A Critical Review and Annotated Bibliography for Heat Exchanger Network Synthesis in the 20th Century

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REVIEWS

A Critical Review and Annotated Bibliography for Heat Exchanger Network Synthesis in the 20th Century

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This paper provides a critical review of the literature on heat-exchanger network synthesis, the most commonly studied problem in process synthesis. After a review of solution methods, we present the chronological milestones in the development of the field and we discuss separately each of 461 related works leading up to the turn of the century. Then, we present several classification schemes of this body of work based on a number of modeling and algorithmic criteria. Finally, we offer a critical assessment of the current status of research in this area and provide suggestions for future research.

1. Introduction

Heat exchanger network synthesis (HENS) is an important field in process systems engineering and has been the subject of a considerable amount of research over the past 40 years. Its significance can be attributed to its role in controlling the costs of energy for a process. The heat-exchanger network (HEN) design problem was introduced into the literature by Ten Broeck[1] in 1944. The first work in grassroots HENS was presented by Hwa[2] in 1965. Then the HENS problem was first rigorously defined by Masso and Rudd[3] in 1969. The basic HENS problem is the following:

Given

(i) a set *H* of hot process streams to be cooled from the inlet temperatures to the outlet temperatures,

(ii) a set *C* of cold process streams to be heated from the inlet temperatures to the outlet temperatures,

(iii) the heat capacities and flow rates of the hot and cold process streams,

(iv) the utilities available and the temperatures or temperature ranges and the costs for these utilities, and

(v) heat-exchanger cost data,

develop a network of heat exchangers with minimum annualized investment and operating costs. For an introduction to the fundamental principles and procedures of HENS, readers are referred to the texts of Shenoy,[4] Smith,[5] Seider et al.,[6] and Biegler et al.[7]

Two thorough reviews on the topic of HENS were contributed by Gundersen and Naess[8] in 1988 and by Ježowski[9,10] in 1994. The objective of this paper is not to supplant these excellent reviews but to complement them. The purpose of our paper is threefold: (1) to provide coverage of work not covered by previous review papers, (2) to provide a critical review of the current state-of-the-art in HENS and become the impetus for future research, and (3) to be a comprehensive and categorized compilation of HENS citations in the 20th century.

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Creating an exhaustive compilation and organization of HENS papers is a complicated task. We have restricted our coverage primarily to include journal papers written in English with the addition of some important works published as Ph.D. theses and conference papers. Some exceptions are made for non-English papers when an English abstract is provided.

The remainder of the paper is structured as follows. Section 2 briefly reviews the major solution methods in HENS. Section 3 gives a listing of HENS milestones with a brief history of HENS along with a description of the ground-breaking work in the field. Section 4 is an annotated bibliography of HENS literature of the 20th century. In section 5, several classification schemes of the annotated HENS works are proposed and discussed. Concluding remarks and a discussion of important open questions in HENS are presented in section 6.

2. HENS Solution Methods

Most of the contributions to HENS research can be classified as either sequential synthesis or simultaneous synthesis methods. Section 2.1 briefly describes different sequential synthesis techniques, while section 2.2 discusses simultaneous synthesis techniques.

2.1. Sequential Synthesis. Sequential synthesis methods use the strategy of dividing the HENS problem into a series of subproblems in order to reduce the computational requirements for obtaining a network design. These methods typically involve partitioning of the HENS problem into a number of intervals, which is usually accomplished by dividing the temperature range of the problem into temperature intervals. These intervals are important for modeling heat exchange while obeying the laws of thermodynamics. The problem is decomposed into a series of target subproblems which are solved successively in order of decreasing significance with respect to the total annual cost of the HEN based on heuristic rules. Generally, this is achieved with the following three problems: the minimum utility usage/cost, the minimum number of exchanger units,

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and the minimum area/capital cost of the network. These problems are solved according to the heuristic of finding the minimum cost network subject to the minimum number of units subject to the minimum utilities cost.[7] There is also the concept of supertargeting for finding the optimal minimum approach temperature used in partitioning of the problem into temperature intervals because the minimum capital cost of the network is a function of this parameter. The sequential synthesis method does not guarantee the design of a network with the minimum annual cost. Sequential synthesis methods are further divided into two subcategories: (1) evolutionary design methods such as the pinch design method (PDM; Linnhoff and coworkers[11−14]), dual temperature (Colbert[15] and Trivedi et al.[16]), and pseudo-pinch methods (Wood et al.,[17] Trivedi et al.,[18] and Rév and Fonyó[19,20]) and (2) mathematical programming techniques based on the sequential solution of continuous and integer linear programs (Cerda et al.[21] and Papoulias and Grossmann[22]) and nonlinear optimization problems (Floudas et al.[23]).

Using pinch-based design methods, after the partitioning of the problem into temperature intervals based on a heat recovery approach temperature (HRAT), the locations of bottlenecks for energy savings are found when determining the minimum utility usage. These bottlenecks are called heat recovery pinch points. The HEN is then decomposed into subnetworks based on the pinch point(s). An initial network design is produced starting from the interval bounded by the pinch point and concluding at an interval bound consisting of either another pinch point or the first or last temperature interval. Successively better networks are evolved based on various design guidelines and heuristic rules until a network with the target number of units is produced. The dual-temperature approach method (DTAM) allows for heat exchange across pinch points using an exchanger minimum approach temperature (EMAT) less than HRAT as a decision variable. DTAM has the tendency to produce networks of fewer units and simpler structure at the cost of increased exchanger area. The pseudo-pinch design method (PPDM; Wood et al.[17]), which relaxes the pinch condition, and the flexible pinch design method (FPDM; Suaysompol and Wood[24]), which has a variable minimum approach temperature, are further modifications of the DTAM with the goal of designing even simpler network configurations.

Sequential synthesis via mathematical programming involves solving the three subproblems in which the HENS problem is decomposed in sequence, with some part of the solution to a previous target problem being parameters in the next. The first problem is the minimum utilities cost problem. This linear programming (LP) problem can be formulated to include the possibility of forbidden matches (Cerda et al.[21] and Papoulias and Grossmann[22]). Among some of the modified models are an LP formulation extended for using the DTAM presented by Ježowski and Friedler[25] and the mixed-integer linear programming (MILP) and mixed-integer nonlinear programming (MINLP) formulations by Galli and Cerda[26−28] allowing for additional structural constraints.

Using the utilities target, an MILP formulation (Cerda et al.[21] and Papoulias and Grossmann[22]) for determining the heat load distribution of the minimum number of matches is solved. Typically, this problem is divided into subproblems at pinch points in order to minimize the number of heat-exchanger units rather than heat-exchange matches. A vertical heat-transfer model proposed by Gundersen and Grossmann[29] and extended by Gundersen et al.[30] was developed to find a target set of stream matches based on rankings to produce networks with lower capital costs for exchanger area. Also along this line of study is a vertical heat-transfer model-based formulation for determining matches and a heat load distribution disregarding the number of matches and solving for an objective based on minimum area costs (Gundersen et al.[31]). The formulations of Galli and Cerda[26−28] are also applicable for determining the minimum number of matches.

Last, a nonlinear programming (NLP) model (Floudas et al.[23]) is applied for the development of a HEN based on a network superstructure solving for the minimum capital cost with respect to the exchanger area subject to the heat load distribution and heat matches derived from the previous target problem.

A more recent sequential synthesis methodology proposed by Zhu and associates[32−36] partitions the HENS problem into “blocks” which are basically a set of enthalpy intervals. A set of matches is determined, and a network is evolved for each block individually. This partitioning into blocks was proposed to reduce the dimensionality of the HENS problem, which is a drawback to most other mathematical programming methods.

2.2. Simultaneous Synthesis. The goal of simultaneous HENS is to find the optimal network without decomposition of the problem. Simultaneous synthesis methods are primarily MINLP formulations of the HENS problem subject to various simplifying assumptions used to facilitate the solution of these complex models.

One of the earliest simultaneous HENS formulations was proposed by Yuan et al.[37] The superstructure developed in this work has the drawback of not allowing splitting or mixing of streams. An MINLP formulation is proposed that does not involve integer variables in the objective.

Floudas and Ciric[38,39] developed the simultaneous match−network hyperstructure model for optimizing all of the capital costs of a HEN at once. This MINLP formulation determines the minimum costs for exchanger units and exchanger area by combining the transshipment model of Papoulias and Grossmann[22] for stream match selection and the network topology hyperstructure model of Floudas et al.[23] for determination of the heat-exchanger areas, temperatures, and the stream flows in the network. The drawback of this formulation is that it is still based on temperature interval partitioning of the HENS problem, and thus the value for HRAT must be specified before solving and, therefore, supertargeting may be required for finding the lowest capital cost network. The simultaneous match−network method was later applied to pseudo-pinch problems by Ciric and Floudas.[40] The hyperstructure model was then even further modified by Ciric and Floudas[41] to include optimization of minimum utilities cost as well. This MINLP formulation does not require any decomposition into design targets and simultaneously optimizes for the lowest annual network cost.

Another MINLP simultaneous synthesis formulation was proposed by Yee and Grossmann.[42] This model is based on the stagewise superstructure representation

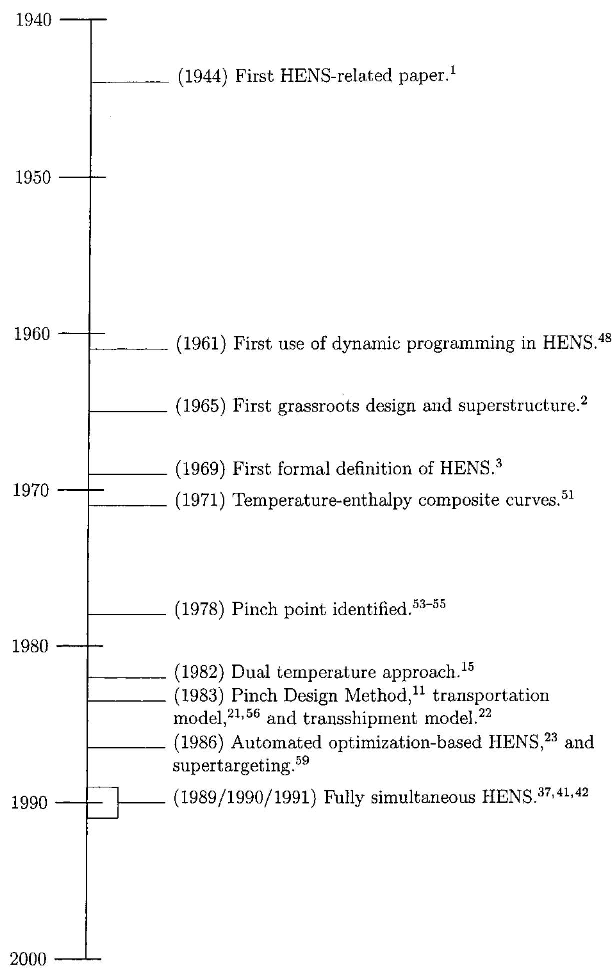

Figure 1.

Timeline of innovation and discovery in HENS.

of Yee et al.[43] in which potential heat exchange between any pair of hot and cold streams may occur in every stage. The assumptions of isothermal mixing, no split stream flowing through more than one exchanger, and no stream bypass make the constraint set linear, while the objective function remains a nonlinear and nonconvex. Daichendt and Grossmann[44−47] have developed a preliminary screening procedure for finding bounds on the objective of this MINLP formulation in order to reduce the computational effort required for solving it.

3. Milestones

There have been many advances in HENS over the years. Figure 1 represents what we consider to be some of the major discoveries in HENS. Chronological milestones in the development of the field have included the following:

- Ten Broeck (1944).[1] First known HENS-related paper.
- Westbrook (1961).[48] First use of mathematical (dynamic) programming for HENS.
- Hwa (1965).[2] First grassroots HENS. First use of separable programming. First use of a superstructure in HENS.
- Rudd (1968).[49] Decomposition of the process synthesis problem into subproblems with HENS being one of them. Early analysis of the HENS problem.
- Masso and Rudd (1969).[3] First formal definition of the HENS problem.
- Kesler and Parker (1969).[50] The first assignment-based method is presented.
- Hohmann Ph.D. thesis (1971).[51] Hohmann−Lockhart composite curves allow calculation of minimum utilities requirement. The $N - 1$ estimate for the minimum number of units is first proposed. This thesis lays some of the groundwork for the pinch design method (PDM) and includes the first annotated bibliography for HENS. Interestingly enough, attempts to publish this work in archival journals were turned down twice.[8]
- McGalliard and Westerberg (1972).[52] First paper incorporating sensitivity issues into HENS.
- Umeda et al. (1978)[53] and Linnhoff and Flower (1978).[54,55] Identification of the heat recovery pinch point.
- Colbert (1982).[15] The first DTAM is presented.
- Linnhoff and Hindmarsh (1983).[11] The PDM is proposed.
- Cerda et al. (1983)[21] and Cerda and Westerberg (1983).[56] The minimum utilities and minimum number of matches problems are mathematically formulated using the transportation model.
- Papoulias and Grossmann (1983).[22] The minimum utilities and minimum number of matches problems are mathematically formulated using the transshipment model.
- Linnhoff and Vredeveld (1984).[57] The first HENS paper involving a retrofit is presented.
- Tjoe and Linnhoff (1986).[58] A HENS retrofit methodology based on pinch design is developed.
- Li and Motard (1986).[59] A supertargeting method is first developed.
- Floudas et al. (1986).[23] The first fully automated HEN design method is proposed with MAGNETS.
- Rév and Fonyó (1986).[19,20] The pseudo-pinch point is identified.
- Jones (1987).[60] First use of the vertical heat-transfer model in HENS.
- Dolan et al. (1989).[61] Simulated annealing is first used in HENS.
- Floudas and Ciric (1989).[38,39] The simultaneous match−network HENS formulation is presented.
- Yuan et al. (1989),[37] Yee and Grossmann (1990),[42] and Ciric and Floudas (1991).[41] Fully simultaneous HENS formulations are proposed.

4. Annotated Bibliography of 20th Century Works

The objective of this section is to provide a comprehensive reference tool for all those interested in HENS. Toward this purpose we separately discuss each of 461 HENS works that were published over the last century. In the next section, we will provide several classification schemes and further discuss these works.

1. Abbas, H. A.; Wiggins, G. A.; Lakshmanan, R.; Morton, W. Heat Exchanger Network Retrofit via Constraint Logic Programming. *Comput. Chem. Eng.* **1999**, *23* (Suppl.), S129−S132.

Heuristics are incorporated with constraint logic programming in an algorithm for HEN retrofit.

2. Aguilera, N.; Nasini, G. Flexibility Test for Heat Exchanger Networks with Uncertain Flowrates. *Comput. Chem. Eng.* **1995**, *19* (9), 1007−1017.

An MILP formulation for testing the flexibility of a HEN with respect to flow-rate variation at the level of heat matches is presented. Forbidden matches and multiple utilities are not considered, and the test only determines flexibility, not optimality.

3. Aguilera, N.; Nasini, G. Flexibility Test for Heat Exchanger Networks with Non-Overlapping Inlet Temperature Variations. *Comput. Chem. Eng.* **1996**, *20* (10), 1227−1240.

An algorithm for the testing of flexibility at the level of heat matches in HENS is described. This paper does not consider forbidden matches or multiple utilities. The presented test is an MILP that considers the whole set of operation points at once.

4. Aguirre, P. A.; Pavani, O.; Irazoqui, H. A. Comparative Analysis of Pinch and Operating Line Methods for Heat and Power Integration. *Chem. Eng. Sci.* **1989**, *44* (4), 803−816.

Designs for heat and power integration using both the PDM and the operating line method are compared for a case with a dominant power load.

5. Aguirre, P. A.; Pavani, O.; Irazoqui, H. A. Optimal Synthesis of Heat-and-Power Systems with Multiple Steam Levels. *Chem. Eng. Sci.* **1990**, *45* (1), 117−129.

The operating line method for heat and power integration into process synthesis is extended for multiple steam levels.

6. Ahmad, S.; Hui, D. C. W. Heat Recovery Between Areas of Integrity. *Comput. Chem. Eng.* **1991**, *15* (12), 809−832.

Pinch technology is used in this approach to the design of HENs considering heat recovery among various process tasks.

7. Ahmad, S.; Linnhoff, B. SUPERTARGETING: Different Process Structures for Different Economics. *J. Energy Resour. Technol.* **1989**, *11* (3), 131−136.

The procedure for pinch design with supertargeting is detailed through the analysis of a case study. It is noted that it is possible to identify topology traps prior to design using supertargeting.

8. Ahmad, S.; Linnhoff, B.; Smith, R. Cost Optimum Heat Exchanger Networks-2. Targets and Design for Detailed Capital Cost Models. *Comput. Chem. Eng.* **1990**, *14* (7), 751−767.

Using the design procedure from the first part (annotation 242), a more sophisticated capital cost model is developed and applied.

9. Ahmad, S.; Polley, G. T. Debottlenecking of Heat Exchanger Networks. *Heat Recovery Syst. CHP* **1990**, *10* (4), 369−385.

Enhancements to the retrofit targeting procedure of Tjoe and Linnhoff (annotation 388) are made. The method is extended for increasing throughput by process debottlenecking. Pressure drop constraints and utility equipment restrictions are examined.

10. Ahmad, S.; Smith, R. Targets and Design for Minimum Number of Shells in Heat Exchanger Networks. *Chem. Eng. Res. Des.* **1989**, *67* (5), 481−494.

A method for targeting the minimum number of shells and near-optimal area in networks of 1−2 exchangers and a design method for developing HENs that approach these targets are described in this paper.

11. Ahmad, S.; Smith, R. Reply to Correspondence from K. Suaysompol, R. M. Wood, B. K. O'Neill and J. R. Roach. *Chem. Eng. Res. Des.* **1990**, *68*, 300−301.

This is a reply to correspondence (annotation 378) regarding the authors' paper (annotation 10). It comments that the correspondence addresses the minimum number of shells issue which is not the key issue in the original paper.

12. Al-Saggaf, A.; Mewes, D. Energy Savings through Heat Integration of Continuous Tank Reactors into Heat Recovery Systems. *Chem. Eng. Process.* **1989**, *26* (1), 81−91.

The heat integration of continuous tank reactors via pinch-based design methods is discussed. Both capital and energy costs are considered in the design stage for the integrated HEN.

13. Al-Saggaf, A.; Mewes, D. Thermal Coupling of Chemical Stirred-Tank Reactors with Other Plant Components. Part 2. *Int. Chem. Eng.* **1992**, *32* (2), 239−264.

Energy liberated by chemical reactions is taken into consideration in HENS. Thermal coupling of stirred-tank reactors with arbitrary plant components is investigated.

14. Al-Saggaf, A.; Mewes, D. Thermal Coupling of Chemical Stirred-Tank Reactors with Other Plant Components. Part 1. *Int. Chem. Eng.* **1992**, *32* (2), 209−238.

Literature concerning the PDM, network evolution and optimization procedures, flexibility, retrofit, heat integration, and overall process synthesis is reviewed and evaluated.

15. Androulakis, I. P.; Venkatasubramanian, V. A Genetic Algorithm Framework for Process Design and Optimization. *Comput. Chem. Eng.* **1991**, *15* (4), 217−228.

An optimization framework based on genetic algorithms is proposed for the solution of process design and optimization problems by stochastic methods. This framework is demonstrated by applying it to the synthesis of a HEN without stream splitting.

16. Asante, N. D. K.; Zhu, X. X. An Automated Approach for Heat Exchanger Network Retrofit Featuring Minimal Topology Modifications. *Comput. Chem. Eng.* **1996**, *20* (Suppl.), S7−S12.

A retrofit procedure consisting of two stages is proposed. In the diagnosis stage, desired topology modifications are identified and selected using MILP models. In the optimization stage, a small superstructure is derived and used to optimize stream splits and configurations.

17. Asante, N. D. K.; Zhu, X. X. An Automated and Interactive Approach for Heat Exchanger Network Retrofit. *Chem. Eng. Res. Des.* **1997**, *75* (A), 349−360.

This paper provides insights into the nature of retrofit design and the role played by topology modification in the design task. Three NLP models are used in the diagnosis stage to sequentially identify individual topology changes with the best potential for heat recovery, and an NLP model is used in the optimization stage to optimize the capital−energy tradeoff within a selected design.

18. Athier, G.; Floquet, P.; Pibouleau, L.; Domenech, S. Optimization of Heat Exchanger Networks by Coupled Simulated Annealing and NLP Procedures. *Comput. Chem. Eng.* **1996**, *20* (Suppl.), S13−S18.

An upper level simulated annealing algorithm is used to define feasible structures in the network, while a lower level NLP algorithm is used to determine continuous operating parameters for these structures.

19. Athier, G.; Floquet, P.; Pibouleau, L.; Domenech, S. Process Optimization by Simulated Annealing and NLP Procedures. Application to Heat Exchanger Network Synthesis. *Comput. Chem. Eng.* **1997**, *21* (Suppl.), S475−S480.

The simulated annealing method with the NLP HENS formulation previously presented (annotation 18) and restated in this work is implemented on some example test problems.

20. Athier, G.; Floquet, P.; Pibouleau, L.; Domenech, S. Synthesis of Heat-Exchanger Network by Simulated Annealing and NLP Procedures. *AIChE J.* **1997**, *43* (11), 3007−3020.

A numerical procedure for solving HENS is proposed. An algorithm is developed for bypassing implementation of MINLP procedures from which difficulties arise in large-scale HENS problems. Solution networks may include stream splitting, nonisothermal mixing, the absence of bypass streams, multiple matches between the same two streams, and dual streams, which were not considered in various prior approaches. The solution strategy involves a master problem solved by simulated annealing that determines the HEN topology with an NLP slave problem that optimizes the operating parameters.

21. Athier, G.; Floquet, P.; Pibouleau, L.; Domenech, S. A Mixed Method for Retrofitting Heat-Exchanger Networks. *Comput. Chem. Eng.* **1998**, *22* (Suppl.), S505−S511.

A two-level strategy for retrofit design is proposed. A simulated annealing algorithm is used to solve the master problem of generating and iteratively modifying a HEN topology. The slave problem involves NLP optimization of the operating parameters of the network.

22. Bagajewicz, M.; Rodera, H. Energy Savings in the Total Site Heat Integration Across Many Plants. *Comput. Chem. Eng.* **2000**, *24* (2−7), 1237−1242.

An extension of previous work for heat integration across two process plants (annotation 340) to a targeting method for multiple process plants is presented.

23. Bagajewicz, M. J.; Manousiouthakis, V. Mass/Heat-Exchange Network Representation of Distillation Networks. *AIChE J.* **1992**, *38* (11), 1769−1800.

The state space approach is introduced to process synthesis to represent distillation networks as composite heat and mass exchange networks. The state space approach qualitatively describes a problem based on the complement of state variables and input−output relations.

24. Bagajewicz, M. J.; Pham, R.; Manousiouthakis, V. On the State Space Approach to Mass/Heat Exchanger Network Design. *Chem. Eng. Sci.* **1998**, *53* (14), 2595−2621.

This paper introduces various aspects of the state space approach for the design of HENs, mass exchanger networks, and interacting heat and mass exchanger networks.

25. Ballut, A. A. Heat Recovery Analysis of an Existing Crude Distillation Unit. *J. Heat Recovery Syst.* **1986**, *6* (5), 361−367.

Possible energy savings in a crude distillation unit are analyzed.

26. Barnes, F. J.; King, C. J. Synthesis of Cascade Refrigeration and Liquefaction Systems. *Ind. Eng. Chem. Process Des. Dev.* **1974**, *13* (4), 421−433.

Graph decomposition and dynamic programming techniques are developed to seek minimum-cost process configurations for cascade refrigeration and gas liquefaction systems.

27. Beautyman, A. C.; Cornish, A. R. H. The Design of Flexible Heat Exchanger Networks. *First U.K. National Conference on Heat Transfer*; IChemE Symposium Series 86; Institution of Chemical Engineers: Leeds, U.K., 1984; pp 547−565.

A strategy for the design of flexible HENs is presented. It is suggested that the placement of bypasses in the network can reduce the need for optimizing control and still maintain maximum energy recovery.

28. Belkebir, B.; Guiglion, C.; Domenech, S.; Pibouleau, L. Synthèse d'un Réseau d'Echangeurs de Chaleur. *Chem. Eng. J.* **1989**, *42*, 119−133.

This is a paper in French with an abstract written in English. An analytical expression giving the optimum energy recovery as a function of the minimum temperature difference is derived. This expression is implemented in an algorithm used for the rapid solution of classical examples.

29. Biegler, L. T.; Grossmann, I. E.; Westerberg, A. W. *Systematic Methods of Chemical Process Design*; Prentice Hall: Upper Saddle River, NJ, 1997.

This text includes chapters on the PDM for HENS, mathematical formulations for sequential and simultaneous synthesis, and process optimization with heat integration.

30. Bochenek, R.; Ježowski, J. Adaptive Random Search Approach for Retrofitting Flexible Heat Exchanger Networks. *Hung. J. Ind. Chem.* **1999**, *27*, 89−97.

Direct search optimization techniques are applied to retrofitting multiperiod or flexible HENs.

31. Boland, D.; Hindmarsh, E. Heat Exchanger Network Improvements. *Chem. Eng. Prog.* **1984**, *80* (7), 47−54.

The techniques by which heat interactions occur between a process, the power system, and distillation system are discussed. Pinch technology methods are used in this analysis.

