A Course in

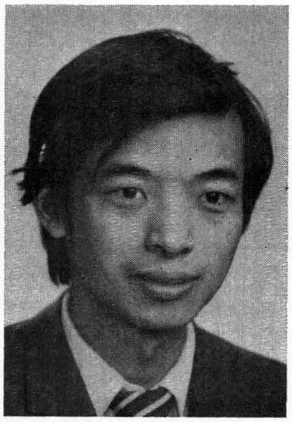
PROCESS SYNTHESIS

Y. A. LIU
Auburn University
Auburn, AL 36849

PROCESS DESIGN CAN BE roughly subdivided into two steps: synthesis and analysis. A great deal of attention has been devoted to the mathematical analysis of process flowsheets, once the flowsheet has been specified. However, the creation, or synthesis, of that flowsheet is not very susceptible to the usual mathematical techniques, and has consequently received relatively less attention in chemical engineering teaching and research. The specification of the chemical and/or physical transformations as well as the selection and interconnection of equipment to implement these transformations to convert the raw materials into desired products on an industrial scale have been regarded, for the most part, an intuitive art.

This article describes a survey course on process synthesis which has been offered to graduate students and qualified seniors at Auburn University since Winter, 1976. The main objective of the course is to introduce to the student the basic techniques and practical applications of process synthesis, emphasizing the systematic generation of economical and energy-efficient process flowsheets. An additional goal of the course is to stimulate interest in process synthesis research among chemical engineering students.

Table 1 presents an outline of the course topics and lectures along with the pertinent references cited in parentheses. The course begins with an introduction to the important problem of optimal synthesis of multicomponent separation sequences, which is concerned with the proper selection of the method and sequence for separating a multicomponent mixture into its respective components. The general techniques which have been developed for solving this problem have included *the optimization (algorithmic) approach* involving some established optimization principles (topic 1), *the heuristic approach* based on the use of rules of thumb (topic 2), and *the evolutionary approach* wherein improvements are systematically made to an initially created feasible flowsheet (topic 3). The lectures emphasize the basic concepts of these approaches along with their strengths and shortcomings for applications to the optimal synthesis of multicomponent separation sequences.



Y. A. Liu received his B.S. from National Taiwan University, M.S. from Tufts University and Ph.D. from Princeton University in 1974. He has been on the chemical engineering faculty at Auburn University since 1974, where he presently holds an alumni associate professorship endowed by the Auburn Alumni Association. His teaching and research interests include process control and synthesis, numerical methods, separation processes, coal desulfurization and magnetochemical engineering. He is an author of over sixty publications and presentations, and an editor of three books on magnetic separation and coal desulfurization.

In topic 4, the preceding synthesis techniques and their combinations are applied to an important process design problem related to energy conservation, namely the synthesis of energy-optimum and minimum-cost networks of exchangers, heater and/or coolers to transfer the excess energy from a set of hot streams to streams that require heating (cold streams). This synthesis problem is relatively well-defined and it has received the greatest attention in the literature. As a result, it is possible to clearly identify the characteristics of energy-optimum and minimum-cost networks and suggest the basic requirements of an effective approach to their synthesis. The lectures include a detailed discussion of the evolutionary block matching method developed at Auburn University and its recent extensions for the synthesis of complex networks, as well as the practical applications of different techniques to the synthesis of energy-optimum and minimum-cost networks for industrial crude unit preheat recovery.

Topics 5 and 6 are concerned with the systematic synthesis of large-scale process flowsheets by *the decomposition (multilevel) approach* together with heuristic and evolutionary methods. Here, the synthesis problem is decomposed into a sequence of smaller and simpler problems (subproblems) which, when solved, generate the flowsheet for the original problem. It is solved by first establishing the sequence of reactions which best convert the raw materials into desired products (reaction path synthesis). The next subproblem is the species allocation and material balancing which involves the synthesis of material flow from raw material and reaction site sources to product, waste and reaction site destinations. During species allocations, the easiest set of separation tasks is sought. The third subproblem is the separation task selection and sequencing discussed previously in Topics 1 to 3. The fourth subproblem involves the specification of auxiliary unit operations which are necessary to achieve the design objectives (auxiliary task assignment). The last subproblem is task integration in which several unit operations are integrated for the reuse of energy and/or material. The lectures emphasize the applications of heuristic and evolutionary methods to the solution of each subproblem along with the overall coordination of the subproblem solutions in the systematic synthesis of large-scale process flowsheets for the manufacture of industrial chemicals.

