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A COMPREHENSIVE SURVEY: APPLICATIONS OF MULTI-OBJECTIVE PARTICLE SWARM OPTIMIZATION (MOPSO) ALGORITHM

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Abstract. Numerous problems encountered in real life cannot be actually formulated as a single objective problem; hence the requirement of Multi-Objective Optimization (MOO) had arisen several years ago. Due to the complexities in such type of problems powerful heuristic techniques were needed, which has been strongly satisfied by Swarm Intelligence (SI) techniques. Particle Swarm Optimization (PSO) has been established in 1995 and became a very mature and most popular domain in SI. Multi-Objective PSO (MOPSO) established in 1999, has become an emerging field for solving MOOs with a large number of extensive literature, software, variants, codes and applications. This paper reviews all the applications of MOPSO in miscellaneous areas followed by the study on MOPSO variants in our next publication. An introduction to the key concepts in MOO is followed by the main body of review containing survey of existing work, organized by application area along with their multiple objectives, variants and further categorized variants.

1. Introduction

Swarm Intelligence (SI) is mainly defined as the behaviour of natural or artificial self-organized, decentralized systems. Swarms interact locally with each other or with external agents i.e. environment and can be in the form of bird flocks, ants, bees etc. Introduced by [85] for optimizing continuous nonlinear functions, Particle Swarm Optimization (PSO) defined a new era in SI. PSO is a population based method for optimization. The population of the potential solution is called as swarm and each individual in the swarm is defined as particle. The particles fly in the swarm

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to search their best solution based on experience of their own and the other particles of the same swarm. PSO started to hold the grip amongst many researchers and became the most popular SI technique soon after getting introduced, but due to its limitation of optimization only of single objective, a new concept Multi-Objective PSO (MOPSO) was introduced, by which optimization can be performed for more than one conflicting objectives simultaneously. MOPSO was proposed by [129] to optimize more than one objective functions. In MOPSO instead of a single solution a set of solutions are determined, also called pareto optimal set. Multi-Objective Optimization (MOO) is sometimes called as vector optimization, since the vector of objectives is optimized instead of a single objective. Multi-objective Optimization Problem (MOP) is basically classified in two ways i.e. Linear and Nonlinear MOP, Convex and Non-Convex MOP. When all objective functions and constraints are linear, then Linear MOP is defined, but if any of the objective or constraint function is nonlinear, then it is a Nonlinear MOP. Likewise if all the objective functions are convex and the feasible region is convex, then it is defined as Convex MOP and for Non-Convex MOP its vice-a-versa. Till date many variants and applications for MOPSO have been developed. The developed applications are in the area of environment, industries, job shop scheduling, engineering, biology and many others. It is not possible to discuss all MOPSO variants and applications in one article; hence the MOPSO study is divided in two parts: applications of MOPSO and variants of MOPSO. In this paper it is tried to summarize all the applications areas of MOPSO, which will be able to provide cognizance for the researchers working in related fields. The remainder of the paper is structured as follows: Section 2 and 3 present the basic concept and algorithm for MOP and standard PSO respectively. Section 4 provides the algorithm, formulation and concepts of MOPSO. Section 5 deals with a bulk of survey material organized by application areas of MOPSO. Section 6 discusses our findings and issues arising from the survey with the future direction to work and concludes.

2. Multi-Objective Optimization

MOP has a number of objectives and usually constraints also. The constraints are needed to be satisfied by any feasible solution (including the optimal solution). MOP is formulated as:

$$\begin{aligned} Minimize/Maximize\ f_n(x), n = 1, 2, \ldots, N; \\ \textit{subject to } g_j(x) \geq, j = 1, 2, \ldots, J; \\ h_k(x) = 0, k = 1, 2, \ldots, K; \\ x_i^{(L)} \leq x_i \leq x_i^{(U)}, i = 1, 2 \ldots, m. \end{aligned} \tag{1}$$

A solution x is a vector of m decision variables $x = (x_1, x_2, ...x_m)^T$. The first set of constraints is inequality constraint for the minimization problem, whereas for maximization problem this constraint converts to less than equals to i.e. $\leq$. Next set of constraints is the equality constraints followed by the last set of constraints called variable bounds, restricting each decision variable x_i to take a value within a lower $x_i^{(L)}$ and an upper $x_i^{(U)}$ bound. In general, for solving the MOPs classical and Artificial Intelligence (AI) techniques are used. Two most popular AI techniques for solving MOPs are Evolutionary Approaches (EAs) and PSO. The EAs along with classical methods are described in this section and PSO in the next section.

2.1. **Classical methods.** The classical methods in order of increasing use of preference information are: Weighted sum method; ε-Constraint method; Weighted metric method; Bensons method; Value function method and Goal programming method. In weighted sum method objectives are scalarized into single objective by pre-multiplying each objective with a user supplied weight. ε-constraint method alleviate the difficulties faced by the weighted sum approach in solving the problems having non-convex objective spaces, by reformulating the MOP by just keeping one of the objectives and restricting the rest of the objectives within user-specified values. In weighted metric method weighted metric such as l_p and l_∞ distance metrics are often used instead of using a weighted sum of the objectives, so weighted metrics are the means of combining multiple objectives into a single objective. Bensons method is similar to weighted metric approach, except that the reference solution is taken as feasible non-pareto optimal solution. In value function method user provides a mathematical value function $U : R^M \to R$, relating all M objectives. The value function must be valid over the entire feasible search space. Goal programming helps to find solutions which attain a predefined target for one or more objective functions. If there does not exist any solution which achieves pre specified targets in all objective functions, the task is to find solutions which minimize deviations from the targets. But if a solution with desired target exists, the task is to identify that particular solution.