32. Boland, D.; Linnhoff, B. The Preliminary Design of Networks for Heat Exchange by Systematic Methods. *Birmingham Univ. Chem. Eng.* **1979**, *373*, 222−228.

A HEN design method based on first analyzing the problem data and then synthesizing the network is discussed. This paper describes early concepts of the PDM.

33. Briones, V.; Kokossis, A. A New Approach for the Optimal Retrofit of Heat Exchanger Networks. *Comput. Chem. Eng.* **1996**, *20* (Suppl.), S43−S48.

This approach for HENS retrofit employs pinch priorities and targets in mathematical programming techniques for an automated method.

34. Briones, V.; Kokossis, A. C. Hypertargets: A Conceptual Programming Approach for the Optimisation of Industrial Heat Exchanger Networks−I. Grassroots Design and Network Complexity. *Chem. Eng. Sci.* **1999**, *54*, 519−539.

A sequential HENS method is proposed in which an area target model is used in the determination of matches. Hypertargets rather than supertargets are used to find HRAT. A network topology formulation is also presented.

35. Briones, V.; Kokossis, A. C. Hypertargets: A Conceptual Programming Approach for the Optimisation of Industrial Heat Exchanger Networks−II. Retrofit Design. *Chem. Eng. Sci.* **1999**, *54*, 541−561.

An existing HEN is audited for possible modifications, and then these modifications are screened using MILP models. The hypertarget concepts (annotation 34) are applied to retrofit HENS.

36. Briones, V.; Kokossis, A. C. Hypertargets: A Conceptual Programming Approach for the Optimisation of Industrial Heat Exchanger Networks—III. Industrial Applications. *Chem. Eng. Sci*. **1999**, *54*, 685−706.

Solutions and analyses of industrial examples for the conceptual programming approach for grassroots (annotation 34) and retrofit (annotation 35) HENS are presented.

37. Calandranis, J.; Stephanopoulos, G. Structural Operability Analysis of Heat Exchanger Networks. *Chem. Eng. Res. Des*. **1986**, *64* (5), 347−364.

An interactive analytical methodology for determining the operability of a HEN is implemented in a computer program with a graphics-based interface for the HEN designer.

38. Carlsson, A.; Franck, P.; Berntsson, T. Design Better Heat Exchanger Network Retrofits. *Chem. Eng. Prog*. **1993**, *89* (3), 87−96.

A method of retrofit HEN design based on pinch technology is presented.

39. Cena, V.; Mustacchi, C.; Natali, F. Synthesis of Heat Exchange Networks: A Non-Iterative Approach. *Chem. Eng. Sci*. **1977**, *32*, 1227−1231.

This work proposes to minimize the utilities and exchanger units cost by structuring the HENS problem into an assignment problem formulation.

40. Cerda, J.; Galli, M. R. Synthesis of Flexible Heat Exchanger Networks—II. Nonconvex Networks with Large Temperature Variations. *Comput. Chem. Eng*. **1990**, *14* (2), 213−225.

Large temperature disturbances in HENS lead to nonconvexities due to “pinch jumps”. The synthesis algorithm and the MILP formulation (annotation 41) are generalized and modified to account for these nonconvexities.

41. Cerda, J.; Galli, M. R.; Camussi, N.; Isla, M. A. Synthesis of Flexible Heat Exchanger Networks—I. Convex Networks. *Comput. Chem. Eng*. **1990**, *14* (2), 197−211.

An MILP formulation for a pinch-based design procedure for convex flexible HENs which accounts for inlet temperature variations only is proposed. Forbidden match constraints are included.

42. Cerda, J.; Westerberg, A. W. Synthesizing Heat Exchanger Networks Having Restricted Stream/Stream Matches Using Transportation Problem Formulations. *Chem. Eng. Sci*. **1983**, *38* (10), 1723−1740.

An algorithm for HENS that involves the formulation, solving, and postprocessing of a series of linear transportation problems is presented. The transportation formulation of Cerda et al. (annotation 43) is used to solve the minimum utility usage. An MILP problem derived from the minimum utility problem is developed to solve the minimum number of matches. This MILP problem is relaxed by ignoring integer constraints and assigning high costs to infeasible and forbidden routes.

43. Cerda, J.; Westerberg, A. W.; Mason, D.; Linnhoff, B. Minimum Utility Usage in Heat Exchanger Network Synthesis. *Chem. Eng. Sci*. **1983**, *38* (3), 373−387.

A formulation of the minimum utility calculation of HENS as a transportation problem is proposed. This formulation accommodates match restrictions, multiple utilities, and utilities available over a range of temperatures. Essentially, the minimum utility calculation of the PDM is automated. The northwest corner algorithm is used to get an initial feasible solution, which is then used in the transportation problem algorithm to solve the problem.

44. Chakraborty, S.; Ghosh, P. Heat Exchanger Network Synthesis: The Possibility of Randomization. *Chem. Eng. J*. **1999**, *72*, 209−216.

A HENS approach based on randomly sampling points from the problem space consisting of all possible networks is presented. This algorithm does not allow for stream splitting.

45. Challand, T. B.; Colbert, R. W.; Venkatesh, C. K. Computerized Heat Exchanger Networks. *Chem. Eng. Prog*. **1981**, *77* (7), 65−71.

This is a short review of HENS with an emphasis on computerized analysis.

46. Chang, C.-T.; Chen, L. The Use of Mixers in Heat Recovery System Design. *Chem. Eng. Sci*. **1997**, *52* (2), 183−197.

Previous mathematical formulations for sequential HENS are modified to take into account the use of mixers as a form of heat exchange.

47. Chang, C.-T.; Chu, K.-K.; Hwang, J.-R. Application of the Generalized Stream Structure in HEN Synthesis. *Comput. Chem. Eng*. **1994**, *18* (4), 345−368.

The formulations for minimum utilities cost and the minimum number of units for sequential HENS are modified to allow for merging of process streams when it is an option in a process. An NLP formulation for network derivation is developed.

48. Chang, C. T.; Yu, T. P. Development of an Evolutionary Stream Merging Method in Heat Exchanger Network Design. *Understanding Process Integration II*; IChemE Symposium Series 109; Institution of Chemical Engineers: Rugby, England, 1988; pp 159−179.

An evolutionary method for reducing the number of units in a network, or loop breaking, is proposed that uses feasibility checks for whole or partial merging of streams.

49. Chato, J. C.; Damianides, C. Second-Law-Based Optimization of Heat Exchanger Networks Using Load Curves. *Int. J. Heat Mass Transfer* **1986**, *29* (8), 1079−1086.

A method for HENS via a “load curve” procedure is developed. The method is based on second-law thermodynamics and is similar to the composite curve method (annotation 139).

50. Chen, B.; Shen, J.; Sun, Q.; Hu, S. Development of an Expert System for Synthesis of Heat Exchanger Networks. *Comput. Chem. Eng*. **1989**, *13* (11/12), 1221−1227.

The knowledge-based design package SPHEN is described. SPHEN uses pinch design rules to construct a HEN, predict performance through simulation, generate flowsheet diagrams, and collect feedback from the user.

51. Cheng, W. B.; Mah, R. S. H. Interactive Synthesis of Cascade Refrigeration Systems. *Ind. Eng. Chem. Process Des. Dev*. **1980**, *19* (3), 410−420.

An interactive strategy is developed for the evolutionary synthesis of minimum-cost refrigeration cascades with multiple heat sources. This strategy leads to improvements on two previously published benchmarks.

52. Ciric, A. R.; Floudas, C. A. A Retrofit Approach for Heat Exchanger Networks. *Comput. Chem. Eng*. **1989**, *13* (6), 703−715.

This retrofit HENS method employs a two-stage approach. In the first stage, an MILP formulation at the level of matches incorporates costs associated with each potential match of streams and involves all possible options for modifications such as which exchangers are to be reassigned or if new ones are to be installed or the need to increase or decrease areas of existing exchangers. The second stage involves postulating a superstructure and formulating it as an NLP problem.

53. Ciric, A. R.; Floudas, C. A. A Comprehensive Optimization Model of the Heat Exchanger Network Retrofit Problem. *Heat Recovery Syst. CHP* **1990**, *10* (4), 407−422.

This paper presents an MINLP formulation of the retrofit HENS problem. Match-exchanger assignments are allowed to be made on the basis of actual area requirements rather than estimates. The MINLP formulation of the problem is solved using generalized Benders decomposition.

54. Ciric, A. R.; Floudas, C. A. A Mixed Integer Nonlinear Programming Model for Retrofitting Heat Exchanger Networks. *Ind. Eng. Chem. Res.* **1990**, *29* (2), 239−251.

The retrofit HENS method involves an MINLP formulation that selects process stream matches and match-exchanger assignments while simultaneously optimizing the network structure. It allows for match-exchanger assignments to be made on the basis of actual area requirements, as opposed to estimates of area and piping costs. The MINLP formulation is solved using the generalized Benders decomposition algorithm.

55. Ciric, A. R.; Floudas, C. A. Application of the Simultaneous Match−Network Optimization Approach to the Pseudo-Pinch Problem. *Comput. Chem. Eng.* **1990**, *14* (3), 241−250.

This paper proposes using three temperature approaches to formulate the pseudo-pinch problem for simultaneous match−network optimization.

56. Ciric, A. R.; Floudas, C. A. Heat Exchanger Network Synthesis without Decomposition. *Comput. Chem. Eng.* **1991**, *15* (6), 385−396.

The simultaneous optimization of utilities, number of matches, and network configuration using PPDMs and strict PDMs is described in this paper. An MINLP formulation using the hyperstructure of Floudas and Ciric (annotation 85) is solved using generalized Benders decomposition.

57. Colberg, R. D.; Morari, M. Analysis and Synthesis of Resilient Heat Exchanger Networks. *Adv. Chem. Eng.* **1988**, *14*, 1−93.

The authors provide an excellent review of the methods for the analysis of HEN resilience. Approaches for the design of resilient HENs are also presented.

58. Colberg, R. D.; Morari, M. Area and Capital Cost Targets for Heat Exchanger Network Synthesis with Constrained Matches and Unequal Heat Transfer Coefficients. *Comput. Chem. Eng.* **1990**, *14* (1), 1−22.

This paper presents two transshipment NLP formulations to calculate the area target and capital cost target for HENS problems. Given any specified number or set of matches and different heat-transfer coefficients and cost laws, this method is designed to predict the tradeoff between area or cost and the number of matches and the effect of forbidden matches upon the minimum area or cost. The solution provides the area or cost target, temperature profiles for each stream, and distribution of heat loads and areas among specific matches.

59. Colberg, R. D.; Morari, M.; Townsend, D. W. A Resilience Target for Heat Exchanger Network Synthesis. *Comput. Chem. Eng.* **1989**, *13* (7), 821−837.

A resilience target for HENS prior to the actual design stage is defined, and an NLP formulation for determining this target based on composite curves is derived.

60. Colbert, R. W. Industrial Heat Exchange Networks. *Chem. Eng. Prog.* **1982**, *78* (7), 47−54.

A DTAM to HENS is proposed. Instead of one approach temperature used in the PDM, two approach temperatures are used by the proposed method.

61. Colmenares, T. R.; Seider, W. D. Heat and Power Integration of Chemical Processes. *AIChE J.* **1987**, *33* (6), 898−915.

An NLP strategy for the integration of heat engines and heat pumps into a process with the temperature interval method is introduced. This NLP strategy identifies the optimal selection of working fluid and the best temperature intervals for integration of heat pumps and heat engines while minimizing the utility usage.

62. Colmenares, T. R.; Seider, W. D. Synthesis of Utility Systems Integrated with Chemical Processes. *Ind. Eng. Chem. Res.* **1989**, *28*, 84−93.

Integration between a process and utilities system is achieved through the use of a superstructure consisting of Rankine cycles in an NLP formulation. Heat and mass integration between adjacent power cycles allows for complex utility systems. The PDM is suggested for generating the HEN design after utilities are fixed and matches are determined from a previous MILP formulation.

63. Corominas, J.; Espuña, A.; Puigjaner, L. A New Look at Energy Integration in Multiproduct Batch Processes. *Comput. Chem. Eng.* **1993**, *17* (Suppl.), S15−S20.

A method for developing a HEN for a multiproduct batch plant is developed. The concept of a macronetwork is introduced to account for different campaigns of different products.

64. Corominas, J.; Espuña, A.; Puigjaner, L. Method to Incorporate Energy Integration Considerations in Multiproduct Batch Processes. *Comput. Chem. Eng.* **1994**, *18* (11/12), 1043−1055.

Energy integration for a multiproduct batch plant is addressed with heuristic procedures for shifting the timing of operations to facilitate energy savings.

65. Correa, D. J. Area Determination of Heat Exchanger Networks Using Dynamic Simulation. *Heat Transfer Eng.* **1998**, *19* (4), 22−28.

A method for using a dynamic simulator for determining the minimum overdesign of exchanger areas is presented. This technique used control algorithms in a nonconventional manner in order to design operable networks.

66. Crozier, R. A. Designing 'Near Optimum' Cooling-Water System. *Chem. Eng.* **1980**, *87* (8), 118−127.

This paper illustrates a heuristic procedure for designing a cooling-water once-through-exchanger system.

67. Daichendt, M. M.; Grossmann, I. E. A Preliminary Screening Procedure for MINLP Heat Exchanger Network Synthesis Using Aggregated Models. *Chem. Eng. Res. Des.* **1994**, *72* (A), 357−363.

An aggregated model of the MINLP formulation of the HENS problem of Yee and Grossmann (annotation 433) is used in a preliminary screening procedure to determine a subset of solutions from the original superstructure that are bounded to a base-case design. This screening procedure reduces the number of binary variables needed to model the problem, eliminates poor solutions, and yields valid lower and upper bounds to the global optimum solution. An erratum appears in a later issue (annotation 68).

68. Daichendt, M. M.; Grossmann, I. E. (Errata) A Preliminary Screening Procedure for MINLP Heat Exchanger Network Synthesis Using Aggregated Models. *Chem. Eng. Res. Des.* **1994**, *72* (A), 708−709.

Better quality figures from Daichendt and Grossmann (annotation 67) are reproduced in this erratum.

69. Daichendt, M. M.; Grossmann, I. E. Preliminary Screening Procedure for the MINLP Synthesis of Process Systems—I. Aggregation and Decomposition. *Comput. Chem. Eng.* **1994**, *18* (8), 663−677.

A synthesis framework based on aggregation and decomposition for preliminary screening is presented. This procedure is applied to heat-integrated distillation sequences in this paper. This same procedure is also applicable to HENS MINLP formulations as is seen in part II (annotation 70). The procedure eliminates a subset of suboptimal alternatives from the problem to yield a reduced superstructure.

70. Daichendt, M. M.; Grossmann, I. E. Preliminary Screening Procedure for the MINLP Synthesis of Process Systems—II. Heat Exchanger Networks. *Comput. Chem. Eng.* **1994**, *18* (8), 679−709.

The application of the preliminary screening procedure (annotation 69) to the MINLP formulation of the HENS problem by Yee and Grossmann (annotation 433) is presented. It is employed to decrease the size and increase the robustness of MINLP models of the HENS problem.

71. Daichendt, M. M.; Grossmann, I. E. Integration of Hierarchical Decomposition and Mathematical Programming for the Synthesis of Process Flowsheets. *Comput. Chem. Eng.* **1997**, *22* (1−2), 147−175.

A framework for the combination of hierarchical process decomposition with mathematical programming techniques is proposed for process flowsheet synthesis to simultaneously optimize the flowsheet at each level of decomposition.

72. Dhallu, N. S.; Johns, W. R. Minimal Cost Heat Exchanger Networks: A Non-Linear Transportation Algorithm. *Understanding Process Integration II*; IChemE Symposium Series 109; Institution of Chemical Engineers: Rugby, England, 1988; pp 117−135.

A linearly constrained transportation model with a nonlinear objective is developed for finding minimum cost HENs. LP lower bounds are developed for the nonconvex objective function.

73. Dolan, W. B.; Cummings, P. T.; Van, M. D. L. Process Optimization via Simulated Annealing: Application to Network Design. *AIChE J.* **1989**, *35* (5), 725−736.

This paper applies simulated annealing to process optimization. The grand canonical simulated annealing algorithm provides better results for HENS than previous work on similar problems.

74. Dolan, W. B.; Cummings, P. T.; Van, M. D. L. Algorithmic Efficiency of Simulated Annealing for Heat Exchanger Network Design. *Comput. Chem. Eng.* **1990**, *14* (10), 1039−1050.

The simulated annealing algorithm efficiently treats the evaluation of change in cost between different randomly generated states, an aspect strongly affecting computation. A new low-cost solution of HENS problem 7SP4 is generated. A data structure that improves the speed of the SA algorithm by two orders of magnitude is introduced.

75. Doldán, O. B.; Bagajewicz, M. J.; Cerdá, J. Designing Heat Exchanger Networks for Existing Chemical Plants. *Comput. Chem. Eng.* **1985**, *9* (5), 483−498.

Based on the goal of minimum fuel consumption in HENS, two new targets are defined: economic process utility usage, and optimal heating utility allocation. An NLP problem is formulated to predict both targets. A slight modification of the transportation-based method (annotation 42) is applied for synthesis of a network.

76. Douglas, J. M. *Conceptual Design of Chemical Processes*; McGraw-Hill: New York, 1988.

The basic procedures for the PDM for HENS along with heat integration of heat engines, heat pumps, and distillation are presented in a chapter of this text.

77. Duran, M. A.; Grossmann, I. E. Simultaneous Optimization and Heat Integration of Chemical Processes. *AIChE J.* **1986**, *32* (1), 123−138.

The procedure for the simultaneous optimization and heat integration of process flowsheets using NLP models is described. The minimum utility and the process flows and temperatures are optimized at the same time. It is postulated that simultaneous process flowsheet and HEN design will save more than determining the process first and then designing the HEN.

78. Elshout, R. V.; Hohmann, E. C. The Heat Exchanger Network Simulator. *Chem. Eng. Prog.* **1979**, *75* (3), 72−77.

Grassroots and retrofit design is done via the Heat Exchanger Network Simulator (annotation 142) using heuristic rules.

79. Engel, P.; Morari, M. Limitations of the Primary Loop-Breaking Method for Synthesis of Heat-Exchanger Networks. *Comput. Chem. Eng.* **1988**, *12* (4), 307−310.

Limitations of the loop-breaking method of Su and Motard (annotation 374) used in HEXTRAN are discussed. A general MILP loop-breaking procedure implemented in RESHEX is described. This method does not have the aforementioned limitations.

80. Fan, L. T.; Hwang, C. L.; Wang, C. S. Optimization of Multistage Heat Exchanger System by the Discrete Maximum Principle. *Chem. Eng. Prog. Symp. Ser.* **1965**, *61* (59), 243−252.

An algorithm utilizing the discrete maximum principle for decision making in the design of multistage heat-exchanger trains is detailed. This has more detailed coverage than previous work (annotation 81).

81. Fan, L. T.; Wang, C. S. *The Discrete Maximum Principle*; John Wiley & Sons: New York, 1964.

The discrete maximum principle is suggested as useful in process design problems. It is applied to various process design problems including HENS.

82. Farhanieh, B.; Sunden, B. Analysis of an Existing Heat Exchanger Network and Effects of Heat Pump Installations. *Heat Recovery Syst. CHP* **1990**, *10* (3), 285−296.

An existing refinery HEN is analyzed using both grassroots via PDM and retrofit design methods in this case study. The integration of heat pumps into the HEN is also investigated.

83. Floudas, C. A. *Nonlinear and Mixed-Integer Optimization: Fundamentals and Applications*; Oxford University Press: New York, 1995.

Over 50% of the section of the book on applied process synthesis is devoted to mathematical programming formulations of HENS problems and subproblems. HENS is the topic of discussion in greater than 20% of this text.

84. Floudas, C. A.; Aggarwal, A.; Ciric, A. R. Global Optimum Search for Nonconvex NLP and MINLP Problems. *Comput. Chem. Eng.* **1989**, *13* (10), 1117–1132.

An approach is introduced for searching for global optima of NLP and MINLP problems by identifying sources of nonconvexities and then partitioning and solving the subproblems using techniques based on generalized Benders decomposition. Several HENS examples are used. This method does not guarantee a global or even a local optimum for this class of problems as shown by Sahinidis and Grossmann.[62]

85. Floudas, C. A.; Ciric, A. R. Strategies for Overcoming Uncertainties in Heat Exchanger Network Synthesis. *Comput. Chem. Eng.* **1989**, *13* (10), 1133–1152.

This work concerns an effort to resolve uncertainties of the HENS problem using a decomposition approach. These uncertainties include nonconvexities in the network optimization task and several combinations of matches that satisfy constraints. An MINLP formulation for simultaneous match–network optimization for HENS is presented and decomposed to a problem with an MILP master problem. An erratum is printed in a later issue (annotation 86).

86. Floudas, C. A.; Ciric, A. R. Corrigendum–Strategies for Overcoming Uncertainties in Heat Exchanger Network Synthesis. *Comput. Chem. Eng.* **1990**, *14* (8), I.

A few minor typographical errors in Floudas and Ciric (annotation 85) are corrected in this erratum.

87. Floudas, C. A.; Ciric, A. R.; Grossmann, I. E. Automatic Synthesis of Optimum Heat Exchanger Network Configurations. *AIChE J.* **1986**, *32* (2), 276–290.

A procedure for automatic generation of a HEN configuration is presented. A superstructure that has embedded HEN configurations that satisfy the minimum utility cost and contain the minimum number of units predicted by the MILP transshipment model of Papoulias and Grossmann (annotation 307) is derived. The HENS problem is decomposed to target minimum utilities, minimum number of units, and minimum investment cost sequentially. This paper is mainly concerned with the development of the superstructure derivation procedure and the NLP formulation for generation of network structures. This is all implemented in the computer program MAGNETS.

88. Floudas, C. A.; Grossmann, I. E. Synthesis of Flexible Heat Exchanger Networks for Multiperiod Operation. *Comput. Chem. Eng.* **1986**, *10* (2), 153–168.

A multiperiod version of the transshipment models for the minimum utilities cost and minimum number of matches target problems is presented to address the issue of HENs that have the flexibility of coping with specified changes in flow rates and inlet and outlet temperatures in a predetermined sequence of time periods.

89. Floudas, C. A.; Grossmann, I. E. Automatic Generation of Multiperiod Heat Exchanger Network Configurations. *Comput. Chem. Eng.* **1987**, *11* (2), 123–142.

An extension of the procedure proposed previously (annotation 88) for HENS under multiperiod operation shows that network generation can be automated using an NLP formulation based on a superstructure representation of possible network topologies.

90. Floudas, C. A.; Grossmann, I. E. Synthesis of Flexible Heat Exchanger Networks with Uncertain Flowrates and Temperatures. *Comput. Chem. Eng.* **1987**, *11* (4), 319–336.

Previous sequential synthesis mathematical programming formulations are coupled with flexibility analysis problems. Flexibility analysis is performed at the level of matches and at the level of network determination.

91. Floudas, C. A.; Pardalos, P. M. *A Collection of Test Problems for Constrained Global Optimization Algorithms*; Lecture Notes in Computer Science No. 455; Springer-Verlag: Berlin, 1990.

This collection includes several HENS test problems presented in the network configuration or simultaneous match–network formulations along with best known solutions at the time of publication.

92. Flower, J. R.; Linnhoff, B. A Thermodynamic-Combinatorial Approach to the Design of Optimum Heat Exchanger Networks. *AIChE J.* **1980**, *26* (1), 1–9.

A thermodynamic-combinatorial approach for network configuration design in HENS is proposed. This method does not allow for stream splits.

93. Fraser, D. M. The Use of Minimum Flux Instead of Minimum Approach Temperature as a Design Specification for Heat Exchanger Networks. *Chem. Eng. Sci.* **1989**, *44* (5), 1121–1127.

It is suggested that rather than using a uniform minimum approach temperature as a basic design parameter in HENS, a uniform minimum flux would allow for approach temperatures that vary by stream type.

94. Fraser, D. M.; Gillespie, N. E. The Application of Pinch Technology to Retrofit Energy Integration of an Entire Oil Refinery. *Chem. Eng. Res. Des.* **1992**, *70*, 395–406.

Pinch technology is used to analyze the possibilities for savings for the retrofit of an oil refinery.

95. Frith, J. F.; Bergen, B. M.; Shreehan, M. M. Optimize Heat Train Design. *Hydrocarbon Process.* **1973**, *52* (7), 89–91.

Computers are used to evaluate design alternatives for the preheat train for crude distillation based on the exchanger area.

96. Galli, M. R.; Cerda, J. Synthesis of Flexible Heat Exchanger Networks–III. Temperature and Flowrate Variations. *Comput. Chem. Eng.* **1991**, *15* (1), 7–24.

The sequential synthesis of flexible HENs is accomplished with a general algorithmic approach which includes modifying previous mathematical formulations of target problems to account for uncertainties in inlet temperatures and flow rates of streams.

97. Galli, M. R.; Cerda, J. A Customized MILP Approach to the Synthesis of Heat Recovery Networks Reaching Specified Topology Targets. *Ind. Eng. Chem. Res.* **1998**, *37*, 2479–2495.

An MILP sequential synthesis strategy is proposed for HENS that allows the designer to specify desired topology features as design targets. This model allows no dual stream activity, has only isothermal mixing of split streams, and allows no bypasses and no split streams flowing through more than one heat exchanger.

