on resource conservation, pollution prevention and energy management.

Specifically, the past two decades have seen the development and/or application of process integration design tools for heat exchange networks (HENs), wastewater reduction and water conservation networks[29,32,33], mass exchange networks (MENs)[27], heat- and energy-induced separation networks (HISENs and EISENs), waste interception networks (WINs) and heat- and energy-induced waste minimization networks (HIWAMINs and EIWAMINs), Hydrogen management[31] to name a few[34].

Pinch analysis techniques have also been extended to various carbon and environmental constrained problems [25]. The first applications were meant to determine the minimum amount of zero or low carbon energy sources needed to meet the regional or sectorial emission limits. The concept was later extended to segregate targeting with regions using unique sets of energy sources, and for targeting retrofits for carbon sequestration in the electricity sector. Furthermore, the pinch analogy was used for energy planning in scenarios involving land and water footprints.

1.7 Pinch Technology

Pinch Analysis is a methodology for minimizing energy consumption of processes by calculating thermodynamically feasible energy targets (or minimum energy consumption) and achieving them by optimizing heat recovery systems, energy supply methods and process operating conditions. It is also known as "process integration", "heat integration", "energy integration" or "pinch technology".

Process integration has already had a profound effect on the chemical process industries, in the form of Pinch Technology and heat-exchanger-network optimization. “Pinch analysis (for energy) has had an enormous amount of application, with thousands of projects having been carried out all over the world. AspenTech’s Nick Hallale, has reported that “Pinch analysis [for energy] has had an enormous amount of application, with thousands of projects having been carried out all over the world. Companies, such as Shell,Exxon, BP-Amoco, Neste Oy, and Mitsubishi, have reported fuel savings of upto 25% and similar emissions reductions, worth millions of dollars per year.”

Among the PI methodologies, Pinch Analysis is currently the most widely used. This is due to the simplicity of its underlying concepts and, specially, to the spectacular results it has obtained in numerous projects worldwide.

Pinch technology is a rigorous, structured thermodynamic approach to energy efficiency that can be used to tackle a wide range of process and utility related problems, such as reducing operating costs, debottlenecking processes, improving efficiency and reducing and planning capital investment

The term "Pinch Technology" was introduced by Linnhoff and Vredeveld[21] in 1979 to represent a new set of thermodynamically based methods that guarantee minimum energy levels in the design of heat exchanger networks. It is a systematic methodology based on thermodynamic principles to achieve utility savings by better process heat integration, maximizing heat recovery and reducing the external utility loads (cooling water and heating steam). Over the last two decades it has emerged as an unconventional development in process design and energy conservation. The term *'Pinch Technology'* is often used to represent the application of the tools and algorithms of Pinch analysis for studying industrial processes. Pinch Technology is a recognized and well proven method in industries such as chemical, petrochemical, oil refining, paper and pulp, food and drinks, steel and metallurgy, etc., leading to an energy saving of 10 to 35%, water saving of the tune of 25 to 40% and hydrogen savings up to 20%. Pinch technology provides a systematic methodology for energy saving in processes and total sites.