2.2. **Evolutionary Algorithms.** The approaches based on EAs are basically subdivided in three types [40]: Aggregating functions; Population-based approaches; Pareto based approaches. Aggregating functions carry the concept of combining all the objectives in a single objective by any arithmetical operation. Due to the linear aggregation functions these methods are not much impressive. Population based approaches use EA's population to diversify the search. [1] presented Vector Evaluated Genetic Algorithm (VEGA), which is considered as the classical example of population-based approaches. In which at each generation sub-populations are generated by proportional selection. If the total population size is N and n is the total number of objectives, the size of subpopulation will be N/n. Population based approaches are simple to employ but their main limitation is the selection scheme, which is not based on pareto optimality. Pareto based approaches were first suggested by [63]. Then to maintain diversity and avoid convergence, nitching and fitness sharing was suggested by [50]. Pareto based approaches are the most popular approaches, divided in two generations. First generation with the fitness sharing, niching combined with pareto ranking, second generation with notion of elitism.

2.3. **Particle Swarm Optimization v/s Evolutionary Algorithms.** PSO is different from EAs in the sense of differences in parent representation, selection of individuals and approaches to parameter tuning as shown in [8]:

- In PSO parent information is contained within each particle while it is shared in Evolutionary Optimization (EO).

- PSO doesn't involve an explicit selection function from its processing which EO does.
- PSO uses a highly directional mutation operation to manipulate individuals while in EO its omnidirectional.
- There is no mechanism for PSO to adapt its velocity step size to a value appropriate to the local region search space, whereas EO includes the severity of mutation for each individual's component.

Different solutions using different methods may produce conflicting scenarios among different objectives. A solution that is optimum with respect to one objective requires a compromise for other objectives. This emphasizes user to choose a solution which is optimal with respect to only one objective [49]. The main goal of MOO is to find a set of solutions which is close to the optimal solutions and diverse enough to represent the true spread of optimal solutions. MOPSO algorithms fulfill both the previous mentioned conditions more directly. The simplicity, low computation cost and increasing popularity of MOPSO enhance its efficiency to solve simple as well as complex natured real life problems.

3. Particle Swarm Optimization

Considering a search space of d-dimension and n particles, whose i^{th} particle at a particular position $X_i(x_{i1}, x_{i2}, \ldots, x_{id})$ is moving with a velocity $V_i(v_{i1}, v_{i2}, \ldots, v_{id})$. Each particle is associated with its particular best, $P_i(p_{i1}, p_{i2}, \ldots, p_{id})$ which is defined by its own best performance in the swarm. Similarly, an overall best performance of the particle with respect to the swarm defined global best is gbest. Each particle tries to modify its position using the following information:

- Current positions,
- Current velocities,
- Distance between the current position and pbest,
- Distance between the current position and gbest.

The movement of the particle is governed by updating its velocity and position attributes.

$$V_i^{t+1} = wV_i^t + c_1 r_1 (x_{pbest} - X_i^t) + c_2 r_2 (x_{gbest} - X_i^t) \tag{2}$$

$$X_i^{t+1} = X_i^t + V_i^{t+1} \tag{3}$$

where w= inertia weight, c_1= cognitive acceleration coefficient, and c_2= social acceleration coefficient, r_1 and r_2 are the random values between 0 and 1, x_{pbest} is the personal best of the particle and x_{gbest} is the global best of the particle. X_i^t is the current position of i^{th} particle at iteration t. V_i^t is the velocity of i^{th} particle at iteration t. Figure 1 presents the flowchart of PSO algorithm. In standard PSO, a minimization problem is considered which tends to find a parameter set $\vec{x}$ a vector of m decision variables: $x = (x_1, x_2, \ldots, x_m)^t$ for single objective i.e.

$$\begin{aligned} &Minimize/Maximize\ f(x); \\ &subject\ to\ x_i^{(L)} \leq x_i \leq x_i^{(U)},\ i = 1, 2, \ldots, m. \end{aligned} \tag{4}$$