98. Galli, M. R.; Cerda, J. A Designer-Controlled Framework for the Synthesis of Heat Exchanger Networks involving Non-Isothermal Mixers and Multiple Units over Split Streams. *Comput. Chem. Eng.* **1998**, *22* (Suppl.), S813–S816.

A sequential synthesis method allowing the designer to specify restrictions on network topology is formulated as a set of MINLP constraints, with the first objective function for determining the minimum utilities cost and the second for the minimum number of units (matches).

99. Galli, M. R.; Cerda, J. Synthesis of Structural-Constrained Heat Exchanger Networks—I. Series Networks. *Comput. Chem. Eng.* **1998**, *22* (7−8), 819−839.

A three-stage framework for sequential HENS is proposed for the design of a network with specified structural conditions. MILP formulations are proposed in which all three stages have nearly the same constraint set with objective functions for constrained utility usage, heat recovery target for the upper network, and minimum number of units (matches) for upper and lower networks.

100. Galli, M. R.; Cerda, J. Synthesis of Structural-Constrained Heat Exchanger Networks-II. Split Networks. *Comput. Chem. Eng.* **1998**, *22* (7−8), 1017−1035.

The MILP framework allowing structural restrictions (annotation 99) is generalized to allow split networks. It remains an MILP by making assumptions as in Yee and Grossmann (annotation 433) for isothermal mixing, no stream bypass, and singular exchange over a split stream.

101. Galli, M. R.; Cerda, J. Synthesis of Heat Exchanger Networks Featuring a Minimum Number of Constrained-Size Shells of 1−2 Type. *Appl. Therm. Eng.* **2000**, *20* (15−16), 1443−1467.

The neighbor-based HENS framework (annotation 97) is updated for constrained-size heat exchangers. Multiple 1−2 shell heat exchangers are incorporated into this method for a minimum number of shells MILP formulation.

102. Gicquel, R. Méthod d'optimisation systémique basée sur l'intégration thermique par extension de la méthode du pincement. *Rev. Gén. Therm.* **1995**, *34* (406).

Starting from the problem of energy recovery from exhaust, an extension of pinch analysis is applied to cogeneration plants with steam production. This paper is written in French with an abstract in English.

103. Gillespie, N. E.; Fraser, D. M. Heat Exchanger Network Synthesis: New Concepts Applied to Old Plants. *S. Afr. J. Chem. Eng.* **1989**, *1* (1), 42−72.

Pinch design tools are demonstrated in an example grassroots design and then applied to the retrofit case study.

104. Glavibuc, P.; Kravanja, Z.; Hombusak, M. Heat Integration of Reactors—I. Criteria for the Placement of Reactors into Process Flowsheet. *Chem. Eng. Sci.* **1988**, *43* (3), 593−608.

The correct placement of plug-flow reactors for their heat integration is examined using pinch method analysis.

105. Govind, R.; Mocsny, D.; Cosson, P.; Klei, J. Exchanger Network Synthesis on a Microcomputer. *Hydrocarbon Process.* **1986**, *65* (7), 53−57.

A computer program is written to apply the temperature interval network design method of Flower and Linnhoff (annotation 92). A graph-theoretical formulation for HENS via this method is also developed.

106. Grimes, L. E.; Rychener, M. D.; Westerberg, A. W. The Synthesis and Evolution of Networks of Heat Exchange that Feature the Minimum Number of Units. *Chem. Eng. Commun.* **1982**, *14*, 339−360.

An algorithm is presented that identifies the minimum utility requirements and pinch points of the HENS problem, partitions the problem, develops a network for each subproblem, and applies an evolutionary method to improve the network. It is an attempt to reduce the effort to solve simple networks.

107. Grossmann, I. E.; Caballero, J. A.; Yeomans, H. Mathematical Programming Approaches to the Synthesis of Chemical Process Systems. *Korean J. Chem. Eng.* **1999**, *16* (4), 407−426.

This is a review of advances in process synthesis using mathematical programming approaches. HENS is a specific topic covered in this review.

108. Grossmann, I. E.; Caballero, J. A.; Yeomans, H. Advances in Mathematical Programming for the Synthesis of Process Systems. *Latin Am. Appl. Res.* **2000**, *30* (4), 263−284.

This review of advances in process synthesis using mathematical programming is a reprint of an earlier article (annotation 107).

109. Grossmann, I. E.; Daichendt, M. M. New Trends in Optimization-Based Approaches to Process Synthesis. *Comput. Chem. Eng.* **1996**, *20* (6/7), 665−683.

An overview of optimization-based design work as well as a list of research challenges for process synthesis is presented in this paper.

110. Grossmann, I. E.; Floudas, C. A. Active Constraint Strategy for Flexibility Analysis in Chemical Processes. *Comput. Chem. Eng.* **1987**, *11* (6), 675−693.

Mathematical formulations for the feasibility test and flexibility index problems in process synthesis are presented and illustrated with HENS examples.

111. Grossmann, I. E.; Kravanja, Z. Mixed-Integer Nonlinear Programming Techniques for Process Systems Engineering. *Comput. Chem. Eng.* **1995**, *19* (Suppl.), S189−S204.

This is an overview of MINLP techniques used in process design and optimization. Topics include branch and bound, outer approximation, generalized Benders decomposition, and the extended cutting plane. Extensions of MINLP methods and logic-based methods are covered. Lists of references for different applications, including HENS, are provided.

112. Grossmann, I. E.; Sargent, R. W. H. Optimum Design of Heat Exchanger Networks. *Comput. Chem. Eng.* **1978**, *2* (1), 1−7.

This is an early examination of the general aspects of HENS formulated as NLPs or MINLPs. The formulations are based on the heuristic rule of Ponton and Donaldson (annotation 320). Test problems 6SP2, 8SP1, 12SP1, 14SP1, and 20SP1 are introduced.

113. Grossmann, I. E.; Yeomans, H.; Kravanja, Z. A Rigorous Disjunctive Optimization Model for Simultaneous Flowsheet Optimization and Heat Integration. *Comput. Chem. Eng.* **1998**, *22* (Suppl.), S157−S164.

The difficulties of the simultaneous process flowsheet optimization and heat integration model of Duran and Grossmann (annotation 77) are analyzed, and a new disjunctive model is proposed. The MINLP reformulation of the disjunctive model is given, and this model is reduced to MILP when only isothermal streams are involved.

114. Guglion, C.; Domenech, S.; Pibouleau, L. Récupération optimale de l'énergie dans les réseaux d'échangeurs de chaleur-I. Etude théorique. *Int. J. Heat Mass Transfer* **1989**, *32* (2), 243−250.

A study of HEN theory relating to optimal energy recovery is done. This paper is written in French with an abstract in English.

115. Guglion, C.; Domenech, S.; Pibouleau, L. Récupération optimale de l'énergie dans les réseaux d'échangeurs de chaleur-II. Etude de cas particuliers et classification des réseaux possibles. *Int. J. Heat Mass Transfer* **1989**, *32* (2), 251−260.

The theoretical results (annotation 114) involving the recoverable energy are studied. It is proved that the function representing recoverable energy is linear on intervals. This paper is written in French with an abstract in English.

116. Guglion, C.; Jannson, J.; Domenech, S.; Floquet, P.; Pibouleau, L. Procédure rapide de choix de réseaux d'échangeurs de chaleur. *Rev. Gén. Therm.* **1996**, *35* (415), 450−468.

A fast heuristic calculation method for choosing exchanger matches and heat loads is presented. This paper is written in French with an abstract in English.

117. Guglion, C.; Pibouleau, L.; Domenech, S. Thermodynamique des réseaux d'échangeurs de chaleur, et possibilitiés de diminuer le nombre d'échangeurs dans ces réseaux—I. Thermodynamique de réseaux d'échangeurs. *Int. J. Heat Mass Transfer* **1992**, *35* (6), 1349−1360.

A rigorous definition of pinch points ensuring in any case the existence of at least one pinch point is presented. This definition of pinch points leads to a study of pinch principles imposed by the optimal energy recovery. This paper is written in French with an abstract in English.

118. Guglion, C.; Pibouleau, L.; Domenech, S. Thermodynamique des réseaux d'échangeurs de chaleur, et possibilitiés de diminuer le nombre d'échangeurs dans ces réseaux—II. Etude des possibilités de diminuer le nombre d'échangeurs. *Int. J. Heat Mass Transfer* **1992**, *35* (6), 1361−1375.

Reduction of the number of heat-exchanger units is explored for the thermodynamic approach (annotation 117). This paper is written in French with an abstract in English.

119. Gulyani, B. B.; Mohanty, B. Heat Recovery Network Design: Graphical Algorithm for Heat Recovery from Flue Gas. *Indian Chem. Eng.* **1999**, *41* (2), 117−120.

The authors devise a simple graphical algorithm for designing a heat recovery network using flue gas based on reduced temperature rectangles.

120. Gundersen, T.; Duvold, S.; Hashemi-Ahmady, A. An Extended Vertical MILP Model for Heat Exchanger Network Synthesis. *Comput. Chem. Eng.* **1996**, *20* (Suppl.), S97−S102.

The vertical MILP model for determining the minimum number of matches for a HEN is extended to address the pairing effect caused by streams with poor film heat-transfer coefficients.

121. Gundersen, T.; Grossmann, I. E. Improved Optimization Strategies for Automated Heat Exchanger Network Synthesis Through Physical Insights. *Comput. Chem. Eng.* **1990**, *14* (9), 925−944.

A vertical MILP transshipment model is developed using physical insights. This model discriminates between sets of matches among hot and cold streams that achieve the same number of units and the same level of heat recovery in which area cost differs. The proposed vertical MILP transshipment model, which is a modification of the model of Papoulias and Grossmann (annotation 307), uses a combination of energy intervals and temperature intervals.

122. Gundersen, T.; Naess, L. The Synthesis of Cost Optimal Heat Exchanger Networks. *Comput. Chem. Eng.* **1988**, *12* (6), 503−530.

This is a very thorough HENS review paper for works up to 1987. It is broken down into major topics of interest and subject areas in HENS.

123. Gundersen, T.; Naess, L. The Synthesis of Cost Optimal Heat Exchanger Networks. *Heat Recovery Syst. CHP* **1990**, *10* (4), 301−328.

This review paper is a reprint of the paper originally published in 1988 (annotation 122).

124. Gundersen, T.; Sagli, B.; Kiste, K. Problems in Sequential and Simultaneous Strategies for Heat Exchanger Network Synthesis. In *Computer-Oriented Process Engineering*; Puigjaner, L., Espuña, A., Eds.; Elsevier: Amsterdam, The Netherlands, 1991; pp 105−116.

This paper compares pinch technology and sequential synthesis with simultaneous MINLP HENS. A case study is used as a basis for the comparison, and the limitations of each method are discussed.

125. Gundersen, T.; Traedal, P.; Hashemi-Ahmady, A. Improved Sequential Strategy for the Synthesis of Near-Optimal Heat Exchanger Networks. *Comput. Chem. Eng.* **1997**, *21* (Suppl.), S59−S64.

A HENS transportation model based on the vertical heat-transfer concept (annotations 120 and 121) for determining the heat load distribution of a network is developed. This formulation is created to lead to the design of networks with low total exchanger area via sequential synthesis.

126. Hall, S. G.; Ahmad, S.; Smith, R. Capital Cost Targets for Heat Exchanger Networks Comprising Mixed Materials of Construction, Pressure Ratings and Exchanger Types. *Comput. Chem. Eng.* **1990**, *14* (3), 319−335.

A method for the prediction of capital cost targets for HENs with mixed materials of construction and mixed pressure ratings is proposed.

127. Hama, A. Computer-Aided Synthesis of Heat Exchanger Networks: An Iterative Approach to Global Optimum Networks. *First U.K. National Conference on Heat Transfer*; IChemE Symposium Series 86; Institution of Chemical Engineers: Leeds, U.K., 1984; pp 567−582.

An iterative algorithm for HENS is proposed based on the HENS tools of the time.

128. Hamed, O. A.; Aly, S. Optimal Synthesis of a Heat-Exchanger Network. *Int. J. Energy Res.* **1991**, *15*, 31−39.

A HEN is designed for a crude fractionation unit. The concentration of this paper is application of techniques for supertargeting the approach temperature.

129. Hamed, O. A.; Aly, S.; Abu-Khousa, E. Heuristic Approach for Heat Exchanger Networks. *Int. J. Energy Res.* **1996**, *20* (9), 797−810.

A heuristic approach to HENS based on pinch technology is developed. It involves three sequential steps. In the preanalysis step, targets are obtained. In the network invention step, the minimum total area is determined. In the evolution step, heat loops are sought and broken to achieve the target minimum number of units. Many different rules and methods previously developed for HENS are incorporated into this heuristic approach.

130. Han, Z.; Zhu, J.; Rao, M.; Chuang, K. T. Determination of Independent Loops in Heat Exchanger Networks. *Chem. Eng. Commun.* **1998**, *164*, 191−204.

An algorithm for locating independent loops in HENs by generating a maximal tree for a given graph and adding edges to the tree is proposed. The set of independent loops produced by the algorithm is proven to be a maximal set of independent loops.

131. Hanson, K. W.; Cornish, A. R. H. An Algorithm to Develop Heat Exchanger Networks with the Minimum Number of Stream Splits and Maximum Energy Recovery. *First U.K. National Conference on Heat Transfer*; IChemE Symposium Series 86; Institution of Chemical Engineers: Leeds, U.K., 1984; pp 583−598.

An MILP formulation is developed for determining the minimum number of stream splits when using the PDM.

132. Hartmann, K.; Kaplick, K. *Analysis and Synthesis of Chemical Process Systems*; Computer-Aided Chemical Engineering; Elsevier: Amsterdam, The Netherlands, 1990.

A review of heuristic and fuzzy methods for evolving HENs computationally is presented in a chapter of this text.

133. Heggs, P. J. Minimum Temperature Difference Approach Concept in Heat Exchanger Networks. *Heat Recovery Syst, CHP* **1989**, *9* (4), 367−375.

Analysis of the minimum approach temperature in HENs shows that all exchanger configurations and flow arrangements that cannot thermodynamically achieve some heat match can be eliminated.

134. Hendry, J. E.; Rudd, D. F.; Seader, J. D. Synthesis in the Design of Chemical Processes. *AIChE J.* **1973**, *19* (1), 1−15.

This process synthesis review article considers theory and applications to topics including HENS.

135. Hesselmann, K. Optimization of the Effective Profit of Heat Exchanger Networks. *J. Heat Recovery Syst.* **1984**, *4* (5), 351−354.

Exergy analysis is applied in the study of the profitability of HENs. The purpose of this paper is to illustrate that HEN design should be based on effective profitability over plant life rather than productiveness at the point of design.

136. Himsworth, J. R.; Cooper, A. C. G. Supercharged Heat Exchanger Networks. *Chem. Eng. Res. Des.* **1993**, *71* (A), 203-211.

A supercharger, an expander which is coupled directly to a compressor, can be used to enhance the performance of a HEN.

137. Hindmarsh, E.; Boland, D.; Townsend, D. W. Maximizing Energy Savings for Heat Engines in Process Plants. *Chem. Eng.* **1985**, pp 38−47.

Techniques for integrating heat engines and heat pumps into HENS via the pinch design methodology are described.

138. Hlavábvcek, V. Synthesis in the Design of Chemical Processes. *Comput. Chem. Eng.* **1978**, *2*, 67−75.

This review of process synthesis primarily focuses on the work published after the review by Hendry et al. (annotation 134). The HENS is a major topic of coverage.

139. Hohmann, E. C. Optimum Networks for Heat Exchange. Ph.D. Dissertation, University of Southern California, Los Angeles, CA, 1971.

This work is the first to note that minimum utility requirements based on a specific minimum approach temperature can be determined directly from stream information. Temperature−enthalpy diagrams, now also known as Hohmann−Lockhart composite curves, are introduced to HENS literature. The $N - 1$ rule for estimating the number of units is also first proposed. This work lays some of the foundation for the PDM. It also includes the first annotated bibliography regarding HENS.

140. Hu, S.; Chen, B.; Shen, J. Nonconvex Feasible Region of Heat Exchanger Networks with Uncertain Stream Parameters. *Chin. J. Chem. Eng.* **1993**, *1* (2), 74−83.

The infeasible hole property of the nonconvex feasible region in HENS is identified. Based on this property, a procedure for flexibility analysis is developed and applied to an example.

141. Hu, S.; Chen, B.; Shen, J. Pinch Analysis of Heat Exchange Problems with Uncertain Parameters. *Tsinghua Sci. Technol.* **1997**, *2* (4), 777−782.

A reduced temperature interval method is introduced in order to allow pinch analysis for HENS problems with uncertain parameters.

142. Huang, F.; Elshout, R. Optimizing the Heat Recovery of Crude Units. *Chem. Eng. Prog.* **1976**, *72* (7), 68−74.

An analysis of HENs for crude units is used to develop a simple computer program, the Heat Exchanger Network Simulator, for designing these networks.

143. Huang, Y. L.; Fan, L. T. Distributed Strategy for Integration of Process Design and Control−A Knowledge Engineering Approach to the Incorporation of Controllability into Exchanger Network Synthesis. *Comput. Chem. Eng.* **1992**, *16* (5), 497−522.

A knowledge engineering based approach for the synthesis of optimal and controllable HENS and MENS is proposed.

144. Huang, Y. L.; Fan, L. T. HIDEN: A Hybrid Intelligent System for Synthesizing Highly Controllable Exchanger Networks. Implementation of a Distributed Strategy for Integrating Process Design and Control. *Ind. Eng. Chem. Res.* **1994**, *33* (5), 1174−1187.

A combination of three artificial intelligence concepts (knowledge engineering, fuzzy logic, and neural networks) is used to develop the application HIDEN for controllable HENS and MENS.

145. Hui, C. W.; Ahmad, S. Minimum Cost Heat Recovery between Separate Plant Regions. *Comput. Chem. Eng.* **1994**, *18* (8), 711−728.

The tradeoff between energy, exchanger capital, and the number of interconnections concerning the heat recovery among several regions of a plant is analyzed. A design procedure for developing a more integrated HEN for a total process plant is outlined.

146. Hui, C. W.; Ahmad, S. Total Site Integration Using the Utility System. *Comput. Chem. Eng.* **1994**, *18* (8), 729−742.

Heat integration between different chemical processes in a plant are addressed using the pinch technology targeting methods for optimizing the common utility system.

147. Hwa, C. S. *Mathematical Formulation and Optimization of Heat Exchanger Networks Using Separable Programming*; AIChE−IChemE Symposium Series 4; AIChE−IChemE: New York, 1965; pp 101−106.

This is the first paper to (a) approach HENS from a completely grassroots design perspective, (b) apply separable programming in the design of a HEN, and (c) use a superstructure in the development of a HENS mathematical model.

148. Irazoqui, H. A. Optimal Thermodynamic Synthesis of Thermal Energy Recovery Systems. *Chem. Eng. Sci.* **1986**, *41* (5), 1243−1255.

Thermal energy recovery systems are designed utilizing thermodynamically optimal operating lines. Heat and power integration are both considered.

149. Isla, M. A.; Cerda, J. Simultaneous Synthesis of Distillation Trains and Heat Exchanger Networks. *Chem. Eng. Sci.* **1987**, *42* (10), 2455−2463.

An MILP mathematical model for the heat integration of distillation trains is developed by generalizing a previous HENS model for variable stream temperatures.

150. Itoh, J.; Shiroko, K.; Umeda, T. Extensive Applications of the T−Q Diagram to Heat Integrated System Synthesis. *Comput. Chem. Eng.* **1986**, *10* (1), 59−66.

An extension of the temperature−enthalpy diagram called the heat demand and supply diagram is proposed for use in heat integration for chemical processes.

151. Ivakhnenko, V. I.; Ostrovskii, G. M.; Berezhinskii, T. A. A Method for Optimal Synthesis of Heat-Exchanger Systems. *Theor. Found. Chem. Eng.* **1983**, *16* (3), 250−255.

A method for HENS based on the assignment problem that does not require equal heat contents (i.e., allowing for utilities) is proposed.

152. Ivanov, B.; Peneva, K.; Bancheva, N. Heat Integration of Batch Vessels at Fixed Time Interval I. Schemes with Recycling Main Fluids. *Hung. J. Ind. Chem.* **1992**, *20*, 225−231.

NLP mathematical models are proposed for heat integration of batch processes in the case where fluids may be removed and returned to the vessels.

153. Ivanov, B.; Peneva, K.; Bancheva, N. Heat Integration in Batch Reactors Operating in Different Time Intervals Part I. A Hot−Cold Reactor System with Two Storage Tanks. *Hung. J. Ind. Chem.* **1993**, *21*, 201−207.

A mathematical model for heat integrating a hot and cold batch vessel operating in different time intervals utilizing two heat storage tanks is presented.

154. Ivanov, B.; Peneva, K.; Bancheva, N. Heat Integration in Batch Reactors Operating in Different Time Intervals Part II. A Hot−Cold Reactor System with a Common Storage Tank. *Hung. J. Ind. Chem.* **1993**, *21*, 209−216.

Mathematical models for heat integrating two batch vessels operating in different time intervals using a common heat storage tank are presented.

155. Ivanov, B.; Peneva, K.; Bancheva, N. Heat Integration in Batch Reactors Operating in Different Time Intervals Part III. Synthesis and Reconstruction of Integrated Systems with Heat Tanks. *Hung. J. Ind. Chem.* **1993**, *21*, 217−223.

Formulations incorporating the models from parts I (annotation 153) and II (annotation 154) for the synthesis of new heat-exchange networks with integrated batch reactors and for integrating batch reactors into existing networks are provided.

156. Ivanov, B.; Peneva, K.; Vaklieva-Bancheva, N. Synthesis of Heat Exchange Networks for Hot-Cold Batch Reactor Systems. *Hung. J. Ind. Chem.* **1995**, *23*, 251−260.

NLP mathematical models including several configurations for HENS incorporating a hot and a cold batch reactor in a fixed time interval are formulated.

157. Iyer, R. R.; Grossmann, I. E. Global Optimization of Heat Exchanger Networks with Fixed Configurations for Multiperiod Design. In *Global Optimization in Engineering Design*; Grossmann, I. E., Ed.; Kluwer Academic: Dordrecht, The Netherlands, 1996; pp 289−308.

The global optimization algorithm for HENS of Quesada and Grossmann (annotation 325) is extended to the synthesis of HENs for multiperiod operation for a fixed configuration.

158. Jegede, F. O.; Polley, G. T. Capital Cost Targets for Networks with Non-Uniform Heat Exchanger Specifications. *Comput. Chem. Eng.* **1992**, *16* (5), 477−495.

The authors develop a modification of the pinch design targeting methods to allow for nonuniform exchanger specifications which can have a major impact on the capital cost of a HEN. The use of an exchanger classification table is suggested as a tool to aid in the design of a HEN in this manner.

159. JeŽowski, J. Heat Exchanger Network Synthesis-Algorithms of Ordered Search. *Inż. Chem. Proc.* **1981**, *2* (1), 45−58.

An algorithm utilizing the ordered search method is developed for HEN design via tree searching techniques.

160. Ježowski, J. Selected Problems of Heat Exchanger Network Synthesis. *Hung. J. Ind. Chem.* **1982**, *10*, 345−356.

Two assignment task based algorithms are developed in an attempt to overcome some of the drawbacks of the evolutionary approach in HENS for minimizing the number of matches.

161. Ježowski, J. Heurystyczna Metoda Syntezy Sieci Wymiennikòw Ciepbla. I. Algorytm Metody. *Inż. Chem. Proc.* **1985**, *6* (2), 249−264.

A heuristic method for HENS is presented which focuses on determining the minimum utilities and number of units for problems without pinch points or stream splitting. This paper is written in Polish with an abstract in English.

162. Ježowski, J. Heurystyczna Metoda Syntezy Sieci Wymiennikòw Ciepbla. II. Przyklady Zastosowan. *Inż. Chem. Proc.* **1985**, *6* (3), 411−426.

The previous heuristic method (annotation 161) is extended to problems with pinch points and stream splitting. This paper is written in Polish with an abstract in English.

163. Ježowski, J. The Modified Temperature Interval Method for Heat Exchanger Network Synthesis. *Hung. J. Ind. Chem.* **1989**, *17* (3), 295−310.

An approach for allowing parallel, serial−parallel, and serial sequences of heat exchangers in networks derived from the PDM is proposed.

164. Ježowski, J. A Simple Synthesis Method for Heat Exchanger Networks with Minimum Number of Matches. *Chem. Eng. Sci.* **1990**, *45* (7), 1928−1932.

A simple method is proposed for designing a HEN with pinch crossing matches allowing the designer to decide prior to synthesis which streams will be contacted in pinch crossing matches. This method does not require a loop-breaking algorithm.

165. Ježowski, J. Linear Programming Based Method of Heat Exchanger Network Synthesis. *Inż. Chem. Proc.* **1990**, *11* (1), 299−312.

A sequential synthesis algorithm using LP to allow calculations on small computers is outlined.

166. Ježowski, J. A Note on the Use of Dual Temperature Approach in Heat Exchanger Network Synthesis. *Comput. Chem. Eng.* **1991**, *15* (5), 305−312.

It is shown that although the use of the DTAM may cause cross-pinching, the "no criss-crossing" rule of the PDM is an unnecessary limitation. A simple method using the DTAM stemming from physical insights for HENS is presented.

167. Ježowski, J. On Match Calculation in Heat Exchanger Network Synthesis. *Inż. Chem. Proc.* **1991**, *12* (2), 203-215.