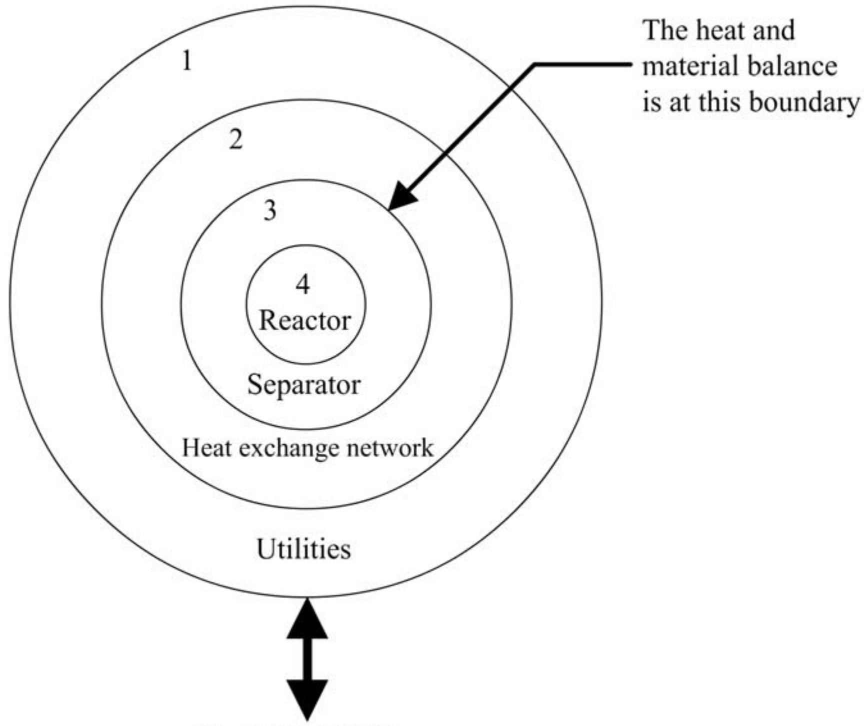

Fig. 1.12 Onion

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Fig. 1.12 illustrates the role of Pinch Technology in the overall process design. The process design hierarchy can be represented by the “onion diagram [1]” as shown below. The design of a process starts with the reactors (in the “core” of the onion which brings chemical changes in the feed). Once feeds, products, recycle concentrations and flow rates are known, the separators (the second layer of the onion) can be designed and based on the requirement of heat for the core and second layer the heat exchange network (the third layer) can be designed. The remaining heating and cooling duties are handled by the utility system (the fourth layer). The process utility system may be a part of a centralized site-wide utility system. The connectivity of the onion diagram with actual process is demonstrated in Fig.1.13 [5].

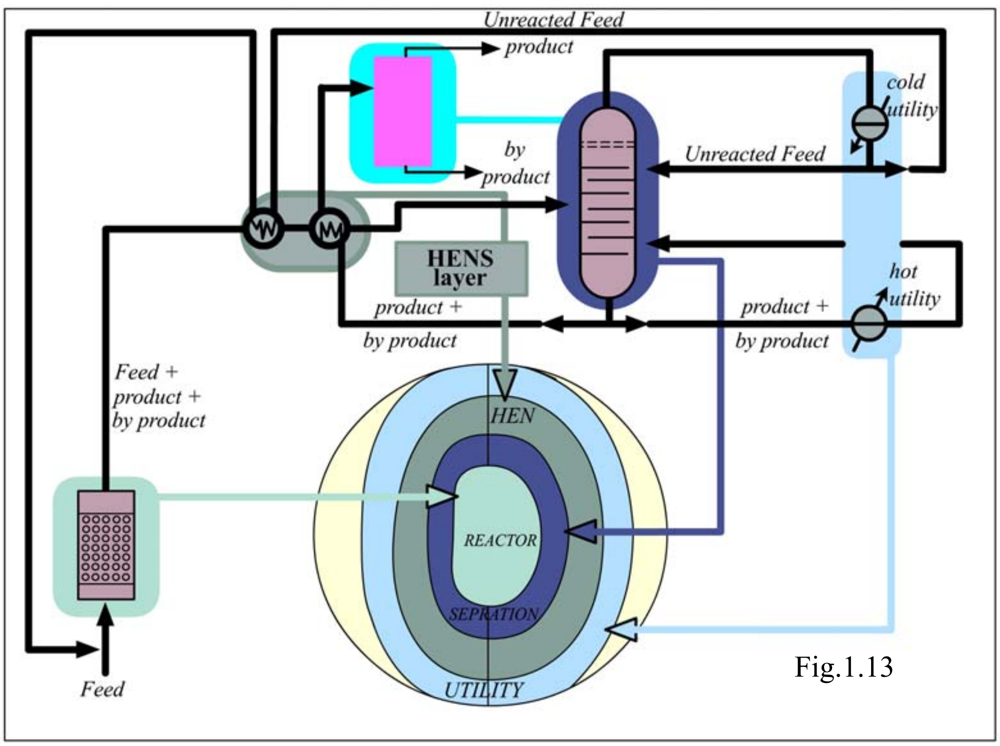

Fig.1.13

A Pinch Analysis starts with the heat and material balance for the process. Using Pinch Technology, it is possible to identify appropriate changes in the core process conditions that can have an impact on energy savings (onion layers one and two). After the heat and material balance is established, targets for energy saving can be set prior to the design of the heat exchanger network.

Pinch analysis deals with about sixty principles and concepts as given in table 1.1

Table 1.1 Principles tools and design rules of Pinch Analysis.

