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Multi-Objective Optimization Applications in Chemical Engineering

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3.1 Introduction

Chemical and related processes are usually optimized for a chosen objective function or criterion, with respect to relevant design and operation variables. Until the end of the last century, economic criteria such as cost and profit were commonly used for optimizing design and operation of processes. In the last decade, multi-objective optimization (MOO) has been used increasingly to optimize chemical engineering applications for conflicting objectives such as conversion, selectivity and yield besides economic criteria. Of late, other performance criteria related to energy, environment and safety are receiving considerable attention in process design and operation optimization. MOO enables optimization of the process with respect to two or more objectives simultaneously, to provide a set of nondominated solutions.

Bhaskar *et al.* (2000) have reviewed reported applications of MOO approach in chemical engineering. Rangaiah (2009) published a monograph on MOO techniques and applications in chemical engineering. In this monograph, Masuduzzaman and Rangaiah (2009) reviewed more than hundred papers on MOO in chemical engineering, from the year 2000 to the middle of 2007. They observed that use of MOO in chemical engineering applications has increased between the years 2003 and 2007. Masuduzzaman and Rangaiah (2009) summarized these MOO applications under five categories: process design and operation;

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petroleum refining and petrochemicals; biotechnology and food technology; pharmaceuticals; and polymerization. In this chapter, we summarize MOO applications in chemical engineering reported from the year 2007 until the end of June 2012.

A good understanding of current optimization practices in chemical engineering is important in both academia and industry. This chapter will help both researchers and practitioners by outlining the MOO applications studied and encouraging them to explore various possibilities. Some studies compared the performance of different algorithms on application problems. The present review makes general comments on the MOO methods used and results obtained in different studies. Hence, this chapter will be useful for finding the applications optimized and in the selection of suitable objective functions and an optimization tool for applications of interest to readers.

Articles on MOO applications in chemical engineering since the year 2007 were identified by searching the Scopus database using the keywords "multiobjective," "multiobjective optimization," and "multi-objective optimization," in the areas of chemical engineering, environmental science and energy, in the article title, keywords and abstract. The source type was journals. Conference papers were thus not included because of their limited availability and they are often extended and later published in journals. The Scopus search missed several relevant articles known to us; hence, a search using Web of Science was also performed. Interestingly, some MOO articles known to us were missed by both these search engines, but were nevertheless included in this review. Of the more than 960 articles identified by the Scopus search, about 230 articles were selected based on their relevance to chemical engineering and related areas.

The selected journal papers for the present review were grouped into six categories: (i) process design and operation; (ii) petroleum refining, petrochemicals and polymerization; (iii) food industry, biotechnology and pharmaceuticals; (iv) power generation and carbon dioxide emissions; (v) renewable energy; and (vi) hydrogen production and fuel cells. The last three categories are new and not separately covered in the review by Masuduzzaman and Rangaiah (2009). This shows that MOO approach is utilized in these areas due to increasing importance and attention given to energy and environment. Grouping articles into categories is somewhat subjective since a particular article can be placed in one or more categories, so readers should browse through more than one category of interest.

Figure 3.1 presents the number of reported MOO applications in different categories of interest to chemical engineers. It can be seen that number of published articles has increased continuously during the period covered. In total, 232 articles have been published on MOO applications in chemical engineering; of these, 97 articles are related to process design and operation. Applications studied in this book are not included in Figure 3.1 and are also not covered in this chapter.

The next section of this chapter presents MOO applications in process design and operation. Section 3.3 reviews applications of MOO in petroleum refining, petrochemical and polymerization. Section 3.4 discusses MOO applications in food industry, biotechnology and pharmaceuticals. Section 3.5 reviews MOO applications in power generation and carbon dioxide emissions, whereas applications related to renewable energy are reviewed in section 3.6. Section 3.7 presents reported MOO articles in hydrogen production and fuel cells. Useful conclusions are drawn from this review at the end of this chapter.

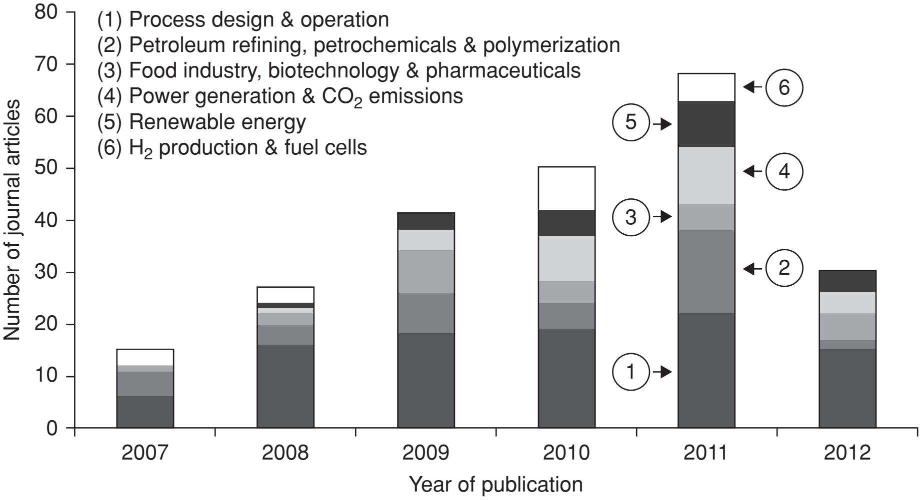

Figure 3.1 *Number of articles on MOO applications in chemical engineering published from the year 2007 until the end of June 2012.*

3.2 MOO Applications in Process Design and Operation

A total of 97 articles were published on the optimization of process design and operation for multiple objectives, during the period 2007 to June 2012. These studies cover a wide range of applications such as parameter estimation, heat exchanger networks, crystallization, pervaporation, distillation, reactive distillation, simulated moving bed reactors, batch plants, supply chain, membrane bioreactors and water purification (see Table 3.1). In all tables in this chapter, journal papers are arranged in chronological and then alphabetical order. Acronyms used in the tables are given after the conclusions section of this chapter.

In the MOO studies on process design and operation (Table 3.1), process economics (e.g., profit, capital/equipment cost and operating cost) is often one performance criterion. Apart from economics, other objectives such as cycle time, hot and cold utilities, heat recovery, productivity, conversion, efficiency, final products qualities, recycle flow rate, number of equipments, environmental impact, pressure drop and so forth are considered as appropriate to the application. In some studies, different indicators are used to account for environmental impact; these include potential environmental index, eco indicator 99, global potential environmental impact, global warming potential, damage to natural resources, IMPACT 2002+ and green degree.

Some studies on the MOO of process design and operation have first developed or improved MOO algorithms and methodologies; they are then used for solving the application problems in process design and operation (e.g., Agarwal and Gupta, 2008a; Barakat *et al.*, 2008; Cauley *et al.*, 2008; Guillen-Gosalbez, 2011). A few studies have compared different MOO algorithms on selected mathematical functions and application problems; examples of such studies are Mjalli *et al.* (2007); Nagrath *et al.* (2010); Lopez-Maldonado

Table 3.1 *Multi-objective optimization applications in process design and operation.*

	Application	Objectives	Method(s)	Comments	Reference(s)
1	Parameter estimation	Simultaneously min. time series and static curve errors	WS method	One solution from the nondominated solutions was chosen to minimize the correlation between the free-run simulation error and the model output.	Barroso *et al.* (2007)
2	Industrial water systems	Min. fresh water consumption and min. cost of network	MO distributed Q-learning; WS with reduced gradient method	Three case studies were solved using the proposed approach. They include single and multiple contaminants, and also a water distribution network in a city.	Mariano-Romero *et al.* (2007)
3	Simulation of multi-stage flash desalination	Max. accuracy to reach global optimum and min. computational effort	MO goal attainment	Conventional numerical methods, MOO based method and ANN with GA based methods, were compared.	Mjalli *et al.* (2007)
4	Pulping process	Max. ISO brightness, max. rupture length, min. specific refining energy, min. extractive content	EA (haploid algorithm)	Net flow and rough set methods were used to rank the obtained non-dominated solutions, based on the preference of the decision maker. Both ranking methods select similar non-dominated solutions.	Renaud *et al.* (2007)
5	Kinetics of vinyl acetate polymerization	Min. error functions for number average molecular weight and initial molecule	MO GA	Kinetic parameters of vinyl acetate polymerization, in the presence of methanol, were estimated.	Sadi and Dabir (2007)

6	Semi-batch reactive crystallization	Max. weight mean size and min. coefficient of variation	NSGA-II	Optimal profiles of feeds for a semi-batch reactive crystallizer were obtained for different crystal size distributions.	Sarkar *et al.* (2007)
7	Injection molding process operation	Min. injection pressure, min. volumetric shrinkage and min. cycle time	MO GA	Design of experiments, Gaussian process for regression and MO GA were used to develop an integrated simulation based optimization system.	Zhou and Turng (2007)
8	Design of shell and tube heat exchangers; Design of heat exchanger networks	Bi- and tri-objective optimization problems from: min. cost, min. utilities, max. energy recovery and min. number of units	NSGA-II-saJG and NSGA-II-sJG	New jumping gene (JG) adaptations improve convergence speed of the algorithm. The obtained tradeoff solutions can be used for better decision making.	Agarwal and Gupta (2008a) and Agarwal and Gupta (2008b)
9	Multi-gravity separator	Max. concentration grade and max. recovery	WS method	Performance of multi-gravity separator was studied experimentally for the effect of drum speed, tilt angle, wash-water flow rate and shake amplitude.	Aslan (2008)
10	Batch distillation and distillation-pervaporation processes	Min. capital investment and min. energy consumption	MO GA	Elite distance-based ranking was used, which was found to be helpful in finding the global Pareto-optimal front efficiently.	Barakat *et al.* (2008)