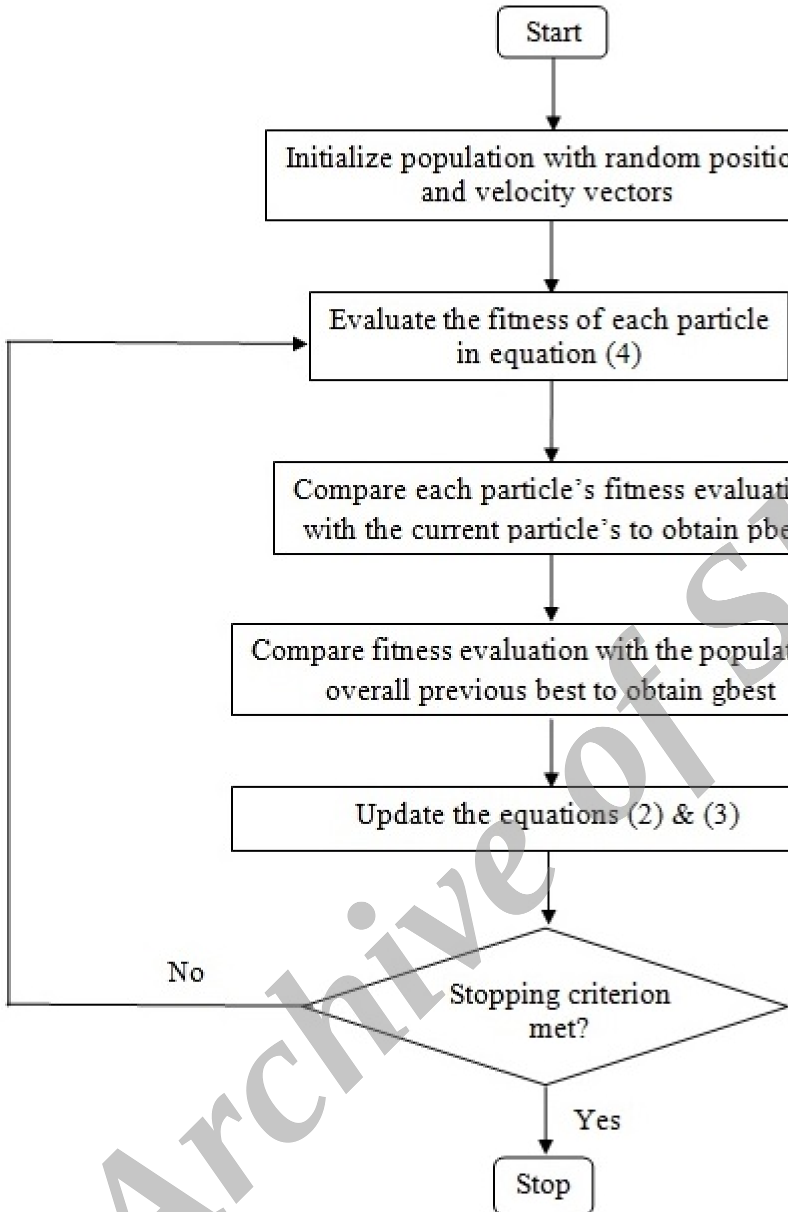

Figure 1. **Particle Swarm Optimization algorithm**

4. Multi-objective Particle Swarm Optimization

In MOPSO velocity update and position update equations remain same as equation (2) and (3) in PSO. All the parameter declared are also same except the objective function. The objective function contains multiple objectives as formulated in equation (1). Figure 2 presents the flowchart of MOPSO algorithm [88] based on a dominance criteria.

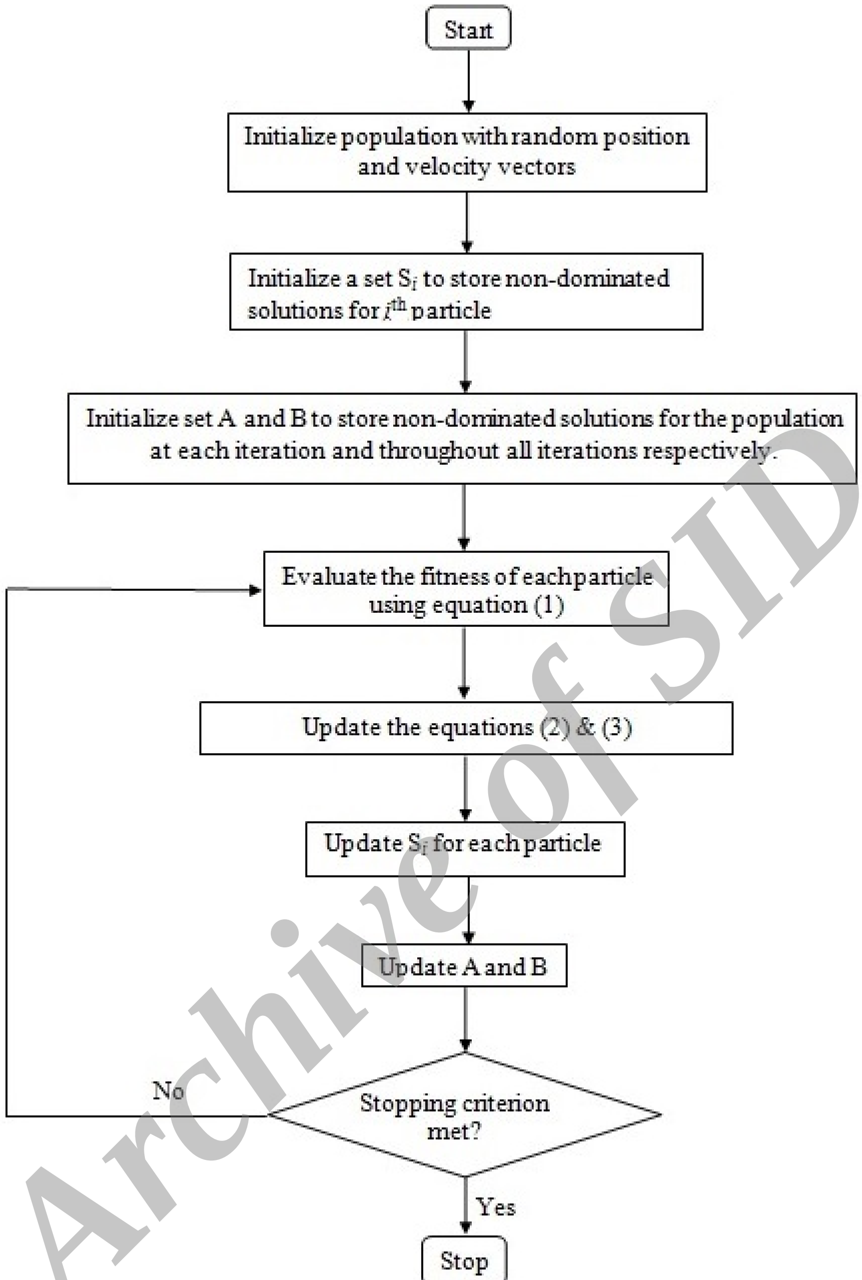

Figure 2. **Multi-objective Particle Swarm Optimization algorithm**

5. Studies on MOPSO Applications

[42] presented the review of literature of MOPSO available till 2006. This section deals with all the literature study done on application areas of MOPSO till date since then, which contains a number of variants developed also. All the literature survey is summarized in table 2.