Principles and Tools	Rules
Basic HEN Design	
Composite Curves[80,81]	Pinch Design Method[109]
Problem Table[82]	Stream Splitting Rules[85]
Threshold Plot[83]	Mixing Rules [86]
Bath Area Target[84]	HEN Evolution[85]
Delta –T Contribution[84]	Topology Traps[84]
Euler & No. of Units Target[82]	Retrofit Design[86]
Grid Diagram[82]	
Pinch Principle[83]	
CP Matrix[85]	
Criss Cross Principle[84]	
Driving Force Plot(s)[86]	
Remaining Problem Analysis[85]	
Loops & Paths[82]	
Supertargeting[84]	
Delta-p Targeting and Supertargeting[87]	
Retrofit Targeting (constant α)[88]	
Area Matrix[89]	
Utility Targeting and Design	
Grand Composite Curve[81]	Furnace Integration[66,67,112]
Utility Composite & Utility Pinches[85]	Heat Engine Placement [40,68-70,94]
Balanced Composites & Balanced Grid[85]	Heat Pump Placement[94]
Total Site Profiles (T-H)[90]	Multiple Utility Optimization[95]
Cooling Water Targets[86]	Low T Process Design[92]
Exergy & Pinch : The N_c-H Plot [72,91]	
Exergy Grand Composites [72,92]	
Low T Shaftwork Target[108]	
Total Site Profiles (N_c-H)[90]	
Power Cycle Targeting [52-59,93]	
Advanced HEN Design	
Rigorous Area Targets [36,37,38,39,96,124]	Constrained HEN Design[101]
Constrained HEN Targeting[115]	Condensing Steam Cycle Power Block Design[102]
Area Matrix Retrofit Targets [37,38,74-78,89]	Diverse pinch concept for heat exchange network synthesis[125]
Area Integrity Matrix[118]	
Area Cost Targets for Different Mils for Construction[39,41-45,107]	
No. of Shells Targets[79,111,123]	
Downstream Paths[97]	
Sensitivity Tables[114]	
Multiple Base Case Targets[98]	
Re-piping & Rerouting Targets[98]	
Non-Convexity[99]	
Resiliency Index[100]	
Time Slice Targets[117]	
Cascade Analysis[110]	
Batch Utility Curves[106]	

Process Design	
The Onion Model[81] Keep Hot Streams Hot & Cold Streams Cold[81] Plus/Minus Principle[116] Column Grand Composite Curves[103] Column Composite Curves[103] Waste Water Targets[113]	Data Extraction Rules[85] Appropriate Placement of Distillation Columns [60-63,104] Appropriate Placement of Evaporators [64-65,105] Waste Water System Design Rules[113]

Now this methodology has become broad based while maintaining its principles still those of heat & power and thermodynamics and its key strategy is to set targets prior to design. Now it addresses systems including distillation, heat pumps, co-generating turbines, furnaces and non-energy objectives such as capital cost, operability and emissions. Hallale has developed the newest member of the pinch family — hydrogen pinch — which is aimed at helping oil refiners better manage their hydrogen balances. Although new, the technology has already had several applications and resulting millions of dollars of savings per year.

Uday V. Shenoy (2011) suggested a single algorithm to establish minimum resource targets for diverse process integration problems including those of heat/mass exchange, water, hydrogen, carbon emission and material reuse networks and proposed unified targeting algorithm (UTA). His analogies for diverse process integration problems are given in Table 1.1.

Table 1.1 Analogies for application of unified targeting algorithm (UTA) to diverse integration problems

(a) Heat and Mass integration		
Variables	Heat Exchange Network	Mass Exchange Network
Level or Quality, unit	Temperature, °C	Composition as mass ratio
Flow	Heat capacity flow rate CP, kW/°C	Mass Flow rate, kg/s
Load or quantity	Heat Load, kW	Mass load, kg/s
High Level Resource/Utility	Hot utility	Process MSAs excess
Low Level Resource/Utility	Cold Utility	External MSAs
Level shifting	$\Delta T_{min}/2$	$\Delta y_{min}/2$ or $\varepsilon/2$
Level sort order(preferred)	Decreasing	Decreasing

(b) Water, hydrogen and carbon emission networks			
	Water Networks	Hydrogen Network	Carbon emission Network
Level or quality	Contaminants	Hydrogen purity	Emission factor
Unit	Concentration in ppm	ratio	tCO2/TJ
Flow	Water flow rate t/h	H_2 flow rate MMscfd or mol/s	Energy in TJ
Load or quantity,	Contaminant load kg/h	H_2 load MMscfd or mol/s	Emission load or carbon foot print, tCO_2
High quality resource	Fresh Water	Make-up H_2 utility	Zero carbon or low carbon resource
Low quality resource	Waste water	Hydrogen purge	Unused or excess energy
Level shifting	0	0	0
Level sort order(preferred	Increasing	Increasing	Increasing

Sharifah R. Wan Alwi and Zainuddin A. Manan(2010) presented STEP (Stream Temperature vs. Enthalpy Plot) as a new graphical tool for simultaneous targeting and design of a HEN that overcomes the key limitations of Composite Curves and the Grid Diagram. The new STEPs are profiles of continuous individual hot and cold streams being mapped on a shifted temperature versus enthalpy diagram that simultaneously show the pinch points, energy targets and the maximum heat allocation (MHA). There work also demonstrates that STEP can provide more realistic solutions for targeting multiple utilities and the minimum network area.