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Table 3.1 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
11	Simulated Moving Bed (SMB)	Max. productivity and min. desorbent consumption	SA and GA	GA (for integer variables) with SA (for continuous variables) was found to be better than SA with BB method, for optimizing SMB system.	Cauley *et al.* (2008)
12	Design of robust, reliable sensor networks	Min. sensor network cost, max. network reliability and max. network robustness to uncertain reliability data	Constraint programming	This study provides robust and cost effective sensor networks that can handle both known and unknown uncertainties.	Kotecha *et al.* (2008)
13	Estimation of kinetic parameters of biochemical reaction systems	Simultaneously min. concentration and slope error criteria	Hybrid DE	Three problems, metabolic pathway with branch points, reversible pathway, and ethanol fermentation were studied. MOO provides better understanding between different error criteria.	Liu and Wang (2008)
14	Parameter estimation: β-mannanase production	Min. differences between experimental and predicted values for cell mass, substrate and product	WS method and PSO	Kinetic parameters suitable for two fermentation experiments were estimated.	Liu *et al.* (2008)
15	Supply chain planning under uncertainty	Min. total cost and max. reliability of model	ε-constraint method	Chance constrained programming has good potential for optimization problems with uncertainty.	Mitra *et al.* (2008)

16	Reaction and species elimination in kinetic mechanisms	Simultaneously min. number of species and reactions	WS method	Full and reduced kinetic models were compared.	Mitsos *et al.* (2008)
17	Design of multipurpose batch plants	Productivity, campaign cost, NPV without investment, batch size, number of pieces of equipment, floor-up indicator, plant line selection score, diversification function	MO tabu search	Applications studied are L-ascorbic acid, 4-(2-quinolinylmethoxy)-phenol and acetylsalicyclic acid.	Mosat *et al.* (2008)
18	Control strategy for batch processes	Operational objectives (max. final product quantity and min. amount of undesired species) and min. standard error of individual ANN predictions	Goal attainment method	Fed-batch reactor and batch polymerization processes were studied for optimal control policies.	Mukherjee and Zhang (2008)
19	Utility system design	Simultaneously min. cost and global warming.	Lexicographic goal programming	Steam (at different pressures) and deareated water are produced by a utility plant using coal, oil and/or natural gas.	Papandreo and Shang (2008)
20	Process design under uncertainly	Max. of profit and min. environmental impact	MO GA	For steam stripping of condensate studied, uncertainty consideration can affect profit and environmental impact.	Sun and Lou (2008)

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Table 3.1 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
21	Reverse osmosis process design	Min. total water price and min. electricity consumption	MO evolutionary method	Investment costs are nearly same for different optimal configurations, while operation costs (electricity and membrane) vary significantly.	Vince *et al.* (2008)
22	Dead-end ultra-filtration	Simultaneously minimize short and long-term fouling	Hierarchical structure optimization	MO control of coagulant dosing is more suitable for controlling both short- and long-term fouling compared to individual controllers.	Zondervan *et al.* (2008)
23	Preferential crystallization for D-L threonine	Max. average crystal size, max. productivity, min. batch time and min. coefficient of variation	NSGA-II	Different regimes, important for one or more performance criteria, are obtained due to relative importance of nucleation and growth.	Bhat and Huang (2009)
24	Supply chain (SC) planning and design	Max. NPV and min. IMPACT 2002+	MO MILP	The model considers long-term strategic decisions and mid-term planning. SC production and distribution network for maleic anhydride was studied.	Bojarski *et al.* (2009)
25	Absorption cooling system design	Min. total annual cost and min. EI 99	ε-constraint method (using CONOPT/ GAMS)	Large equipments (i.e., higher cost) are required for designing absorption cycle with lower energy consumption (i.e. sustainable).	Gebreslassie *et al.* (2009)

26	Petlyuk sequences (dividing wall columns)	Min. heat duty and min. number of stages in main column and prefractionator	Modified NSGA-II	Non-dominated solutions have nearly equal size of pre-fractionator but different sizes of main column. Feed stage in pre-fractionator depends on the composition and nature of feed mixture.	Gutierrez-Antonio and Briones-Ramirez (2009)
27	Domestic waste water treatment plant	Max. influent flow rate of waste water, min. exit effluent concentration and min. plant operating cost.	NSGA-II	Kinetic parameters in activated sludge model were estimated using plant data. Optimal operating conditions, that give better plant performance without affecting effluent quality, were proposed.	Iqbal and Guria (2009)
28	Dual monolithic catalytic convertor	Min. CO emission and min. difference between integral of catalyst distribution function over volume and catalytic surface area over volume	Micro-GA	Optimal distribution of catalyst was determined.	Kim *et al.* (2009)
29	VOC (volatile organic components) and solvent recovery processes	Several problems from: max. PBT, max. NPW, min potential environmental index (PEI) and individual categories of PEI	NSGA-II	Design and operation problems were optimized for VOC recovery process, whereas only design of solvent recovery process was studied. Benefits of individual categories of PEI as objectives were explored.	Lee and Rangaiah (2009)
30	Middle vessel batch distillation (MVBD)	Min. operating cost and min. investment cost	Modified DE with non-constrain-dominated sorting	Dynamic optimization of MVBD reduces operating cost compared to the conventional temperature control.	Leipold *et al.* (2009)

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Table 3.1 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
31	Environmentally conscious design of chemical processes and products	Min. equipment investment cost, and min. environmental impacts of material and energy flows	NSGA-II	The proposed approach was illustrated on pressure-swing distillation (PSD) and extractive distillation for di-methyl production. The latter has lower values for both objectives compared to PSD.	Li *et al.* (2009)
32	Fault tolerant control (FTC) synthesis	Max. stability of FTC synthesis problem and min. FTC optimal cost	Semidefinite programming	Effects of nonlinear terms were transformed to indices. Sum of squares approach was used to obtain zero value of different indices.	Ma and Yang (2009)
33	Industrial grinding operation	Max. throughput and max. percentage passing of mid-size classes.	NSGA-II	MOO of grinding operation under parametric uncertainty improves the performance by 5% compared to that by deterministic optimization.	Mitra (2009)
34	Resilient supply chain-uncertainty analysis	Min. overall planning cost and max. demand satisfaction for maximum possible demand margin	Fuzzy approach	Fuzzy approach is suitable for solving large-scale supply-chain planning problems under uncertainty.	Mitra *et al.* (2009)
35	Pervaporation process for VOC removal	Min. treatment cost and max. percent toluene removal	NSGA-II	Vacuum and condensation costs are the main contributors to the treatment cost.	Nemmani *et al.* (2009)
36	Solvent and process design for separation and reactive systems	(1a) max. relative volatility between solutes, max. solvent power, min. solvent molecular weight (MW) and min. toxicity; (1b) max. solvent selectivity, max. distribution coefficient, min. solvent losses, min. MW, min. heat of vaporization and min. toxicity;	MO SA	Solvent and process were designed for two applications: (i) a solvent recovery plant based on: (a) extractive distillation, (b) liquid-liquid extraction & distillation, and (ii) extractive fermentation for ethanol.	Papadopoulos and Linke (2009)

		(2) max. solvent selectivity, max. distribution coefficient, max. density difference between nutrient and solvent phases, min. solvent losses, min. MW and min. toxicity			
37	Rotary regenerator	Min. pressure drop and max. effectiveness	NSGA-II	Variations in both objectives with respect to important design parameter are presented.	Sanaye and Hajabdollahi (2009)
38	Scheduling of a semiconductor wafer fabrication plant	Bi- and tri-objective problems from: min. average cycle time (ACT), min. standard deviation of ACT, min. average waiting time, min. number of batches in work-in-progress, min. total number of stored batches and max. facility average utilization	MO GA	ANN was used for computing objectives. The approach was tested for an industrial-size example, and found to be efficient for complex semiconductor wafer fabrication systems.	Senties *et al.* (2009)
39	Global supply chain planning under uncertainty	Min. cost and min. risk	ε-constraint method (multi-cut-L-shaped method)	Stochastic linear programming approach is cost effective for solving global multi-product supply-chain problems.	You *et al.* (2009)
40	Pulping process and beer production	Pulping process: max. ISO brightness, max. rupture length, min. refining energy and min. extractive content Beer production: simultaneously min. difference between predicted and target values for five compounds in beer	Diploid GA	Robust RSM (rough set method) is proposed to rank the obtained nondominated solutions based on the preference of the decision maker. The proposed approach is demonstrated on one mathematical and two application problems.	Vafaeyan and Thibault (2009)
41	SMB and Varicol processes for enantio-separation of racemic pindolol	Three cases: max. raffinate and extract purities; and max. recovery of S-pindolol and min. desorbent flow rate (at both operation and design stages)	NSGA-II-JG	Optimized solutions were verified experimentally. For same amount of desorbent consumption, Varicol process is better than simulated moving bed (SMB) for high purity or recovery of S-pindolol.	Zhang *et al.* (2009)

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Table 3.1 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
42	Screening of batch process alternatives	Min. cost, min. cumulative energy demand and min. hazard	WS method	The modified framework was illustrated for the production of 4-(2-methoxyethyl)-phenol, considering seven potential synthesis routs.	Albrecht *et al.* (2010)
43	Extractive dividing wall column (DWC)	Simultaneously min. total number of stages, extracting agent flow rate, and heat duty	MO GA	DWC design with minimum energy consumption is related to minimum annual operating cost, minimum GHG emission and high thermodynamic efficiency.	Bravo-Bravo *et al.* (2010)
44	Grooved micro-mixer	Max. mixing index at the outlet section and min. pressure drop in the mixing channel	NSGA-II	Two surrogate modeling techniques: radial basis function and response surface model were used. Some nondominated solutions obtained were validated using CFD.	Cortes-Quiroz *et al.* (2010)
45	Solar assisted absorption cooling system	Min. total annual cost of cooling system and min. EI 99 indicator (for environmental impact)	ε-constraint method (using customized BB method)	Environmental impact of absorption cooling system can be significantly reduced by using more solar collectors.	Gebreslassie *et al.* (2010)
46	Synthesis and planning of sustainable processes	Min. cost and min. cost due to climate change	ε-constraint method (with spatial BB method)	This study considered uncertainty and environmental impacts of a process at the early stage of process development. Four examples with similar objectives were discussed: synthesis of biofuels, process network, H_2 supply chain, and chemical supply chain.	Grossmann and Guillen-Gosalbez (2010)