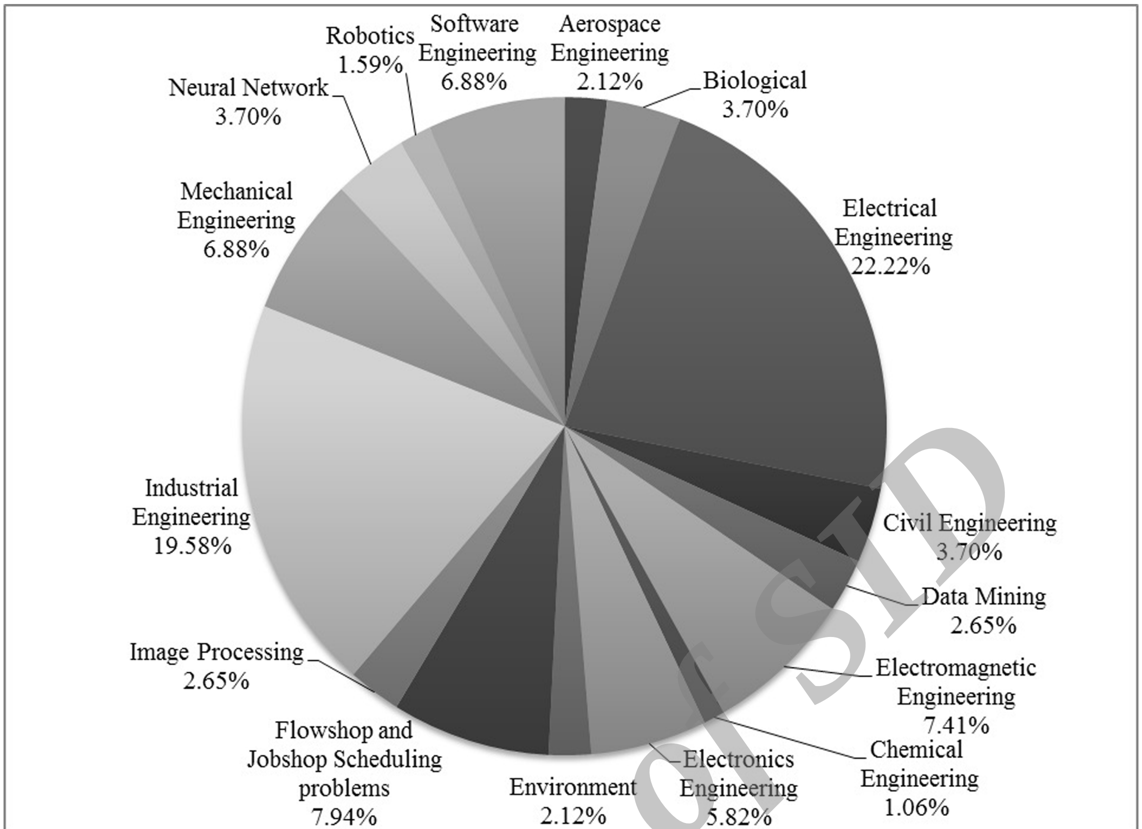

FIGURE 3. **Area wise published applications of MOPSO**

The separation of the articles based on approaches and applications was performed on the basis of as follows: if the article had taken an application MOP problem as the basic problem, then applied any already developed variant for solving it, or incorporated some changes in the algorithm for the same problem, or developed a variant, the article was included in application area; on the other hand if the article is contained more into developing the variant, or mainly after developing the variant it is followed by an example of real world problem, then it was classified in approach. There are some articles which are part of both application and approach due to the newly developed variants, supposed to be discussed in both. This section is divided in sub-sections of application areas as shown in figure 3. The number of papers found using MOPSO for solving below mentioned areas were 189 till the mid of October, 2012. Figure 3 describes the wide applicability of MOPSO in Industrial Engineering, Electrical Engineering and then in other areas.

5.1. **Aerospace Engineering.** [19] applied MOPSO to solve off-line two-dimensional flight path optimizations compliant with operational constraints, using single and MO problem formulation. [73] applied pareto dominance strategy to Vector Evaluated PSO (VEPSO) and formed Elitist VEPSO (EVEPSO) for solving a typical multi-mode resource levelling problem, in which activity duration depends on committed resources, project deadlines and other constraints. [140] performed Multi-Objective (MO) design optimization of laminated composite plates using Message Passing Interface

(MPI). For the purpose they applied architecture-based parallel version of VEPSO algorithm, the essence of the peer-to-peer paradigm model of communication and synchronous evaluation. [203] worked to solve the economic-statistical optimization design of $\bar{X}$ and S charts. Proposed algorithm achieved well-spread pareto optimal solutions for MOP, with fast convergence to true pareto optimal front.

5.2. **Biological Sciences.** [79] applied MOPSO in molecular docking problem, which aims to find a good position and orientation for docking a small molecule to a larger receptor molecule. The intra-molecular energies occurring between the atoms of the flexible ligand was simultaneously to be optimized with the inter-molecular energies between the ligand and the macro-molecule. [105] mined the bi-clusters from a microarray datasets with main emphasis on finding maximum bi-clusters with lower mean squared residue and higher row variance. [104] presented a clustering approach to cluster genes and for highly related conditions in sub portion of microarray data. The genes exhibit high correlation over the subset of condition. [23] worked to find the structure and the parameters of a gene regulatory network by using hybrid genetic programming and MOPSO. It helps in finding the simplified genetic network which predicts data of genetic line in different environment. [90] worked on MOPSO to find bi-clusters on expression data and to prevent conflict among the data in a microarray technique as several objectives have to be optimized at the same time. [133] tried to reduce the number of cancerous cells and limiting the use of anti-cancerous drug by optimizing the cancer chemotherapy with respect to conflicting treatment using MOPSO by decomposing several scalar aggregation problem and reducing the complexity. [114] modelled PSO using non-dominated and crowding distance sorting to identify non-redundant disease related genes with high sensitivity, specificity and accuracy.

5.3. **Chemical Engineering.** [162] used MOPSO for electrochemical machining process for optimizing the measures of process performance like dimensional accuracy, tool life and material removal rate keeping the constraints temperature, choking and passivity in subject. [161] optimized the condition of producing α-amylase for the saccharification process using MOPSO which leads high conversion of starch to glucose which results in high yield of ethanol through fermentation.