It is ample clear that process integration technique can result in huge benefits in process industries and therefore, significant amount of research work is going on throughout the world both in academic as well as commercial arena on process integration[5]. Table 1.2 provides information about Academic developers whereas Table 1.3 provides information about commercial developers of process integration

Table 1.2 : Academic developers of process integration

S. No.	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	http://www.tu-harburg.de/vt3/

	and Plant Engineering, Hamburg, Germany	
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

Table 1.3: Commercial developers of process integration

S. No.	Commercial 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/

References:

1. Linnhoff B, D.W. Townsend, D. Boland, G.F. Hewitt, B.E.A. Thomas, A.R.Guy, and R.H.Marsland, "User Guide on Process Integration for the Efficient Use of Energy", *IChemE*,Rugby, U.K. (1982).
2. Tracking Industrial Energy Efficiency and CO_2 emissions, in support of G8 plan of action, Vol 1, International Energy Agency, OECD Publishing 2007
3. Thore Berntsson, Lennart Persson Elmeroth, Jessica Algehed, Erik Hektor, Per-Åke Franck, Anders Åsblad, Filip Johnsson, Anders Lyngfelt, Börja Gevert, Tobias Richards, Towards a Sustainable Oil Refinery, Pre – study for larger co-operation projects, Report – CEC 2008:1, Chalmers University of Technology, Goteborg, January 2008.
4. A Process Integration Primer by Truls Gundersen, SINTEF Energy research, International Energy Agency, Implementing agreement on process integration, Annex. I, 10 May, 2000.
5. P. Raskovic, Process integration approach for energy saving and pollution prevention in industrial plants, Faculty of Technology Engineering, Leskovac, Serbia, 2007.
6. Pinch Analysis for the effective use energy, water & hydrogen, Natural Resources, Canada, ISBN 0-662-34964-4, Catalogue # M39-96/2003E, 2003.
7. Raymond R. Tan, Dominic C.Y. Foo, Pinch analysis approach to carbon constrained energy sector planning, Energy 32 (2007) 1422 – 1429.
8. Mahmoud M. El-Halwagi, Pollution prevention through process integration, ISBN 0-12-236845-2,Second impression, Elsevier Inc., 2003
9. Marijana Despotovic, Ana Savic, BozidarRadenkovik, An example of process integration in E-Education system, Actaoeconomicaetinformatica 2/2006.
10. Miguel J. Bagajewicza1, Robert Phama1, Vasilios Manousiouthakis, On the state space approach to mass/heat exchanger network design, Chemical Engineering Science,Volume 53, Issue 14, 15 July 1998, Pages 2595-2621
11. Hans Skrifvarsa, IiroHarjunkoskia, TapioWesterlunda, ZdravkoKravanja∗, Ray Pörn, Comparison of different MINLPnext term methods applied on

certain chemical engineering problems, Computers & Chemical Engineering Volume 20, Supplement 1, 1996, Pages S333-S338

12. Xinyu Shao, Xinyu Li, Liang, GaoChaoyong Zhang, integration of process, planning and scheduling- A modified genetic algorithm based approach, Computers & Operations Research Volume 36, Issue 6, June 2009, Pages 2082-2096.
13. Ian C Kemp, Pinch Analysis and process integration, a user guide on process integration for effective use of energy, IChem^{E}, Elsevier Limited, 2007.
14. IEA International workshop, 2004(www.eccj.or.jp/intnl/03workshop/pdf/2_2.pdf)
15. Ferenc Friedler, Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction, Applied Thermal Engineering, Volume 30, Issue 16, November 2010, Pages 2270-2280
16. Olusegun Folorunso and Gladys Adewale, "Pinch Analysis as a Knowledge Management Tool for Optimization in Supply Chain" Computer and Information Science Vol. 4, No. 1; January 2011, pp:79-89
17. http://goliath.ecnext.com/coms2/gi_0199-13219147/Optimize-shift-scheduling – using-pinch.html (Chemical Engineering, 1 July, 2010)
18. Chemical Engineering Progress, July 2001, P:07
19. Chemical Engineering Science, Vol. 47. No. 8, pp. 208-2091, 1992.
20. Adonyi R, Romero J, Puigjaner L, Friedler F. Incorporating heat integration in batch process scheduling. Applied Thermal Eng. 20 03; 23(14):1743–62.
21. Linnhoff B., Townsend D. W., Boland D., Hewitt, G. F., Thomas B. E. A., Guy A. R. and Marsland R. H., Institution of Chemical Engineers, Geo E. Davis B, User guide on process integration for efficient use of energy, Chemical Engineering Science, Volume 39, Issue 3, 1984, Pages 619-620.
22. Mahmoud M. El-Halwagi, Process Integration, Process Systems Engineering, Volume 7, Elsevier Inc., 2006.
23. Timonen J., Antikainen M., Huuhka P. (2006). Competitiveness Through Integration in Process Industry Communication. Evaluation report. Technology programme report 11/2006. National Technology Agency of Finland (TEKES). Helsinki.