47	Chemical supply chains under uncertainty	Max. NPV and max. joint probability of satisfying all targets defined in each damage category of EI 99	ε-constraint method (spatial BB method)	Use of natural resources is the main contributor to the environmental impact caused by the supply chain operation.	Guillen-Gosalbez and Grossmann (2010)
48	Design of calorific value adjustment process	Min. operating cost and max. index of performance of natural gas liquids	Heuristic procedure involving search region reduction	Here, distance between trial solution and ideal solution was minimized. This study focused on cost-effective adjustment of calorific value in offshore regasification terminals.	Kim *et al.* (2010)
49	Air handling unit (AHU)	Min. cooling output (i.e., energy required) and min. supply air temperature	SPEA	Using the operating data from a two-day period, a neural network model was developed and then used in the optimization.	Kusiak and Li (2010)
50	Heat exchanger network synthesis	Min. cold utility consumption, min. hot utility consumption, min. number of heat exchanger units and min. total heat exchanger area	NIMBUS with GAMS	Synheat model was used for generating different superstructures. Although TAC was not an objective, MOO approach gives lower TAC compared to TAC obtained by single objective optimization for two examples studied.	Laukkanen *et al.* (2010)

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Table 3.1 (Continued)

	Application	Objectives	Method(s)	Comments	Reference(s)
51	Liquid-solid circulating fluidized bed-protein recovery	Bi- and tri-objective problems from: max. production rate, max. protein recovery and min. amount of ion exchange resin	NSGA-II-aJG	Systematic MOO using two and three objectives, provide additional insights about the system. As expected, design stage optimization gives better results than the operational optimization.	Mazumder *et al.* (2010)
52	Integration of scheduling and control	Max. profit and max. reliability index	ε-constraint method	Utility of robust integration of scheduling and control layers in the presence of uncertainty is demonstrated.	Mitra *et al.* (2010)
53	Multi-product batch chemical process	Max. revenue, min. investment cost, min. operation cost and min. total production time	NSGA-II	The batch process has four processing steps and three products. The obtained non-dominated solutions are better than the optimal solutions reported earlier.	Mokeddem and Khellaf (2010a)
54	PID controller tuning for pH control	Min. error between reference signal and output and min. cost of control	WS method with GA; NSGA-II	Tuning of controller parameters using NSGA-II is better than WS method with GA.	Mokeddem and Khellaf (2010b)
55	Flux balance analysis using soft constraints	Bi- and tri-objective problems from: max. urea secretion, max. albumin synthesis, max. NADPH and glutathione synthesis	Linear physical programming (LPP)	LPP performs better than WS method and goal programming, for the application studied, namely, hepatocyte function in a simulated bioartificial level system.	Nagrath *et al.* (2010)

56	Shell and tube heat exchanger design (HED)	Min. total annual cost and max. heat recovery	NSGA-II	Pareto-optimal front is due to tube pitch ratio, tube length and number of tubes.	Sanaye and Hajabdollahi (2010)
57	Multi-effect distillation desalination system	Min. cost of water production and max. exergetic efficiency	GA with SA	The system studied includes a thermo-vapor compressor. Selection of an optimal solution from the non-dominated solutions was discussed.	Sayyaadi *et al.* (2010)
58	Scheduling of semiconductor manufacturing plants	Bi- and tri-objective problems for min. of average facility utilization, average cycle time (ACT), standard deviation of ACT, average waiting time, number of batches in work-in-progress and/or total number of stored batches	MO GA	ANN/MO GA approach can be easily applied for solving difficult job scheduling problems. The tri-objective optimization is useful for refining the decision taken based on findings of bi-objective optimization.	Senties *et al.* (2010)
59	Economy and CO_2 emissions tradeoff under uncertainty	Max. expected NPV and max. expected CO_2 emissions	ε-constraint method	MOO for analyzing energy-efficiency investments under uncertainty was explored with an application to a chemical pulp mill.	Svensson and Berntsson (2010)
60	Iron/chromium sulfates from ferrochromium alloy	Simultaneously max. conversions of Cr and Fe	WS method	Effects of sulfuric acid, perchloric acid and ammonium sulfate on the conversion were studied.	Wenzel *et al.* (2010)

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Table 3.1 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
61	Acetone-chloroform separation	Min. purity of chloroform, min. purity of acetone and min. amount of recycling	Sandwiching approach	Separation by pressure swing distillation was optimized.	Asprion *et al.* (2011)
62	Water distribution network design	Min. network investment cost and max. resilience index	SPEA-2	Several resilience indexes were analyzed for water distribution network design.	Banos *et al.* (2011)
63	Reactive distillation (RD) for transesterification	Min. reboiler energy, max. n-butyl acetate flow rate and max. methanol flow rate	NSGA-II	RD for trans-esterification of methyl acetate and n-butanol to produce n-butyl acetate, was simulated using HYSYS. Decision variables were selected based on sensitivity analysis.	Behroozsarand and Shafiei (2011)
64	Batch process retrofitting	Min. process cost, min. raw material cost, min. energy consumption, min. energy utility and waste cost and min. global warming potential	-	Retrofit alternatives were generated using path flow indicators, and ranked according to their effects on the objectives.	Bumann *et al.* (2011)
65	Membrane bioreactor for waste water treatment	Min. conversion of NH3 + ammonium nitrogen and soluble biodegradable substrate, max. weighted productivity	–	Based on the results obtained, a new operating strategy for the submerged membrane bioreactor (SMBR) was proposed.	Buzatu and Lavric (2011)

66	Semi-continuous water networks	Min. fresh water consumption and min. combined investment and operating costs	MO GA	The obtained solutions have increased the use of waste water from the storage tank and also increased the use of regenerated water.	Dogaru and Lavric (2011)
67	Robust integrated design and control of processes	Min. total cost and max. process controllability	Goal attainment and SQP	The proposed methodology for integrated design and linear MPC was applied to activated sludge processes. Resulting MPC has better disturbance rejection.	Francisco *et al.* (2011)
68	Cascade controller design	Min. concentration of organic matter in effluent and max. methane flow rate	–	Here, MO cascade control system was developed for an anaerobic digester.	Garcia-Dieguez *et al.* (2011)
69	Pervaporation – VOC removal from water	Simultaneously min. feed pumping, membrane replacement, vacuum and condensation, capital and treatment costs	NSGA-II	Membrane replacement cost is not significant compared to other costs in the objectives.	Gopal and Satyanarayana (2011)
70	Petrochemical supply chain	Min. cost, damage to human health, damage to ecosystem and depletion of natural resources	ε-constraint method	Methodology to determine an objective subset that preserves dominance structure, was presented and applied to heat exchanger design and petrochemical supply chain.	Guillen-Gosalbez (2011)
71	Scheduling and control of CSTRs	Max. profit and max. deviation from target steady states	ε-constraint method	The approach was applied to three case studies. It does not consider process uncertainty in the formulation.	Gutierrez-Limon *et al.* (2011)

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Table 3.1 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
72	Design of sustainable processes	Max. profit and min. total environmental impact, for two examples: hydrodealkylation and bio-diesel processes	MO SA with jumping gene operation	Expert system was used to diagnose waste sources, followed by optimal manipulation of design and operational variables to reduce waste production.	Halim and Srinivasan (2011)
73	Water using networks	Min. total fresh water consumption rate, min. total number of interconnections and min. throughput of water network	CONOPT and BARON in GAMS	The three optimizations are performed sequentially. Five examples were solved, and better network designs were achieved.	Li and Chang (2011)
74	Robust control of uncertain (bio)chemical processes	For a jacketed tubular reactor: max. conversion and max. energy consumption; For a fed-batch bioreactor: max. productivity and max. yield	NNC method with Lyapunov differential equations for dynamic optimization	Robustness is incorporated as constraints in the problem formulation. More robust solutions generally have lower value of performance.	Logist *et al.* (2011)
75	Heat exchanger network synthesis	Min. total annual cost and EI 99	ε-constraint and goal methods	Three examples were solved, and both MOO techniques were found to be equally good for these problems.	Lopez-Maldonado *et al.* (2011)
76	Straight grate iron ore induration process	Max. throughput and max. Tumble index	NSGA-II	Combination of first principles model with ANN-based approximate model was found to be beneficial for optimization.	Mitra and Majumder (2011)

77	Design and planning of supply chains	Max. profit and min. environmental impact (EI 99)	Symmetric fuzzy linear programming using CPLEX/GAMS	Production facilities, warehouses and distribution centers were considered in the optimization. A supply chain network for four products and a pulp and paper industry, both in Portugal, were studied.	Pinto-Varela *et al*. (2011)
78	Synthesis of recycle and reuse networks	Min. total annual cost and min. environmental impact (EI 99)	ε-constraint method	Three examples with different numbers of waste streams, equipments requiring water and fresh water sources, were studied.	Ponce-Ortega *et al*. (2011)
79	Cyclone separator design	Min. pressure drop and min. cut point	Modified NSGA-II	CFD and GA were used to develop an ANN model for a cyclone separator prior to its MOO using NSGA-II.	Safikhani *et al*. (2011a)]
80	Square cyclone separator design	Max. collection efficiency and min. pressure drop	NSGA-II	CFD and GA were used to develop an ANN model for a square cyclone prior to MOO.	Safikhani *et al*. (2011b)
81	Volatile organic compounds (VOC) and solvent recovery processes	Several problems from: max. PBT, max. NPW, min. emission of ethyl acetate, min. energy consumption, min. PEI, max. GD, min. IETH, min. IMPACT 2002+ and individual categories of PEI, GD, IETH and IMPACT 2002+.	NSGA-II	Operation of VOC recovery process and design of solvent recovery process were optimized. Four environmental indicators, namely, PEI, GD, IETH and IMPACT 2002+ with their individual categories were used as objectives. Use of IMPACT 2002+ as the environmental indicator is recommended.	Sharma *et al*. (2011)

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Table 3.1 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
82	Integrated water/waste waster networks (IWWN)	Min. usage of fresh water and min. total cost	GA in MATLAB	Sub-optimal topologies were obtained after ranking IWWN according to each of the four criteria (max. outlet conc., max. inlet conc., max. fresh water consumption and max. contaminant load). After optimization, water can be completely reused internally, and the topologies obtained differed in the direction of interlinking streams.	Tudor and Lavric (2011)
83	Compressor aided distillation sequences with heat integration	Simultaneously min. energy requirement and total annual cost	Normalized adaptive min-max WS	The proposed MOO approach can find solutions in concave regions of Pareto-optimal front with better distribution. Compression of column top vapor stream and pressure change in the thermally coupled columns were considered.	Alcantara-Avila *et al*. (2012)
84	Lab scale thickener	Max. underflow solid percent and min. bed height of thickener	Grey rational analysis (GRA)	Contribution of each parameter is weighted according to its importance.	Aslan *et al*. (2012)
85	Batch process scheduling	Min. environmental impact per unit product and max. profitability	MO GA with local search	MO GA has integer decision variables only, and its solutions are improved, using local search, for continuous variables. This hybrid approach can find the Pareto-optimal front efficiently.	Capon-Garcia *et al*. (2012)