5.4. **Civil Engineering.** [16] presented an analysis of a selective withdrawal from thermally stratified reservoir using MOPSO for minimizing deviation from outflow water quality targets of temperature, dissolved oxygen, total dissolved solids, and potential of hydrogen. [62] used MOPSO for parameter estimation of conceptual rainfall-runoff model and for calibrating sacramento soil moisture accounting which is having 13 parameters. They tested the algorithm for three case studies. [163] generated pareto optimal solution using MOPSO for solving the reservoir operation problem using a variable size External Repository (ERP) and crowded comparison operator to have solution diversity with a incorporation of Elitist Mutation (EM) operator in addition. [107] provided a hybridised non-dominated sorting PSO which choose the gbest and pbest for swarm members of MOPSO without using external archive that provide an accurate pareto set. The algorithm was used to calibrate

NAM/MIKE 11 rainfall runoff model. [164] proposed elitist MOPSO for generating efficient pareto-optimal solution for operation and management of water resources. [11] combined MOPSO with crowding distance approach and non-domination sorting to find pareto optimal solution to optimize water supply to downstream demand points and sediment removal from the reservoir through release control. [183] incorporated mutations variation from genetic algorithm and external archiving technique and crowding distance sorting algorithm into the conventional MOPSO algorithm. The dispatch of the Yuecheng reservoir was optimized for the upper Zhanghe river of the Haihe basin for typical floods occurred in history.

5.5. **Data Mining.** [45] described a MOPSO algorithm that works with numerical and discrete attributes, avoiding the necessity of a previous discretization step and also the induced classifiers that present good results in terms of the Area Under Curve (AUC) metric. [5] classified the problem of rule mining as MOP problem and proposed pareto based chaotic MOPSO which can help in mining the accurate and comprehensible rules from the last population in only single run. [46] applied MOPSO in data mining to increase the performance of the previously developed algorithm by the same authors and proposed new algorithm with validated results. [206] used MOPSO for designing the novel classifiers and optimizing the performance aspects of conventional classifiers which can be performed due to effectiveness and powerfulness of MOPSO. [208] used multi-sub-swarm to find multi-solutions for multilayer ensemble pruning model. In which each base classifier generates an oracle output and each layer uses proposed algorithm to generate a different pruning based on previous output and forms multilayer ensemble pruning model.

5.6. **Electrical Engineering.** [196] proposed a fuzzified MOPSO and implemented to dispatch the electric power considering both economic and environmental issues, as the conventional economic power dispatch only save fuel but not able to handle the environment requirement. [1] discussed the Environment Economic Dispatch (EED) problem. A clustering technique was used to manage the size of pareto-optimal set and fuzzy based mechanism to extract the best compromise solution. [20] minimized the total fuel cost of generation and environmental pollution caused by fossil based thermal generating units. An acceptable system performance was also maintained in terms of limits on generators real and acceptable outputs, bus voltages etc. [75] employed MOPSO for solving congestion problem in power system for smooth and non smooth cost function by using realistic frequency and voltage dependent load flow model. [3] used MOPSO to solve the EED problem using fuzzy clustering method. [14] proposed MOPSO based optimization technique to reduce the computational time and space complexity for supporting multimedia application over wireless environment due to high convergence capability and simplicity. [22] used chaotic MOPSO for EED problem. The fuel cost and pollutant emission were found to be reduced by large number as compared to conventional MOPSO. [53] used MOPSO to design the model of surface mount permanent magnet class of electric machine with good accuracy and consideration of non-linearity. [54] applied MOPSO to optimally design a Proportional-Integral-Derivative (PID) controller for separately excited DC motor. [66] presented a hybrid MOPSO for EED problem based on PSO and Differential Evolution (DE). PSO with time variant acceleration coefficients explores the entire search space while the DE was used to exploit the sub space with sparse space. [178] dealt with determining optimal capacitor sizes in a radial distribution system, for which MO multi-stage PSO technique was used for capacitor sizing. [2] solved the optimal power flow problem using MOPSO with an objective of competing and non-commensurable cost and voltage stability enhancement. [4] employed Single Value Decomposition (SVD) to evaluate EM mode controllability to the two Static Synchronous Series Compensator (SSSC) control signals. MOPSO was used to optimize the composite objective function like damping actor, and the damping ratio of undamped Electromagnetic (EM) modes. [34] proposed the solution for the problem of EED using pareto archived MOPSO satisfying the operational constraint of operation. [37] designed a brushless DC wheel motor using enhanced MOPSO based on pareto dominance, archiving external and truncated Cauchy distribution. [58] incorporated Distribution Generations (DG) for electrical distribution system based MOPSO. The proposed concept can be used on both radial and meshed network which incorporated DG, which is an important factor due to its increasing use, motivated by reduction in power loss, voltage profile improvement, meeting future load demand etc. [86] designed a photovoltaic (PV) grid connected systems using MOPSO. It intends to suggest the optimal number of system devices and optimal PV module installation details. The economic and environment benefits achieved were maximized during the systems operational lifetime period. [106] applied adaptive MOPSO for reactive power optimization and voltage control which was used to reduce the power system loss by adjusting the reactive power variables such as generator voltage, transformer tap setting and other sources of reactive power. [122] considered the energy saving measures in China and proposed MOPSO model for energy efficient scheduling in which coal consumption rate and NOx emission along with operating cost was considered. [136];[137] studied the problem of daily MO optimal operation management with the distribution system of fuel cell power plants and a technique based on fuzzy self adaptive hybrid MOPSO. They applied it to control the problems like electrical energy losses, electrical energy cost and total pollutant emission by the fuel cell. [9] designed Proportional plus Integral (PI) controller based on MOPSO. They checked the performance of the two-area identical/different thermal reheat systems interconnected with stiff/elastic tie-lines using Integral Squared Error (ISE), Linear Quadratic Performance Index (LQPI) and MOPSO criterions. [72] presented MOPSO based state space pruning and also analyzed the impact that transmission line have on both Monte Carlo simulation and population based intelligent search technique. [111] tried to overcome the blindness of PSO and improve the calculation speed using combined Priority-List (PL) method. Adaptive mutation was applied to improve the diversity of particles. [174] minimized the congestion cost, load curtailment and generation cost of the system under contingency to restore the equilibrium of operating point. Load curtailment and generation cost had been optimized without breaching line flow constraint for congestion management. [211] used the two lbests MOPSO to design the PID controllers for two Multi-Input Multi-Output (MIMO) systems as distillation column plant and longitudinal control system of the super manoeuvrable F18/HARV fighter aircraft. [12] designed a MOPSO based hybrid Wind/PV/hydrogen/fuel cell generation system to supply power demand. [13] worked on optimal allocation of Flexible Alternating Current Transmission System (FACTS) devices. Applied MOPSO was based on m-objective PSO method, which considered both power system costs and security so as to obtain control of line power flow, bus voltages and short circuit currents at desired levels, hence improvement of power system security margins. [15] solved MO day-ahead Dynamic EED (DEED) problem, considering the effect of wind power generators. [18] proposed Accelerated MOPSO (AMOPSO) for optimal MO reactive power dispatch. [30] worked on suitable installation of FACTS devices in existing networks for more power transfer and to determine optimal Static Var Compensator (SVC) installation scheme for the required Loading Margin (LM). The results were validated on the IEEE 24-bus reliability test system and Taipower 345-kV transmission network. [59] proposed few modifications in MOPSO for planning of electrical distribution systems incorporating distributed generation. The risk factor taken in both papers (with [169]) is taken as a function of the Contingency Load-Loss Index (CLLI) to measure load loss under contingencies, and the degree of network constraints violations. [97] applied MOPSO for solving a non-linear constrained EED problem. An external archive, novel pbest and lbest updating criteria were employed for solving the problem. [99] considered the convergence performance and solution quality for solving the power supply curve of Electric Arc Furnace (EAF) steelmaking process, combining rapid search ability of MOPSO and the global development ability of Pheromone sharing Mechanism (PM) algorithm. [131] applied MOPSO for congestion management to relieve congestion and improve transient security level simultaneously. [169] applied MOPSO based on the principles of fuzzy pareto-dominance to find out and rank the non-dominated solutions on the pareto-approximation front. Proposed planning approach was validated on a typical 100-node distribution system. [181] discussed an application of MOPSO for Dynamic Economic Load Dispatch (DELD) problem solution with transmission losses. The objective was to minimize the total operating cost over a dispatch period, while achieving a set of constraints: the load demand balance in terms of equality constraints, ramp rates in terms of dynamic constraints and generation capacity in terms of inequality constraints. [185] worked towards finding the optimum gains of the PID controller to control the voltage and frequency of the generating system within the permissible limit. Used algorithms Enhanced PSO, MOPSO, and Stochastic PSO had more stable and faster convergence towards the best PID gains with minimum computational time. [189] applied adaptive grid method to maintain the external particle swarm in MOPSO proposed in [43] abbreviated as CMOPSO. Cognitive radio can optimize the performance of radio. [193] designed strategies to overcome the infeasible solutions in the search space in PSO algorithm to deal with this complex MOPSO problem. The approach was tested on a 200 turbine layout problems and claimed to be effective. [210] proposed distinctive features in the algorithm for solving EED problem for particle updating, mutation operator and to update the global particle leaders. The testing was done on IEEE 30-bus test system. [213] applied interactive MOO algorithm based on preference for the calculation of the cost function minimization. They applied interactive genetic algorithm for optimization of populations, composition of target weight value was optimized by converting to weighted single objective function solving by PSO.