Topic 7 presents a relatively new technique for solving process synthesis problems, namely, *the thermodynamic approach.* The lectures begin with a review of the thermodynamic availability principle and the second law analysis along with their applications to energy conversion and conservation and to process design and evaluation. The applications of thermodynamic principles to the synthesis of energy-optimum heat exchanger networks and to the analysis of energy consumption of separation processes are then discussed. The remaining lectures are concentrated on the development and demonstration of the thermodynamic approach as a simple and unifying method for the analysis and synthesis of different energy conservation (integration) schemes in distillation systems.

The course concludes with a survey of other process synthesis problems and solution methods, and a summary of the status of current research and industrial applications of process synthesis techniques (topic 8).

. . . the author shares the suggestion of many chemical engineers that process design education should be more oriented toward emphasis upon analysis alone.

The course meets three times a week for fifty-minute lectures over a ten-week quarter. Although the book by Rudd, Powers and Siirola, *Process Synthesis*, Prentice-Hall (1973), is often quoted in lectures, a textbook which adequately covers the recent developments in process synthesis does not exist. Consequently, an organized set of course notes has been prepared for the students. These notes have been revised before each course offering since 1976 to include the latest literature. Class work is comprised of weekly homework problems and a comprehensive term paper. Typical subjects of homework problems and term papers are listed in Table 1.

In closing, the author shares the suggestion of many chemical engineers that process design education should be more oriented toward synthesis, rather than the usual emphasis upon analysis alone. It is hoped that the detailed course outline and references presented in this article will assist other interested faculty in establishing similar courses in process synthesis and in bringing a better balance between analysis and synthesis in process design education. □

TABLE 1
Course Outline and References

1. **Optimization (Algorithmic) Approach to Process Synthesis: An Introduction to Selected Optimization Methods and Their Applications to the Optimal Synthesis of Multicomponent Separation Sequences**

1.1 An Introduction to Optimization Approach to Process Synthesis
1.2 Basic Concepts of Dynamic Programming (1, 2)
1.3 Application of Dynamic Programming to the Optimal Synthesis of Multicomponent Separation Sequences (3-5)
1.4 An Introduction to Branch and Bound Methods and Their Comparison with Dynamic Programming for the Optimal Synthesis of Multicomponent Separation Sequences (6, 7)
1.5 Applications of Dynamic Programming to Other Process Synthesis Problems (8-12)

Typical Homework: Optimal Selection of Separation Methods and Synthesis of Separation Sequences for

Multicomponent Mixtures by Dynamic Programming

2. Heuristic Approach to Process Synthesis: Heuristic Synthesis of Multicomponent Separation Sequences

2.1 An Introduction to Heuristic Approach to Process Synthesis

2.2 Published Heuristics for the Optimal Synthesis of Multicomponent Separation Sequences (4, 13-26)

2.3 An Ordered Heuristic Procedure for the Optimal Synthesis of Multicomponent Separation Sequences (27)

Typical Homework: Applications of Heuristic and Ordered Heuristic Procedures to the Optimal Synthesis of Multicomponent Separation Sequences; Heuristics for Complex Multiple-Section Distillation Systems and Their Applications (22, 23)

3. Evolutionary Approach to Process Synthesis: Evolutionary Synthesis of Multicomponent Separation Sequences

3.1 An Introduction to Evolutionary Approach to Process Synthesis (24-26, 39-40)

3.2 Evolutionary Synthesis of Multicomponent Separation Sequences (24-26)

3.3 An Overview of Published Literature on the Optimal Synthesis of Multicomponent Separation Sequences (5, 11, 13-39)

Typical Homework: Heuristic-Evolutionary Synthesis of Multicomponent Separation Sequences; Optimal Synthesis of Separation Sequences in the Manufacture of Detergents from Petroleum