86	Gas cyclone separator	Min. pressure drop and min. cut-off diameter	NSGA-II	ANN models for simulating cyclone performance were developed and then used in MOO. The optimized design is better than the Stairmand design.	Elsayed and Lacor (2012)
87	Model predictive control (MPC) of semi-batch reactors	Simultaneous max. of production of two products	MO-NLMPC	A MO-nonlinear MPC (MO-NLMPC) approach was applied to three semi-batch reactors.	Flores-Tlacuahuac *et al.* (2012)
88	Semi-batch reactor	Max. reactor productivity and max. joint failure probability	GA Matlab (gamultiobj)	Problem formulation considers technological constraints, uncertainty in safety boundaries and random fluctuation in control variables.	Dan and Maria (2012)
89	Environmental consideration in chemical process design	Min. total cost and min. total environmental impact	ε-constraint	Here, effect of feedstock quality and use of additional waste treatment units on the economic-environmental tradeoff is explored.	Garcia and Caballero (2012)
90	VOC (volatile organic compound) removal using a rotating packed bed (RPB)	Min. TAC and max. VOC removal	NSGA-II	VOC removal using a RPB (high gravity or HiGee) was analyzed. One solution from the Pareto-optimal front was compared with the conventional stripper design. Sensitivity and uncertainty analyses have also been performed.	Gudena *et al.* (2012)
91	Control structure design	Min singular value rule and min. μ-interaction measure	MO BB	The proposed MOO technique was illustrated for hydrodealkylation of toluene, and is shown to be much faster.	Kariwala and Cao (2012)

(*continued*)

Table 3.1 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
92	Optimal control of chemical processes using ACADO toolkit (www.acadotoolkit.org)	For catalyst mix in a tubular reactor: max. production and min. amount of catalyst; For fed-batch reactor: max. yield of two products; For a jacketed tubular reactor: max. conversion and max. heat recovery	WS, NNC, NBI and enhanced NNC methods	Three applications were studied. Use of MOO approach with optimal control methods improves the real time decision making.	Logist *et al.* (2012)
93	Process design for economic and environmental objectives	Bi- and tri-objective problems from: max. benzene production, min. annual cost and min. environmental indicators (GWP, AP, POCP, HTP, EP)	NSGA-II	For hydro-dealkylation process, several bi-objective optimization problems were solved to reduce the number of objectives. Finally, a tri-objective optimization problem was solved.	Ouattara *et al.* (2012)
94	Design of chemical supply chains	Max. NPV, min. ecosystem quality, min. human health and min. damage to natural resources	ε-constraint method using CPLEX/GAMS	PCA (principal component analysis) was used to identify redundant environmental objectives, which facilitates MOO and decision making.	Pozo *et al.* (2012)
95	Shaft furnace roasting process	Min. air fuel ratio, max. yield and min. energy consumption	Hybrid intelligent control algorithm (based on MO evaluation)	The proposed algorithm was tested and implemented on the industrial process. The optimal operation of shaft furnace has better economics, security and stability.	Yan *et al.* (2012)
96	Green production strategies	Min. total cost, max. total yield, min. total pollution and max. energy/resource saving	Response surface method and LINGO (GAMS)	Numerical examples were constructed and implemented to illustrate the solution models.	Zhou *et al.* (2012)

et al. (2011); Chaudhari and Gupta (2012) and Logist *et al.* (2012). Weighted sum, ε-constraint, NNC, NSGA-II, and MO GA are commonly used MOO techniques for optimizing process design and operation applications.

3.3 MOO Applications in Petroleum Refining, Petrochemicals and Polymerization

Petroleum refining, petrochemicals and polymerization industries are related, and hence these are grouped together. Petroleum refining uses a significant amount of energy to produce many valuable products from crude petroleum, and also produces a significant amount of pollutants that affect the environment. Further, it has safety concerns due to the significant fire and explosion potential of crude, intermediates and products. Petrochemical industries produce a variety of products such as olefins, styrene, phthalic anhydride and 1,3-butadine. Some of these products are polymerized into polymers having desired molecular weight and properties.

At the time of writing, there have been 40 studies on MOO applications in petroleum refining, petrochemicals and polymerization since the year 2007 (Table 3.2). Studies on petroleum refining have employed objectives such as profit, investment cost, energy and water consumptions, yield, conversion, emission of greenhouse gases and hydrocarbon inventory. Cost, productivity, and selectivity are generally used to evaluate performance of petrochemical processes. Polymerization processes have employed objectives such as monomer conversion, degree of polymerization, and batch time.

The applications studied in petroleum refining include crude distillation unit, steam reformer, fuel blending, fluidized catalytic cracker, thermal cracker, naphtha pyrolysis, gas separation, hydrogen network and liquefaction of natural gas (Table 3.2). In petrochemicals, styrene reactors, phthalic anhydride reactor systems and butadiene production were studied for MOO. Finally, in polymerization, low-density polyethylene tubular reactor, polymer filtration, nylon-6 and injection molding were optimized for multiple objectives. Some studies have compared performance of a few MOO algorithms on selected applications; these include Agrawal *et al.* (2007); Khosla *et al.* (2007); Sankararao and Gupta (2007); Ramteke and Gupta (2008 and 2009a); Gujarathi and Babu (2009); Abo-ghander *et al.* (2010) and Sankararao and Yoo (2011). MOO algorithms are developed or improved in some of these studies.

Sometimes, changes in an optimization algorithm may be required due to specific characteristics of a problem; for example, chromosome structure is modified for scheduling of multiproduct polymer plants (Ramteke and Srinivasan, 2011). Sadhukhan and Smith (2007) presented a methodology for structural decomposition of a large-scale industrial system. Zhai *et al.* (2011) have used weighted sum method to select a solution from the obtained Pareto-optimal front.

3.4 MOO Applications in the Food Industry, Biotechnology and Pharmaceuticals

The use of optimization tools for applications in food technology, biotechnology and pharmaceuticals is increasing continuously (Figure 3.1). In this group, 25 journal articles

Table 3.2 *Multi-objective optimization applications in petroleum refining, petrochemicals and polymers.*

	Application	Objectives	Method(s)	Comments	Reference(s)
1	Low-density polyethylene (LDPE) tubular reactor	Bi- and tri-objective problems from max. ethylene conversion, min. normalized side products and min. compression power	NSGA-II, NSGA-II-JG, and NSGA-II-aJG	Design optimization gives significant improvement in process performance compared to operation optimization.	Agrawal *et al.* (2007)
2	Industrial steam reformer of methane	Max. methane conversion and min. stoichiometric parameter	GA with WS method	MO dynamic optimization was performed for feed switching and operating conditions.	Alizadeh *et al.* (2007)
3	Fuel oil blending	Bi- and tri-objective problems from max. profit, min. quality give away, max. production, min. use of light products and max. calorific value	NSGA-II and NSGA-II-aJG	In all, five problems were studied. For problem 1, NSGA-II-aJG converges faster than NSGA-II.	Khosla *et al.* (2007)
4	Oil upgrading system (petroleum refinery)	Max. product quality, max. purity, max. yield and max. conversion for individual basic elements (part of subsystem)	DICOPT (GAMS) along with constraint relaxation	A systematic methodology for structural decomposition of large scale industrial systems was developed and applied to design an oil upgrading system.	Sadhukhan and Smith (2007)
5	Industrial FCC unit	Bi- and tri-objective problems from max. gasoline yield, min. %CO in flue gas and min. airflow rate	MO SA and NSGA-II, and their JG and aJG versions	The algorithms were tested for four benchmark and two FCC problems. The study recommends MO SA-aJG algorithm.	Sankararao and Gupta (2007)
6	Polymer filtration	Max. filter lifetime and min. mass of debris that escape the filter	NSGA-II	One-hundred filter configurations with specific debris profile were analyzed.	Fowler *et al.* (2008)

7	Naphtha pyrolysis process	Simultaneously max. yields of ethylene and propylene.	NSGA-II without and with SQP	The hybrid approach converges faster than NSGA-II, and also gives a wider Pareto-optimal front.	Gao *et al.* (2008)
8	Steam methane reforming process	Min. H_2 production cost and min. CO_2 emissions	MO GA	Results show that CO_2 emissions can be reduced by about 16% for 0.5% increase in H_2 production cost.	Mansilla *et al.* (2008)
9	Nylon-6 polymerization	Bi- and tri-objective problems from: min. batch time, min. amount of cyclic dimer in the product, max. conversion of monomer	NSGA-II-aJG and MO SA-aJG Biomimetic NSGA-II-aJG	NSGA-II-aJG gives better distribution of nondominated solutions compared to MO SA-aJG. This algorithm is computationally efficient for optimization problems with changes in scenario (e.g. number of decision variables and their ranges).	Ramteke and Gupta (2008) Ramteke and Gupta (2009a)
10	Gas separation system for upgrading crude synthetic natural gas	Max. synthetic natural gas (SNG) recovery and min. specific power consumption	MO EA	Different membrane configurations are studied. Integration between reaction and separation sections reduces production cost significantly. Process with CO_2 capture was also optimized for carbon capture ratio and production cost.	Gassner *et al.* (2009)

(*continued*)

Table 3.2 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
11	Adiabatic styrene reactor	Bi- and tri-objective problems from max. styrene productivity, selectivity and yield	MO DE III, and hybrid MO DE	Hybrid MO DE is efficient in converging to the Pareto-optimal front.	Gujarathi and Babu (2009)
12	Oxidative coupling of CH_4 in a SCMCR	Two problems: max. CH_4 conversion and max. selectivity of desired product; and max. of yield and min. of reactor length	NSGA-II-JG	Both operation and design optimization of a simulated countercurrent moving bed chromatographic reactor (SCMCR) were studied.	Kundu *et al.* (2009)
13	Phthalic anhydride (PA) reactor system	Max. yield and min. total length of catalyst bed	Altruistic-NSGA-II-aJG	Altruistic-NSGA-II-aJG performed better than traditional algorithms on three test problems, and on industrial PA reactor system. It was also used to simulate carcinogenesis. Ramteke and Gupta (2009a) used biomimetic NSGA-II-aJG for PA reactor system.	Ramteke and Gupta (2009b)
14	Propane precooled gas-phase liquefaction of natural gas	Four case studies from: min. total shaft work, min. capital cost, min. total annual cost and min. hydrocarbon inventory	NSGA-II	This study shows potential for obtaining significant efficiency gains. The obtained Pareto fronts have discontinuity, which is useful in selecting one solution from the set of non-dominated solutions.	Shah *et al.* (2009)