A method for calculating heat load distributions while meeting the minimum number of units target in pinch design is proposed.

168. Ježowski, J. SYNHEN: Microcomputer Directed Package of Programs for Heat Exchanger Network Synthesis. *Comput. Chem. Eng.* **1992**, *16* (7), 691−706.

The computer package SYNHEN is described. SYNHEN is a combination of dual temperature pinch design and mathematical programming methods for sequential HENS. An evolution-based approach is used for the actual network design level step.

169. Ježowski, J. The Pinch Design Method for Tasks with Multiple Pinches. *Comput. Chem. Eng.* **1992**, *16* (2), 129−133.

A method for HENS is proposed that uses the PDM with multiple pinches without using the "inverse pinch" of Trivedi et al. (annotation 395).

170. Ježowski, J. Heat Exchanger Network Grassroot and Retrofit Design. The Review of the State-of-the-Art: Part I. Heat Exchanger Network Targeting and Insight Based Methods of Synthesis. *Hung. J. Ind. Chem.* **1994**, *22*, 279−294.

This is the first in an extensive two-part review paper on HENS. This part is primarily concerned with topics including the PDM, DTAM, various HENS targets, and supertargeting.

171. Ježowski, J. Heat Exchanger Network Grassroot and Retrofit Design. The Review of the State-of-the-Art: Part II. Heat Exchanger Network Synthesis by Mathematical Methods and Approaches for Retrofit Design. *Hung. J. Ind. Chem.* **1994**, *22*, 295−308.

This second part of an extensive HENS review primarily covers mathematical methods for HENS. Some major topics covered are sequential synthesis, global or simultaneous synthesis, knowledge-based systems, and mathematical methods for retrofit network design.

172. Ježowski, J.; Bochenek, R.; Jeżowska, A. Pinch Locations at Heat Capacity Flow-Rate Disturbances of Streams for Minimum Utility Cost Heat Exchanger Networks. *Appl. Therm. Eng.* **2000**, *20* (15−16), 1481−1494.

The determination of pinch-point locations for HENs allowing heat capacity flow-rate disturbances is approached with MILP optimization.

173. Ježowski, J.; Friedler, F. A Note on Targeting in the Design of Cost Optimal Heat Exchanger Networks. *Chem. Biochem. Eng. Q.* **1991**, *5* (1−2), 1−9.

An simple algorithm for supertargeting and determining the utilities target is proposed and illustrated by examples.

174. Ježowski, J.; Friedler, F. A Simple Approach for Maximum Heat Recovery Calculations. *Chem. Eng. Sci.* **1992**, *47* (6), 1481−1494.

The basic model is similar to the transshipment model of Papoulias and Grossmann (annotation 307). A basic algorithm with extensions for multiple utilities and forbidden matches is presented. The dual stream approach is included to increase the energy recovery in problems with forbidden matches. The basic algorithm is used to calculate the maximum residual heat flows for EMAT less than HRAT. This algorithm requires less computational effort than other pinch design algorithms.

175. Ježowski, J.; Hahne, E. Heat Exchanger Network Synthesis by a Depth First Method—A Case Study. *Chem. Eng. Sci.* **1986**, *41* (12), 2989−2997.

A tree search method for deriving a network by a depth first search of a synthesis matrix is studied. Results are compared to other previously published tree search HENS method results.

176. Ježowski, J.; Jeżowska, A. Analiza Metod Obliczania Minimalnej Liczby Aparatów W Preoptymalizacji Sieci Wymiennikww Ciepbla. *Inż. Chem. Proc.* **1997**, *18* (1), 19−37.

An analysis of the approach for determining the number of shells in HENS is provided. This paper is written in Polish with an abstract in English.

177. Ježowski, J.; Jeżowska, A. Computer Aided Designing of Heat Exchanger Networks. *Hung. J. Ind. Chem.* **1997**, *25* (2), 127−135.

The HENS computer package HEATREC, in which TARGET and SIMHEN are included, is described. These programs apply pinch design for networks.

178. Ježowski, J.; Jeżowska, A. Modyfikacja Elastycznych Sieci Wymienników Ciepbla I. Analiza Problemu I Podstawy Metody. *Inż. Chem. Proc.* **1997**, *18* (4), 613−634.

An algorithm for the retrofit HENS problem is proposed in which sensitivity tables are used. This paper is written in Polish with an abstract in English.

179. Ježowski, J.; Jeżowska, A. Modyfikacja Elastycznych Sieci Wymienników Ciepbla II. Przykblady Zastosowania Strategii Modyfikacji. *Inż. Chem. Proc.* **1997**, *18* (4), 635−660.

This paper illustrates the application of the flexible HENS retrofit strategy (annotation 179) to an industrial case. This paper is written in Polish with an abstract in English.

180. Ježowski, J.; Jeżowska, A. Some Remarks on Heat Exchanger Networks Targeting Under Uncertainty. *Hung. J. Ind. Chem.* **1999**, *27* (1), 17−24.

This paper provides an analysis of previously proposed methods for the design of flexible HENs.

181. Ježowski, J.; Kuciel, E. Method of Synthesis of the Optimal Network of Heat Exchangers. *Inż. Chem.* **1979**, *9* (3), 621−630.

Generating a tree with network structure and exchanger parameters is suggested as a method for HENS.

182. Ježowski, J. M.; Shethna, H. K.; Bochenek, R. J.; Castillo, F. J. L. On Extensions of Approaches for Heat Recovery Calculations in Integrated Chemical Process Systems. *Comput. Chem.* **2000**, *24* (5), 595−601.

The transshipment model for minimum utility cost calculation is extended for nonpoint utilities. A method is proposed for determining minimum utilities cost and pinch-point locations in the case of flow-rate disturbances.

183. Johns, W. R.; Williams, M. J. Cost-Optimal Heat Exchange Network Synthesis. *ESCAPE−4*; IChemE Symposium Series 133; Institution of Chemical Engineers: Rugby, England, 1994; pp 247−255.

A technique based on the transportation algorithm is developed for solving HENS modeled as linearly constrained transportation problem with a nonconvex objective.

184. Jones, D. A.; Yilmaz, A. N.; Tilton, B. E. Synthesis Techniques for Retrofitting Heat Recovery Systems. *Chem. Eng. Prog.* **1986**, *82* (7), 28−33.

Techniques for retrofit design of HENS using the HEXTRAN computer package are described.

185. Jones, S. A. Methods for the Generation and Evaluation of Alternative Heat Exchanger Networks. Ph.D. Dissertation, ETH Zürich, Zürich, Switzerland, 1987.

A sophisticated sequential HENS method is developed. Heat load distributions for a problem can be enumerated subject to targets for the minimum number of matches as well as network area effects based on vertical heat-transfer ideas. All feasible serial network flow configurations may be enumerated for a given heat load distribution. Flexibility issues are also discussed.

186. Jones, S. A.; Rippin, D. W. T. The Generation of Heat Load Distributions in Heat Exchanger Network Synthesis. *Process Syst. Eng. PSE ′85 Symp. Ser.* **1985**, *92*, 157−177.

In sequential HENS, all of the possible heat load distributions for a problem can be enumerated using Altherr's algorithm for a convex hull in the problem solution space in which the heat load distributions are its vertices.

187. Jung, S.; Lee, I.; Yang, D. R.; Chang, K. S. Synthesis of Maximum Energy Recovery Networks in Batch Processes. *Korean J. Chem. Eng.* **1994**, *11* (3), 162−171.

Heuristics are proposed for the maximum heat recovery in batch plants for cases of cocurrent and countercurrent heat exchange.

188. Kafarov, V. V.; Meshalkin, V. P. Formalization of the Synthesis of Heat Exchange Systems as Problems of Known Values by the Use of Two-Lobed Diagrams. *Dokl. Akad. Nauk SSSR* **1979**, *246*, 60−64.

A method is proposed for developing a two-lobed HEN diagram as a tool for designing HENs.

189. Kalitventzeff, B.; Maréchal, F. Optimal Insertion of Energy Saving Technologies in Industrial Processes: A Web-Based Tool Helps in Developments and Co-ordination of a European R & D Project. *Appl. Therm. Eng.* **2000**, *20* (15−16), 1347−1364.

The web-based EXSYS II expert system for energy system design in process synthesis is described.

190. Kane, M.; Favrat, D. Approche de conception et d'optimisation de centrale solaire intégrée á cycle combiné inspirée de la méthode du pincement (partie II: réseau d'échangeurs de chaleur). *Int. J. Therm. Sci.* **1999**, *38* (6), 512−524.

Pinch technology is used for the design of a HEN for an integrated solar combined cycle system. This paper is written in French with an abstract in English.

191. Kelahan, R. C.; Gaddy, J. L. Synthesis of Heat Exchange Networks by Mixed Integer Optimization. *AIChE J.* **1977**, *23* (6), 816−822.

An adaptive random search algorithm that incorporated heuristic rules is applied to HENS in an early treatment of the problem as a mixed-integer problem.

192. Kemp, I. C. Applications of the Time-Dependent Cascade Analysis in Process Integration. *Heat Recovery Syst. CHP* **1990**, *10* (4), 423−435.

Cascade analysis is used in the design of heat-integrated batch process case studies.

193. Kemp, I. C. Some Aspects of the Practical Application of Pinch Technology Methods. *Chem. Eng. Res. Des.* **1991**, *69* (6), 471−479.

Some of the more generally useful advances in the PDM are reviewed and their use by process engineers for different practical situations is suggested.

194. Kemp, I. C.; Deakin, A. W. The Cascade Analysis for Energy and Process Integration of Batch Processes Part 1: Calculation of Energy Targets. *Chem. Eng. Res. Des.* **1989**, *67* (5), 495−509.

Time-dependent cascade analysis based on pinch technology is used to obtain maximum heat recovery and maximum direct heat-exchange targets for heat integration of batch processes.

195. Kemp, I. C.; Deakin, A. W. The Cascade Analysis for Energy and Process Integration of Batch Processes Part 2: Network Design and Process Scheduling. *Chem. Eng. Res. Des.* **1989**, *67* (5), 510−516.

Heat recovery by direct heat exchange rather than heat storage is achieved through rescheduling batch processes. Targets developed using cascade analysis are used in HEN design.

196. Kemp, I. C.; Deakin, A. W. The Cascade Analysis for Energy and Process Integration of Batch Processes Part 3: A Case Study. *Chem. Eng. Res. Des.* **1989**, *67* (5), 517−525.

The procedure described in parts 1 (annotation 194) and 2 (annotation 195) are used for the design of a network integrating batch reactors.

197. Kemp, I. C.; MacDonald, E. K. Energy and Process Integration in Continuous and Batch Processes. *Innovation in Process Energy Utilisation*; IChemE Symposium Series 105; Institution of Chemical Engineers: Rugby, England, 1987; pp 185−200.

This work is primarily focused on developing procedures for the heat integration of batch processes using time-dependent cascade analysis.

198. Kemp, I. C.; MacDonald, E. K. Application of Pinch Technology to Separation, Reaction and Batch Processes. *Understanding Process Integration II*; IChemE Symposium Series 109; Institution of Chemical Engineers: Rugby, England, 1988; pp 239−257.

A general overview of heat integration of distillation, continuous reactors, and batch processes via pinch design principles is presented.

199. Kesler, M. G.; Parker, R. O. Optimal Networks of Heat Exchange. *Chem. Eng. Prog. Symp. Ser.* **1969**, *65* (92), 111−120.

A technique for solving HENS problems using a combination of an assignment algorithm and LP algorithms is developed.

200. Kim, S. W.; Lee, H. P.; Pek, U. H.; Park, S. W. Synthesis of Heat Exchanger Network by Optimizing the Minimum Temperature Difference. *Hwahak Konghak* **1992**, *30* (3), 318−327.

A supertargeting method for determining the minimum approach temperature based on a previous method (annotation 242) is proposed. A software package is developed and applied to an industrial process. This paper is written in Korean with an abstract in English.

201. Kleinshrodt, F. J., III; Hammer, G. A. Exchanger Networks for Crude Units. *Chem. Eng. Prog.* **1983**, *79* (7), 33−38.

The computer programs PROCESS and HEXTRAN are used in the design of a HEN for a crude unit allowing efficiency, flexibility, and energy usage to be analyzed at the same time.

202. Klemes, J.; Kostenko, Y. T.; Tovazhnyanskii, L. L.; Kapustenko, P. A.; Ul'ev, L. M.; Perevertailenko, A. Y.; Zulin,

B. D. The Pinch Design Method for Energy-Saving Oil-Refining Plants. *Theor. Found. Chem. Eng.* **1999**, *33* (4), 379–390.

The pinch method for HENS is applied to an oil-refining plant in the Ukraine.

203. Klemebvs, J.; Ptábvcník, R. Computer-Aided Synthesis of Heat Exchanger Network. *J. Heat Recovery Syst.* **1985**, *5* (5), 425–435.

A computer program called HENS System applying the techniques involved in pinch methods is developed.

204. Klemebvs, J.; Ptábvcník, R. Synthesis of Optimal Heat-Exchanger Networks. *Theor. Found. Chem. Eng.* (*Teoreticheskie Osnovy Khimicheskoi Tekhnologii*) **1987**, *21* (4), 300–309.

The HENS System (annotation 203) is described and demonstrated.

205. Kobayashi, S.; Umeda, T.; Ichikawa, A. Synthesis of Optimal Heat Exchange Systems—An Approach by the Optimal Assignment Problem in Linear Programming. *Chem. Eng. Sci.* **1971**, *26*, 1367–1380.

The HENS problem is simplified and formulated as an optimal assignment problem to derive feasible networks.

206. Konukman, A. E.; Camurdan, M. C.; Akman, U. Synthesis of Energy-Optimal HEN Structures with Specified Flexibility Index through Simultaneous MILP Formulation. In *Proceedings of PRES 99: 2nd Conference on Process Integration, Modelling and Optimization for Energy Saving and Pollution Reduction*; Friedler, F., Klemes, J., Ercsey, Z., Eds.; Hungarian Chemical Society: Budapest, 1999.

A one-stage superstructure-based simultaneous synthesis method based on the work of Yee and Grossmann (annotation 433) is presented. The assumption of a convex feasible region allows the method to find minimum utility networks given a flexibility target.

207. Konukman, A. E. S.; Akman, U.; Camurdan, M. C. Optimal Design of Controllable Heat-Exchanger Networks Under Multi-Directional Resiliency-Target Constraints. *Comput. Chem. Eng.* **1995**, *19* (Suppl.), S149–S154.

Retrofit design is accomplished given a set of resiliency-target constraints using a single constrained nonlinear optimization problem. This method only allows the alteration of existing exchanger area and bypass fractions.

208. Kotjabasakis, E.; Linnhoff, B. Sensitivity Tables for the Design of Flexible Processes (1)—How Much Contingency in Heat Exchanger Networks Is Cost-Effective. *Chem. Eng. Res. Des.* **1986**, *64* (3), 197–211.

A design procedure is proposed for HENS that uses sensitivity tables for making decisions for the tradeoffs between cost effectiveness and flexibility of the design.

209. Kotjabasakis, E.; Linnhoff, B. Flexible Heat Exchanger Network Design: Comments on the Problem Definition and on Suitable Solution Techniques. *Innovation in Process Energy Utilisation*; IChemE Symposium Series 105; Institution of Chemical Engineers: Rugby, England, 1988; pp 155–171.

A combination of the PDM and sensitivity tables is used the evaluate the three-way tradeoff between operating costs, capital costs, and flexibility requirements in HENS.

210. Kotjabasakis, E.; Linnhoff, B. Sensitivity Table for the Design of Flexible Processes (2)—A Case Study. *Understanding Process Integration II*; IChemE Symposium Series 109; Institution of Chemical Engineers: Rugby, England, 1988; pp 181–203.

An industrial retrofit case is approached using the sensitivity tables (annotation 208) to demonstrate situations of debottlenecking, fouling, and other issues.

211. Kovabvc, A.; Glavibvc, P. Retrofit of Complex and Energy Intensive Processes—I. *Comput. Chem. Eng.* **1995**, *19* (12), 1255–1270.

Thermodynamic and computational methods are combined for retrofit HENS. The grand composite and extended grand composite curves are used to eliminate unattractive structures. MINLP is used for optimizing the network using a superstructure.

212. Kovabvc-Kralj, A.; Glavibvc, P. Retrofit of Complex and Energy Intensive Processes. *Comput. Chem. Eng.* **1997**, *21* (Suppl.), S517–S522.

A method to optimize retrofits in complex and energy-intensive continuous processes with sequential structural and parameter optimization is developed. This combined sequential approach performs a sequential retrofit of a superstructure obtained with pinch analysis, using the ASPEN PLUS material flow optimization and MINLP or NLP algorithms.

213. Kovabvc-Kralj, A.; Glavibvc, P. Simultaneous Retrofit of Complex and Energy Intensive Processes—III. *Comput. Chem. Eng.* **2000**, *24* (2–7), 1229–1235.

The simultaneous structural and parameter optimization retrofit approach (annotation 214) is applied to a methanol plant case study.

214. Kovabvc-Kralj, A.; Glavibvc, P.; Kravanja, Z. Retrofit of Complex and Energy Intensive Processes—II: Stepwise Simultaneous Superstructural Approach. *Comput. Chem. Eng.* **2000**, *24* (1), 125–138.

The previous combined sequential approach (annotations 211 and 212) is extended to a stepwise simultaneous and parameter optimization retrofit approach. The approach involves generating a superstructure by pinch analysis, formulating an MINLP model, and solving the relaxed NLP.

215. Krajnc, M.; Glavibvc, P. Energy Integration of Mechanical Heat Pumps with Process Fluid as Working Fluid. *Chem. Eng. Res. Des.* **1992**, *70* (7), 407–420.

Pinch design techniques are employed in the integration of mechanical heat pumps with HENS.

216. Krajnc, M.; Glavibvc, P. The Influence of Different Temperature Contributions on Heat Integrated Process Structure. *Chem. Eng. Res. Des.* **1995**, *73* (A), 880–888.

A comparison of different methods for determining temperature contributions to the minimum approach temperature is provided. Guidelines for determining which method to use in different cases are given.

217. Kravanja, Z.; Glavibvc, P. Heat Integration of Reactors—II. Total Flowsheet Integration. *Chem. Eng. Sci.* **1989**, *44* (11), 2667–2682.

The extension of second law analysis from the HEN to the overall energy balance for a process enables the simultaneous integration of various types of energy-active apparatus and hot feeds into a process flowsheet. The methods employed are similar to classic pinch analysis methods.

218. Kravanja, Z.; Glavibvc, P. Cost Targeting for HEN through Simultaneous Optimization Approach: A Unified Pinch Technology and Mathematical Programming Design of Large HEN. *Comput. Chem. Eng.* **1997**, *21* (8), 833–853.

Simultaneous process flowsheet and HEN optimization is carried out using direct search optimization and implicit modeling in the simultaneous optimization step and an aggregated NLP model for the final HEN design. Match-dependent area targeting for capital costs of the HEN is applied in the simultaneous step.

219. Kuzichkin, N. V.; Viktorov, V. K. A Thermodynamic Euristic Method for the Synthesis of Optimal Thermal Systems. *Theor. Found. Chem. Eng.* **1998**, *32* (6), 577−581.

Two heuristic criteria for application to a sequential combinatorial method are explored.

220. Lababidi, H. M. S.; Alatiqi, I. M.; Nayfeh, L. J. Energy Retrofit Study of an Ammonia Plant. *Appl. Therm. Eng.* **2000**, *20* (15−16), 1495−1503.

A retrofit study of an ammonia plant is performed using pinch technology.

221. Lakshmanan, R.; Bañares-Alcántara, R. A Novel Visualization Tool for Heat Exchanger Network Retrofit. *Ind. Eng. Chem. Res.* **1996**, *35*, 4507−4522.

The retrofit thermodynamic diagram is introduced and used as a visualization tool for developing retrofit solutions by inspection for case studies.

222. Lakshmanan, R.; Bañares-Alcántara, R. Retrofit by Inspection Using Thermodynamic Process Visualization. *Comput. Chem. Eng.* **1998**, *22* (Suppl.), S809−S812.

The retrofit thermodynamic diagram is introduced as a visual tool for developing retrofit designs by inspection.

223. Lambert, A. J. D. Minimization of Number of Units in Heat Exchanger Networks Using a Lumped Approach. *Comput. Chem. Eng.* **1994**, *18* (1), 71−74.

An MILP model of the minimum number of units problem of HENS based on heat balances for each stream (lumped approach) rather than temperature intervals is proposed. The generation of the set of combinations of the minimum active number of active matches is faster compared to the transportation and transshipment models by reducing the number of continuous variables with lumping.

224. Lang, Y. D.; Biegler, L. T.; Grossmann, I. E. Simultaneous Optimization and Heat Integration with Process Simulators. *Comput. Chem. Eng.* **1988**, *12* (4), 311−327.

Process optimization and HENS are performed simultaneously using sequential process synthesis modules. Explicit and implicit modeling schemes are used to interface flowsheet optimization with the heat integration problem. These methods implemented using the FLOWTRAN process simulator coupled with MAGNETS for HENS derivation.

225. Lee, H.; Lee, I.; Yoo, K. The System Separation Method for the Optimal Target of Heat Exchanger Network Synthesis with Multiple Pinches. *Korean J. Chem. Eng.* **1995**, *12* (5), 589−592.

The issue of multiple pinch points is addressed with the system separation method which subdivides the HENS problems into independent subsystems with one pinch point.

226. Lee, H.; Yoo, K. A Study on Optimal Heat Exchanger Network Synthesis Using System Separation Method. *Hwahak Konghak* **1994**, *32* (3), 288−299.

A computer program is developed based on the system separation method for the determination of minimum temperature difference and total cost targets prior to HEN design. This paper is written in Korean with an abstract in English.

227. Lee, I. Toward the Synthesis of Global Optimum Heat Exchanger Networks Under Multiple-Periods of Operation. *Korean J. Chem. Eng.* **1991**, *8* (2), 95−104.

An algorithm for network evolution is presented for designing multiperiod HENs meeting the minimum number of units and maximum energy recovery targets.

228. Lee, I. Synthesis of Heat Exchanger Networks with Minimum Number of Units for Pinched Problems. *Korean J. Chem. Eng.* **1992**, *9* (3), 117−127.

A network evolution algorithm is proposed which combines elements of various other evolutionary methods to design networks meeting the energy recovery and number of units targets.

229. Lee, I.; Reklaitis, G. V. Toward the Synthesis of Global Optimum Heat Exchanger Networks: The Unpinched Case. *Chem. Eng. Commun.* **1989**, *75*, 57−88.

A network evolution algorithm is proposed that evolves a HEN using a heuristic procedure that exploits newly defined heat load loops in a network diagram.

230. Lee, K. F.; Masso, A. H.; Rudd, D. F. Branch and Bound Synthesis of Integrated Process Designs. *Ind. Eng. Chem. Fundam.* **1970**, *9* (1), 48−58.

This is an early look at the use of branch and bound techniques for HENS by creating a cost matrix and then developing a bounding problem. Test problems 4SP1 and 6SP1 are introduced.

231. Lewin, D. R. A Generalized Method for HEN Synthesis using Stochastic Optimization−II. The Synthesis of Cost-Optimal Networks. *Comput. Chem. Eng.* **1998**, *22* (10), 1387−1405.

HENS with stream splitting allowed leads to a nonlinear optimization model whose solution is used to determine the fitness of each HEN generated by the proposed genetic algorithm.

232. Lewin, D. R.; Wang, H.; Shalev, O. A Generalized Method for HEN Synthesis Using Stochastic Optimization−I. General Framework and MER Optimal Synthesis. *Comput. Chem. Eng.* **1998**, *22* (10), 1503−1513.

An approach for HENS based on genetic algorithms is presented. Disallowing stream splitting in the network results in an LP parametric optimization problem and an MILP optimization problem.

233. Li, H.; Yao, P. Using Process Energy Integration Technology in the Energy-Saving Retrofit of Large Scale Complex Chemical Process System. *Chin. J. Chem. Eng.* **1998**, *6* (3), 277−282.

The use of pinch-based methods for retrofitting large-scale processes is examined.

234. Li, Y.; Motard, R. L. Optimal Pinch Approach Temperature in Heat-Exchanger Networks. *Ind. Eng. Chem. Fundam.* **1986**, *25* (4), 577−581.

A method for determining the approach temperature for HENS prior to any design by using estimation calculations is proposed.

235. Li, Z. H.; Hua, B. Modeling and Optimizing for Heat Exchanger Networks Synthesis Based on Expert System and Exergo-Economic Objective Function. *Comput. Chem. Eng.* **2000**, *24* (2−7), 1223−1228.

A superstructure for HENS is developed with stream splits based on an expert system. An MINLP HENS model with an exergo-economic objective function is proposed.

236. Linnhoff, B. New Concepts in Thermodynamics for Better Chemical Process Design. *Proc. R. Soc. London A* **1983**, *386*, 1−33.

This paper presents a review of second law analysis for chemical processes. It also includes a review of work that had been done in HENS with regards to pinch design.

237. Linnhoff, B. New Concepts in Thermodynamics for Better Chemical Process Design. *Chem. Eng. Res. Des.* **1983**, *61*, 207−223.

This review paper is a reprint of the paper originally published in the Proceedings of the Royal Society of London (annotation 236).

238. Linnhoff, B. Pinch Technology for the Synthesis of Optimal Heat and Power Systems. *J. Energy Resour. Technol.* **1989**, *111*, 137−147.