4. Optimal Synthesis of Heat Exchanger Networks

4.1 An Introduction to Optimal Synthesis of Heat Exchanger Networks (5, 11, 41-44)

4.2 Characteristics of Energy-Optimum and Minimum-Cost Heat Exchanger Networks and Basic Requirements of an Effective Approach to the Optimal Synthesis of Heat Exchanger Networks (44, 56, 60, 63)

4.3 A Simple and Practical Approach to the Optimal Synthesis of Heat Exchanger Networks (Evolutionary Block Matching Method): Minimum Area Algorithm, and Heuristic and Evolutionary Rules (44)

4.4 Further Topics on Optimal Synthesis of Heat Exchanger Networks

- A. Determination of Minimum Utility Requirements by the Problem Table (56, 60, 63)
- B. Synthesis of Heat Exchanger Networks by Temperature Interval Method (60, 63)
- C. Systematic Evolutionary Synthesis of Energy-Optimum and Minimum-Cost Heat Exchanger Networks (44, 60, 63, 64)
- D. Application of Evolutionary Block Matching Method to the Optimal Synthesis of Complex Heat Exchanger Networks: Temperature-Dedependent Heat Capacities, Different Heat Transfer Coefficients Among Process/Utility Streams and Phase Changes of Process Streams (65)

4.5 An Overview of Published Literature on the Optimal Synthesis of Heat Exchanger Networks (5, 6, 11, 41-65)

Typical Homework: Optimal Synthesis of Heat Exchanger Networks for Industrial Crude Unit Preheat Recovery; Comparison of Algorithmic, Heuristic and Evolutionary Methods for the Optimal Synthesis of Heat Exchanger Networks; Concept of the Degree of Freedom and the Shifting and Merging of Exchangers, Heaters and/or Coolers (63); Development of New Evolutionary Rules for the Synthesis of Energy-Optimum and Minimum-Cost Heat Exchanger Networks.

5. Decomposition (Multilevel) Approach to Process Synthesis

5.1 An Introduction to Decomposition (Multilevel) Approach to Process Synthesis (66-68)

5.2 Optimal Synthesis of Chemical Process Flowsheets Based on Task Assignment and Integration (69-70)

5.3 Strategy for Task Assignment to Make Up the Differences in Process State Variables (69, 70)

5.4 Heuristics for Task Integration to Simplify the Initial Process Flowsheet (42, 69, 70)

5.5 Multilevel Approach to Process Synthesis with Multiple Performance Indices (70, 71)

5.6 An Overview of Four General Approaches to Process Synthesis: Optimization (Algorithmic), Heuristic, Evolutionary and Decomposition (Multilevel) Approaches (5, 11)

Typical Homework: Synthesis of Complete Process Flowsheets for the Manufacture of Industrial Chemicals such as Vinyl Chloride from Acetylene and Ethylene (72) and Nitric Acid from Ammonia (73) by Task Assignment and Integration

6. Heuristic and Evolutionary Synthesis of Chemical Process Flowsheets

6.1 An Overview of Heuristic and Evolutionary Synthesis of Chemical Process Flowsheets (38-40, 74-76, 81-82)

6.2 Heuristic Synthesis of Initial Process Flowsheets

- A. Heuristic Approach to Reaction Path Synthesis (77-79)
- B. Heuristic Synthesis of Material Flow from Reaction Paths (77, 80)
- C. Heuristic Approach to Separation Task Selection and Sequencing (4, 13-27)
- D. Heuristic Approach to Auxiliary Task Assignment and Integration (42, 69, 70)

6.3 Evaluation Functions and Evolutionary Rules for Modifying the Initial Process Flowsheets (82)

- A. Evaluation Functions of a Given Process Flowsheet
- B. Evolutionary Rules for Minimizing the Redundency in Process Flowsheets

Typical Homework: Heuristic and Evolutionary Synthesis of Complete Process Flowsheets for the Manufacture of Industrial Chemicals such as Octanes from Butanes (83)