15	Design and operation of an LPG thermal cracker	Bi- and tri-objective problems from: max. ethylene production, max. propylene production, max. ethylene selectivity, max. run length, min. severity index and min. total heat duty per year	NSGA-II-aJG	First-principles model of an LPG thermal cracker was used. Design optimization may give better solutions than operation optimization.	Nabavi *et al.* (2009); Nabavi *et al.* (2011)
16	Dehydrogenation of ethyl benzene to styrene with hydrogenation of nitrobenzene to aniline	Max. yield of styrene and max. conversion of nitrobenzene	NNC and NBI	A catalytic membrane reactor was used for coupled reactions. Both NNC and NBI methods gave evenly distributed Pareto-optimal fronts.	Abo-ghander *et al.* (2010)
17	Thermo-chemical production of synthetic natural gas from biomass	Max. yield of synthetic natural gas, max. electrical efficiency and min. specific investment cost	MO EA	Three different process setups were studied. Reactive and separation sections were integrated, where external utilities were replaced by waste and intermediate process streams.	Gassner and Marechal (2010)
18	Industrial styrene reactor	Bi- and tri-objective problems from max. productivity, max. selectivity and max. yield	MO DE	MO DE gave a wider range and better spread of non-dominated solutions compared to those in the past work which used NSGA.	Gujarathi and Babu (2010)
19	Hydrodealkylation of toluene to benzene	Max. NPV, max. NPV with inclusion of environmental impact costs, min. global potential environmental impact (GPEI) and min. GPEI based on environmental priority strategies	SA and TS	Five different topologies for hydrodealkylation of toluene to benzene were considered; these differed in the presence or absence of recycle stream and heat integration.	Martins and Costa (2010)

(*continued*)

Table 3.2 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
20	Chilling train system design and operation in ethylene plants	Min. ethylene loss rate and min. exergy-accounted energy consumption and max. hydrogen recovery rate	ε-constraint method with DICOPT (GAMS)	Effect of compressor location, flash drum temperature and pressure on different objectives was studied.	Zhang *et al.* (2010)
21	Crude distillation unit (CDU)	Min. CO_2 emissions and max. net revenue from CDU	NSGA-II (real coded)	Utilities cost and CO_2 emissions were simultaneously targeted using the grand composite curve of pinch analysis. This study allows selection of crude blend at different levels of CO_2 emissions.	Al-Mayyahi *et al.* (2011)
22	Synthesis gas sweetening with amines	Min. energy consumption, min. amine circulation rate and max. CO_2 recovery	NSGA-II	This study provides optimal values of important decision variables in the synthesis gas sweetening process.	Behroozsarand and Zamaniyan (2011)
23	Fed-batch emulsion copolymerization reactor for styrene and butyl acrylate	Max. monomer overall conversion and min. error between glass transition temperature profile and a designed profile	EA	Non-dominated solutions were analyzed using multi-attribute utility theory, to select one of them. Selected solution was successfully implemented on a laboratory reactor.	Benyahia *et al.* (2011)
24	Acrylic fiber production plant	Max. profit and min. total environmental impact	NNC method	This study provides useful information for production schedule in a batch plant.	Capon-Garcia *et al.* (2011)
25	Toluene/n-heptane separation in a membrane unit	Max. permeation flux and max. toluene selectivity	MO GA	ANN model was developed and used for optimization. Temperature and feed concentration are the main contributors for the Pareto-optimal front.	Farshad *et al.* (2011)

26	Refinery hydrogen network	Min. operating cost and min. investment cost of equipment	WS method with LINGO system	PSA (pressure swing adsorption) should be used for producing hydrogen from the high pressure off-gas and from reforming unit. The low pressure off-gas and PSA residual should be purified using a membrane unit.	Jiao *et al.* (2011)
27	Natural gas production network design	Max. NPV and max. total flow rate of individual flows of CO_2 entering LNG plants	Hierarchical MOO approach	A rigorous decomposition method was used for solving the stochastic pooling problem.	Li *et al.* (2011)
28	Scheduling of multiproduct polymer plant	Three bi-objective problems from min. makespan, min. number of late orders, min. positive lateness and max. customer satisfaction	NSGA-II with special chromosome structure	The proposed chromosome structure for scheduling problems enables to satisfy all constraints except one (taken care by penalty function approach) throughout search.	Ramteke and Srinivasan (2011)
29	Industrial FCC unit	Min. %CO in flue gas and min. air flow rate	Robust MO SA (rMOSA)	Proposed rMOSA is shown to be better than simple MO SA, NSGA-II and NSGA-II-JG, on four benchmark functions and industrial FCC unit.	Sankararao and Yoo (2011)
30	Reliquefaction of LNG	Max. exergetic efficiency and min. unit cost	NSGA-II	Optimization of reliquefaction of boil off gas was studied. One optimal point, based on the distance from the ideal point, was selected.	Sayyaadi and Babaelahi (2011)
31	Styrene reactor	Simultaneously max. styrene conversion and selectivity	TS and GA for MOO problems	Two cases with and without catalyst deactivation were studied. TS was found to be faster than GA for this problem.	Shahhosseini and Vakili (2011)

(*continued*)

Table 3.2 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
32	Production of 1,3-butadiene	Min. energy consumption, max. green degree, max. purity and max. recovery of 1,3-butadiene	NSGA-II	The process consists of extractive distillation, common distillation and solvent recovery sections. After MOO, it has less energy consumption and lower environmental impact.	Tian *et al.* (2011)
33	Ethylene oxide reactor	Max. ethylene oxide production, max. ethylene oxide selectivity and max. safety factor	Objective based gradient method (OBGA)	Net flow method was used to rank the obtained nondominated solutions.	Vandervoort *et al.* (2011)
34	Injection molding	Max. quality of parts and min. manufacturing cost	MO GA	WS method was used to select a solution from the Pareto-optimal front.	Zhai *et al.* (2011)
35	Oil-spill response planning	Min. total cost and max. effective responses	ε-constraint method	The model considered oil properties, spilled amount, hydrodynamics, weather and sea conditions. Two case studies were described. A small change in response time span can significantly affect operating cost and response operation.	Zhong and You (2011)

36	Fixed bed maleic anhydride	Bi- and tri- objective problems from max. productivity, min. operating cost and min. waste byproducts (CO + CO_2)	Alt-NSGA-II-aJG, NSGA-II-aJG	Alt-NSGA-II-aJG performed better than NSGA-II-aJG for bi-objective problems, whereas NSGA-II-aJG was found to be better for tri-objective problems.	Chaudhari and Gupta (2012)
37	Styrene reactor (adiabatic, steam-injected and isothermal reactors)	Simultaneously max. productivity, yield and selectivity	Dual population EA	The obtained nondominated solutions for steam-injected reactor are better than adiabatic reactor and partially better than isothermal reactor. Finally, net flow method was used to rank the obtained non-dominated solutions.	Fettaka *et al.* (2012)
38	Hydrocarbon biorefinery supply chains	Min. expected annual cost and min. financial risk	ε-constraint method with multi-cut L shaped decomposition method	Both demand and supply uncertainties are considered in the problem formulation. Effectiveness of the proposed approach is demonstrated considering biomass gasification + FT synthesis and fast pyrolysis + hydro-processing, and four case studies.	Gebreslassie *et al.* (2012)

used the MOO approach from the year 2007 until June 2012 (Table 3.3). The applications studied in the food industry were lactic acid production, baking of bread, thermal processing and milk concentration. Large-scale metabolic networks, protein recovery, flux balance for metabolic networks and bio-synthesis factory were optimized for multiple objectives in the biotechnology area. In the pharmaceutical industry, applications such as drug design, bioremediation, antibiotic and penicillin V production, scheduling and product development were studied for MOO.

In food technology, performance objectives are related to product quality and water content (which affects the shelf life of products). Productivity and conversion are the commonly used objectives for biotechnology and pharmaceutical applications; these applications have other specific objectives, and these can be seen in Table 3.3. Reported applications in this group used well-established MOO algorithms that include both deterministic and stochastic methods. A few studies developed optimization methodologies due to specific problem requirements (e.g., MO evolutionary graph algorithm and non-inferior set estimation).

3.5 MOO Applications in Power Generation and Carbon Dioxide Emissions

In recent years, researchers have applied MOO techniques for the design and operation of power plants. In all, 29 studies on MOO in power generation including carbon dioxide emissions and capture are summarized in Table 3.4; there was no MOO study in power generation in the year 2007 and there was only one article in the year 2008. Pulverized coal power plants and their retrofitting were studied for multiple objectives. Some of the works focused on natural gas power plants, integrated gasification and combined-cycle power plants and cogeneration plants. Power production capacities of these applications varied significantly. Further, MOO was applied to distributed power generation using multiple facilities and distribution network planning. Several studies focused on carbon dioxide capture.

In the studies summarized in Table 3.4, capital cost, fuel cost, emissions of CO, CO_2 and NO_x, exergetic efficiency and net power are the commonly used objectives. There are several types of environmental impact, and so some of these studies have more than two objectives. As is the case with publications in other categories, a few studies have considered improvement and/or modifications in MOO algorithms, and then these algorithms were used to optimize the selected applications (e.g., Cai *et al.*, 2009; Wu *et al.*, 2009; Hammache *et al.*, 2010; Lu *et al.*, 2011; Subramanyan *et al.*, 2011). Sayyaadi *et al.* (2011) have used a fuzzy approach for selection of one solution from the obtained Pareto-optimal front.