5.7. **Electromagnetic Engineering.** [69] used MOPSO to design a planar multilayer coating, which have high power of absorption of desired range of frequencies and angles. Optimal absorber design lies in minimizing the reflection coefficient for the desired range mentioned and the thickness, the electric and magnetic properties of each layer. [27] tested MOPSO for finding the pareto optimal front and for designing of planar multilayered EM absorbers. [71] designed a dual band base station antennas for mobile communications using MOPSO with fitness sharing (MOPSO-fs) which presented two design one with five element array operating in Global System for Mobile (GSM) 1800/Universal Mobile Telecommunications System (UMTS) frequency band while other had six element operating in UMTS/Wireless Local Area Network (WLAN) frequency bands. [110] presented a MOPSO which works on novel risk management for virtual enterprise using a Constructional Distributed Decision Making (CDDM) model. The model has two level the top and base level which describes the decision process of the owner and the partners respectively. [116] designed an ultra wide band planar antenna using MOPSO with inclusion of a notch ranging from 5 GHz to 6 GHz. [25] designed an Ultra-Wide Band (UWB) linear array of antipodal vivaldi antenna in time-domain using MOPSO. It attained a pareto front for the two conflicting objectives of sidelobe level and beam-width. For a different number of elements optimization was performed in both uniform and non-uniform cases. [134] provided the concept of Meta-PSO used to enhance the global search capability and to improve the algorithm convergence. [10] applied MOPSO to find the optimum machine design. They reduced the cogging torque with minimum loss in the output torque in Permanent Magnet Synchronous Machine (PMSM). [17] integrated MOPSO with crowding distance and roulette wheel to design the configuration of pumping lasers of Raman amplifier. This implementation resulted in obtaining the pump laser wavelengths and power to maximize the amplifier on-off gain by maintaining the flatness of the gain over the used bandwidth. [26] presented a vivaldi antenna for reduction of three parameters as transient distortion, reflection coefficient and cross polarization level. [39] proposed external archiving for Jiles-Atherton vector hysteresis model parameter identification and claimed to have promising results. Proposed algorithm was evaluated in terms of quality of solutions and robustness and was found to be competitive with compared algorithms. [68] worked on optimizing different design cases from antenna and microwave problems using MOPSO, MOPSO with fitness sharing (MOPSO-fs), and the Generalized DE (GDE3). These algorithms were compared and evaluated against other evolutionary algorithms to show the superiority of proposed algorithms to solve such type of problems. [148] presented an approach of selecting multiple guiders to lead a swarm toward a pareto-front. Mutation operator was applied on particles and members in external archive. Crowding distance of solutions in objective and variable space was considered to maintain the diversity of solutions, resulting in better distribution of solutions. [173] applied the finite difference time domain Computational EM (CEM) tool for EM Compatibility (EMC) shielding enclosure design using Peer-to-Peer MOPSO (P2P-MOPSO) technique.