7. Thermodynamic Approach to Process Synthesis

7.1 An Introduction to Thermodynamic Approach to Process Synthesis

7.2 An Introduction to the Thermodynamic Available Energy (Available Useful Work) and the Second Law Analysis (84-91)

- A. Some Background on Thermodynamic Laws and Efficiencies
- B. The Second Laws Efficiency and Thermodynamic Available Energy

Continued on page 212.

fer Controlled Dissolution of an Isolated Sphere," Int. J. Heat Mass Transfer *14*, 395 (1971).
10. Aris, R.: *The Mathematical Theory of Diffusion and Reaction in Permeable Catalysts*, Vol. 1, Clarendon Press (Oxford, UK) 1975.
11. Labowsky, M. and D. E. Rosner: "Conditions for 'Group' Combustion of Droplets in Fuel Clouds. I. Quasi-Steady Predictions," in Proc. Symposium on *Evaporation/Combustion of Fuel Droplets*, Amer. Chem. Soc., Adv. in Chem. Series, No. 166, 63-69 (1978).
12. Rosner, D. E.: "Governing Conservation Principles and Constitutive Laws," Chapter 2 of Short Course: *Introduction to the Fluid Mechanics of Combustion*, EXXON Research and Engineering Co., Florham Park, NJ (December, 1980).
13. Munz, N. and P. Eisenklam: "The Modelling of a High Intensity Spray Combustion Chamber," *Sixteenth Symposium (International) on Combustion*, The Combustion Inst. (Pittsburgh, PA), 593-604, 1976.
14. Swithenbank, J., I. Poll, D. D. Wright and M. W. Vincent: "Combustor Design Fundamentals," *14th Symposium (International) on Combustion*, The Combustion Inst., Pittsburgh, PA 627-638 (1973).
15. Long, M. B., B. F. Webber, and R. K. Chang: "Instantaneous Two-Dimensional Concentration Measurements in a Jet Flow by Mie Scattering," Appl. Phys. Letters *34*, 22-24 (1979); see also M. B. Long, B. T. Chu, and R. K. Chang: "Instantaneous Two-Dimensional Gas Concentration Measurements by Light Scattering," paper AIAA-80-1370, presented at the AIAA 13th Fluid & Plasma Dynamics Conference, 14-16 July 1980, Snowmass, CO, AIAA J. (in press).
16. Gosman, A. D., *et al.*: *Heat and Mass Transfer in Recirculating Flows*, Academic Press (New York, NY), 1969; see also: *Proc. Third Int. Conf. on Numerical Methods in Fluid Mechanics*, Springer-Verlag, 60, 1973.
17. Caretto, L. S.: "Mathematical Modeling of (Combustor) Pollutant Formation," in *Energy and Combustion Science* (N. Chigier, ed.), Pergamon Press (Oxford, UK), 1979, 44-73.
18. Squires, A. M.: "Clean Power from Coal," Science *169*, 821-828 (1970).
19. Rosner, D. E.: "Mass Transfer from Combustion Gases," Presented at the AIChE 73rd Annual Meeting, 16-20 November 1980, Chicago, IL (session on Combustion Fundamentals). Ms. No. 4606.
20. Pritchett, J. W., T. R. Blake and S. K. Garg: "A Numerical Model of Gas Fluidized Beds," AIChE Chemical Engineering Progress Symposium Series (in press 1980).

PROCESS SYNTHESIS

Continued from page 186.

7.3 Thermodynamic Availability Analysis and Its Applications to Energy Conversion and Conservation and to Process Design and Evaluation (85, 86, 92-102)

7.4 Thermodynamic Availability Analysis of Heat-Exchange Process and Its Applications to the Synthesis of Energy-Optimum Heat Exchanger Networks (44, 60, 63-65, 103)

7.5 Thermodynamic Analysis of Energy Consumption of Separation Processes of Relevance to the Synthesis of Energy-Efficient Separation Processes (14, 104-106).