3.6 MOO Applications in Renewable Energy

Currently, several countries are focusing on energy production using renewable energy sources. Biodiesel and bioethanol are the main liquid biofuels. Design and operation of these processes have been considered for MOO (Table 3.5). For example, ethanol production using second generation feed-stocks was optimized by Chen and Wang (2010), and Sharma

Table 3.3 *Multi-objective optimization applications in the biotechnology, food and pharmaceutical industries.*

	Application	Objectives	Method(s)	Comments	Reference(s)
1	Energy and flux balance for large-scale metabolic networks	Bi-objective problems from max.: albumin synthesis, urea secretion, ATP synthesis, NADPH synthesis and glutathione synthesis	NNC method	MOO studies were carried out for gluconeogenic and glycolytic hepatocytes. MOO analysis may explain some features of metabolic control of hepatocytes.	Nagrath *et al.* (2007)
2	Lactic acid production using extractive fermentation	Max. overall productivity, max. conversion and max. yield	Fuzzy approach and hybrid DE	Continuous fermentation processes (with and without extraction and cell recycling) were studied. Cell recycling significantly increases productivity of fermentation process for lactic acid.	Lin and Wang (2008)
3	Ethanol biosynthetic pathway	Max. ethanol production and min. metabolic burden	Modified SPEA	S-system and generalized mass action kinetic models were compared with Michaelis–Menten type approach.	Link *et al.* (2008)
4	Baking of flat bread in an impingement oven	Four objectives to min. variations of crumb temperature, moisture content, surface color change and relative volume from their respective targets	MO GA	An ANN was developed using experimental data, and then used in the optimization of jet temperature, velocity, and baking time to achieve the desired qualities of bread.	Banooni *et al.* (2009)
5	Scheduling dispensing and counting in pharmaceutical manufacturing	Simultaneous min. of maximum lateness, make-span and number of late jobs	Greedy algorithm and variable neighborhood descent	The proposed methodology rapidly automates and improves the production scheduling process in secondary pharmaceutical manufacturing.	Ciavotta *et al.* (2009)

(*continued*)

Table 3.3 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
6	Baking system	Bi- and tri-objective problems from crispness, brownness and moisture content	WS method	Two cases were studied. Use of MOO approach can improve the flexibility of the baking system.	Hadiyanto *et al.* (2009)
7	Protein recovery using a liquid-solid circulating fluidized bed ion-exchange system	Bi- and tri-objective problems from max. fraction of protein recovered, max. production rate and min. amount of solid required	NSGA-II-aJG	A sensitivity analysis was performed to check model robustness and effects of variables on objectives. Tri-objective optimization results are more meaningful than bi-objective results.	Mazumder *et al.* (2009)
8	*De novo* drug design	Min. binding affinity to ER (estrogen receptor)-alpha and max. binding affinity to ER-beta	MO evolutionary graph algorithm (MEGA)	MEGA combines EA with graph design for de novo drug design. It was used to design a molecule which shows selectivity for two target receptors (i.e., negative and positive targets).	Nicolaou *et al.* (2009)
9	Flux balancing for metabolic network analysis	Max. poly(3-hydroxybutyrate) production rate and 2-dehydro-3-deoxy-phosphogluconate aldolase (EDA) flux; Max. succinic acid production and max. biomass production	Noninferior set estimation (NISE)	NISE method was adapted for solving MO flux balance analysis, and was used for two applications. NISE was more efficient than ε-constraint method for the applications studied.	Oh *et al.* (2009)
10	Whey fermentation for lactose oxidation	Max. productivity and min. cost of substrate	Fuzzy approach with random search	Optimal profile of feed flow rate was obtained.	Petrov and Ilkova (2009)

11	Metabolic productivity	Max. cellular metabolic productivity and min. Gibbs free energy	NSGA-II-JG and GA in MATLAB toolbox	Cellular metabolic productivity and Gibbs free energy are not conflicting in nature.	Xu *et al.* (2009)
12	Thermal sterilization for packaged foods	Max. thiamine retention, Max. texture retention and min. process time	Aggregating function with random search	Several aggregating functions were studied on test problems and for the application. Optimal retort temperature profiles were obtained.	Abakarov *et al.* (2009)
13	Production of probiotic biomass, lipase and endospores	Max. biomass, max. lipase and max. spore yields	GA	Effect of operating conditions on formation of biomass, endospores and lipase by Bacillus coagulans RK-02, was studied experimentally.	Das *et al.* (2010)
14	Bioremediation of Cr(VI)	Min. cost of treatment and min. treatment time	GA (MATLAB tool box)	Batch and continuous bioremediation experiments were carried out using indigenous microorganisms, and a model was developed for optimization.	Jeyasingh (2010)
15	Multi-product biosynthesis factory	Max. serine synthesis flux ratio and max. tryptophan synthesis flux ratio	NSGA-II	A model for predicting serine and trptophan flux ratios in *E. coli* was developed. Results obtained by optimization are consistent with fermentation studies in the literature.	Lee *et al.* (2010)
16	Reduce aggregation of protein	Max. relative area of dimer peak after 48 hours and max. shelf life	Aggregate objective and GA	An ANN was used to model experimental data, before its use for optimization.	Khan *et al.* (2011)

(*continued*)

Table 3.3 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
17	Biological networks	Five objectives related to biological behavior	Distributed cooperation model of MO GA	A dynamic model for the yeast-cell cycle was optimized to find kinetic parameters.	Maeda *et al.* (2011)
18	Glycopeptide antibiotic production	Max. product concentration and min. production media cost	ε-constraint method	Two parameters in the model were estimated using experimental data. Then, the model was used to optimize batch and fed-batch fermentation operation. One Pareto-optimal solution was validated experimentally.	Maiti *et al.* (2011)
19	Gene knockout strategies for *E. coli*	Max. ATP, target metabolic and biomass productions, and min. nutrient uptake, redox production and Euclidean norm	Power law type composite objective function	Reduced model of central metabolism from the literature, having 72 metabolites and 95 reactions, was used in the optimization.	Maria *et al.* (2011)
20	Penicillin V production	Min. weighted sum of unit production cost (UPC) and TCI, and min. environmental index; min. UPC and TCI.	MO GA	Process was simulated in SuperPro, and it was interlinked with MATLAB for optimization purposes.	Taras and Woinaroschy (2011)

21	Mode and flow rate trajectories for bioreactor operation	Simultaneously max. yield and productivity	NSGA-II	A methodology for finding optimal mode and flow-rate trajectories of a bioreactor, was presented and illustrated on three case studies.	Mandli and Modak (2012)
22	Product development in pharmaceutical industry	Bi- and tri-objective problems from: max. NPV, min. risk and min. make-span	NSGA-II	NSGA-II was coupled with a discrete event simulator. The approach considers uncertainty and risk involved, and also gives flexibility in decision making.	Perez-Escobedo *et al.* (2012)
23	Falling-film evaporator system for milk concentration	Min. TCC and AOC	NSGA-II in MS Excel	An Excel based MOO algorithm was developed and tested. Both discrete and continuous variables were considered for tube length and diameter.	Sharma *et al.* (2012)
24	Design of bioprocesses	Min. unit production cost, min. capital investment, min. environmental impact, max. L-lysine concentration, min. biomass concentration	NIMBUS with GA	Interactive MOO framework was developed using NIMBUS, GA (in Matlab) and SupePro. It was applied to optimize L-lysine production.	Taras and Woinaroschy (2012)
25	Experimental design of dynamic bioprocesses	Bi-, tri- and four-objective problems from: A-, D-, E-, M- and ME-criteria, correlation, production and tracking objective	ACADO toolkit	The proposed MOO approach was illustrated on a fed-batch bioreactor and LotkaVolterra fishing model. The results obtained can be used in decision making.	Telen *et al.* (2012)

Table 3.4 *Multi-objective optimization applications in power generation and CO_2 capture.*

	Application	Objectives	Method(s)	Comments	Reference(s)
1	Energy network	Max. NPV and min. CO_2 emissions	ε-constraint method	Substitution of coal with bagasse was considered, and the analysis shows that this can meet the renewable energy target of South Africa.	Beck *et al.* (2008)
2	Environmental / economic dispatch	Min. emissions (NO_x) and min. fuel cost	MO chaotic PSO (MOCPSO)	Proposed MOCPSO performed better than MO PSO.	Cai *et al.* (2009)
3	Coal-fired boiler	Min. NO_x emissions and min. heat-rate penalty	NSGA-II	Support vector regression was used for modeling a 160 MW unit. After MOO, boiler, selective catalyst reaction system and air preheater were optimized using GA for lowest operating cost.	Si *et al.* (2009)
4	Coal-fired utility boiler	Min. unburned carbon in fly ash and min. NO_x emissions	MO cellular GA (MOCell) and NSGA-II	Support vector regression was used for predicting NO_x emissions and unburned carbon in fly ash, of a 300 MW boiler. MOCell gives better distribution of nondominated solutions compared to NSGA-II.	Wu *et al.* (2009)
5	CO_2 capture and sequestration (CCS)	Min. total cost of CCS and max. sequestrated volume of CO_2	Mixed Integer Programming	Case study described is for Jing-Jin-Ji region of China.	Zheng *et al.* (2009)

6	Natural gas combined cycle with CO_2 capture using monoethanolamine	Min. cost of energy and min. lifecycle global warming potential	EA based on queuing and clustering	A simple gas turbine model, CO_2 capture model in Aspen Plus and process integration model (for finding net steam turbine power output, number of exchangers and total heat exchange area) were employed together.	Bernier *et al.* (2010)
7	Black liquor gasification combined cycle	Max. total exergetic efficiency and min. product cost	MO EA	Replacement of recovery boiler with a gasifier reduces the product cost.	Fani *et al.* (2010)
8	Cogeneration plant (CGAM problem)	Max. exergy efficiency, min. total cost (including pollution tax rate) and min. specific pollutant rate	MOSAHiC	MOSAHiC (multi-objective self-adaptive algorithm for highly constrained problems) performed better than NSGA-II on six unconstrained and two constrained test functions.	Hammache *et al.* (2010)
9	Injection system for low-emission combustors	Min. CO and min. NO_x emissions	SPEA	ANN model was first developed based on CFD simulations. MOO reduces both objectives compared to their values for the existing lean premixed, prevaporized injection system.	Laraia *et al.* (2010)

(*continued*)