This paper explains the relationship between pinch technology and second law analysis. Some of the claims are as follows: (1) exergy losses are inevitable in HENS, (2) pinch technology is a special case of second law analysis, (3) second law analysis is fundamentally true but devoid of relevant constraints for HENS, and (4) pinch technology expresses second law analysis with the constraints “built in”.

239. Linnhoff, B. Pinch Analysis—A State-of-the-Art Overview. *Chem. Eng. Res. Des.* **1993**, *71* (A), 503−522.

This is a review of pinch technology broken down into all of the major subject areas related to pinch analysis. The state-of-the-art methods of 1993 for pinch analysis is discussed. Over 80 citations are included in this review.

240. Linnhoff, B. Use Pinch Analysis to Knock Down Capital Costs and Emissions. *Chem. Eng. Prog.* **1994**, *90* (8), 33−57.

This is an overview of pinch design technology including a summary of the basic concepts as well as a description of more recent developments including pressure drop, multiple-base-case design, distillation columns, low-temperature design, batch processes, water pinch, total site integration, and emissions.

241. Linnhoff, B.; Ahmad, S. SUPERTARGETING: Optimum Synthesis of Energy Management Systems. *J. Energy Resour. Technol.* **1989**, *111* (3), 121−130.

Pinch technology is reviewed, and a method for supertargeting is introduced. An optimum approach temperature for pinch design is found by estimating and analyzing the total cost.

242. Linnhoff, B.; Ahmad, S. Cost Optimum Heat Exchanger Networks—1. Minimum Energy and Capital using Simple Models for Capital Cost. *Comput. Chem. Eng.* **1990**, *14* (7), 729−750.

Methods for the optimization of the driving force based on capital costs and energy requirements are developed. HENS is performed using the PDM and the driving force plot.

243. Linnhoff, B.; Flower, J. R. Synthesis of Heat Exchanger Networks—I. Systematic Generation of Energy Optimal Networks. *AIChE J.* **1978**, *24* (4), 633−642.

The “temperature interval method” which later becomes part of the basis of the PDM for HENS is developed.

244. Linnhoff, B.; Flower, J. R. Synthesis of Heat Exchanger Networks—II. Evolutionary Generation of Networks with Various Criteria of Optimality. *AIChE J.* **1978**, *24* (4), 642−654.

An evolutionary method of deriving better HENs starting with an initial feasible network is proposed. This work is part of the basis for the PDM.

245. Linnhoff, B.; Hindmarsh, E. The Pinch Design Method for Heat Exchanger Networks. *Chem. Eng. Sci.* **1983**, *38* (5), 745−763.

This paper is an early but comprehensive presentation of the details for using the PDM in HENS.

246. Linnhoff, B.; Kotjabasakis, E. Design of Operable Heat Exchanger Networks. *First U.K. National Conference on Heat Transfer*; IChemE Symposium Series 86; Institution of Chemical Engineers: Leeds, U.K., 1984; pp 599−618.

A procedure for the synthesis of operable networks based on simple insights and a grid diagram is presented.

247. Linnhoff, B.; Mason, D. R.; Wardle, I. Understanding Heat Exchanger Networks. *Comput. Chem. Eng.* **1979**, *3*, 295−302.

This is a discussion of fundamental topics in HENS including the significance of temperature difference, the role of multiple utilities, the number of units, stream splitting and multiple matching, and the roles of constraints and uncertain data.

248. Linnhoff, B.; Polley, G. T.; Sahdev, V. General Process Improvements Through Pinch Technology. *Chem. Eng. Prog.* **1988**, *84* (6), 51−58.

This is a review of pinch technology principles as well as a description of how pinch analysis is useful for process cost savings.

249. Linnhoff, B.; Smith, R.; Williams, J. D. The Optimization of Process Changes and Utility Selection in Heat Integrated Processes. *Chem. Eng. Res. Des.* **1990**, *68* (3), 221−236.

The problem of process flowsheet design is examined using pinch technology.

250. Linnhoff, B.; Townsend, B. Designing Total Energy Systems. *Chem. Eng. Prog.* **1982**, *78* (7), 72−80.

The criteria for the appropriate placement of heat engines and heat pumps in a HEN for total energy systems is discussed.

251. Linnhoff, B.; Townsend, D. W.; Boland, D.; Hewitt, G. F.; Thomas, B. E. A.; Guy, A. R.; Marsland, R. H. *A User Guide on Process Integration for the Efficient Use of Energy*; IChemE: Rugby, England, 1982.

A thorough discussion of the PDM for HENS and heat engine and pump integration is provided along with other tools for total energy system design.

252. Linnhoff, B.; Turner, J. Simple Concepts in Process Synthesis Give Energy Savings and Elegant Designs. *Birmingham Univ. Chem. Eng.* **1980**, *363*, 742−746.

This paper presents an outline of some of the ideas and topics which later become important in the PDM.

253. Linnhoff, B.; Turner, J. A. Heat-Recovery Networks: New Insights Yield Big Savings. *Chem. Eng.* **1981**, 56−70.

The decomposition, targeting, and design procedures of the as yet unnamed PDM are detailed in this paper.

254. Linnhoff, B.; Vredeveld, D. R. Pinch Technology Has Come of Age. *Chem. Eng. Prog.* **1984**, *80* (7), 33−40.

Some of the shortcomings of pinch design are addressed. Retrofit designs are made by applying pinch design principles.

255. Linnhoff, B.; Witherell, W. D. Pinch Technology Guides Retrofit. *Oil Gas J.* **1986**, 54−65.

Pinch technology is employed in the retrofit of an ethylene process.

256. Liporace, F. S.; Pessoa, F. L. P.; Queiroz, E. M. Automatic Evolution of Heat Exchanger Networks with Simultaneous Heat Exchanger Design. *Braz. J. Chem. Eng.* **1999**, *16* (1), 25−40.

The AtHENS software is developed for HENS based on the PDM. The paper describes the module for network evolution which includes improved loop identification and loop breaking and incorporates header pressure drop and shell sizing aspects of heat-exchanger design.

257. Liporace, F. S.; Pessoa, F. L. P.; Queiroz, E. M. The Influence of Heat Exchanger Design on the Synthesis of Heat Exchanger Networks. *Braz. J. Chem. Eng.* **2000**, *17* (4−7), 735−750.

In the context of the PDM, the AtHENS application (annotation 256) is updated to include network design criteria to identify infeasible exchanger unit designs during the network evolution stage.

258. Liu, Y. A. Process Synthesis: Some Simple and Practical Developments. In *Recent Developments in Chemical Process and Plant Design*; Liu, Y. A., McGee, H. A., Epperly, W. R., Eds.; John Wiley & Sons: New York, 1987; pp 147−260.

This design book includes a chapter on process synthesis with a very large section covering HENs. HENS topics covered include PDM, evolutionary synthesis methods, heuristics for matching, loop breaking, multipass HENS, and DTAM.

259. Liu, Y. A.; Pehler, F. A.; Cahela, D. R. Studies in Chemical Process Design and Synthesis—Part VII: Systematic Synthesis of Multipass Heat Exchanger Networks. *AIChE J.* **1985**, *31* (3), 487−491.

A simple method for designing a HEN employing multipass heat exchangers is presented. Estimation of the number of shells as well as stream matching characteristics is described.

260. Locke, B. Process Rearrangement—Designing from New. *Energy World* **1984**, *2*, 2−5.

A brief and general overview of energy-saving methods in design is given.

261. Lona, L. M. F.; Fernandes, F. A. N.; Roque, M. C.; Rodrigues, S. Developing an Educational Software for Heat Exchangers and Heat Exchanger Networks Projects. *Comput. Chem. Eng.* **2000**, *24* (2−7), 1247−1251.

The heat-exchanger simulator (HES) has been improved and is used as educational software for the design of shell and tube heat exchangers and HENs.

262. Luus, R. Optimization of Heat Exchanger Networks. *Ind. Eng. Chem. Res.* **1993**, *32* (11), 2633−2635.

The direct search optimization procedure is applied to HENS to find the global optimum of the problem defined in Quesada and Grossmann (annotation 325).

263. Ma, K.; Hui, C.; Yee, T. F. Constant Approach Temperature Model for HEN Retrofit. *Appl. Therm. Eng.* **2000**, *20* (15−16), 1505−1533.

An MILP model for HEN retrofit is proposed. A two-step solution procedure is proposed to overcome the problems associated with the nonconvexities of the MINLP model. First the constant approach temperature MILP model is solved to determine the fixed network structure, and then the MINLP model is solved for determining match reassignments.

264. Maiorano, M.; Sciubba, E. Heat Exchangers Networks Synthesis and Optimisation Performed by an Exergy-Based Expert System. *Int. J. Appl. Thermodyn.* **2000**, *3* (1), 1−19.

A knowledge-based expert system (HENEA) is developed for HEN design. HENEA uses design rules based on heuristics and physical principles.

265. Maréchal, F.; Kalitventzeff, B. SYNEP1: A Methodology for Energy Integration and Optimal Heat Exchanger Network Synthesis. *Comput. Chem. Eng.* **1989**, *213* (4/5), 603−610.

The computer application SYNEP1 is described. This HENS tool uses a combination of decomposition-based mathematical programming and heuristic synthesis methods to aid nonexpert users in designing grassroots or retrofit HENs.

266. Marechal, F.; Kalitventzeff, B. Targeting the Minimum Cost of Energy Requirements: A new Graphical Technique for Evaluating the Integration of Utility Systems. *Comput. Chem. Eng.* **1996**, *20* (Suppl.), S225−S230.

The problem of minimum cost of utilities is solved with MILP optimization, and integrated composite curves are used as a graphical tool for understanding the integration or nonintegration of streams.

267. Maréchal, F.; Kalitventzeff, B. Energy Integration of Industrial Sites: Tools, Methodology and Application. *Appl. Therm. Eng.* **1998**, *18* (11), 921−933.

Pinch-based heat integration methods are extended to the total industrial site heat integration. Each process is treated as one cold and one hot stream for the site scale problem.

268. Markowski, M. Reconstruction of a Heat Exchanger Network Under Industrial Constraints—The Case of a Crude Distillation Unit. *Appl. Therm. Eng.* **2000**, *20* (15−16), 1535−1544.

The HEN retrofit of a crude distillation unit using a pinch-based approach is presented.

269. Marselle, D. F.; Morari, M.; Rudd, D. F. Design of Resilient Processing Plants—II. Design and Control of Energy Management Systems. *Chem. Eng. Sci.* **1982**, *37* (2), 259−270.

Resilience for HENs is defined, and other properties of resilient networks are stated and deduced. A heuristic design method for structurally resilient networks with respect to inlet parameter variations is proposed.

270. Masso, A. H.; Rudd, D. F. The Synthesis of System Designs—II. Heuristic Structuring. *AIChE J.* **1969**, *15* (1), 10−17.

This is one of the earliest papers to define the HENS problem. A basic evolutionary synthesis procedure for HENS design is outlined. Test problems 5SP1, 7SP1, and 7SP2 are introduced.

271. McGalliard, R. L.; Westerberg, A. W. Structural Sensitivity Analysis in Design Synthesis. *Chem. Eng. J.* **1972**, *4*, 127−138.

A basic procedure for analyzing structural sensitivity and incorporating it into process synthesis is outlined. This method is then applied to HENS.

272. Menzies, M. A.; Johnson, A. I. Synthesis of Optimal Energy Recovery Networks using Discrete Methods. *Can. J. Chem. Eng.* **1972**, *50*.

A program to design HEN is created by incorporating a combination of systematic decomposition of a process design problem and branch-and-bound optimization.

273. Mizsey, P.; Rév, E. The Use of Flowsheet Simulators in Heat Exchanger Network Synthesis. *Hung. J. Ind. Chem.* **1991**, *19* (4), 293−299.

A revised version of this paper was published later. See annotation 274.

274. Mizsey, P.; Rév, E. The Use of Flowsheet Simulators in Heat Exchanger Network Synthesis (REVISED). *Hung. J. Ind. Chem.* **1992**, *20* (2), 91−97.

An MINLP formulation is developed for optimizing a HEN covering structure obtained from the diverse-pinch technique (annotation 338) used in HENS.

275. Mocsny, D.; Govind, R. Decomposition Strategy for the Synthesis of Minimum-Unit Heat Exchanger Networks. *AIChE J.* **1984**, *30* (5), 853−856.

The authors proposed determination of the minimum number of matches by decomposing the set of all possible matches into subsets and then eliminating those matches that do not meet specific criteria.

276. Morgan, S. W. Use Process Integration to Improve Process Designs and the Design Process. *Chem. Eng. Prog.* **1992**, *88* (9), 62−68.

An introduction to pinch analysis as well as its utility in process design is presented.

277. Muraki, M.; Hayakawa, T. Practical Synthesis Method for Heat Exchanger Network. *J. Chem. Eng. Jpn.* **1982**, *15* (2), 136−141.

A three-stage method for HENS using hand calculations is presented. The preanalysis stage uses a problem table. The initial network generation stage employs a simple algorithm. The evolution stage is carried out with heuristic rules based on stream splitting.

278. Murty, G. K.; Mallick, A. K. Design of a Heat Exchanger Network. *Chem. Age India* **1986**, *37* (3), 195−198.

This paper presents a short overview of HENS technology.

279. Nie, X. R.; Zhu, X. X. Heat Exchanger Network Retrofit Considering Pressure Drop and Heat-Transfer Enhancement. *AIChE J.* **1999**, *45* (6), 1239−1254.

A two-stage model for HENS retrofit is developed. A mathematical formulation for screening to determine units requiring additional area is followed by combined unit and shell-based optimization considering serial and parallel shell arrangements.

280. Nielsen, J. S.; Hansen, M. W.; bay Joergensen, S. Heat Exchanger Network Modelling Framework for Optimal Design and Retrofitting. *Comput. Chem. Eng.* **1996**, *20* (Suppl.), S249−S254.

Object-oriented modeling is used to create a HENS problem representation and simulated annealing to solve this problem in order to extend HENS to include concurrent exchangers as well as heat capacity flow rates that are not constant. The computer software HEN Explorer is developed in this approach to HENS.

281. Nielsen, J. S.; Hansen, M. W.; Kristensen, K. P. Retrofit and Optimisation of Industrial Heat Exchanger Networks: A Complete Benchmark Problem. *Comput. Chem. Eng.* **1997**, *21* (Suppl.), S469−S474.

An industrial retrofit HENS problem is used as an example for presenting a realistic HENS problem.

282. Nilsson, K.; Sundén, B. Optimizing a Refinery using the Pinch Technology and the MIND Method. *Heat Recovery Syst. CHP* **1994**, *14* (2), 211−220.

A Swedish refinery is analyzed using pinch technology and the MIND method, an MILP industrial energy system optimization tool. The HEN of the distillation system is analyzed using pinch techniques.

283. Nishida, N.; Kobayashi, S.; Ichikawa, A. Optimal Synthesis of Heat Exchange Systems—Necessary Conditions for Minimum Heat Transfer Area and their Applications to Systems Synthesis. *Chem. Eng. Sci.* **1971**, *26*, 1841−1856.

An analysis of HENS determining some of the necessary conditions for a locally optimal structure is conducted. An algorithm for evolving networks with graphical aids called heat content diagrams is proposed.

284. Nishida, N.; Liu, Y. A.; Lapidus, L. Studies in Chemical Process Design and Synthesis—III. A Simple and Practical Approach to the Optimal Synthesis of Heat Exchanger Networks. *AIChE J.* **1977**, *23* (1), 77−93.

An evolutionary minimum area network synthesis algorithm is presented. This work is an early look at methods later modified and included in the PDM.

285. Nishida, N.; Stephanopoulos, G.; Westerberg, A. W. A Review of Process Synthesis. *AIChE J.* **1981**, *27* (3), 321−351.

This review article covers many process synthesis topics in detail, one of which is HENs. This 1981 review is very well organized and presents tables cross-matching HENS topics with HENS papers.

286. Nishimura, H. A Theory for the Optimal Synthesis of Heat Exchanger Systems. *J. Opt. Theory Appl.* **1980**, *30* (3), 423−450.

An optimization method for HENS is created using a combination of a tool called a heat spectrum diagram and a set of theorems derived from the maximum principle.

287. Nishitani, H.; Kunugita, E. On the Vector Optimization of Heat Exchange. *J. Chem. Eng. Jpn.* **1982**, *15* (6), 475−480.

Early and simple mathematical formulations are developed using vector optimization for finding heat-exchange matches based on different objective functions for minimizing utilities and possibly approximate exchanger size.

288. Nishitani, H.; Shimizu, K.; Kunugita, E. Optimal Design of Heat Exchanger Network with a Large Number of Uncertain Parameters. *Electr. Eng. Jpn.* **1989**, *109* (3), 118−129.

This paper suggests that the design problem must be solved by reducing the number of constraints in the optimization problem based on the characteristics of the problem. An iterative method is presented that repeats the optimal design and feasibility tests. The problem is reduced for use with a specific software NMPS-6.

289. Nishitani, H.; Kutsuwa, K. S.; Kunugita, E. Design of Heat Exchanger Networks with Uncertainty in Overall Heat Transfer Coefficients. *J. Chem. Eng. Jpn.* **1988**, *21* (4), 375−381.

A graphical design method is proposed to address the issue of flexibility of a network with respect to overall heat-transfer coefficients.

290. Obeng, E. D. A.; Ashton, G. J. On Pinch Technology Based Procedures for the Design of Batch Processes. *Chem. Eng. Res. Des.* **1988**, *66*, 255−259.

Previously published techniques (annotation 197) for using pinch technology for heat integration of batch processes are appraised.

291. O'Reilly, M. Personal View. *Birmingham Univ. Chem. Eng.* **1984**, *410*, 46−47.

This is a short communication comparing the use of PROCESS and HEXTRAN software that utilize the DTA method to the PDM.

292. Ostrovsky, G. M.; Ivakhnenko, V. I.; Vinokurov, M. G. O.; Berezhinsky, T. A. Synthesis of Heat Exchanger Networks. *Hung. J. Ind. Chem.* **1985**, *13* (1), 107−119.

The HENS problem is simplified so that the assignment algorithm of LP could be used to solve for a minimum cost of utilities and heat-exchanger units.

293. O'Young, D. L.; Jenkins, D. M.; Linnhoff, B. The Constrained Problem Table for Heat Exchanger Networks. *Understanding Process Integration II*; IChemE Symposium Series 109; Institution of Chemical Engineers: Rugby, England, 1988; pp 75−115.

An algorithm is developed for determining the minimum utility usage based on pinch technology's temperature interval method for problems with restrictions on matches.

294. Özgen, C.; Babcc, N.; Gürkan, T.; Tosun, I. Designing Heat-Exchanger Networks for Energy Savings in Chemical Plants. *Energy* **1989**, *14* (12), 853−861.

The PDM is applied to a monomer plant in this case study. The new retrofit design would show a marked improvement over the previous network design.

295. Papalexandri, K. P.; Patsiatzis, D. I.; Pistikopoulos, E. N.; Ebbesen, L. Heat Integration Aspects in a Crude Preheat Refinery Section. *Comput. Chem. Eng.* **1998**, *22* (Suppl.), S141−S148.

A mass/heat-exchange-based representation presented previously (annotation 303) is utilized in the retrofit of the HEN of a crude preheat refinery section.

296. Papalexandri, K. P.; Pistikopoulos, E. N. A Multiperiod MINLP Model for Improving the Flexibility of Heat Exchanger Networks. *Comput. Chem. Eng.* **1993**, *17* (Suppl.), S111−S116.

This paper covers retrofitting HENs with variable operating conditions. With the assumption of no dual streams, a multiperiod network representation is used in an MINLP formulation of the retrofit HENS problem. The MINLP model couples synthesis techniques for HEN multiperiod operation and retrofit strategies. An iterative scheme may be used to integrate this problem with flexibility analysis.

297. Papalexandri, K. P.; Pistikopoulos, E. N. An MINLP Retrofit Approach for Improving the Flexibility of Heat Exchanger Networks. *Ann. Oper. Res.* **1993**, *42* (1−4), 119−168.

This paper addresses the problem of redesigning a HEN in order to improve its flexibility. The multiperiod MINLP approach of Floudas and Grossmann (annotation 89) is utilized in the generation of a multiperiod hyperstructure network representation used in the simultaneous optimization of the operation costs and retrofit investment costs of the retrofit HENS problem. The desired flexibility target is achieved through an iterative procedure between the flexibility analysis and the MINLP retrofit HENS problem.

298. Papalexandri, K. P.; Pistikopoulos, E. N. A Multiperiod MINLP Model for the Synthesis of Flexible Heat and Mass Exchange Networks. *Comput. Chem. Eng.* **1994**, *18* (11/12), 1125−1139.

An integrated hyperstructure representation and a multiperiod MINLP model are developed for heat- and mass-exchange network synthesis. The issue of parameters that vary by discrete values is addressed in this model.

299. Papalexandri, K. P.; Pistikopoulos, E. N. Synthesis and Retrofit Design of Operable Heat Exchanger Networks. 1. Flexibility and Structural Controllability Aspects. *Ind. Eng. Chem. Res.* **1994**, *33* (7), 1718−1737.

Structure controllability criteria for HENS are developed and utilized in an MINLP formulation for grassroots or retrofit HENS.

300. Papalexandri, K. P.; Pistikopoulos, E. N. Synthesis and Retrofit Design of Operable Heat Exchanger Networks. 2. Dynamics and Control Structure Considerations. *Ind. Eng. Chem. Res.* **1994**, *33* (7), 1738−1755.

A framework where controllability issues are considered in the grassroots or retrofit HENS design without decomposition is proposed which can be coupled with the iterative method (annotation 299). This method allows both structural and control alternatives to be explored simultaneously.

301. Papalexandri, K. P.; Pistikopoulos, E. N. Synthesis of Cost Optimal and Controllable Heat Exchanger Networks. *Chem. Eng. Res. Des.* **1994**, *72* (A), 350−356.

A framework for grassroots heat-exchanger synthesis for optimal and controllable networks based on the hyperstructure representation of Ciric and Floudas (annotation 85) is proposed.

302. Papalexandri, K. P.; Pistikopoulos, E. N. A Process Synthesis Modelling Framework Based on Mass/Heat Transfer Module Hyperstructure. *Comput. Chem. Eng.* **1995**, *19* (Suppl.), S71−S76.

A process modeling framework is proposed allowing for a flowsheet hyperstructure for mass/heat exchanger network synthesis to be developed.

303. Papalexandri, K. P.; Pistikopoulos, E. N. Generalized Modular Representation Framework for Process Synthesis. *AIChE J.* **1996**, *42* (4), 1010.

A mass/heat-exchanger module for building superstructures for the synthesis of combined mass and HENs is introduced.

304. Papalexandri, K. P.; Pistikopoulos, E. N. A Decomposition-Based Approach for Process Optimization and Simultaneous Heat Integration. *Chem. Eng. Res. Des.* **1998**, *76* (3), 273−286.

A heat integration superstructure for process synthesis exploiting interactions between structure, operating conditions, and heat recovery is proposed. A decomposition solution method is described, and operability aspects for the model are discussed.

305. Papastratos, S.; Isambert, A.; Depeyre, D. Computerized Optimum Design and Dynamic Simulation of Heat Exchanger Networks. *Comput. Chem. Eng.* **1993**, *17* (Suppl.), S329−S334.

The computer program CAD-HEN, based on thermodynamic principles, is developed to design HENs that are flexible and controllable as well as near-optimal. SpeedUp is used for dynamic simulation and response analysis of a HEN.

306. Papoulias, S. A.; Grossmann, I. E. A Structural Optimization Approach in Process Synthesis—I. Utility Systems. *Comput. Chem. Eng.* **1983**, *7* (6), 695−706.

The general synthesis problem is modeled as an MILP problem that allows for simultaneous structural and parameter optimization and uses a superstructure. This model is used for designing utility systems in this paper.

307. Papoulias, S. A.; Grossmann, I. E. A Structural Optimization Approach in Process Synthesis—II. Heat Recovery Networks. *Comput. Chem. Eng.* **1983**, *7* (6), 707−721.

An LP transshipment model for the minimum utilities problem with and without restricted matches and an

MILP transshipment model for the minimum number of units with possible stream splitting and mixing are developed. The temperature range is partitioned into temperature intervals according to pinch design rules.

308. Papoulias, S. A.; Grossmann, I. E. A Structural Optimization Approach in Process Synthesis—III. Total Processing Systems. *Comput. Chem. Eng.* **1983**, *7* (6), 723−734.

The models of the two previous parts (annotations 306 and 307) are used with the MILP model for total process systems synthesis developed in this paper.

309. Parkinson, A. R.; Liebman, J. S.; Pedersen, C. O.; Templeman, A. B. The Optimal Design of Resilient Heat Exchanger Networks. *AIChE Symp. Ser.* **1982**, *78* (214), 85−98.

A depth-first branch-and-bound method for resilient HEN design is developed. Resilience is maintained through feasibility tests.

310. Pehler, F. A.; Liu, Y. A. Studies in Chemical Process Design and Synthesis: VI. A Thermoeconomic Approach to the Evolutionary Synthesis of Heat Exchanger Networks. *Chem. Eng. Commun.* **1984**, *25*, 295−310.

A modified evolutionary synthesis method including rules for minimizing the number of heat-exchanger units is proposed.