7.6 Thermodynamic Availability Analysis of Distillation Systems and Its Application to the Synthesis of Energy Conservation (Integration) Schemes in Distillation Systems (107-109)
- A. Thermodynamic Availability Diagram for Representing Distillation Systems (107)
- B. Minimization of the Available Energy Loss Through Energy Integration (107-109)
- C. Approximate Minimization of the Available Energy Loss on the Temperature-Enthalpy Diagram (107)
- D. Synthesis of Energy Conservation (Integration) Schemes for Multicomponent Distillation Systems through Systematic Manipulations on the Temperature-Enthalpy Diagram (107)

7.7 Analysis and Synthesis of Energy Conservation (Integration) Schemes in Distillation Systems
- A. Multieffect Distillation (Cascade Columns) (14, 110)
- B. Use of Feed as a Reboiling or Condensing Medium (14)
- C. Heat Pumps (14, 105, 106, 111, 112)
- D. Intermediate Reboilers (Interreboilers) and Condensers (Intercondensers) (14, 104, 106)
- E. Combined Use of Heat Pumps and Intermediate Reboilers/Condensers (113, 114)
- F. Distillation with Secondary Reflux and Vaporization: SRV Distillation (115-117)
- G. Heat-Exchange Integration (Use of Heat Exchanger Networks): Decomposition Approach to the Optimal Synthesis of Heat-Integrated Multicomponent Separation Sequences (10, 31-33)

7.8 Applications of Thermodynamic Approach to Other Process Synthesis Problems (9, 12, 40, 50, 118, 119)

Typical Homework: Synthesis of Energy Conservation (Integration) Schemes of Multicomponent Distillation Systems

8. A Survey of Other Process Synthesis Problems and Solution Methods: Current Trends in Research and Developing Prospects for Industrial Applications

8.1 An Introduction to Fault Tree Synthesis of Chemical Processes (120-126)

8.2 An Introduction to the Structure Parameter Approach for Solving Steady-State and Dynamic Process Synthesis Problems (127-133)

8.3 Current Status of Development and Applications of Process Synthesis Techniques: Research Needs and Opportunities

Typical Homework: Comprehensive Term Papers on Such Topics as (1) Ordered Heuristic Procedures for the Optimal Synthesis of Multicomponent Separation

Sequences; (2) Heuristic Synthesis of Reaction Paths for the Manufacture of Industrial Chemicals; (3) Heuristic and Evolutionary Synthesis of Large-Scale Process Flowsheets; (4) Applications of Thermodynamic Principles to Process Synthesis; and (5) Analysis and Synthesis of Energy Conservation Schemes in Distillation Systems.