24. Alan P. Rossiter and Jimmy D. Kumana, "Pollution Prevention and Process Integration – Two Complementary Philosophies", in Waste Minimization through Process Design, A. P. Rossiter (ed.), McGraw-Hill, New York, 1995, pp. 43-49.
25. Raymond R. TAN, Recent Trends in Pinch Analysis for Carbon Emissionsand Energy Footprint Problems, 2010, http://www.aidic.it/pres09/webpapers/16Tan.pdf
26. http://canmetenergy-canmetenergie.nrcan rncan.gc.ca/fichier.php/codectec/En/2003-118/2003-118e.pdf
27. El-Halwagi, M. M. and V. Manousiouthakis, 1989, "Synthesis of Mass Exchange Networks", AIChE J., 35(8), 1233-1244.
28. Shenoy, U.V. (1995). "Heat Exchanger Network Synthesis: Process Optimization by Energy and Resource Analysis". Includes two computer disks. Gulf Publishing Company, Houston, TX, USA. ISBN 0884153916.
29. Hallale, Nick. (2002). A New Graphical Targeting Method for Water Minimisation. Advances in Environmental Research. 6(3): 377-390
30. Nick Hallale, Ian Moore, Dennis Vauk, "Hydrogen optimization at minimal investment", Petroleum Technology Quarterly (PTQ), Spring (2003)
31. Agrawal, V. and U. V. Shenoy, 2006, "Unified Conceptual Approach to Targeting and Design of Water and Hydrogen Networks", AIChE J., 52(3), 1071-1082
32. Wang, Y. P. and Smith, R. (1994). Wastewater Minimisation. Chemical Engineering Science. 49: 981-1006
33. Prakash, R. and Shenoy, U.V. (2005) Targeting and Design of Water Networks for Fixed Flowrate and Fixed Contaminant Load Operations. Chemical Engineering Science. 60(1), 255-268.
34. *J Chem Technol Biotechnol* **78**:1011–1021
35. B. Linhhoff, Pinch analysis- a state of the art overview, Trans I ChemE, Vol.71, Part-A, Sept. 1993, pp: 503-522
36. Medardo Serna, Arturo Jimenez, (2004), "An area targeting algorithm for the synthesis of heat exchanger networks", Chemical Engineering Science, 59, 2517 – 2520.

37. B. Mohanty, S. Khanam, (2006), "Optimal Area Targeting of Heat Exchanger Network Using Non-linear Programming", Heat and Mass Transfer Conference, 1173-1181.
38. A. Akbar, M.R. Omidkhah, M.R. Hojjati, (2008), "Heat exchanger network area targeting considering stream allocation to shell or tubes", Computers and Chemical Engineering, 32, 3143–3152.
39. James Varghese, Santanu Bandyopadhyay, (2011), "Improved area—energy targeting for fired heater integrated heat exchanger networks", Chemical engineering research and design.
40. Weijin Leng, Ali Abbas, Rajab Khalilpour, Pinch Analysis for Integration of Coal-fired Power Plants with Carbon Capture, 20th European Symposium on Computer Aided Process Engineering -ESCAPE20.
41. T. Gundersen, L. Naess, (1988), "The Synthesis Of Cost Optimal Heat Exchanger Networks an industrial review of the state of the art, Comput. & em. Eiagng, 12, No. 6, 503-530,
42. M. Akbarnia, M. Amidpour, A. Shadaram, (2009), " A new approach in pinch technology considering piping costs in total cost targeting for heat exchanger network", chemical engineering research and design, 87, 357–36.
43. K. Suaysompol , R.M. Wood, (1993), " Estimation of the installed cost of heat exchanger networks", Internutional Jourrlal of Production Economics, 29, 303-312.
44. Mubarak Ebrahim, Al- Kawari, (2000), "Pinch technology: an efficient tool for chemical-plant energy and capital-cost saving", Applied Energy, 65, 45-49.
45. Medardo Serna-González, José María Ponce-Ortega, (2011), "Total cost target for heat exchanger networks considering simultaneously pumping power and area effects", Applied Thermal Engineering, 31, 1964-1975.
46. T.K. Zhelev, K.A. Semkov, (2004), "Cleaner flue gas and energy recovery through pinch analysis", Journal of Cleaner Production, 12, 165–170.
47. Kazuo Matsuda, Shigeki Tanaka, Masaru Endou, Tsutomu Iiyoshi, (2011), " Energy saving study on a large steel plant by total site based pinch technology", Applied Thermal Engineering , 1-6.
48. A.I.A. Salama, (2005), "Numerical techniques for determining heat energy targets in pinch analysis", Computers and Chemical Engineering, 29, 1861–1866.