311. Peneva, K.; Ivanov, B.; Bancheva, N. Heat Integration of Batch Vessels at Fixed Time Interval—II. Schemes with Intermediate Heating and Cooling Agents. *Hung. J. Ind. Chem.* **1992**, *20*, 233−239.

This paper proposes mathematical models for network design using external and jacket heat exchangers for processes that do not allow fluids to be removed from batch vessels.

312. Pethe, S.; Singh, R.; Knopf, F. C. A Simple Technique for Locating Loops in Heat Exchanger Networks. *Comput. Chem. Eng.* **1989**, *13* (7), 859−860.

This short note demonstrates the use of a simple matrix technique for identifying loops. The breaking of these loops may reduce capital network costs when deriving a HEN using pinch methods.

313. Pho, T. K.; Lapidus, L. Topics in Computer-Aided Design: Part II. Synthesis of Optimal Heat Exchanger Networks by Tree Searching Algorithms. *AIChE J.* **1973**, *19* (6), 1182−1189.

HENS is performed by creating a synthesis matrix representing the structure of an exchanger network, constructing a decision tree diagram to represent all feasible networks, and then using tree searching methods such as depth-first or partial enumeration to find a near-optimal HEN. Test problem 10SP1 is introduced.

314. Picon-Nunez, M. P.; Polley, G. T. Applying Basic Understanding of Heat Exchanger Network Behaviour to the Problem of Plant Flexibility. *Chem. Eng. Res. Des.* **1995**, *73* (A), 941−952.

The function and behavior of HENs are analyzed in order to provide insight and understanding of flexibility problems.

315. Polley, G. T. Selecting Stream Splits in Heat Exchanger Network Design. *Heat Recovery Syst. CHP* **1995**, *15* (1), 85−94.

A method for stream split selection for use in the PDM is presented.

316. Polley, G. T.; Amidpour, M. Don't Let the Retrofit Pinch Pinch You. *Chem. Eng. Prog.* **2000**, *96* (11), 43−48.

The problems with existing retrofit analysis approaches are examined and a structural targeting procedure is proposed that involves decomposing the problem and analyzing separate components individually.

317. Polley, G. T.; Heggs, P. J. Don't Let the Pinch Pinch You. *Chem. Eng. Prog.* **1999**, *95* (12), 27−36.

Some of the weaknesses of pinch design methodologies are demonstrated. Then, using a proposed decomposition procedure, off-the-shelf design software that utilizes pinch technology is used for HENS taking these practical drawbacks into account.

318. Polley, G. T.; Shahi, M. H. P. Interfacing Heat Exchanger Network Synthesis and Detailed Heat Exchanger Design. *Chem. Eng. Res. Des.* **1991**, *69* (A), 445−457.

Detailed heat-exchanger design considerations such as physical properties of the fluids, stream-fouling resistances, and exchanger-allowable pressure drops are explored.

319. Polley, G. T.; Shahi, M. H. P.; Jegede, F. O. Pressure Drop Considerations in the Retrofit of Heat Exchanger Networks. *Chem. Eng. Res. Des.* **1990**, *68* (A), 211−220.

The flow considerations of network topology are incorporated as part of the targeting procedures in retrofit HENS.

320. Ponton, J. W.; Donaldson, R. A. B. A Fast Method for the Synthesis of Optimal Heat Exchanger Networks. *Chem. Eng. Sci.* **1974**, *29* (12), 2375−2377.

This paper proposes a fast HENS heuristic rule that requires always matching of the hot stream of highest inlet temperature with the cold stream of lowest outlet temperature. Test problem 4SP2 is introduced.

321. Pozna, A.; Ivanov, B.; Vaklieva-Bancheva, N. Design of a Heat Exchanger Network for a System of Batch Vessels. *Hung. J. Ind. Chem.* **1998**, *26* (3), 203-211.

An MINLP formulation for HENS incorporating existing batch vessels is proposed.

322. Ptábvcn×c1k, R.; Klemebvs, J. An Application of Mathematical Optimization Methods in Heat-Exchange Network Synthesis. *Comput. Chem. Eng.* **1988**, *12* (2/3), 231−235.

This paper describes the theory behind the optimization technique for the computer design program HENS II. The method presented is a combination of mathematical optimization and evolutionary and heuristic methods.

323. Puspita, N. F.; Fuchino, T.; Muraki, M. Synthesis of Heat Exchanger Networks Considering Location of Process Stream Sources. *J. Chem. Eng. Jpn.* **1998**, *31* (3), 330−339.

A simultaneous evolutionary HENS method is proposed that optimizes on the basis of the total annual cost of the network.

324. Qassim, R. Y.; Silveira, C. S. Heat Exchanger Network Synthesis: The Goal Programming Approach. *Comput. Chem. Eng.* **1988**, *12* (11), 1163−1165.

The minimum utility consumption problem of HENS is formulated as a goal programming problem. This model allows the assignment of quantitative preferences to each utility in relation to one another in ways other than cost. It also permits the modification of the location of the pinch point in the network during the synthesis procedure.

325. Quesada, I.; Grossmann, I. E. Global Optimization Algorithm for Heat Exchanger Networks. *Ind. Eng. Chem. Res.* **1993**, *32* (3), 487−499.

A global optimization algorithm for HENS with fixed topology is presented. The fixed topology corresponds to a configuration within the superstructure of Yee and Grossmann (annotation 433). The optimization model is simplified by assuming that the area cost function is linear and that the driving force is calculated by the arithmetic mean temperature difference.

326. Raghavan, S. Heat Exchanger Network Synthesis: A Thermodynamic Approach. Ph.D. Dissertation, Purdue University, West Lafayette, IN, 1977.

This work includes an early proposal to uncouple the utilities and fixed costs in HENS. A mathematical model and a branch-and-bound algorithm are proposed for HENS optimization.

327. Ranade, S. M.; Jones, D. H.; Zapata-Suarez, A. Impact of Utility Costs on Pinch Designs. *Hydrocarbon Process.* **1989**, *68* (7), 39−43.

The significance of utility costs in pinch design for both grassroots and retrofit HENS is analyzed.

328. Rathore, R. N. S.; Powers, G. J. A Forward Branching Scheme for the Synthesis of Energy Recovery Systems. *Ind. Eng. Chem. Process Des. Dev.* **1975**, *14* (2), 175−181.

An early HENS method by forward branching depth-first tree search is proposed.

329. Ratnam, R.; Patwardhan, V. S. Sensitivity Analysis for Heat Exchanger Networks. *Chem. Eng. Sci.* **1991**, *46* (2), 451−458.

A computational procedure for generating sensitivity information without the need for repeated matrix inversions is developed and illustrated with examples.

330. Reddy, B. S.; Venkata Seshaiah, P. A Thermodynamic Approach to the Design of Heat Exchanger Networks. *Chem. Eng. World* **1997**, *32* (9), 145−150.

This article presents a short overview and outline of the development of pinch technology for HENS.

331. Reddy, B. S.; Venkata Seshaiah, P. Basic Concepts of Heat Exchanger Network Design. *Chem. Eng. World* **1997**, *32* (6), 55−58.

This article presents a short review of HENS via pinch-based design methods.

332. Reddy, B. S.; Venkata Seshaiah, P.; Subbarayudu, D. Optimum Design of Process Networks. *Chem. Eng. World* **1998**, *33* (9), 113−117.

This paper presents a review of the developments for supertargeting to determine the optimal approach temperature in pinch-based design methods.

333. Reddy, K. A.; Rao, C. D. P.; Davies, G. S. Synthesis of Multipass Heat Exchanger Networks. *AIChE J.* **1998**, *44* (4), 999−1002.

A methodology for designing multipass HENs is proposed. A set of rules for matching is developed, and the minimum number of shells target is used rather than for minimum number of units.

334. Reimann, K. A.; Steiner, M. The Dynamics of Heat Exchanger Networks—Two Design Aids. *Understanding Process Integration II*; IChemE Symposium Series 109; Institution of Chemical Engineers: Rugby, England, 1988; pp 205−220.

Two design aids in the form of a set of simple rules and a dynamic simulation program are presented as a means for considering the aspects of dynamics and control at an early stage in HEN design.

335. Rév, E.; Fonyó, Z. Synthesis of Heat Exchanger Networks. *Chem. Eng. Commun.* **1982**, *18*, 97−106.

A case study is used to determine the preferable arrangements of the most simple systems. A recursive heuristic algorithm for HENS is defined by applying the principles and criteria determined from the case study.

336. Rév, E.; Fonyó, Z. Additional Pinch Phenomena Providing Improved Synthesis of Heat Exchange Networks. *Hung. J. Ind. Chem.* **1986**, *14*, 181−201.

This paper discusses the PDM as well as hidden and pseudo pinch situations which may arise in the network design.

337. Rév, E.; Fonyó, Z. Hidden and Pseudo Pinch Phenomena and Relaxation in the Synthesis of Heat-Exchange Networks. *Comput. Chem. Eng.* **1986**, *10* (6), 601−607.

This short note proposes rules for hidden pinches and pseudo pinches to avoid violation of the minimum energy usage and overcomplicated structures when using the PDM.

338. Rév, E.; Fonyó, Z. Diverse Pinch Point Concept for Heat Exchange Network Synthesis: The Case of Different Heat Transfer Conditions. *Chem. Eng. Sci.* **1991**, *46*, 1623−1634.

The diverse-pinch concept is developed. A supertargeting method based on the diverse pinch taking into account film heat-transfer coefficients is developed.

339. Rév, E.; Fonyó, Z. Comments on Diverse Pinch Concept for Heat Exchanger Network Synthesis. *Chem. Eng. Sci.* **1993**, *48* (3), 627−628.

This short letter corrects some previously published data (annotation 338) and explains the significance of the diverse-pinch concept.

340. Rodera, H.; Bagajewicz, M. J. Targeting Procedures for Energy Savings by Heat Integration across Plants. *AIChE J.* **1999**, *45* (8), 1721−1742.

Pinch-based maximum energy savings models are presented for total heat integration across two process plants.

341. Roosen, P.; Grobss, B. Optimization Strategies and their Application to Heat Exchanger Network Synthesis. *Chem. Eng. Technol.* **1996**, *19* (2), 185−191.

Evolutionary strategy optimization is developed from insights garnered from previous methods involving thermodynamic and discrete optimization approaches to HENS. A module to apply the algorithms is coupled to ASPEN PLUS.

342. Roque, M. C.; Lona, L. M. F. The Economic of the Detailed Design of Heat Exchanger Networks Using the Bell Delaware Method. *Comput. Chem. Eng.* **2000**, *24* (2−7), 1349−1353.

A comparison of impact on HEN design cost between the Bell Delaware and Kern methods for calculating heat-transfer coefficients is presented.

343. Rudd, D. F. The Synthesis of System Designs: I. Elementary Decomposition Theory. *AIChE J.* **1968**, *14* (2), 343−349.

The process design problem is analyzed and decomposed into several subproblems, with HENS being one of them. An early analysis of the HENS subproblem in process synthesis is carried out.

344. Saboo, A. K.; Morari, M. Design of Resilient Processing Plants—IV. Some New Results on Heat Exchanger Network Synthesis. *Chem. Eng. Sci.* **1984**, *39* (3), 579−592.

A design procedure for resilient HENs is proposed to deal with inlet temperature variations. This method is based on the PDM.

345. Saboo, A. K.; Morari, M. RESHEX: An Interactive Software Package for the Synthesis and Analysis of Resilient Heat-Exchanger Networks—I. *Comput. Chem. Eng.* **1986**, *10* (6), 577−589.

This is an overview of the RESHEX program structure, features, and functions in its use in HENS. A case study is used to demonstrate the abilities of RESHEX.

346. Saboo, A. K.; Morari, M.; Colberg, R. D. RESHEX: An Interactive Software package for the Synthesis and Analysis of Resilient Heat-Exchanger Networks—II. *Comput. Chem. Eng.* **1986**, *10* (6), 591−599.

The algorithms used in the RESHEX program are described. Utility targeting and feasibility and resilience testing are done using existing algorithms. An LP formulation is proposed for surface area targeting that modifies the MILP transshipment model of Papoulias and Grossmann (annotation 307) such that it does not divide the problem into two parts by the pinch point, and a tolerance is allowed on the overall energy balances.

347. Saboo, A. K.; Morari, M.; Colberg, R. D. Resilience Analysis of Heat Exchanger Networks—I. Temperature Dependent Heat Capacities. *Comput. Chem. Eng.* **1987**, *11* (4), 399−408.

Resilience tests for HENs are developed. An NLP formulation is given for the general case for flow-rate and temperature disturbances, and an MILP formulation is used for the special case of a HEN with piecewise constant heat capacities.

348. Saboo, A. K.; Morari, M.; Colberg, R. D. Resilience Analysis of Heat Exchanger Networks—II. Stream Splits and Flowrate Variations. *Comput. Chem. Eng.* **1987**, *11* (5), 457−468.

The general resilience test (annotation 347) is simplified for some common industrial cases. Procedures for testing HEN resilience are developed for the cases of stream splits, large temperature disturbances, and flowrate variations.

349. Saboo, A. K.; Morari, M.; Woodcock, D. C. Design of Resilient Processing Plants—VIII. A Resilience Index for Heat Exchanger Networks. *Chem. Eng. Sci.* **1985**, *40* (8), 1553−1565.

A resilience index (RI) is defined so that the flexibility of a HEN with respect to inlet and target temperatures of the process streams can be quantified.

350. Sagli, B.; Gundersen, T.; Yee, T. F. Topology Traps in Evolutionary Strategies for Heat Exchanger Network Synthesis. In *Computer Applications in Chemical Engineering*; Bussemaker, H. T., Iedema, P. D., Eds.; Process Technology Proceedings 9; Elsevier: Amsterdam, The Netherlands, 1990; pp 51−58.

The ability of mathematical programming and evolutionary design approaches for HENS for overcoming topology traps is examined. The absence of a connection between the best design for a different number of exchangers is identified as a topology trap.

351. Sama, D. A. Difference between Second Law Analysis and Pinch Technology. *Trans. ASME* **1995**, *117*, 186−191.

This paper rebuts some of the claims of Linnhoff regarding second law analysis (annotation 238). Arguments for second law analysis as a HENS tool are made.

352. Sama, D. A. The Use of the Second Law of Thermodynamics in Process Design. *J. Energy Resour Technol.* **1995**, *117*, 179−185.

The benefits of using second law analysis are described. A set of guidelines for design using second law analysis are presented. HENS is given particular attention in this paper.

353. Santos, L. C.; Zemp, R. J. Energy and Capital Targets for Constrained Heat Exchanger Networks. *Braz. J. Chem. Eng.* **2000**, *17* (4−7), 659−669.

A procedure is developed for improving network area targeting in HENS. The potential use of multipass shell and tube heat exchangers is included.

354. Seider, W. D.; Seader, J. D.; Lewin, D. R. *Process Design Principles: Synthesis, Analysis and Evaluation*; John Wiley & Sons: New York, 1999.

The fundamental HENS methods are presented in this text. Pinch design methodology as well as basic mathematical programming LP and MILP formulations for HENS subproblems are described.

355. Shelton, M. R.; Grossmann, I. E. Optimal Synthesis of Integrated Refrigeration Systems—I. Mixed-Integer Programming Model. *Comput. Chem. Eng.* **1986**, *10* (5), 445−459.

A network representation is developed for synthesizing minimum cost refrigeration systems that are integrated with HENs. This integrated refrigeration system is formulated as an MILP problem.

356. Shelton, M. R.; Grossmann, I. E. Optimal Synthesis of Integrated Refrigeration Systems-II. Implicit Enumeration Scheme. *Comput. Chem. Eng.* **1986**, *10* (5), 460−477.

A solution technique for the minimum cost refrigeration system integrated with HENs (annotation 355) is proposed. The presence of multiple pinch points is exploited in a net heat flow model used within an implicit enumeration scheme.

357. Shenoy, U. V. *Heat Exchanger Network Synthesis*; Gulf Publishing Co.: Houston, TX, 1995.

This book is a comprehensive look at different methods for HENS. The mathematical programming portion presents GAMS code for solving different problems, although the problem formulations are not explicitly listed. Appendix B provides a thorough listing of 43 HENS test problems.

358. Shenoy, U. V.; Sinha, A.; Bandyopadhyay, S. Multiple Utilities Targeting for Heat Exchanger Networks. *Chem. Eng. Res. Des.* **1998**, *76* (A), 259−272.

An algorithm for multiple utilities targeting is developed based on the principle that it is optimal to increase the load on the cheapest utility while increasing the total utility usage. Optimum load distribution plots and total annual cost curves are employed in supertargeting the approach temperature when using multiple utilities.

359. Shethna, H. K.; Ježowski, J. M.; Castillo, F. J. L. A New Methodology for Simultaneous Optimization of Capital and Operating Cost Targets in Heat Exchanger Network Synthesis. *Appl. Therm. Eng.* **2000**, *20* (15−16), 1577−1587.

This paper proposes an MILP transportation formulation based on temperature intervals for simultaneous optimization of utilities costs, heat load distribution, and capital cost targets. Multiple utilities are allowed, while split streams are disallowed.

360. Shethna, H. K.; Ježowski, J. M.; Castillo, F. J. L. Generalized Transshipment Model for Targeting of Multiple Utilities in Heat Exchanger Networks. *Inż. Chem. Proc.* **2000**, *21* (4), 625−643.

An LP transshipment formulation is developed for determining the minimum utilities cost target in HENS extended to cases with multiple utilities and utilities that span more than one temperature interval.

361. Siddiqui, A. R.; Malhotra, A.; Chawla, O. P. Optimization of a Heat Exchanger Chain Consisting of Two Cold Streams. *Eng. Opt.* **1984**, *7*, 157−166.

The discrete maximum principle is applied to a heat-exchanger train case with two cold streams and several hot streams.

362. Silva, M. L.; Zemp, R. J. Retrofit of Pressure Drop Constrained Heat Exchanger Networks. *Appl. Therm. Eng.* **2000**, *20* (15−16), 1469−1480.

A HEN retrofit procedure for simultaneously accounting for the distribution of heat-transfer area and pressure drop availability at the targeting stage is implemented as an NLP problem.

363. Smith, G. J.; Parker, D. An Integrated Approach to Heat Exchanger Network (HEN) Design and Analysis. *Understanding Process Integration II*; IChemE Symposium Series 109; Institution of Chemical Engineers: Rugby, England, 1988; pp 327−342.

An interactive HENS program called MIDAS is developed. MIDAS employs a HEN design and analysis method based on pinch design rules.

364. Smith, R. *Chemical Process Design*; McGraw-Hill: New York, 1995.

This book presents a hierarchical coverage of process design. There are two chapters concerning HENS targets. The chapter on HENS energy targets covers temperature intervals, the pinch point, and enthalpy−temperature diagrams among other issues. The chapter on HENS capital costs covers the number of units, area targets, shell targets, and total costs.

365. Smith, R. State of the Art in Process Integration. *Appl. Therm. Eng.* **2000**, *20* (15−16), 1337−1345.

An overview of the recent advances in process integration is presented, including a section on HENs.

366. Sorin, M.; Paris, J. Combined Exergy and Pinch Approach to Process Analysis. *Comput. Chem. Eng.* **1997**, *21* (Suppl.), S23−S28.

The integration of pinch analysis to the thermodynamic analysis of processes by the exergy load distribution method allows the identification of process changes which are most likely to produce a desired effect without great computational efforts.

367. Sorin, M.; Paris, J. Integrated Exergy Load Distribution Method and Pinch Analysis. *Comput. Chem. Eng.* **1999**, *23* (4/5), 497−507.

Intended exergy yield is proposed as a performance criteria for chemical process. The HEN is considered to be a single unit before final design. Pinch analysis is combined with exergy analysis for guiding process design.

368. Sorbvsak, A.; Kravanja, Z. Simultaneous MINLP Synthesis of Heat and Power Integrated Heat Exchanger Networks. *Comput. Chem. Eng.* **1999**, *23* (Suppl.), S143−S147.

The simultaneous synthesis model of Yee and Grossmann (annotation 433) is extended to also optimize pressure drops and heat-transfer coefficients.

369. Souto, J. A.; Casares, J. J.; Rodr×c1guez, A. Rule-Based System for the Synthesis of Heat Exchanger Networks. *Expert Syst. Appl.* **1992**, *5*, 111−119.

A rule-based system for HENS called RICPERT is developed based on the work of Ponton and Donaldson (annotation 320) with additional heuristics also included.

370. Srinivas, B. K.; El-Halwagi, M. M. Synthesis of Combined Heat and Reactive Mass-Exchange Networks. *Chem. Eng. Sci.* **1994**, *49* (11), 2059−2074.

The problem of combined heat and reactive mass exchange networks is introduced. A two-stage targeting procedure is proposed for the solution of this problem.

371. Stephanopoulos, G.; Westerberg, A. W. Modular Design of Heat Exchanger Networks. *Chem. Eng. Commun.* **1980**, *4*, 119−126.

This paper addresses the modular decomposition in the design of HENs. A strategy is proposed for improving an existing design through modularization.

372. Stoltze, S.; Mikkelsen, J.; Lorentzen, B.; Petersen, P. M.; Qvale, B. Waste-Heat Recovery in Batch Processes Using Heat Storage. *J. Energy Resour. Technol.* **1995**, *117*, 142−149.

A procedure is proposed for incorporating the minimum number of heat storage tanks into HENs to achieve maximum energy savings as determined by pinch analysis.

373. Strelow, O. Eine allgemeine Berechnungsmethode für Wärmeübertragerschaltungen. *Forsch. Ingenieurwes.* **1997**, *63*, 255−261.

When HENs are treated as coupled heat exchangers, a simple method is developed to use coupled matrix equations for the calculation of variables in a HEN. This paper is written in German with an abstract in English.

374. Su, J.; Motard, R. L. Evolutionary Synthesis of Heat-Exchanger Networks. *Comput. Chem. Eng.* **1984**, *8* (2), 67−80.

An evolutionary network synthesis technique based on the searching and breaking of all heat load loops is proposed. This procedure is integrated into the PDM.

375. Suaysompol, K.; Wood, R. M. The Flexible Pinch Design Method for Heat Exchanger Networks Part I: Heuristic Guidelines for Free Hand Designs. *Chem. Eng. Res. Des.* **1991**, *69* (6), 458−464.

The flexible PDM (FPDM) is outlined in this paper. The heat exchangers are not constrained by a rigid minimum approach temperature difference. Instead, a variable approach temperature concept is proposed.

376. Suaysompol, K.; Wood, R. M. The Flexible Pinch Design Method for Heat Exchanger Networks Part II: FLEXNET-Heuristic Searching Guided by the A* Algorithm. *Chem. Eng. Res. Des.* **1991**, *69* (6), 465−470.

The FPDM (annotation 375) is implemented in the computer-aided design package FLEXNET. The A* heuristic search algorithm is employed to locate cost-effective solutions for the HENS problem.

377. Suaysompol, K.; Wood, R. M. Estimation of the Installed Cost of Heat Exchanger Networks. *Int. J. Prod. Econ.* **1993**, *29*, 303−312.

A procedure for including piping costs in the estimation of costs for alternative network designs is presented.

378. Suaysompol, K.; Wood, R. M.; O'Neill, B. K.; Roach, J. R. Correspondence regarding Targeting and Design for Minimum Number of Shells in HENs. *Chem. Eng. Res. Des.* **1990**, *68* (A), 299−300.

Comments regarding a paper by Ahmad and Smith (annotation 10) and the appropriateness of using pinch decomposition for HENS.

379. Sunden, B. Analysis of the Heat Recovery in Two Crude Distillation Units. *Heat Recovery Syst. CHP* **1988**, *8* (5), 483−488.

Two crude distillation unit cases are studied, and HENs are designed using pinch methodology.

380. Swaney, R. E. Thermal Integration of Processes With Heat Engines and Heat Pumps. *AIChE J.* **1989**, *35* (6), 1003−1016.

An extended MILP transportation array based on the work of Cerda et al. (annotation 43) is introduced. This array includes the use of heat engine and heat pump sinks and rejection sources as well as power utility input or output.

381. Tantimuratha, L.; Asteris, G.; Antonopoulos, D. K.; Kokossis, A. C. A Conceptual Programming Approach for the Design of Flexible HENS. In *ESCAPE−10*; Pierucci, S., Ed.; Elsevier: Amsterdam, The Netherlands, 2000; pp 967−972.

A conceptual tool is developed to address flexibility in HENS based on the area target model (annotations 34−36).

382. Tantimuratha, L.; Kokossis, A. C.; Müller, F. U. The Heat Exchanger Network Design as a Paradigm of Technology Integration. *Appl. Therm. Eng.* **2000**, *20* (15−16), 1589−1605.

The combination of different optimization technologies for HENS is studied. Computational experimentation suggests that simulated annealing platforms could be significantly improved by employing knowledge from pinch analysis or MILP screening models.

383. Telang, K. S.; Chen, X.; Pike, R. W.; Knopf, F. C.; Hopper, J. R.; Saleh, J.; Yaws, C. L.; Waghchoure, S.; Hedge, S. C. An Advanced Process Analysis System for Improving Chemical and Refinery Processes. *Comput. Chem. Eng.* **1999**, *23* (Suppl.), S727−730.

A process analysis system is developed which integrates programs for online optimization, chemical reactor analysis, flowsheeting, pinch analysis for HENS, and pollution indices.

384. Ten Broeck, H. Economic Selection of Exchanger Sizes. *Ind. Eng. Chem.* **1944**, *36* (1), 64−67.

This is the first known HENS-related paper. Given the network configuration, the heat-exchanger equations are solved with an economic objective in mind for designing a heat-exchanger train.