Table 3.4 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
10	Power and cogeneration technology—NGCC and CHP	Min. specific investment cost and min. CO_2 emissions	Queuing MO optimizer (QMOO)	Different power-generation techniques for natural gas combined cycle (NGCC) plants were evaluated based on their thermodynamics, economics and CO_2 emissions. Li *et al.* (2010b) considered combined heat and power (CHP) plant.	Li *et al.* (2010a and 2010b)
11	Methanol / electricity polygeneration system	Max. NPV and min. greenhouse gases (CO_2 equivalent)	ε-constraint method	Superstructure and global optimization are used. Certain technological combinations are found to be better than others under specific circumstances.	Liu *et al.* (2010)
12	Integrated gasification combined cycle (IGCC) plant	Max. plant efficiency, min. CO_2 emission and min. SO_x emission	Parameter space investigation approach using stochastic simulation	CFD model of coal gasifier was developed, and stochastic CFD simulation results were compared with those for an approximate gasifier model in ASPEN Plus. Both deterministic and stochastic MOO were performed.	Shastri and Diwekar (2011)
13	ALSTOM gasifier	Min. IAE (integral of absolute error) index for six different scenarios	NSGA-II	A nondominated solution, which allows the largest coal quality variation under disturbance and load conditions, was selected.	Xue *et al.* (2010)

14	Natural gas-fired combined cycle power plant	Max. plant exergy efficiency, min. total cost rate and min. CO_2 emissions	NSGA-II	Supplementary firing at the inlet of the heat recovery steam generator increases efficiency of natural gas-fired combined cycle power plant.	Ahmadi *et al.* (2011)
15	Gas turbine power plant with preheater	Min. total cost rate, max. exergy efficiency and min. CO_2 emissions	NSGA-II	Sensitivity analysis of the obtained nondominated solutions was performed.	Barzegar Avval *et al.* (2011)
16	Retrofit of a pulverized coal power plant	Min. levelized cost of electricity and min. water use	NSGA-II	Retrofitting of a hypothetical 550 MW plant with CO_2 capture (using MEA) and compression system was studied.	Eslick and Miller (2011)
17	Solvent absorption carbon capture plants	Max. net power and max. CO_2 capture rate; max. CO_2 capture rate and min. cost of electricity	NSGA-II	Combined simulation, heat integration and optimization, is used to optimize a power plant with CO_2 capture and sequestration technology.	Harkin *et al.* (2011)
18	Environmental / economic dispatch problem	Min. fuel cost and min. emission effects	Enhanced MO DE and MO DE	Enhanced MO DE, which uses a local random search operator to reach near to the Pareto-optimal front, performed better than MO DE.	Lu *et al.* (2011)
19	Steam and power system of an ethylene plant	Min. PEI (potential environmental index) and min. operating cost	ε-constraint, WS, minimum distance to utopia point and global criterion method	Generating complete Pareto-optimal front is important. For the ethylene utility plant studied, the Pareto-optimal front has two regions, which are important for decision making.	Martinez and Eliceche (2011)

(*continued*)

Table 3.4 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
20	Integrated gasification combined cycle plant	Min. cost of energy and max. energy efficiency; Max. energy efficiency and min. IMPACT 2002+	–	Sixteen scenarios from the combination of four different feed-stocks and four alternative plant topologies for electricity and hydrogen production were analyzed.	Perez-Fortes *et al.* (2011)
21	Cogeneration system (CGAM problem)	Max. exergetic efficiency, min. cost rate of product and min. environmental impact	MO PSO and NSGA-II	A fuzzy approach was used for selecting one solution from a set of non-dominated solutions, and it was compared with the nearest solution approach.	Sayyaadi *et al.* (2011)
22	Distribution network planning	Min. total cost of electricity and min. total emissions	NSGA-II and Immune-GA based method	Fuel cells, micro turbine and gas turbine were considered for producing electricity.	Soroudi *et al.* (2011)
23	Power and hydrogen coproduction with CO_2 capture	Min. CO_2 emissions, max. current density of solid oxide fuel cell and max. efficiency	Minimization of SOO problems (MINSOOP)	Stochastic modeling and MOO were implemented in the Advanced Process Engineering Simulator of National Energy Technology Laboratory (NETL), and then used for the application.	Subramanyan *et al.* (2011)
24	Distributed generation planning	Max. profit, min. weighted sum of technical violation risk and min. annual amount of pollutant gases	NSGA-II	Photovoltaic, wind turbine, fuel cell, micro turbine, gas turbine and diesel engine were considered for electricity production. Performance of three distribution scenarios was compared.	Zangeneh *et al.* (2011)

25	Natural gas combined cycle plant	Min. cost of electricity and min. global warming potential	EA based on queuing and clustering	Fossil natural gas with mitigation options, and fossil and synthetic natural gases with CO_2 capture were explored using a process model, lifecycle assessment and MOO.	Bernier *et al.* (2012)
26	Pulverized coal power plant	Min. total cost of plant and min. global/local environmental impact	ε-constraint method	Design of pollution control devices for retrofitting power plants, using MOO was developed and illustrated on a 500 MW plant.	Cristobal *et al.* (2012)
27	Combined power and desalination plant design	Max. exergetic efficiency, min. total cost rate of products and min. environmental impacts	MO GA	MOO, reliability and sensitivity analyses of a combined gas turbine (65 MW) and multi-stage desalination plant (42,165 m^3/day), were performed.	Hosseini *et al.* (2012)
28	Combined power and desalination plant design	Max. total exergetic efficiency and min. total cost of products	MO GA	A plant for 40 MW power and 14,000 m^3/day of fresh water was modeled and optimized. Air preheating requires higher capital investment but improves both objectives.	Shakib *et al.* (2012)

Table 3.5 *Multi-objective optimization applications in renewable energy.*

	Application	Objectives	Method(s)	Comments	Reference(s)
1	Renewable energy system for pollution mitigation	Min. production cost and min. environmental impact	MOO methodology	Photovoltaic, wind turbine and bio-gasifier plant were considered for Kavaratti island in India.	Ashraf *et al.* (2008)
2	Biomass (wood) gasification plant of 40 MW capacity	Tradeoff between total investment cost and exergy efficiency	MOO-LENI	Air, oxygen and steam for gasification, internal combustion engine and gas turbine combined cycle were considered. Further, operating conditions for minimum tar formation were identified.	Brown *et al.* (2009)
3	Synthetic natural gas (SNG) from wood	Max. SNG production, max. electricity output and min. grass-roots cost	MOO-LENI	The proposed methodology was suitable for conceptual design of biofuel plants considering heat integration.	Gassner and Marechal (2009)
4	Corn-based ethanol supply chain in Italy	Min. total daily impact over the entire life cycle and min. operating costs	CPLEX/GAMS	Supply chain includes biomass cultivation, drying, storage and transport, and ethanol production and distribution.	Zamboni *et al.* (2009)
5	Bio-ethanol by continuous fermentation with cell recycling and extraction	Max. ethanol productivity, max. glucose conversion and max. xylose conversion	Fuzzy goal attainment approach with HDE	Addition of inter-stage extraction enhances fermentation process. Sensitivity of optimal solution was performed. It was found that dilution rate and substrate concentration in feed are the most important decision variables.	Chen and Wang (2010)

6	Biodiesel production	Max. purity of products and min. energy requirements	MO GA	Two alkali-catalyzed processes using vegetable oil as feedstock were optimized and compared.	Di Nicola *et al.* (2010)
7	Small hybrid power systems with renewable energy	Min. cost of energy and min. greenhouse gas emissions of the system during its lifetime	NSGA-II	Lead acid batteries and hydrogen storage as well as several types of electricity production were considered.	Katsigiannis *et al.* (2010)
8	Load dispatch of power systems	Min. coal consumption, min. pollutants emission, min. CO_2 emissions and min. retrofit cost of the power system	WS method	Load dispatch of a power system was optimized by including carbon capture and renewable energies. Effects of weights and forecast load demand were studied.	Yongping *et al.* (2010)
9	Bioethanol by continuous fermentation with cell recycling	Max. ethanol productivity and max. glucose conversion	Fuzzy goal attainment approach with HDE	For optimal design, sensitivity of each objective and constraint with respect to decision variables was studied. Dilution rate and glucose concentration in feed are the most important decision variables.	Wang and Lin (2010)
10	Integrated solar combined cycle system in a 400 MW plant	Max. exergetic efficiency and min. total cost rate of operation	MO EA	One solution was selected from the Pareto-optimal front. Sensitivity of non-dominated solutions was performed for fuel cost, interest rate, construction period and solar operation period.	Baghernejad and Yaghoubi (2011)

(*continued*)

Table 3.5 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
11	Regional biomass and bioenergy supply chains	Six MOO problems: max. profit and min. one footprint for carbon, water, land, energy, water pollution or food-to-energy	ε-constraint method	Different feedstocks, heat and power integration, and technology integration were considered in the biomass and bio-energy supply chain network.	Cucek *et al.* (2011)
12	Combined synthetic natural gas (SNG) and electricity production	Max. profit from biomass and min. environmental impact indicator (ecoscarcity06 and EI 99)	MO EA	Effects of configuration, integration, efficiency and plant scale on environment were studied. Ecoscarcity06 favors electricity production, whereas EI 99 favors SNG production.	Gerber *et al.* (2011)
13	Supply chain for ethanol using first- and second-generation feedstock	Max. NPV and min. total greenhouse gas emissions	CPLEX/GAMS	A case study for Northern Italy is reported. First generation technology is economical, but second generation or hybrid infrastructures are required to meet EU targets for global warming mitigation. Giarola *et al.* (2012) studied optimization with and without green credits; they also considered different technologies as decision variables.	Giarola *et al.* (2011), and Giarola *et al.* (2012)
14	Supply chain for sugar and ethanol from sugarcane in Argentina	Max. NPV and min. global warming potential GWP100; max. NPV and min. EI 99	ε-constraint method	Operating conditions and supply chain topology affect environmental burden. LCA-based environmental indicators: GWP100 and EI 99 are also conflicting.	Mele *et al.* (2011)
15	Biomass conversion system planning	Max. profit and min. environmental burden (EI 99)	ε-constraint method using CPLEX/GAMS	Model for selecting feedstock, processing technology and products to optimize economic and environmental objectives, was described and applied to planning of a bio-refinery in Mexico.	Santibaez-Aguilar *et al.* (2011)