49. Mubarak Ebrahim, Al-Kawari, (2000), "Pinch technology: an efficient tool for chemical-plant energy and capital-cost saving", Applied Energy, 65, 45-49.
50. V. Vaaclavek, A. Novotn , J. Dedkov, (2003), " Pressure as a further parameter of composite curves in energy process integration", Applied Thermal Engineering, 23, 1785–1795.
51. Barbara B. Botros, John G. Brisson, (2011), "Targeting the optimum steam system for power generation with increased flexibility in the steam power island design", Energy, 36, 4625-4632.
52. Martin J. Atkins, Andrew S. Morrison, Michael R.W. Walmsley, (2010), "Carbon Emissions Pinch Analysis (CEPA) for emissions reduction in the New Zealand electricity sector", Applied Energy, 87, 982–987.
53. Ali Ghannadzadeh, Simon Perry, Robin Smith, (2011), "Cogeneration targeting for site utility systems", Applied Thermal Engineering, 1-7.
54. Damien Crilly, Toshko Zhelev, (2008), "Emissions targeting and planning: An application of CO2 emissions pinch analysis (CEPA) to the Irish electricity generation sector", Energy, 33, 1498–1507.
55. M. Gadalla, F. Emun, T. Majozi, L. Jiménez, Environmental Design of IGCC through Pinch Analysis, Process Integration and Parameters Analysis, 19th European Symposium on Computer Aided Process Engineering – ESCAPE19.
56. Juan M. Salazar, Urmila M. Diwekar, Stephen E. Zitney, (2011), "Rigorous-simulation pinch-technology refined approach for process synthesis of the water–gas shift reaction system in an IGCC process with carbon capture", Computers and Chemical Engineering, 35, 1863–1875.
57. F. Emun, M. Gadalla, T. Majozi, D. Boe, (2010), "Integrated gasification combined cycle (IGCC) process simulationand optimization", Computers and Chemical Engineering, 34, 331–338.
58. H. Axelsson, S. Harvey, A.AAsblad, T. Berntsson, (2003), "Potential for greenhouse gas reduction in industry through increased heat recovery and/or integration of combined heat and power", Applied Thermal Engineering, 23, 65–87.
59. Russell F. Dunn, Greg E. Bush, (2001), "Using process integration technology for CLEANER production", Journal of Cleaner Production, 91–23.
60. Angelo Lucia, Amit Amale, Ross Taylor, (2008), "Distillation pinch points and more", Computers and Chemical Engineering, 32, 1342–1364.

61. H. F. Akande, K.R. AJAO, (2009), "Energy Integration Of Crude Distillation Unit Using Pinch Analysis", Researcher, 1(2).
62. K. liebmann, V. R. Dhole, M. Jobson, (1998), "Integrated Design of a Conventional crude oil distillation tower using pinch analysis", Institute of chemical engineers Trans IChemE, 76, part A.
63. M. Ga dalla, Z. Olujic, l. Sun, A. De Rijke , P. J. Jansens, "Pinch analysis-based approach to conceptual design of internally heat-integrated distillation columns", Chemical Engineering Research and Design, 83(A8), 987–993.
64. A. Piacentino , E. Cardona, (2010), "Advanced energetics of a Multiple-Effects-Evaporation (MEE) desalination plant. Part II: Potential of the cost formation process and prospects for energy saving by process integration", Desalination, 259, 44 –52.
65. M. Higa, A.J. Freitas, A.C. Bannwart, R.J. Zemp, (2009), "Thermal integration of multiple effect evaporator in sugar plant", Applied Thermal Engineering, 29, 515–522.
66. Steffen zagermann , Thomas gangler,(1994), "Process Integration In Consideration Of Pressure Drops And With Integration of Furnaces", Computers chem. Engng, 18, S719-S723.
67. Stephen G. Hall, Bodo Linnhoff,(1994), "Targeting for Furnace Systems Using Pinch Analysis", Ind. Eng. Chem. Res.,33, 3187-3195.
68. R. Benstead and F.W. Sharman, (1990), "Heat Pumps and Pinch Technology", Heat Recovery Systems & CliP, 10, 4, 387-398.
69. Saidas m. Ranade, (1988), "new insights on optimal integration of heat pumps in industrial sites", Heat Recovery Systems & ClIP Vol. 8, No. 3, 255-263.
70. Chi-I Tuan, Yi-Lung Yeh, Chi-Jen Chen, Ting-Chien Chen, (2011), "Performance assessment with Pinch technology and integrated heat pumps for vaporized concentration processing", Journal of the Taiwan Institute of Chemical Engineers.
71. Z. Kravanja, P. Glavic', (1989), "Heat Integration of Reactors-II. Total Flowsheet Integration", Chemical Engineering Science, Vol. 44, No. 11, 2667-2682.
72. Zainuddin abdul manan, Foo sheek hian, (2009), "Combining pinch and exergy analysis for process improvement-a case study on an aromatics complex", jurnal teknologi, 33(F), 9-16.