REFERENCES

1. Rudd, D. F. and C. C. Watson, *Strategy of Process Engineering*, Wiley (1968), Chap. 8, pp. 212-250.
2. Roberts, S. M., *Dynamic Programming in Chemical Engineering and Process Control*, Academic Press (1964).
3. Rudd, D. F., G. J. Powers and J. J. Siirola, *Process Synthesis*, Prentice-Hall (1973), Chapters 2 and 5, pp. 23-57 and pp. 155-208.
4. Hendry, J. E. and R. Hughes, *Chem. Eng. Prog., 68*, No. 6, 20 (1972).
5. Hendry, J. E., D. F. Rudd and J. D. Seader, *AIChE J., 19*, 1 (1973).
6. Lee, K. F., A. H. Masso and D. F. Rudd, *Ind. Eng. Chem. Fund., 9*, 48 (1970).
7. Westerberg, A. W. and G. Stephanopoulos, *Chem. Eng. Sci., 30*, 963 (1975).
8. Powers, G. J. and R. L. Jones, *AIChE J.*, 19, 1204 (1973).
9. Barnes, F. J. and C. J. King, *Ind. Eng. Chem. Proc.* **Des. Dev., *13*, 421 (1974).**
10. Rathore, R. N. S., K. A. Van Wormer and G. J. Powers, *AIChE J., 20*, 491 and 940 (1974).
11. Hlavacek, V., *Computers and Chem. Eng. J., 2*, 76 (1978).
12. Cheng, W. B. and R. S. H. Mah, *Ind. Chem. Proc. Des. Dev., 19*, 410 (1980).
13. Rudd, D. F., G. J. Powers and J. J. Siirola, *Process Synthesis*, Prentice-Hall (1973), Chap. 5, pp. 155-208 and Chap. 8, pp. 281-239.
14. King, C. J., *Separation Processes*, 2nd Edition, Chap. 13, "Energy Requirements of Separation Processes." McGraw-Hill, New York (1980).
15. Lockhart, F. J., *Petrol. Refiner, 26*, No. 8, 105 (1947).
16. Harbert, W. D., *Petroleum Refiner, 36*, No. 3, 169 (1957).
17. Souder, M., *Chem. Eng. Prog., 60*, No. 2, 75 (1964).
18. Heaven, D. L., "Optimum Sequencing of Distillation Columns in Multicomponent Fractionation," M. S. thesis, University of California, Berkeley, 1970.
19. Nishimura, H. and Y. Hiraizumi, *Intern. Chem. Eng., 11*, 188 (1971).
20. Thompson, R. W. and C. J. King, *Synthesis of Separation Schemes*, Technical Report No. LBL-614, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, 1972.
21. Thompson, R. W. and C. J. King, *AIChE J., 18*, 941 (1972).
22. Tedder, D. W., "The Heuristic Synthesis and Topology of Optimal Distillation Networks," Ph.D. dissertation, University of Wisconsin, Madison, Wisconsin, 1976.
23. Tedder, D. W. and D. F. Rudd, *AIChE J., 24*, 303, 315 and 323 (1978).
24. Seader, J. D., and A. W. Westerberg, ***AIChE J., 23***, 951 (1977).
25. Nath, R., "Studies in the Synthesis of Separation Processes," Ph.D. Dissertation, University of Houston, Houston, Texas, 1977.
26. Nath, R. and R. L. Motard, "Evolutionary Synthesis of Separation Processes," 85th National Meeting, AIChE, Philadelphia, June 4-8, 1978.
27. Liu, Y. A., V. Nadgir and D. Ricks, "A Simple Heuristic Procedure for the Optimal Synthesis of Multicomponent Separation Sequences," Department of Chemical Engineering, Auburn University (1980).
28. Rod, V. and J. Marek, *Collect. Czech, Chem. Comm., 24*, 3240 (1959).
29. Petlyuk, F. B., V. M. Platonov and D. M. Slavinskii, *Inter. Chem. Eng., 5*, 555 (1965).
30. McGalliard, R. L. and A. W. Westerberg, *Chem. Eng. J., 4*, 127, (1972).
31. Stupin, W. J. and F. J. Lockhart, *Chem. Eng. Prog., 68*, No. 10, 71 (1972).
32. Freshwater, D. C. and B. D. Henry, *The Chem. Engr. (London)*, No. 201, 533 (1975).
33. Freshwater, D. C., and E. Ziopou, *Chem. Eng. J., 11*, 215 (1976).
34. Rodrigo, B. F. R. and J. D. Seader, ***AIChE J., 21***, 885 (1975).
35. Gomez, M. A. and J. D. Seader, *AIChE J., 22*, 970 (1976).
36. Bakhshi, V. S. and J. L. Gaddy, "Optimal Synthesis of Separation Systems by Flowsheet Simulation," 70th Annual Meeting of AIChE, New York, Nov., 1977.
37. Siirola, J. J., "Progress Toward the Synthesis of Heat-Integrated Distillation Schemes," paper 47a, 85th National AIChE Meeting, Philadelphia, June 4-8, 1978.
38. Stephanopoulos, G., and A. W. Westerberg, *Chem. Eng. Sci., 31*, 195 (1976).
39. Mahalec, V. and R. L. Motard, *Computers and Chem. Eng. J., 1*, 149 (1977).
40. King, C. J., D. W. Gantz and F. J. Barnes, *Ind. Eng. Chem. Proc. Des. Dev., 11*, 271 (1972).
41. Rudd, D. F. and C. C. Watson, *Strategy of Process Engineering*, Wiley (1968) pp. 40-42, 93-97 and 137-141.
42. Rudd, D. F., G. J. Powers and J. J. Siirola, *Process Synthesis*, Prentice-Hall (1973), Chap. 6.
43. Takamatsu, T., I. Hashimoto and K. Nishitani, *Japanese Systems and Control, 19*, 409 (1975).
44. Nishida, N., Y. A. Liu and Leon Lapidus, *AIChE J., 23*, 77 (1977).
45. Hwa, C. S., *AIChE-IChE Symp. Ser.*, No. 4, 101 (1965).
46. Kesler, M. G. and R. O. Parker, *Chem. Eng. Symp. Ser.*, No. 92, 111 (1969).
47. Masso, A. H. and D. F. Rudd, *AIChE J., 15*, 10 (1969).
48. Nishida, N., S. Kobayashi and A. Ichikawa, *Chem. Eng. Sci., 26*, 1841 (1971).
49. Kobayashi, S., T. Umeda and A. Ichikawa, *Chem. Eng. Sci., 26*, 1367 (1971).
50. Menzies, M. A. and A. I. Johnson, *Can. J. Chem.*