5.8. **Electronics Engineering.** [91] used binary MOPSO for Wireless Sensor Network (WSN) by proposing binary clustering method. It determines the best set of cluster and selects the best cluster head using cluster head selection algorithm. [32] used MOPSO for floor-planning of Very Large Scale Integrated (VLSI) network. The method provides a well distributed pareto front and provides multiple layout schemes for the users. [150] prepared a new approach for WSN with an energy efficient model with a good coverage of WSN, which is used to use transmit data to a high energy communication node by communicating with each other. [179] presented a novel shunt power filter design using MOPSO. It can help in dealing with different conflicting objectives, power filter components continuous and discrete objectives and specified filter reactive power compensation services. [180] presented a discrete search optimization approach to solve the hybrid power filter compensator with design of C-type filter and fixed capacitor using discrete MOPSO. [36] improved the safety and efficiency of the air transport by optimization of national Air Route Network (ARN) by solving the Crossing Waypoint Location (CWL). They presented comprehensive learning MOPSO to minimize airline cost and flight conflict. [6] considered the ideal degree of nodes and battery power consumption of the sensor nodes to obtain energy-efficient solution for WSN using PSO based clustering algorithm. [7] applied MOPSO for Mobile Ad-hoc Network (MANET) to optimize the number of clusters in an ad-hoc network as well as energy dissipation in nodes to provide an energy-efficient solution and reduce the network traffic. This problem had two conflicting objectives i.e. the degree difference and energy consumption. [35] kept sequence-pair representation and imported the concept of co-evolutionary algorithm into MOPSO. Proposed algorithm was tested on MCNC benchmarks and claimed to have better performance, well distributing pareto front, and multiple layout schemes. [60] proposed velocity-free MOPSO with centroid. Centroid was considered to update the particle position. Particles in swarm were supposed to have only position without velocity. [141] solved the problem of determination of 9 unknown Field-Effect Transistor (FET) model elements with technological limitations for optimum scattering parameters and operation bandwidth.

5.9. **Environmental Sciences.** [108] applied MOPSO for comprehensive land-use planning problem in China with a case study in Yicheng, China. They concluded that the integration of Geographic Information System (GIS) technique and MOPSO with Constriction factor, Crossover and Mutation operator (MOPSO-CCM) is a promising and efficient approach for solving the land-use zoning problem. [109] applied the Parallelized MOPSO (PMOPSO) to optimize soil sampling network of Hengshan County in loess hilly area in China. Besides objectives, model had considered building area, water area and steep slope as sampling barriers. [118] optimized land-use arrangement based on quantitative and qualitative parameters. They used geospatial information system to prepare the data and to study different spatial scenarios during model development. [197] worked on optimizing and adjusting water saving agricultural planting structure. They incorporated chaos technology with ergodicity to improve the searching performance of MOPSO.

5.10. **Flowshop and Jobshop Scheduling Problem.** [28] minimized makespan, total flow time and completion time variance simultaneously to solve the MO flowshop scheduling problem, which is position-based local search method. [101] used variable neighbourhood PSO for solving MO flexible job shop scheduling problem. The objective was to minimize the flow time and the make-span. [158] solved a bi-criteria permutation flow shop scheduling problem, where simultaneous minimization of weighted mean completion and weighted mean tardiness is required. [92] applied PSO to fuzzy job shop scheduling problem by converting it into a continuous optimization problem and then an effective MOPSO was applied to the problem. [143] used MOPSO to solve the no-wait scheduling problem with makespan and maximum tardiness criteria. [102] designed the MOPSO to solve the MO flexible job shop scheduling problem. The position particle has two components operation order and machine selection, and has variable length strategy. [175] used MOPSO for job shop scheduling problem with multiple objectives which included minimization of makespan, total tardiness and total machine idle time. A mutation operator was introduced and diversity verification was used. [176] provided a MOPSO for flowshop scheduling problem which help in minimization of makespan, mean flow, and machine idle time. [95] combined the improved ant colony algorithm with PSO for MO to solve the flexible job shop scheduling problem. The PSO part searched the optimal position and made it the starting position of the ant while ant algorithm searched the global optimization by the use merit positive feedback and structure of the solution. [99] solved the open shop scheduling problem using PSO with MOs by modifying the particle position representation, particle velocity and particle movement. [130] combined MOPSO with local search to solve the flexible job shop scheduling problem. PSO was used to search the solution space and the local search was used to reassign the machine to operation and to reschedule the result obtained from PSO, which increases the convergence speed of the algorithm. [135] solved the flexible job shop scheduling problem using MOPSO by minimizing the completion time, total machine workload, and biggest machine workload by adopting the linear weighting method. [187] solved the bi-objective job shop scheduling problem using MOPSO with sequence dependent setup times and ready times. [188] combined PSO with genetic operators for MO job shop scheduling problem for simultaneous minimization of weighted mean flow time and total penalties of tardiness and earliness. [198] tried to solve the problem of trapping in local minima in MOPSO for flowshop scheduling and applied heuristic algorithms to generate initial solutions and then Baldwinian learning mechanism, adopting pareto dominance relation and crowding distance.