73. André L.H. Costa, Eduardo M. Queiroz, (2009), "An extension of the problem table algorithm for multiple utilities targeting", Energy Conversion and Management, 50, 1124–1128.
74. Yao Wang, Jian Du, Jintao W et. al., (2003), "Application of total process energy-integration in retrofitting an ammonia plant", Applied Energy, 76, 467–480.
75. Xiao Feng, Jing Pu, Junkun Yang, Khim Hoong Chu, (2011), "Energy recovery in petrochemical complexes through heat integration retrofit analysis", Applied Energy , 88, 1965–1982.
76. Marcone Lopes Silva, Roger Josef Zemp, (2000), "Retrofit of pressure drop constrained heat exchanger networks", Applied Thermal Engineering, 20, 1469-1480.
77. M.H. Panjeshahi, E. Ghasemian Langeroudi, N. Tahouni, (2008), "Retrofit of ammonia plant for improving energy efficiency", Energy, 33, 46 – 64.
78. Zhaolin Gu, Zhonghua Tao, Nan Xu, Yun Li, (2007), "Retrofitting of a distillery based on process synthesis", Energy Conversion and Management, 48, 335–343.
79. B.B. Gulyani, S. Khanam, B. Mohanty, (2009), "A new approach for shell targeting of a heat exchanger network", Computers and Chemical Engineering, 33, 1460–1467.
80. Haung, F. and Elshout, R. V., 1976, "Optimizing the heat recovery of crude units", Chem Eng Prog, 72(7), 68-74.
81. Linnhoff, B., Townsend, D.W., Boland, D., Hewitt,G.F., Thomas, B.E.A., Guy, A.R. and Marshland, R.H.,1982, "User Guide on Process Integration for the Efficient use of energy", (IChem,Rugby, UK).
82. Linnhoff, B., and Flower, J.R., 1978, "Synthesis of heat exchanger networks: Part 1: Systemic generation of energy optimal networks", AIChE j, 24(4): 633-642. Part-II: "Evolutionary generation of networks with various criteria of optimality", AIChE J, 24(4): 642-654.
83. Linnhoff, B., Mason, D.R. and Wardle, I. 1979. "Understanding heat exchanger networks", Comp & Chem Eng, 3: 295-302.
84. Linnhoff, B. and Ahmad, S., 1990, "Cost optimum heat exchanger networks, Part 1: minimum energy and capital using simple models for capital cost", Comp & Chem Eng, 14(7):751-767.

85. Linnhoff, B. et al, 1986, "Pinch Analysis Foundation Training Course",(Linnhoff March Ltd.,Tabley Court, Moss Lane, Over Tabley, Knutsford, Wa16 0PL, Uk).

86. UMIST, MSc Course in Process Integration Taught since 1984 by the Centre for Process Integration, UMIST< Manchester, UK. PO Box 88.

87. Polley, G.T., Panjeh Shahi, M.H. and Jegede, F.O., 1990, "Pressure drop considerations in the retrofit of heat exchanger networks", Trans IChemE, 68, (Part A): 211-220.

88. Tjoe, T.N. and Linnhoff, B., 1986, "Using Pinch technology for process retrofit", Chem Eng, 47-60, April 28.

89. Shokoya, C.G., 1992, "Retrofit of heat exchanger networks for debottlenecking and energy savings", PhD Thesis, (University of Manchester (UMIST), UK).

90. Dhole, V.R. and Linnhoff, B., 1993, Total site targets for fuel, co-generation emissions, and cooling paper presented at ESCAPE-II Conference, Toulouse, France,October 1992. To appear in Comp & Chem Eng, 17(Suppl): s101-s109.

91. Linnhoff, B., "Pinch technology for the synthesis of optimal heat and power system", Trans ASME, J of Energy Resource Technol, 111(3): 137-147.

92. Dhole, V.R. and Linnhoff, B., 1993, "Overall design of subambient plants", paper presented at ESCAPE-III Conference, Graz, Austria, July.

93. Dhole, V.R., 1993, "Setting total site target for utility systems involving combined cycles", paper presented at ASME Cogen Turbo Power, The 7th Congress and Exposition, Bournemouth, UK. September.

94. Townsend, D.W. and Linnhoff, B., 1983, "Heat and power networks in process design, Part I: Criteria for placement of heat engines and heat pumps in process networks", AIChE J, 29(5): 748-771.

95. Parker, S.J., 1989, "Super targeting for multiple utilities", PhD Thesis, (University of Manchester (UMIST), UK).

96. Saboo, a. K., Morari, M. and Colberg, R.D., 1986, "RESHEX-An interactive software package for the synthesis and analysis of resilient heat exchanger networks", Part I: Program description and application, Comp & Chem Eng, 10(6): 577-589. Part-II Discussion of area targeting and network synthesis algorithms, Comp & Chem Eng, 10(6); 591-599.

97. Linnhoff, B. and Kotjabasakis, E. 1986, “Process optimization: downstream paths for operable process design”, Chem Eng Prog, 23-28 May.

98. Jones, P.S., 1991, “Targeting and design for heat exchanger network under multiple base case operation”, PhD Thesis, (University of Manchester (UMIST), UK).

99. Calandranis, J. and Stephanopolous G., 1986, “Structural operability analysis of heat exchanger networks”, Chem Eng Res Des, 64(5): 347-364.