Eng., *50*, 290 (1972).
51. Pho, T. K. and L. Lapidus, *AIChE J.*, *19*, 1182 (1973).
52. Ponton, J. W. and R. A. B. Donaldson, *Chem. Eng. Sci.*, *29*, 3275 (1974).
53. Siirola, J. J., "Status of Heat Exchanger Network Synthesis," paper 42a, 76th National AIChE Meeting, Tulsa, Oklahoma (1974).
54. Rathore, R. N. S. and G. J. Powers, *Ind. Eng. Chem. Proc. Des. Dev.*, *14*, 175 (1975).
55. Shah, J. V. and A. W. Westerberg, "Evolutionary Synthesis of Heat Exchanger Networks," Paper 60c, AIChE Annual Meeting, Los Angeles, Nov. (1975).
56. Hohmann, E. C. and F. J. Lockhart, "Optimum Heat Exchanger Network Synthesis," paper 22a, AIChE National Meeting, Atlantic City, N.J., September (1976).
57. Hwang, F. and R. Elshout, *Chem. Eng. Prog.*, *72*, No. 7, 68 (1976).
58. Kelahan, R. C. and J. L. Gaddy, "Synthesis of Heat Exchange Networks by Mixed Integer Optimization," paper 22c AIChE National Meeting, Atlantic City, N.J., September (1976).
59. Elshout, R. V. and E. C. Hohmann, "Energy Conservation by Computer Simulation," paper 34b, 85th National AIChE Meeting, Philadelphia, PA, June (1978).
60. Flower, J. R. and B. Linnhoff, "A Thermodynamic-Combinational Approach to the Design of Optimum Heat Exchanger Networks," paper 34e, 85th National AIChE Meeting, Philadelphia, PA, June (1978).
61. Hohmann, E. C. and D. B. Nash, "A Simplified Approach to Heat Exchanger Network Analysis," paper 34a, 85th National AIChE Meeting, Philadelphia, PA, June (1978).
62. Grossmann, I. E. and R. W. H. Sargent, *Computers and Chem. Eng. J.*, *2*, 1 (1978).
63. Linnhoff, B. and J. R. Flower, *AIChE J.*, *24*, 633 and 642 (1978).
64. Umeda, T., J. Itoh and K. Shiroko, *Chem. Eng., Prog.*, *74*, No. 7, 70 (1978).
65. M. Elliott, "Applications of the Evolutionary Block Matching Method to the Optimal Synthesis of Complex Heat Exchanger Networks," Department of Chemical Engineering, Auburn University, (1980).
66. Rudd, D. F. and C. C. Watson, *Strategy of Process Engineering*, Wiley (1968), Chap. 10, pp. 282-305.
67. Rudd, D. F., G. J. Powers and J. J. Siirola, *Process Synthesis*, Prentice-Hall (1973), Chapters 1 and 6.
68. Rudd, D. F., *AIChE J.*, *14*, 343 (1968).
69. Umeda T., A. Shindo and A. Ichikawa, *Chem. Eng. Sci.*, *29*, 2033 (1974).
70. Umeda, T. and A. Ichikawa, *Chem. Eng. Sci.*, *30*, 699 (1975).
71. Liu, Y. A., D. C. Williams, N. Nishida and Leon Lapidus, "Studies in Chemical Process Design and Synthesis: IV. Optimal Synthesis of Process Systems with Vector-Valued or Multiple Performance Indices," Paper No. 23b, AIChE National Meeting, Atlantic City, NJ, September (1976).
72. Weissermel, K. and H. J. Arpe, *Industrial Organic Chemistry*, Verlag-Chemic, New York, (1978), pp. 192-196.