385. Terrill, D. L.; Douglas, J. M. A *T−H* Method for Heat Exchanger Network Synthesis. *Ind. Eng. Chem. Res.* **1987**, *26*, 175−179.

The use of temperature−enthalpy diagrams is promoted for visualizing different effects produced by alternative HEN designs.

386. Terrill, D. L.; Douglas, J. M. Heat-Exchanger Network Analysis. 1. Optimization. *Ind. Eng. Chem. Res.* **1987**, *26* (4), 685−691.

To determine optimum flows in a process, it is useful to have an estimate of the HEN cost. This paper presents a procedure for approximating the HEN and then determining optimal process stream flows to be used in the network design.

387. Terrill, D. L.; Douglas, J. M. Heat-Exchanger Network Analysis. 2. Steady-State Operability Evaluation. *Ind. Eng. Chem. Res.* **1987**, *26* (4), 691−696.

Simple design options and alternatives, such as exchanger overdesign and bypass streams, are discussed for increasing the operability of a HEN.

388. Tjoe, T. N.; Linnhoff, B. Using Pinch Technology for Process Retrofit. *Chem. Eng.* **1986**, *93* (4), 47−60.

The use of pinch technology for retrofit HENS is demonstrated with examples and an industrial case study.

389. Towler, G. P. Integrated Process Design for Improved Energy Efficiency. *Renewable Energy* **1996**, *9* (1−4), 1076−1080.

This is a very brief introduction to some principles of pinch analysis.

390. Townsend, D. W.; Linnhoff, B. Designing Total Energy Systems by Systematic Methods. *Birmingham Univ. Chem. Eng.* **1982**, *378*, 91−97.

A brief overview of the concepts involved in the PDM is presented.

391. Townsend, D. W.; Linnhoff, B. Heat and Power Networks in Process Design−Part I: Criteria for Placement of Heat Engines and Heat Pumps in Process Networks. *AIChE J.* **1983**, *29* (5), 742−748.

This paper describes the criteria for the appropriate placement of heat engines and heat pumps into a process based in part on insights drawn from pinch technology.

392. Townsend, D. W.; Linnhoff, B. Heat and Power Networks in Process Design−Part II: Design Procedure for Equipment Selection and Process Matching. *AIChE J.* **1983**, *29* (5), 748−771.

A design procedure incorporating the qualitative guidelines (annotation 391) to select the best placement for heat engines or heat pumps into a process based on pinch analysis is outlined.

393. Trivedi, K. K.; O'Neill, B. K.; Roach, J. R. Synthesis of Heat Exchanger Networks with Designer Imposed Constraints. *Chem. Eng. Commun.* **1988**, *69*, 149−168.

A network evolution design method proposes partitioning of a HENS problem at the temperatures where the number of imposed constraints changes and then design of the network sequentially upward from the cold end. The minimum utilities transshipment model of Papoulias and Grossmann (annotation 307) is modified to allow for additional temperature intervals.

394. Trivedi, K. K.; O'Neill, B. K.; Roach, J. R. A New Dual-Temperature Design Method for the Synthesis of Heat Exchanger Networks. *Comput. Chem. Eng.* **1989**, *13* (6), 667−685.

The PDM and DTAM are briefly reviewed, and problems in past work are identified. A dual-temperature design method with a pseudo pinch point is introduced, and new heuristics are developed. This simple design algorithm incorporates the specification of two approach temperatures−network and individual exchanger temperatures−and additional utility consumption prior to design.

395. Trivedi, K. K.; O'Neill, B. K.; Roach, J. R. Synthesis of Heat Exchanger Networks Featuring Multiple Pinch Points. *Comput. Chem. Eng.* **1989**, *13* (3), 291−294.

Design guidelines for problems with multiple pinch points are presented. This method employing an "inverse" pinch point allows for the use of existing pinch design rules or the dual-temperature approach design method.

396. Trivedi, K. K.; O'Neill, B. K.; Roach, J. R.; Wood, R. M. A Best-First Search Strategy for Energy Relaxation in MER Heat Exchanger Networks. *Engi. Opt.* **1990**, *16*, 165−189.

The minimum energy consumption target is formulated as an MINLP and solved using a best-first search method. This problem is used in loop-breaking and identifying topology traps.

397. Trivedi, K. K.; O'Neill, B. K.; Roach, J. R.; Wood, R. M. Systematic Energy Relaxation in MER Heat Exchanger Networks. *Comput. Chem. Eng.* **1990**, *14* (6), 601−611.

An alternative loop-breaking method and energy relaxation technique for use in pinch-based design of HENs is presented.

398. Trivedi, K. K.; Roach, J. R.; O'Neill, B. K. Shell Targeting in Heat Exchanger Networks. *AIChE J.* **1987**, *33* (12), 2087−2090.

A systematic procedure is developed for targeting the minimum number of shells.

399. Uhlenbruck, S.; Vogel, R.; Lucas, K. Heat Integration of Batch Processes. *Chem. Eng. Technol.* **2000**, *23* (3), 226−229.

OMNIUM is demonstrated to be useful for improving heat integration of batch processes when used recursively.

400. Umeda, T. Computer Aided Process Synthesis. *Comput. Chem. Eng.* **1983**, *7* (4), 279−309.

This overview of process synthesis provides quotations from other review papers on process synthesis. Specifics details regarding HENS are not presented. The paper presents process synthesis methodologies in a structured manner.

401. Umeda, T.; Harada, T.; Shiroko, K. A Thermodynamic Approach to the Synthesis of Heat Integration Systems in Chemical Processes. *Comput. Chem. Eng.* **1979**, *3*, 273−282.

The computer programs HERP and HENS are developed and used in the application of the thermodynamic evolutionary HENS method developed by the authors.

402. Umeda, T.; Itoh, J.; Shiroko, K. Heat Exchange System Synthesis. *Chem. Eng. Prog.* **1978**, *74* (7), 70−76.

An early HENS strategy with some of the basic concepts of the PDM is proposed. Through the use of $T-H$ charts and heuristics, a network is designed for the maximum energy recovery and minimum exchanger area targets.

403. Uztúrk, D.; Konukman, A. E.; Boyaci, C.; Akman, U. Operability of an Autothermal Reactor Linked to a Flexible Heat-Exchanger Network. *Comput. Chem. Eng.* **1996**, *20* (Suppl.), S943−948.

The critical temperature deviations that cause runaway behavior for an autothermal fixed-bed catalytic reactor are considered in the design of a retrofit HEN.

404. Vaidyaraman, S.; Maranas, C. D. Optimal Synthesis of Refrigeration Cycles and Selection of Refrigerants. *AIChE J.* **1999**, *45* (5), 997−1017.

A methodology is developed for optimizing refrigeration cycle configuration with simultaneous refrigerant selection. A case of integration with a process HEN is examined.

405. Vaklieva-Bancheva, N.; Ivanov, B. B.; Shah, N.; Pantelides, C. C. Heat Exchanger Network Design for Multipurpose Batch Plants. *Comput. Chem. Eng.* **1996**, *20* (8), 989−1001.

An MILP problem formulation is used to design HENs for multipurpose batch plants considering only the direct mode of heat integration. This formulation takes account of the additional scheduling complications due to energy integration between different products in the same campaign.

406. van Reisen, J. L. B.; Grievink, J.; Polley, G. T.; Verheijen, P. J. T. The Placement of Two-Stream and Multistream Heat-Exchangers in an Existing Network Through Path Analysis. *Comput. Chem. Eng.* **1995**, *19* (Suppl.), S143−S148.

Path analysis is a prescreening and decomposition method used in the analysis of HEN retrofit design. It evaluates the economic potential of subnetworks and uses existing retrofit analysis procedures.

407. van Reisen, J. L. B.; Polley, G. T.; Verheijen, P. J. T. Structural Targeting for Heat Integration Retrofit. *Appl. Therm. Eng.* **1998**, *18* (5), 283−294.

An extension of Path Analysis (annotation 406) is presented for the HENS retrofit problem leading to retrofit by structural targeting.

408. Varbanov, P. S.; Klemebvs, J. Rules for Paths Construction for HENs Debottlenecking. *Appl. Therm. Eng.* **2000**, *20* (15−16), 1409−1420.

A heuristic topology modification procedure is developed to complement the network pinch method (annotations 16 and 17) for HEN retrofit.

409. Vaselenak, J. A.; Grossmann, I. E.; Westerberg, A. W. Heat Integration in Batch Processing. *Ind. Eng. Chem. Process Des. Dev.* **1988**, *25* (2), 357−366.

A heuristic rule is proposed for pairing batch tanks in their heat integration. In the case of cocurrent heat exchange, an MINLP is suggested for further improving the solution provided by the heuristic.

410. Vieira, A. J. M.; Pessoa, F. L. P.; Queiroz, E. M. Fluid Dynamical Considerations on Heat Exchanger Networks. *Braz. J. Chem. Eng.* **2000**, *17* (1), 19−27.

A model is developed for determining the total annual cost for a HEN including the influence of pumping costs due to shell-side and tube-side pressure drops.

411. Viktorov, V. K. Combinatory Estimation Method of Synthesizing Optimal Heat-Exchanger Networks by the Enthalpy−Temperature Diagram. *Theor. Found. Chem. Eng.* **1993**, *27* (3), 298−300.

The use of $T-H$ diagrams is incorporated into the combinatorial estimation method in order to estimate the efficiency of branches in the tree.

412. Viktorov, V. K. New Combinatorial Method for Synthesis of Heat Exchanger Networks. *Chem. Eng. Res. Des.* **1995**, *73* (A), 915−918.

A combinatorial estimation method for HENS is proposed in which a design tree is searched using estimating functions for the minimum leading to solutions more quickly than branch-and-bound but not guaranteed optimal.

413. Viktorov, V. K. Comparison between Pinch Design Methods and Combinatory Methods in the Synthesis of Heat Exchanger Networks. *Theor. Found. Chem. Eng.* **1996**, *30* (1), 89−92.

The author compares the PDM to his method of HENS by combinatorial estimation methods, which look for solutions to the problem of transferring maximum power by the minimal number of exchangers. This method is more complicated than pinch methods and prohibits stream splitting.

414. Viswanathan, M.; Evans, L. B. Studies in the Heat Integration of Chemical Process Plants. *AIChE J.* **1987**, *33* (11), 1781−1790.

The out-of-kilter algorithm (OKA) is used to solve the transportation or transshipment network flow problems of HENS. The respective models are modified for OKA and forbidden and restricted matches can be handled. The dual stream approach is proposed to overcome the heat recovery limitations proposed by forbidden matches.

415. Wang, K.; Qian, Y.; Huang, Q.; Yao, P. New Model and New Algorithm for Optimal Synthesis of Large Scale Heat Exchanger Networks without Stream Splitting. *Comput. Chem. Eng.* **1999**, *23* (Suppl.), S149−S152.

A simultaneous HENS MINLP formulation is proposed. The superstructure does not allow for stream splitting. A genetic algorithm is developed and applied in solving the HENS model.

416. Wang, K.; Yao, P.; Yuan, Y.; Yu, F.; Shi, G. A New Retrofit Approach for Heat Exchanger Networks-Improved Genetic Algorithm. *Chin. J. Chem. Eng.* **1997**, *5* (4), 347−358.

A genetic algorithm for flexibility analysis and retrofit of a HEN is developed.

417. Wang, P.; Hua, B.; Qian, Y. An Improved Approach to the Design of Flexible Heat Exchanger Networks. *Chem. Eng. Technol.* **1997**, *20* (5), 309−312.

When using sensitivity tables for flexible HENs, errors can become large. A simple method for error analysis is provided in which nonlinearities and interaction effects are considered for flexible HENS.

418. Wang, Y. P.; Chen, Z. H. Rapid Analysis of Heat Recovery in Industrial Plants. *Heat Recovery Syst. CHP* **1989**, *9* (3), 183−187.

An economic analysis method is developed for quickly estimating the energy savings, capital investment, and payback period for a HEN prior to design. A procedure for optimizing the minimum approach temperature is also proposed.

419. Wang, Y. P.; Chen, Z. H.; Groll, M. A New Approach to Heat Exchanger Network Synthesis. *Heat Recovery Syst. CHP* **1990**, *10* (4), 399−405.

This paper presents an annual cost model for HENS. A mathematical programming approach is presented with the objective function consisting of energy and capital costs, with the minimum temperature difference being the variable to be optimized.

420. Wells, G. L.; Hodgkinson, M. G. The Heat Content Diagram Way to Heat Exchanger Networks. *Process Eng.* **1977**, 59−63.

A list of heuristic rules for HENS is proposed. A design procedure based on these heuristics is outlined.

421. Westbrook, G. Use this Method to Size Each Stage for Best Operation. *Hydrocarbon Process. Pet. Refin.* **1961**, *40* (9), 201−206.

An early use of dynamic programming is applied to a simple multistage heat-exchanger system design problem.

422. Westerberg, A. W. A Review of Process Synthesis. In *Computer Applications to Chemical Engineering*; Squires, R. G., Reklaitis, G. V., Eds.; ACS Symposium Series 124; American Chemical Society: Washington, DC, 1980; pp 54−87.

This is a thorough review of process synthesis up to 1980. A summary of all major HENS topics and techniques are presented.

423. Westerberg, A. W. Synthesis in Engineering Design. *Comput. Chem. Eng.* **1989**, *13* (4/5), 365−376.

Process design for various engineering fields is reviewed. There is a section dedicated specifically to HENS.

424. Westphalen, D. L.; Wolf Maciel, M. R. Pinch Analysis Based on Rigorous Physical Properties. *Braz. J. Chem. Eng.* **1999**, *16* (3), 279−284.

The problem table method for utilities targeting in pinch design is modified in order to take into account physical properties calculations. It is useful in situations when phase change occurs and heat capacity flow rates are no longer constant.

425. Whistler, A. M. Heat Exchangers as Money Makers. *Pet. Refin.* **1948**, *27* (1), 83−86.

This is an early work discussing how heat exchangers could be used for heat recovery to save money in chemical processes. Utilities cost plots based on money saved versus approach temperatures are provided.

426. Wolff, A. Some Problems of the Industrial Application of the Heat Recovery Network Synthesis Approach. *Hung. J. Ind. Chem.* **1986**, *14* (4), 377−392.

A tree search algorithm for network evolution in HENS is developed to complement pinch design analysis. This approach includes the use of multipass shell and tube heat exchangers.

427. Wolff, A. Synthesis of Energy Recovery Networks by Heuristic-Combinatorial Algorithm. *Hung, J. Ind. Chem.* **1986**, *14*, 105−124.

A tree search algorithm for HENS subject to a maximum heat recovery objective is proposed. This approach includes the use of multipass shell and tube heat exchangers.

428. Wolff, A. The Sensitivity Analysis of a Crude Oil Preheating Network. Multi-Passes Shell and Tube Heat Exchangers. *Hung. J. Ind Chem.* **1989**, *17* (2), 191−219.

An approach is proposed for investigating the sensitivity of individual multipass shell and tube heat exchangers, HENs, and the behavior of the units in the context of the entire network.

429. Wood, R. M.; Hasan, M. Improved Heat Exchanger Networks for Energy Conservation in Palm Oil Refineries. *Int. J. Food Sci. Technol.* **1987**, *22*, 209−218.

Pinch design targeting procedures are used to examine the design of a HEN used in the palm oil refining industry. Improved networks are designed based on this analysis.

430. Wood, R. M.; Suaysompol, K.; O'Neill, B. K.; Roach, J. R.; Trivedi, K. K. A New Option for Heat Exchanger Network Design. *Chem. Eng. Prog.* **1991**, *87* (9), 38−43.

The PPDM is outlined. PPDM is based on thermodynamic principles and provides increased flexibility over PDM. The PPDM method simplifies the DTAM by decomposing it into two subnetworks similar to the PDM.

431. Wood, R. M.; Wilcox, R. J.; Grossmann, I. E. A Note on the Minimum Number of Units for Heat Exchanger Network Synthesis. *Chem. Eng. Commun.* **1985**, *39*, 371−380.

This work shows that it is possible to obtain networks conforming to the target number of units $N - 1$, where N is the total number of streams, proposed in PDMs for an entire network, rather than each subnetwork defined by pinches. A novel arrangement for stream splitting, mixing, and bypasses is proposed to allow for designs with fewer heat exchangers and sometimes achieve the $N - 1$ target for the minimum number of units, even if there is a pinch point. A modified version of the MILP transshipment model can be used to predict the true minimum of units.

432. Yee, T. F.; Grossmann, I. E. Optimization Model for Structural Modifications in the Retrofit of Heat Exchanger Networks. *Proceedings of the First International Conference on FOCAPO*; Elsevier Science: New York, 1987; pp 653−662.

An MILP assignment−transshipment formulation for retrofit HENS is proposed. It is an extension of the MILP transshipment model (annotation 307).

433. Yee, T. F.; Grossmann, I. E. Simultaneous Optimization Models for Heat Integration−II. Heat Exchanger Network Synthesis. *Comput. Chem. Eng.* **1990**, *14* (10), 1165−1184.

The superstructure of part I (annotation 435) is used in an MINLP model used to design cost optimal HENs where utility cost, exchanger areas, and the selection of matches are optimized simultaneously. Assumptions are similar to those used previously (annotation 435). The superstructure does not account for split streams going through two or more exchangers in series, the case of bypasses, or split streams going through several exchangers in series.

434. Yee, T. F.; Grossmann, I. E. A Screening and Optimization Approach for the Retrofit of Heat-Exchanger Networks. *Ind. Eng. Chem. Res.* **1991**, *30* (1), 146−162.

A two-stage retrofit approach for HENS is proposed. The prescreening stage involves an economic evaluation of the problem. In the optimization stage, a superstructure is constructed and an MINLP formulation is solved for determining the retrofit design.

435. Yee, T. F.; Grossmann, I. E.; Kravanja, Z. Simultaneous Optimization Models for Heat Integration−I. Area and Energy Targeting and Modeling of Multi-Stream Exchangers. *Comput. Chem. Eng.* **1990**, *14* (10), 1151−1164.

A model for simultaneous targeting of energy and area for HENS is introduced. It can incorporate multistream heat exchangers. A stagewise superstructure allowing for different possibilities and sequences for matching streams with the assumption of isothermal mixing is presented. The targeting model uses NLP formulations for the simultaneous energy and area minimization or area minimization with fixed utility use. This model can account for differences in heat-transfer coefficients and constraints on matches, and it has no need to fix HRAT or EMAT. Nonconvex terms appear in the objective function.

436. Yee, T. F.; Grossmann, I. E.; Kravanja, Z. Simultaneous Optimization Models for Heat Integration−III. Process and Heat Exchanger Network Optimization. *Comput. Chem. Eng.* **1990**, *14* (11), 1185−1200.

The heat integration representation of part I (annotation 435) is embedded in a process flowsheet or superstructure in order to perform simultaneous optimization of the HEN and the process. It is assumed that only one hot and one cold utility are available at the two extreme ends of the superstructure. NLP and MINLP formulations are presented for combined optimization of the process and the HEN. Heat integration constraints involve nonlinear terms. Design constraints on the HEN are easily incorporated.

437. Yu, H.; Fang, H.; Yao, P.; Yuan, Y. A Combined Genetic Algorithm/Simulated Annealing Algorithm for Large Scale System Energy Integration. *Comput. Chem. Eng.* **2000**, *24* (8), 2023−2035.

An algorithm is developed for HENS based on combining the GA and SA algorithms. Results show faster convergence than either SA or GA alone, with a higher probability of locating a global optimum.

438. Yu, H.; Yao, P.; Yuan, Y. Study of Total Process Energy Integration. *Chin. J. Chem. Eng.* **1999**, *7* (2), 182−188.

The HENS problem is extended to include the heating effects of heat engines, heat pumps, reactors, and separations into designing what is termed a pseudo-HEN.

439. Yuan, X.; Pibouleau, L.; Domenech, S. Experiments in Process Synthesis via Mixed-Integer Programming. *Chem. Eng. Process.* **1989**, *25* (2), 99−116.

A general purpose algorithm for solving MINLP problems is developed and applied to HENS and multistage reactor optimization. A superstructure for HENS is developed that does not allow stream splitting or stream mixing. An MINLP formulation is proposed for simultaneous synthesis for HENS.

440. Zachoval, J.; Konecny, Z.; Navratil, O. New Ways in Heat-Exchange Network Design. *J. Heat Recovery Syst.* **1985**, *5* (5), 403−406.

This is a short review of analysis methods in HENS employed in the chemical industry of Czechoslovakia in 1985.

441. Zamora, J. M.; Grossmann, I. E. A Comprehensive Global Optimization Approach for the Synthesis of Heat Exchanger Networks with No Stream Splits. *Comput. Chem. Eng.* **1997**, *21* (Suppl.), S65−S70.

An algorithm for the solution of the MINLP HENS model of Yee and Grossmann (annotation 433) with assumption of no stream splits is presented. A class of approximating planes for LMTD upper bounds is introduced.

442. Zamora, J. M.; Grossmann, I. E. A Global MINLP Optimization Algorithm for the Synthesis of Heat Exchanger Networks with No Stream Splits. *Comput. Chem. Eng.* **1998**, *22* (3), 367−384.

An algorithm for the solution of the MINLP HENS model of Yee and Grossmann (annotation 433) is presented. Linear area cost, arithmetic mean temperature difference driving forces, and no stream splitting are assumptions used in the simplification of the solution method.

443. Zhang, J.; Zhu, X. X. Simultaneous Optimization Approach for Heat Exchanger Network Retrofit with Process Changes. *Ind. Eng. Chem. Res.* **2000**, *39* (12), 4963−4973.

A systematic method for HEN retrofit is proposed in which modification to the network topology is considered simultaneously with changes to the process parameters such as stream flow rates and temperatures.

444. Zhao, X. G.; O'Neill, B. K.; Roach, J. R.; Wood, R. M. Heat Integration for Batch Processes Part 1: Process Scheduling Based on Cascade Analysis. *Chem. Eng. Res. Des.* **1998**, *76* (A), 685−699.

An MILP formulation based on cascade analysis is proposed for the scheduling of batch processes with heat integration.

445. Zhao, X. G.; O'Neill, B. K.; Roach, J. R.; Wood, R. M. Heat Integration for Batch Processes Part 2: Heat Exchanger Network Design. *Chem. Eng. Res. Des.* **1998**, *76* (A), 700−710.

A three-step HENS method for batch/semicontinuous processes is presented. First, an initial individual design is created using continuous process HENS. Then, rematching design using MILP considers the relationship for all time intervals. The final overall design looks at the tradeoff between energy and capital costs among time intervals.

446. Zhelev, T.; Boyadjiev, C.; Kantcheva, S. Renovation of Heat Exchanger Networks. *Hung. J. Ind. Chem.* **1987**, *15*, 403−414.

An algorithm for retrofit HENS is developed in which a network is retrofitted through comparison of a grass-roots network design for the problem.

447. Zhelev, T. K.; Boyadzhiev, K. B. A Method for the Optimal Synthesis of Heat Exchanger Systems. Part I. Primary Sequence for Coupling/Matching of Streams. *Int. J. Chem. Eng.* **1988**, *28* (3), 543−547.

A heuristic is proposed for matching streams in order to develop an initial approximation for a feasible HEN. The approach first arranges the cold and hot streams in decreasing order of their final and initial temperatures, respectively, and then sequentially matches pairs of streams.

448. Zhelev, T. K.; Boyadzhiev, K. B. A Method for the Optimal Synthesis of Heat Exchanger Systems. Part II. Optimal Synthesis with a given Sequence for Coupling/Matching of Ordered Initial Streams. *Int. J. Chem. Eng.* **1988**, *28* (3), 548−553.

An algorithm for developing multiple network variations using an initial HEN approximation matching sequence from the heuristic of part I (annotation 447) is presented.

449. Zhelev, T. K.; Boyadzhiev, K. B. A Method for the Optimal Synthesis of Heat Exchanger Systems. Part III. Optimal Pairs of Streams Exchanging Heat. *Int. J. Chem. Eng.* **1988**, *28* (3), 554−558.

A heuristic in addition to the one of part I (annotation 447) is presented. An algorithm incorporating both heuristics for finding the matches sequence is developed.

450. Zhelev, T. K.; Varbanov, P. S.; Seikova, I. HEN's Operability Analysis for Better Process Integrated Retrofit. *Hung. J. Ind. Chem.* **1998**, *26* (2), 81−88.

An operability analysis approach for existing HENs is developed for networks working in conditions of process stream parameter variation.

451. Zhu, F. X. X.; Vaideeswaran, L. Recent Research Development of Process Integration in Analysis and Optimisation of Energy Systems. *Appl. Therm. Eng.* **2000**, *20* (15−16), 1381−1392.

This article provides an overview of the recent advances in process integration and energy system optimization, including sections on total site energy profiles, HEN retrofit, and debottlenecking.

452. Zhu, J.; Han, Z.; Rao, M.; Chuang, K. T. Identification of Heat Load Loops and Downstream Paths in Heat Exchanger Networks. *Can. J. Chem. Eng.* **1996**, *74* (6), 876−882.

Heat load loops and downstream paths are identified using a representation of a HEN as the combination of the node adjacency matrix, and the stream table is used as a basis.

453. Zhu, J. Y.; Rao, M.; Chuang, K. T. A New Method to Determine the Best Units for Breaking Heat Load Loops of Heat Exchanger Networks. *Ind. Eng. Chem. Res.* **1999**, *38* (4), 1496−1503.