16	Biodiesel and chemicals from rapeseed oil	Max. NPV and min. environmental impact	ε-constraint method	Four choices for crude glycerine (waste, 80% purity, 95% purity and succinic acid production) were considered. Sensitivity analysis for variation in prices of important materials was also performed.	Vlysidis *et al.* (2011)
17	Bioethanol using cold enzyme starch hydrolysis	Max. cell mass concentration, max. ethanol concentration and max. starch utilization ratio	WS method	Response surface methodology was employed to model experimental results. Cold enzyme hydrolysis has potential for bio-ethanol industry.	Yingling *et al.* (2011)
18	Biomass-to liquids supply chain	Min. annualized total cost and min. greenhouse-gas emissions	ε-constraint method	Distributed, centralized and distributed-centralized processes were considered and illustrated for Iowa state. Conversion technologies need to be improved for commercial production of liquid transportation fuels from biomass.	You and Wang (2011)
19	Solar Rankine cycles with reverse osmosis desalination	Min. specific environmental impact and min. specific total cost	ε-constraint method	Coupling reverse osmosis with solar collectors can reduce environmental impact significantly but total cost increases slightly.	Salcedo *et al.* (2012)
20	Bioethanol by fermentation integrated with pervaporation	Max. ethanol productivity and max. xylose conversion	MO DE	Integration of pervaporation with fermentation improves ethanol production significantly. Further, use of pervaporation was found to be better than inter-stage extraction for continuous ethanol removal from the fermentor.	Sharma and Rangaiah (2012)
21	Design and operation of a biodiesel plant	For design: max. profit and min. fixed capital investment; for operation: max. profit and min organic waste	MO DE with tabu list	A biodiesel plant, using waste cooking oil as feedstock, was optimized for economic and environmental objectives. Further, for a selected design, operation optimization was performed to explore the effect of feed flow rate variation.	Sharma and Rangaiah (2013)

and Rangaiah (2012). Biomass-based gasification plants and synthetic natural gas from wood were also optimized for multiple objectives. MOO studies on supply chains for biomass, bio-energy and bio-fuels were also reported (e.g., Zamboni *et al.*, 2009; Cucek *et al.*, 2011).

Some of the studies summarized in Table 3.5 focused on optimization of individual units (e.g., Yingling *et al.*, 2011), whereas others considered optimization of complete plants (e.g., Gerber *et al.*, 2011). In total 22 articles related to MOO of renewable energy production were reported from the year 2007 to June 2012. Important objectives employed in these studies are cost, energy efficiency, water consumption, environmental impact, productivity and conversion. Most of the reported studies in Table 3.5 used MOO methods from the literature, and both deterministic and stochastic approaches are equally used in these studies.

3.7 MOO Applications in Hydrogen Production and Fuel Cells

In this category, a total of 19 MOO studies were published from the year 2007 to June 2012 (Table 3.6). MOO applications relating to hydrogen production include methane steam reforming, photovoltaic-battery-hydrogen storage system and hydrogen plant with CO_2 absorber. In these applications, hydrogen production rate, energy cost and CO_2 emission are considered as objectives.

Fuel cells have high conversion efficiency compared to traditional technologies. Since the early 2000s, several studies have improved the design and operation of different types of fuel cells for multiple objectives. These studies considered both individual fuel cells (polymer electrolyte membrane fuel cells, solid oxide fuel cells, alkaline fuel cells, fuel cell electrode assembly, phosphoric acid fuel-cell systems, molten carbonate fuel cell) and their systems. The cost of fuel-cell systems, efficiency, current density and size of stack were used as objectives in the design and operation of fuel cells (Table 3.6).

Distributed energy systems and supply chains were optimized for multiple objectives by a few researchers (Ren *et al.*, 2010; Sabio *et al.*, 2010). MOO techniques used in the applications summarized in Table 3.6 are mostly those developed by other researchers, and they include both deterministic and stochastic methods.

3.8 Conclusions

This chapter summarized reported applications of MOO in chemical engineering in the five years since the review by Masuduzzaman and Rangaiah (2009). There have been recent applications of MOO in the areas of fuel cells, power plants and renewable energy. Nowadays, considerable attention is given to energy, environment and safety as performance objectives. A total of 232 articles were published in different journals from the year 2007 to June 2012; hence, on average, about 40 applications of MOO are reported yearly in this period. In some reported studies, earlier application problems were modified, and then the process was optimized using the same or improved algorithms whereas, in other reported studies, new applications were optimized for the first time for multiple

Table 3.6 *Multi-objective optimization applications in hydrogen production and fuel cells.*

	Application	Objectives	Method(s)	Comments	Reference(s)
1	PEM (polymer electrolyte membrane) fuel cell	Tradeoff between efficiency and cost of the fuel cell system	fminimax in MATLAB optimization tool box	Current density greatly influences both objectives for the 50 kW system studied.	Na and Gou (2007)
2	Solid oxide fuel cell system of 50 kW	Min. investment cost and max. efficiency	MOO-LENI	Optimal fuel cell system configurations have excess heat at high temperature, which can be converted into electricity.	Palazzi *et al.* (2007)
3	Methane steam reforming for H_2 production	Max. H_2 production rate and max. recovery yield; Max. H_2 production rate and min. sweep gas flow rate	NSGA	Use of steam as the sweep gas in the membrane reactor can produce more H_2 at higher yield, compared to N_2 sweep gas.	Yu *et al.* (2007)
4	Methanol synthesis and H_2 production	Max. major product rate, min. major reactant rate and min. exergy loss	NSGA-II	Catalytic membrane reactors were analyzed for two applications. For methanol synthesis, nondominated solutions are scattered, whereas Pareto-optimal front is linear for H_2 production.	Cheng *et al.* (2008)
5	Fuel cell membrane electrode assembly	Max. cell current density at given voltage and min. production costs.	WS method	Only a range of specific designs gives good tradeoff between costs and performance.	Secanell *et al.* (2008)

(*continued*)

Table 3.6 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
6	Phosphoric acid fuel system	Min. volumetric flow rate of fuel gas and min. volumetric flow rate of oxidant gas	Similar to ε-constraint method	Linear regression and ANN models were developed based on CFD simulations, and then used in the optimization.	Zervas *et al.* (2008)
7	PEM fuel cell system	Tradeoff between efficiency of stack and size of stack	WS method using LINDOGlobal	The effective size-efficiency tradeoff should have efficiency between 40–47%.	Ang *et al.* (2010)
8	Photovoltaic-battery-hydrogen storage system	Min. total annual cost and min. quantity of electricity exchanged with grid	MO PSO	For a remote island in France, different sources/ combinations of energy generation are suggested for short and medium terms.	Avril *et al.* (2010)
9	Tubular solid oxide fuel cell	Max. gravimetric and also volumetric power densities	Lexicographic approach using fmincon in MATLAB	Model was validated against experimental data. Significant improvement is possible in the volumetric power density compared to the gravimetric density.	Bhattacharyya and Rengaswamy (2010)
10	Industrial H_2 plant with CO_2 absorber and methanator	Max. H_2 production and also export steam flow rate	MO GA/NSGA (in MATLAB tool box)	Studied process consists of steam reformer, shift convertors, CO_2 absorber and methanator (instead of PSA). Model results are comparable to industrial data.	Montazer-Rahmati and Binaee (2010)

11	Solid oxide fuel cell reactor for oxidative coupling of methane	Bi- and tri-objective problems: max. C_2 (ethane and ethylene) production, min. production of side products and max. power	NSGA-II-aJG	Decision variables were selected based on the sensitivity analysis. MOO improves the present operation (i.e., C_2 production increased by 95% with a slight increase in side products).	Quddus *et al.* (2010)
12	Distributed energy system	Min. energy cost and min. CO_2 emission.	Compromise Programming	Photovoltaic, fuel cell and gas turbine were considered for electricity production.	Ren *et al.* (2010)
13	Strategic planning with risk control of H_2 supply chains	Min. expected total discounted cost and min. specific financial risk (worst case)	ε-constraint method	In the problem formulation, several technologies for H_2 production, storage and transportation, were considered.	Sabio *et al.* (2010)
14	Biogas-fueled hybrid system for electricity and hydrogen production	Min. electricity cost and max. plant efficiency	–	Molten carbonate fuel cell system was integrated with micro gas turbine (for electricity) and PSA for H_2 production. Pinch analysis was used for optimal configuration of heat exchangers.	Verda and Nicolin (2010)
15	PEM fuel cell for vehicles	Max. produced work, max. energy efficiency, max. exergy efficiency and min. cost of work produced	WS method using GA	Hydrogen-fueled fuel cell with 68 kW capacity was studied. Objectives were normalized. 48 sets of different weights were used to get alternative designs.	Mert *et al.* (2011)

(*continued*)

Table 3.6 *(Continued)*

	Application	Objectives	Method(s)	Comments	Reference(s)
16	Molten carbonate fuel cell system coupled with H_2 production	Min. unit cost of electricity and max. electrical efficiency	–	Pinch analysis was used for optimal configuration of heat exchangers, and ANN model was employed in one step of optimization. Optimization was performed for the lifetime of the system.	Nicolin and Verda (2011)
17	PEM fuel cells	Min. non-uniformity of the flow field and min. sensitivity of flow rates in the middle equivalent channel	WS method	Gas diffusion layer deformation greatly affects the flow distribution.	Peng *et al.* (2011)
18	Alkaline fuel cell (AFC)	Tradeoff between efficiency and power	Product with a weighting factor ($F = F_1^{weight} F_2$)	Power output and efficiency equations were derived. An optimum electrolyte concentration exists at different temperatures of AFC.	Zhang *et al.* (2011a)
19	Molten carbonate fuel cell	Tradeoff between power and efficiency	Product with a weighting factor	Equations for cell voltage, power output, efficiency and entropy production rate were derived.	Zhang *et al.* (2011b)

objectives. NSGA-II and related algorithms are commonly used by researchers to optimize the performance of studied processes for multiple objectives. Some researchers have developed problem-specific optimization methodologies. Only a few published works considered selection of one solution from the set of tradeoff solutions. This could be due to some subjectivity involved in the selection. However, this also indicates the need for further research on selection of one solution for implementation from the Pareto-optimal front.

Acronyms

ANN – artificial neural network
BB – branch and bound
DE – differential evolution
EA – evolutionary algorithm
EI 99 – eco-indicator 99
GA – genetic algorithm
GAMS – general algebraic modeling system
HDE – hybrid differential evolution
LINGO – linear interactive general optimizer
max. – maximization
min. – minimization
MO – multi-objective
MOO – multi-objective optimization
NBI – normal boundary intersection
NNC – normalized normal constraint
NPV – net present value
NSGA-II – nondominated sorting genetic algorithm
PSO – particle swarm optimization
SA – simulated annealing
SPEA – strength Pareto evolutionary algorithm
SQP – sequential quadratic programming
WS – weighted sum

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