73. Shreve, R. N. and J. A. Brink, Jr., *Chemical Process Industries*, 4th Edition, McGraw-Hill (1979), pp. 288-289.
74. Powers, G. J., *Chem. Eng. Progr.*, *68*, No. 8, 88 (1972).
75. Rudd, D. F., G. J. Powers and J. J. Siirola, *Process Synthesis*, Prentice-Hall (1973), Chap. 8, pp. 281-303.
76. Siirola, J. J. and D. F. Rudd, *Ind. Eng. Chem. Fund.*, *10*, 353 (1971).
77. Rudd, D. F., G. J. Powers and J. J. Siirola, *Process Synthesis*, Prentice-Hall (1973), pp. 40-47.
78. Waddams, A. L., *Chemicals from Petroleum*, John Murray, London (1973).
79. Wiseman, P., *An Introduction to Industrial Organic Chemistry*, 2nd Edition Applied Science Publishers, Ltd., London (1979).
80. Rudd, D. F., G. J. Powers and J. J. Siirola, *Process Synthesis*, Prentice-Hall (1973), pp. 82-92 and problem 32, pp. 103-104.
81. Mahalec, V. and R. L. Motard, *Computers and Chem. Eng. J.*, *1*, 57 (1977).
82. Mahalec, V. and R. L. Motard, *Computers and Chem. Eng. J.*, *1*, 149 (1977).
83. Rudd, D. F., G. J. Powers and J. J. Siirola, *Process Synthesis*, Prentice-Hall (1973), problems 12 and 15, pp. 256-257 and problem 1, p. 303.
84. Keenan J. H., *Thermodynamics*, Wiley (1944), Chapter XVII, "Availability."
85. Bruges, E. A. *Available Energy and the Second Law Analysis*, Butterworths, London, (1959).
86. Gaggioli, R. A., Editor, *Thermodynamics: Second Law Analysis*, ACS Symp. Ser. No. 122, American Chemical Society, Washington, D. C. (1980).
87. Denbigh, D. G., *Chem. Eng. Sci.*, *6*, 1 (1956).
88. Gaggioli, R. A., *Chem. Eng. Sci.*, *16*, 87 (1961).
89. Gaggioli, R. A., *Chem. Eng. Sci.*, *17*, 523 (1962).
90. Haywood, R. W., *J. Mech. Eng. Sci.*, *16*, 160 and 258 (1974).
91. Sussman, M. V., *Chem. Eng. Prog.*, *76*, No. 1, 37 (1980).
92. Riekert, L., *Chem. Eng. Sci.*, *29*, 1613 (1974).
93. Riekert, L., *Chemical Engineering in a Changing World: Proceedings of the Plenary Sessions of the First World Congress on Chemical Engineering*, Edited by W. T. Koetsier, Elsevier, Amsterdam (1976), pp. 483-494.
94. Berg, C. A., *Technology Review*, *96*, February (1974); also in *Mech. Eng.*, 96, No. 5, 30-42 (1974).
95. Ford, K. W., G. I. Rochlin and R. H. Socolow, *Efficient Use of Energy API Conference Proceedings*, No. 25, American Institute of Physics, New York (1975), Part I.
96. Hamel, B. B. and H. L. Brown, NBS Publication No. 403, National Bureau of Standards, Washington, DC, June (1976), pp. 57-64.
97. Chiogioli, M. H., *Energy Conservation*, Marcel Dekker, Inc., New York (1979), Chap. 3.
98. Bailie, R. C., *Energy Conversion Engineering*, Addison-Wesley, Reading, MA (1978), pp. 110-117.
99. Gaggioli, R. and P. J. Petit, *Chemtech*, *7*, 495 (1977).
100. Michaelides, E. E., *Proceedings of the 14th Inter-*