A systematic method for loop breaking is developed in which the effects of heat loads and interactions of units on energy relaxation are taken into account. Constrained heat-exchanger units that cannot absorb any transferred energy are used to find the best units for breaking loops.

454. Zhu, X. X. Automated Synthesis of HENs Using Block Decomposition and Heuristic Rules. *Comput. Chem. Eng.* **1995**, *19* (Suppl.), S155−S160.

An automation of the block decomposition methods presented by Zhu et al. (annotation 459) is described in this work. Heuristic rules for a match selection are based on temperatures and heat load calculations using MILP methods to determine the best set of matches rather than a single best match.

455. Zhu, X. X. Automated Design Method for Heat Exchanger Network using Block Decomposition and Heuristic Rules. *Comput. Chem. Eng.* **1997**, *21* (10), 1095−1104.

An automated synthesis method for HENS based on the block concept simplifies the design problem by decomposing it into a number of blocks. After block decomposition, targeting principles and heuristic rules developed in this paper are used to carry out the design of the HEN. An MILP model is used in the selection of matches and an MINLP model is used in the determination of optimal split ratios.

456. Zhu, X. X.; Asante, N. D. K. Diagnosis and Optimization Approach for Heat Exchanger Network Retrofit. *AIChE J.* **1999**, *45* (7), 1488−1503.

A three-stage procedure for retrofit HENS is proposed. First, promising options for modifications are identified using LP and MILP formulations with a heat recovery goal rather than total cost. Then, impractical options are screened out based on cost, safety, and operability issues. Last, options are optimized using an MILP formulation for network modification.

457. Zhu, X. X.; O'Neill, B. K.; Roach, J. R.; Wood, R. M. Kirchhoff's Law and Loop-Breaking for the Design of Heat Exchanger Networks. *Chem. Eng. Commun.* **1993**, *126*, 141−153.

Kirchhoff's law for electrical networks is proposed as a method for breaking loops in the design of HENS using pinch design techniques by using the temperature differences as the driving forces.

458. Zhu, X. X.; O'Neill, B. K.; Roach, J. R.; Wood, R. M. A Method for Automated Heat Exchanger Synthesis Using Block Decomposition and Non-Linear Optimization. *Chem. Eng. Res. Des.* **1995**, *73* (A), 919−930.

The block concept leads to a simplified block-based superstructure reducing the dimensions of mathematical programming models. A strategy is proposed to overcome the deficiencies of mathematical programming techniques by allowing blocks to encompass a number of intervals, thus reducing the problem size. A region for initiating NLP optimization is located by applying a supertargeting approach.

459. Zhu, X. X.; O'Neill, B. K.; Roach, J. R.; Wood, R. M. A New Method for Heat Exchanger Network Synthesis Using Area Targeting Procedures. *Comput. Chem. Eng.* **1995**, *19* (2), 197−222.

An alternative heuristic to the pinch method is presented. Total cost targets are used to determine optimal HRAT prior to the initial design of the HEN. This introduces blocks, quasi-composite curves, and the matching matrix.

460. Zhu, X. X.; O'Neill, B. K.; Roach, J. R.; Wood, R. M. Area-Targeting Methods for the Direct Synthesis of Heat Exchanger Networks with Unequal Film Coefficients. *Comput. Chem. Eng.* **1995**, *19* (2), 223−239.

Composite curves are decomposed into a number of blocks using the methods in Zhu et al. (annotation 459).

Table 1. Topics in HENS[a]

	before 1980	1980−1989	1990−2000
analysis-general	343, 283, 142, 425, 420, 188	25, 379, 327	352, 350, 342, 119
dual streams		106, 414	174, 83
exergy/second law analysis	401	135, 238, 49	352, 351, 366, 367
flexibility/resilience/ controllability/sensitivity/ operability	271	288, 344, 349, 88, 89, 90, 110, 37, 289, 269, 387, 346, 59, 347, 348, 208, 210, 209, 309, 201, 246, 27, 57, 185, 334, 428	297, 296, 207, 96, 301, 314, 375, 376, 329, 143, 3, 305, 417, 30, 206, 227, 450, 65, 299, 300, 144, 180, 178, 179, 416, 172, 182, 157, 141, 140, 381
multipass heat exchangers		398, 10, 259, 426, 428	378, 11, 333, 176, 101, 353
operating line method		148, 5, 4	
pressure drop/piping			318, 319, 9, 279, 362, 410, 368
retrofit design		52, 184, 388, 294, 429, 432, 446, 254, 210, 255, 103	297, 296, 406, 17, 16, 2, 41, 40, 319, 33, 54, 53, 38, 403, 221, 212, 82, 30, 9, 456, 279, 434, 222, 407, 450, 35, 299, 300, 295, 281, 178, 179, 211, 416, 94, 36, 214, 213, 220, 263, 268, 362, 408, 316, 461, 233, 443, 1
topology traps			7, 350, 124, 338, 397, 396

[a] Numbers in this table refer to the annotated works of section 4.

Table 2. Heat Integration Topics[a]

	before 1980	1980−1989	1990−2000
batch processes		197, 198, 409, 194, 195, 196, 290, 444	445, 321, 405, 152, 311, 153, 154, 155, 372, 156, 399, 63, 64, 187, 192
continuous reactors		104, 197, 198, 12, 216	14, 13, 438
distillation processes		31, 149, 198	23, 69
heat engines/heat pumps/ refrigeration systems	26	380, 391, 392, 51, 61, 137, 250, 355, 356	136, 82, 438, 404, 215
MENS and separations		198	24, 303, 295, 23, 302, 438, 370, 298
process integration		77, 306, 308, 217, 195, 62, 391, 392, 150, 224, 148, 436	5, 4, 218, 31, 249, 145, 6, 13, 113, 71, 304, 451, 365, 383
plant/site integration			6, 145, 146, 267, 340, 22

[a] Numbers in this table refer to the annotated works of section 4.

The deficiency of widely differing heat-transfer coefficients in terms of area penalty is overcome with the concepts of Rév and Fonyó (annotation 338) coupled with the block method. This approach allows different stream structures to be compared prior to design and attractive structures to be derived from further synthesis and optimization.

461. Zhu, X. X.; Zanfir, M.; Klemebvs, J. Heat Transfer Enhancement for Heat Exchanger Network Retrofit. *Heat Transfer Eng.* **2000**, *21* (7), 7−18.

A targeting strategy is developed for allowing heat-transfer enhancement to be an option for HEN retrofit.

5. Classifications of the Annotated Works

The previous section discussed separately each HENS work. Here, we provide an overview of these works through several different classification schemes as shown in Tables 1−8.

5.1. Topics in HENS. Table 1 lists HENS citations according to various specific topics of interest in this field of research. *General analysis* includes citations for papers dealing with basic analysis of the HENS problem or some major issue in HENS. The *dual stream* approach in HENS allows for the possibility of hot process streams acting as cooling streams and cold process streams used as cooling streams within the network. Another name for dual streams is hot-to-hot or cold-to-cold streams. *Exergy analysis* involves analysis in HENS based on the second law of thermodynamics. *Flexibility*, *resilience*, *controllability*, *sensitivity*, and *operability* topics consider how easy networks are to control and operate and how flexible HENs are in cases of parameter variation. The topic of *mixing* considers the idea of mixing different flows of the same stream type at different temperatures. *Multipass heat exchangers* allow streams to exchange heat in several passes, as opposed to the single pass of standard countercurrent exchangers. The *operating line method* is a method for designing a HEN by using an operating curve determined from the problem data as a tool. *Pressure drop* considerations are important for networks with large distances between exchangers. HEN *retrofit design* involves the modification of an existing network for a new process. *Topology traps* are limitations in evolutionary HENS methods which may prevent the possibility of finding the globally optimal design.

5.2. Heat Integration Topics. Table 2 lists citations related to the heat integration in processes synthesis. Heat integration is a strategy for optimizing a process task or a whole process and the HEN at the same time. This table is not an all-inclusive listing of articles related to heat integration in process design. Instead it lists papers that heavily incorporate the models and techniques developed in HENS research. The *process integration* label lists papers that involve general heat integration in process synthesis. *Plant* or *site* integration includes articles concerning heat integration for multiple processes across an entire plant or site. The other categories also cover specific process heat integration issues, such as *batch processes*, *continuous reactors*, *distillation systems*, *heat pumps and engines*, and *mass-exchange network synthesis (MENS) and separations*. From the latter category, we have included only papers in which there is an explicit HENS component.

5.3. Pinch Technology and Other Evolutionary Methods. Various procedures and techniques related to pinch technology are organized in Table 3. First, the works in the *PDM*, *DTAM*, and *PPDM* are listed. These are the three major pinch-based design procedures. In

Table 3. Pinch Technology and Other Evolutionary Methods[a]

	before 1980	1980–1989	1990–2000
precursors of the pinch method	139, 243, 244, 247, 402, 32	252	
PDM		253, 245, 390, 395, 344, 106, 388, 204, 163, 254, 238, 248, 241, 251, 236, 237	366, 239, 282, 117, 38, 193, 6, 242, 8, 240, 102, 317
DTAM		60, 395, 291	166, 168
PPDM		394, 337, 336	55, 99, 100, 430
Specific Topics			
temperature interval partitioning	243	117, 93, 393	
enthalpy interval partitioning			58, 121, 120, 125
utilities target		43, 307, 380, 61, 114, 115, 28, 66, 293, 424	174, 266, 358, 360
shell target		398, 10, 259	378, 11, 333, 176
no. of units target	139, 247	42, 307, 431, 164, 223, 275	228, 116, 118, 167
area/capital cost target	384, 95	386, 8	58, 158, 242, 126, 338, 339, 377, 358, 273, 274, 342, 410, 353
supertargeting		234, 418, 241, 7	242, 419, 338, 126, 339, 128, 358, 216, 34, 35, 36, 226, 200, 332, 173
loop breaking/ stream splits		79, 374, 312, 48, 131, 162	457, 397, 453, 452, 130, 396
multiple pinch points		395	169, 225, 172
network evolution	244, 320, 401, 270, 284, 283, 32, 402	51, 335, 92, 374, 371, 277, 385, 133, 229, 393, 127, 161, 310, 447, 448, 105, 449, 162	323, 129, 315, 341, 227, 228, 190, 350, 256, 257
case study only		25, 379, 103	202
review/overview	247	238, 248, 260, 251, 236, 237, 278	239, 357, 240, 389, 276, 354, 331, 330

[a] Numbers in this table refer to the annotated works of section 4.

a pinch-based method, *temperature intervals* are used to partition the problem and to determine pinch points. *Enthalpy intervals* are sometimes used in conjunction with temperature intervals for allowing exchanger area cost to be considered in early design steps. PDMs are a sequential approach to HENS and involve determining various design targets in a specific order. The *utilities target* determines the minimum utility usage. The *shell target* determines the number of shells in the heat exchangers. The *number of units target* is for determining a minimum number of heat exchangers required in the design of the network. The *heat load distribution* is the set of stream matches and the amount of heat exchanged between them. The *area target* is for determining the heat-exchanger area for the network, which directly influences the *capital cost* of the network. *Supertargeting* involves determining the optimal approach temperature to partition the temperature range of the problem for lowest total cost. *Loop breaking* is a specific technique used in reducing heat-exchanger matches for the network. Some HENS problems have *multiple pinch points* which need to be taken into account in the problem analysis. *Network evolution* involves the evolution of new and better network configurations. Some works only contain *case studies* which describe the design of a specific HEN for some industrial or hypothetical cases without the development of new methodologies or concepts. Last, *reviews* and *overviews* of pinch-based design methods are listed.

5.4. Modeling and Solution Techniques. Optimization and other mathematical methods have become increasingly common in HENS research as seen in Table 4. Early work involved fitting the HENS problem to the *assignment problem*. *Branch-and-bound* techniques are important considering the use of discrete variables in modern HENS formulations. *Block decomposition* decomposes the problem into enthalpy blocks rather than temperature intervals. *Direct search* methods involve heuristics for searching a HENS problem tree. The *discrete maximum principle* is used for solving multistage optimization problems. *Disjunctive programming* methods are an alternative to MILP formulations and provide new algorithms for dealing with the combinatorial aspects of the problem. *Dynamic programming* provides a framework for decomposing an optimization problem into a nested family of subproblems to be solved recursively. *Genetic algorithms* are a type of search algorithm used to mathematically “evolve” HENS networks. *Goal programming* is a deterministic optimization strategy. *Knowledge-based systems* are a type of artificial intelligence which utilize a large database of problem information in order to make design decisions. *Prescreening* is used to reduce the feasible space of a formulation prior to solving. *Random search* techniques randomly search a problem tree for a solution. *Randomization* methods involve random sampling of the problem space to find a solution. *Separable programming* is an extension of LP that approximates nonlinear functions using piecewise linear approximations. *Sequential synthesis* is a stepwise HENS method. *Simulated annealing* techniques couple deterministic and stochastic optimization methods. *Simultaneous synthesis* solves HENS in inclusive formulations. The *state space approach* involves relations between input, state, and output variables. *Tree searching* techniques are used for traversing trees of network configurations. The *transportation*, *transsshipment*, and *vertical heat-transfer* models are used to represent the transfer of heat from hot streams to cold streams solving for heat load distributions by formulating the problem using the respective mathematical models. Some *reviews* of mathematical methods in HENS are listed. Several of the most common optimization formulations used in HENS are organized in Table 5 and include models used in sequential as well as simultaneous approaches to HENS.

5.5. Software, Reviews, and Test Problem Collections. Table 6 is a listing of journal articles partly or completely devoted to describing various HENS software packages and programs. Although a detailed discussion of commercial and educational software is outside the scope of this paper, we have provided Table 7, which lists some of the major software packages

Table 4. Modeling and Solution Techniques[a]

	before 1980	1980−1989	1990−2000
assignment problem/algorithm/model	199, 205, 39	160, 292, 432 151	
branch and bound	230, 272, 326	309	
block decomposition			460, 454, 459, 458, 455
constraint logic programming			1
direct search			262, 30
discrete maximum principle	81, 80	286, 361	
disjunctive programming			113
dynamic programming	421, 26		
genetic algorithms			15, 232, 231, 416, 437, 415
goal programming		324	
knowledge-based systems		50	143, 144, 369, 189, 235, 264
preprocessing/prescreening			67, 68, 69, 70, 406
random search	191		
randomization			44
separable programming	147		
sequential synthesis	326	43, 42, 307, 87, 85, 86, 265, 88, 89, 90, 345, 346, 380, 185	419, 174, 58, 46, 96, 41, 40, 168, 75, 55, 98, 99, 97, 47, 34, 36, 165, 100, 101, 124
simulated annealing		73	21, 20, 18, 19, 74, 280, 382, 437
simultaneous synthesis		85, 86, 439	56, 435, 433, 442, 441, 206, 299, 300, 301, 235, 359, 124, 415, 368
state-space approach			23, 24
tree search	328, 313, 181	159, 175, 426, 427	412, 413, 219
transportation model		43, 42, 75, 380, 186, 185, 72	125, 359, 183
transshipment model		307, 88, 432, 393	46, 121, 120, 34, 182
vertical heat-transfer model			185, 121, 120, 125
miscellaneous	147, 112, 84	322, 302, 325	373
review			29, 83, 111, 171, 357

[a] Numbers in this table refer to the annotated works of section 4.

Table 5. Mathematical Programming Formulations[a]

	before 1980	1980−1989	1990−2000
utilities cost	205	43, 307, 380, 324, 88, 61, 393	174, 98, 99, 100, 360
no. of matches/units/shells	39	42, 307, 414, 292, 88, 287, 186, 185	121, 120, 125, 98, 99, 34, 445, 100, 101
area/network topology		89, 185, 72	58, 325, 34, 183
simultaneous match network		85, 86	
simultaneous HENS		439	56, 435, 433, 206, 299, 300, 301, 235, 359, 415
simultaneous process and HEN synthesis		77, 306, 308	436, 405, 71, 113, 304, 298
retrofit HENS		52, 432	297, 296, 54, 53, 456, 279, 434, 299, 300, 214, 263

[a] Numbers in this table refer to the annotated works of section 4.

Table 6. Computer Programs and Applications[a]

	before 1980	1980−1989	1990−2000		before 1980	1980−1989	1990−2000
AtHENS			256, 257	HEXTRAN		45, 184, 201, 291	
CAD-HEN			305	HIDEN		144	
EXSYS II			189	MAGNETS		87	
FLEXNET			376	MIDAS		363	
FLOWTRAN		224		OMNIUM			399
GA-HEN			232, 231	PROCESS		291	273, 274
HEN Simulator	142, 78			RESHEX		345, 346, 79	
HEATREC			177	RICPERT			369
HERP & HENS	401			SpeedUp			305
HENEA			264	SIMHEN			177
HEN Explorer			280	SPHEN		50	
HENS System		203, 204		SYNEP1		265	
HENS II		322		SYNHEN			168
HES			261	TARGET			177

[a] Numbers in this table refer to the annotated works of section 4.

available, along with their Web addresses. An Internet address is also provided for the AIChE software directory where more information about HENS packages may be found. Review papers, book chapters, books, and test problem collections are referenced in Table 8.

6. Conclusions

The HENS field has received a great deal of attention as demonstrated by the number of journal papers published in this area in the past 40 years (Figure 2). As Figure 3 demonstrates, a large range of journals have contributed to this body of literature.

Figure 2 indicates that HENS research activity peaked in the late 1980s/early 1990s concurrent with advances in optimization algorithms and computer hardware that for the first time made possible the solution of simultaneous synthesis problems and heat integration problems. Discounting this peak, there is a trend indicating that the number of HENS papers is continuing to increase.

Table 7. Commercial and Educational Software

package	organization	web address
Aspen Pinch	AspenTech	http://www.aspentech.com/
dk-PINCH	dk-TEKNIK	http:// www.dk-teknik.com/
HEATEXSET	N/A	http:// www.softhome.com.tw/soft/chemeng1.htm
HeatNet	NEL	http:// www.ppds.co.uk/
HX-NET	Hyprotech	http:// www.hyprotech.com/
INTEGRITY	ESDU	http:// www.esdu.com/
MAGNETS	CMU	http:// egon.cheme.cmu.edu/Group/MINLP.html
PinchExpress	Linnhoff March	http:// www.linnhoffmarch.com/
PinchLENI	EPFL	http:// www.epfl.ch/
PRO_PI	CIT/IEA	http:// www.cit.chalmers.se/
Sprint	UMIST	http:// www.cpi.umist.ac.uk/software/
SuperTarget	Linnhoff March	http:// www.linnhoffmarch.com/
SYNHEAT	CMU	http:// egon.cheme.cmu.edu/Group/MINLP.html
THEN	MPRI	http:// www.mpri.lsu.edu/ThenFrame.htm
software directory	AIChE	http:// www.aiche.org/software/

Table 8. HENS Reviews[a]

	before 1980	1980−1989	1990−2000
HENS	247	122, 123, 238, 440, 251, 236, 237, 57, 278	170, 171, 239, 240, 389, 276, 14, 331, 330
process synthesis	134, 138	285, 400, 423, 422	111, 107, 109, 108, 365, 451
chapters in books		258, 76	29, 83, 354, 132
books			357
test problem collections	112		91, 357

[a] Numbers in this table refer to the annotated works of section 4.

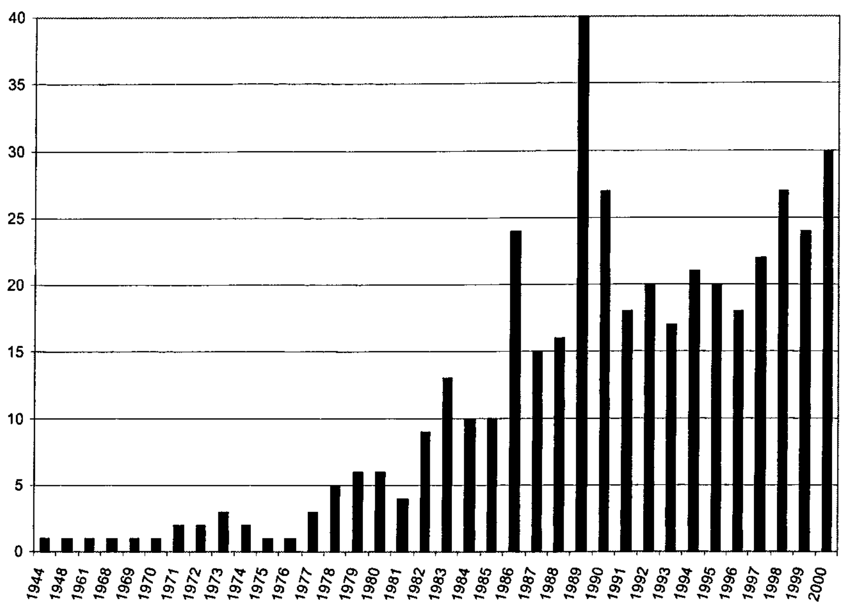

Figure 2. Number of HENS journal papers annually.

Publications in this area indicate that the research conducted is gaining in diversity because we are witnessing a constant diversification of modeling and solution approaches. Many of them, especially in recent years, involve mathematical programming techniques. We also note that the large number of case studies and software that have been developed for industrial use clearly demonstrates that the gap between theory and practice is essentially nonexistent in HENS.

While considerable effort has been directed toward the development of new or improved HENS techniques, several open areas of interest remain:

1. One of the most pressing open questions in this field is in regard to the quality of the solutions provided by existing heuristics, such as the several variants of pinch methodology. Little progress has been made in characterizing the relative performance of these HENS methods in a rigorous manner. For example, it is not known whether any existing decomposition technique is guaranteed to provide solutions within some predetermined range of the true optimum or whether the true optimum may be missed by several orders of magnitude in the worst possible scenario. Systematic analyses of HENS techniques, as well as other process synthesis tasks, are necessary in order to quantitatively determine the comparative value of each method's unique features. *Analytical results—as opposed to computational comparisons and case studies—are long overdue.*

2. HENS and many of its subproblems have recently been proven to be $\mathcal{NP}$ hard in the strong sense,[63] thus refuting the possibility for the existence of exact optimization algorithms that are fast (polynomial). This result motivates further development of heuristics and approximations for large HENS problems. Assuming that existing heuristics do not offer any useful worst-case performance guarantees, *there is a strong need for the development of HENS approximation algorithms*

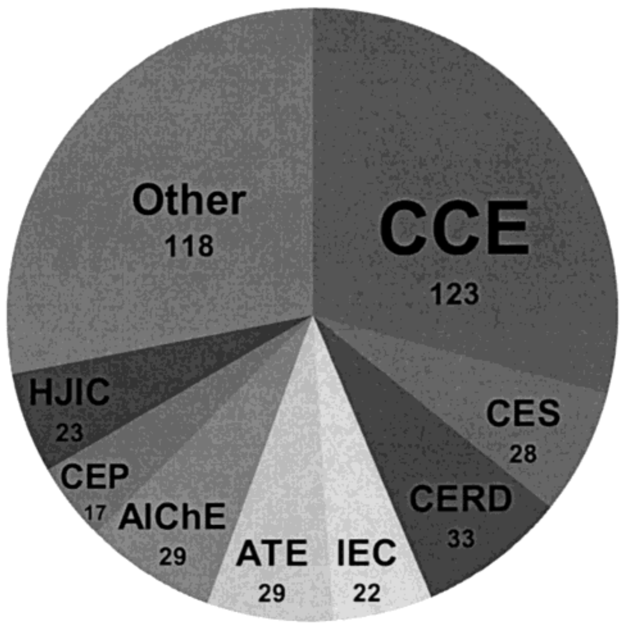

Figure 3. Division of HENS journal papers by journal title.

that run in polynomial time and have a performance guarantee for the quality of the solutions they provide.

3. Despite recent advances in optimization, considerable work remains to be done to solve simultaneous HENS formulations. In addition to the combinatorial complexity of the problem, another major obstacle remaining is the presence of local optima in these formulations, which calls for *more robust formulations and/or more efficient global optimization algorithms*.

4. Although various simultaneous synthesis methods have drawn close, they are limited by a number of restrictive simplifying assumptions including isothermal mixing, no split stream following through more than one exchanger, and no stream bypass. There has yet to be a proposal of *a truly complete formulation of the HENS problem without any simplifying assumptions*.

5. To press further and incorporate these proposed HENS concepts with other aspects of process synthesis would then be the next task in *advancing heat integration methods*.

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Notation

AIChE = *AIChE J.*
ATE = *Appl. Therm. Eng.*, formerly *Heat Transfer Syst. CHP*, formerly *J. Heat Transfer Syst.*
CCE = *Comput. Chem. Eng.*
CEP = *Chem. Eng. Prog.*
CERD = *Chem. Eng. Res. Des.*
CES = *Chem. Eng. Sci.*
DTAM = dual-temperature approach method
EMAT = exchanger minimum approach temperature
FPDM = flexible pinch design method
HEN = heat-exchanger network
HENS = heat-exchanger network synthesis
HJIC = *Hung. J. Ind. Chem.*
HRAT = heat recovery approach temperature
IEC = *Ind. Eng. Chem.* (including *Fundam.*, *Res.*, and *Proc. Des. Dev.*)
LMTD = log mean temperature difference
LP = linear programming
MENS = mass-exchange network synthesis
MILP = mixed-integer linear programming
MINLP = mixed-integer nonlinear programming
PDM = pinch design method
PPDM = pseudo pinch design method
TIAT = temperature interval approach temperature

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