100. Rant, Z., 1956, “Exergie, einneues Wort fur technische Arbietsfahiskeit”, Forschungs-Ingenieur-Wesen, 22: 36.

101. O’Young, Y., 1992, “Constrained heat exchanger networks: targeting and design”, PhD Thesis, (University of Manchester (UMIST), UK).

102. Linnhoff, B. and Alanis< F. J. 1989, “A systems approach based on pinch technology to commercial power station design”, paper presented at ASME Winter Annual Meeting, San Francisco. Ca. USA 10-15 December.

103. Dhole, V. R. and Linnhoff, B.,1993, “Distillation column targets”, submitted and accepted by Europ Symp on computer Applications in Process Engineering ESCAPE-1 Elsinore,Denmark, May 24-28 1992.(Extended version to be printed in Comp & Chem Eng, 17(6).

104. Linnhoff, B., Dunford, H. and Smith, R. 1983, “The pinch design method of heat exchanger networks”, Chem Eng Sci, 38(5): 745-763.

105. Smith, R. and Jones, P.S., 1990, “The optimal design of integrated evaporation system”, Heat Recovery System & CHP, 10(4) 341-368.

106. Germouti, I.D., 1991, “Integration of batch processes for energy savings and debottlenecking”, MSc Thesis (University of Manchester (UMIST), UK).

107. Hall, S. G., Ahmad, S. and smith, R., 1990, “Capital cost targets for heat exchanger networks comprising mixed materials of construction, pressure ratings and exchanger types”, Comp & Chem Eng, 14(3): 319-335.

108. Linnhoff, B. and Dhole, V. R., 1993, “Targeing for CO_2 emissions for total sites”, Chem Eng Technol, 16: 252-259.

109. Linnhoff, B. and Hindmarsh, E., 1983, “The pinch design method of heat exchanger networks”, Chem Eng Sci, 38(5): 745-763.

110. Kemp, I. C. and Deakin, A. W., 1989, “The cascade analysis for energy and process integration of batch processes”, Chem Eng Res Des, 67: 495-525.

111. Ahmad, S. and Smith. R., 1989, “Targets and design for minimum number of shells in heat exchanger networks”, Chem Eng Res Des, 67(5): 481-494.

112. Linnhoff, B and De Leur, j., 1988, "Appropriate placement of furnaces in the integrated process" paper presented at IChemE Symposium 'Understanding Process Integration II' 22-23 March, UMIST, Manchester. UK.
113. Wang, Y. P. and Smith, R., 1993, "Wastewater minimization", submitted to Chem Eng Sci.
114. Kotjabasakis, E. and Linnhoff, B., 1986, "Sensitivity tables for the design of flexible process (I)-How much contingency in heat exchanger networks is cost-effective", Chem Eng Res Des. 64: 197-211.
115. Cerda, J., Westerberg, A. W., Mason, D. and Linnhoff, B., 1983, "Minimum utility usage in constrained heat exchanger networks-A transportation problem" Chem Eng Sci, 38(3): 373-387.
116. Linnhoff B., and Parker, S., 1984, "Pinch technology has come of age", Chem Eng Prog, 33-40, july.
117. Obeng, E. D. A. and Ashton, G. J., 1988, "On pinch technology based procedures for the design of batch processes", Chem Eng Res Des, 66: 255-259.
118. Ahmad, S. and Hui, D. C. W., 1991," Heat recovery between areas of integrity", Comp & Chem Eng, 15(12): 809-832.
119. *Uday V. Shenoy*, "Unified targeting algorithm for diverse process integration problems of resource conservation networks", chemical engineering research and design 8 9 (2 0 1 1) 2686–2705
120. Mihaela Morar, Paul Serban Agachi, "Review: Important contributions in development and improvement of the heat integration techniques", Computers and Chemical Engineering 34 (2010) 1171–1179
121. T. Gundersen and L. Naess, "The synthesis of cost optimal heat exchanger networks- an industrial review of the state of the art", Heat Recovery Systems & CHP Vol. I0, No. 4, pp. 301-328, 1990
122. Sharifah R. Wan Alwi and Zainuddin A. Manan, "STEP—A new graphical tool for simultaneous targeting and design of a heat exchanger network", Chemical Engineering Journal 162 (2010) 106–121.
123. B.B. Gulyani, S. Khanam and B. Mohanty, A new approach for shell targeting of a heat exchanger network, Computers and Chemical Engineering 33 (2009) 1460–1467

124. Medardo Serna and Arturo Jime’nez., An area targeting algorithm for the synthesis of heat exchanger networks, Chemical Engineering Science 59 (2004) 2517 – 2520
125. Rev, E., Fonyo, Z., 1991. Diverse pinch concept for heat exchange network synthesis: the case ofdi6erent heat transfer conditions. Chemical Engineering Science 46 (7), 1623.