5.11. **Image Processing.** [89] enhanced the contrast of grey level digital images by keeping the mean image intensity preserved for better viewing consistence and effectiveness. This was performed by increasing the information content in the image via a continuous intensity transform function. [145] presented a novel method for unsupervised classification of hyperspectral images. The method solves the problem like clustering, feature detection, and class estimation in an automatic and unsupervised way. The MOPSO solves the problem effectively by reducing the bands used for classification task. [138] used the MO Constriction PSO (MOCPSO) for MO pixel level image fusion. Approach had given better results, overcome the limitations of conventional method, simplified the method and achieved the optimal fusion metrics. [168] used MOPSO for Panchromatic (Pan) sharpening of a

Multispectral (MS) image which could transfer spatial details of Pan image into high resolution MS image, by preserving the colour information of the low resolution MS image. [113] applied cultural-based MOPSO model for image compression quality assessment. They obtained different optimal quantization tables for different classes of images.

5.12. **Industrial Engineering.** [76] presented the PSO technique to solve the MO optimal power plant operation problem which requires an optimal mapping between unit load demand and pressure set point in a fossil fuel power plant. [204] employed three versions of bi-PSO with high effectiveness to solve the semi desirable facility location problem. The objectives were minimization of transportation costs and undesirable effects. [94] used the hybrid MOPSO in naphtha industrial cracking furnace, in which hybridisation of MOPSO along with artificial neural network is used in operational optimization of the furnace. [100] solved the bin packing problem which is widely used in loading of tractor trailer, airplanes etc. The work mainly focused on minimization of wasted space. [159] solved the mixed model assembly line sequencing problem. A hybrid MO algorithm was used to obtain pareto front which can be minimized simultaneously, based on PSO and Tabu Search (TS). [82] solved the multi criteria of optimal allocation of human resource issue using MOPSO which involves how to divide humans of limited availability among multiple demands that optimizes current issues. [142] tested MOPSO for topology optimization of complaint mechanism. MOPSO combined with material mask overlay strategy to obtain single material complaint topologies using honeycomb discretization. [157] discussed the time-cost trade-off problem in project management and for which MOPSO was used to determine the alternative for the problem. [192] presented MOPSO approach for inventory classification where inventory items were classified on the basis of minimizing cost, maximizing inventory turnover ratio and inventory correlation. Also it does not need a pre defined number of group that items are divided into. [24] used MOPSO for vehicle routing problem with time windows by allowing particle to conduct a dynamic trade off between objectives to reach stability. It provided an adaptation of the Jumping Frog Optimization algorithm incorporating some principles of MOO. [57] studied MOPSO to design and equally distribute the tolerances among the various components of mechanical assembly and also to enhance the operation of particle swarm optimizer. [155] applied the concept of MOPSO to select the most appropriate project from a group of proposals as in the problem the total benefit has to be maximized and the cost and total risk to be minimized. [38] provided a multi-loop proportional integral controller in control engineering based on MOPSO with updating velocity vector by Gaussian distribution. [147] considered the rough grinding and smooth grinding process using PSO algorithm. Three objectives were considered for optimization that is minimization of production cost, maximization of production rate and surface finished based on thermal damage, wheel wear parameter and machine tool stiffness. [207] solved the time-cost-quality trade-off problem using fuzzy MOPSO. The objective of the problem was to decide a combination of the construction method by which the cost and time can be minimized with a good quality of the project. [126] considered the problem of cylindrical helical gear design and tried to solve it by changing the MO in single objective by weighted average and proposed a MOPSO method for the problem. [139] gave a method to solve the Open Vehicle Routing Problem (OVRP) using MOPSO, which is a mixture of MO mathematical model of the homogenous and competitive OVRP. [167] evaluated the best individual in the local by introducing the simulated annealing algorithm in MOPSO. Fitness was judged by the shared function based on object vector. The results obtained were in better convergence speed and stability which was used for airfoil shape aerodynamic optimization. [197] studied the Supply Chain (SC) sourcing strategy design with respect to price, exchange rate risks, and supplier reliability. MO Binary PSO (MOBPSO) was developed to evaluate the robustness sourcing strategies under price, exchange rate and demand risks. [33] presented fitness sharing strategy and dynamic archiving strategy to improve the performance of MOPSO. They developed an improved grouping method based on MOPSO. The method was applied to the optimization in a piston-cylinder selective assembly problem. [55] integrated a setup of neural network models with PSO, called SI neural networks system for optimizing the selection of machining parameters in high-speed milling processes. [56] applied MOPSO to solve multidisciplinary design optimization problems with the aim of extending the formulation of collaborative optimization from single to multiple objectives. Race car design problem was taken as an example of application for three objective functions. [65] applied MOPSO for finding the optimal combination of corrosion rate parameters for a refining process in the oil industry. The main parameters considered in corrosion control were flow, concentration of sulfur species, chromium content, total acid number and temperature. [74] proposed a hybrid approach with data mining based on MOPSO, called Intelligent MOPSO (IMOPSO). They obtained efficient solutions by MOPSO approach. Then, the Generalized Rule Induction (GRI) had been used for extracting rules from efficient solutions of MOPSO. Then, the extracted rules improved the solutions for large-sized problems. [80] presented a multi-stage SC network by formulating a mixed integer programming problem and solved it by using MOPSO and NSGA-II. The comparison was concluded that: MOPSO generates more pareto solutions in less time and NSGA-II provides better quality results. [81] proposed MOPSO based on pareto-optimal solutions for control of batch process and claimed to give a very good diversity of solutions. [83] solved MO dynamic facility layout problem with unequal-size departments and pick-up/drop-off locations. Firstly developing mathematical model, then applying MOPSO for near solutions and then applying heuristics to prevent overlapping and reduce unused gaps between the departments. [87] worked on optimization of the activated sludge process in a wastewater treatment plant. The model was developed by multilayer perceptron neural network. [88] applied three variants of MOPSO and modelled and optimized an existing Heating, Ventilating and Air Conditioning (HVAC) system. They claimed of upto thirty percent of energy saving and found MO Decreasing Inertia Weight PSO (MO-DIWPSO) outperforming than other two variants. [103] solved the problem of network optimization of Reverse Logistics (RL), which is a NP-hard problem of complex system optimization. The model of the problem was developed and solved using a hybrid approach with MOPSO. [149] dealt with integrated SC in a form of MO decision-making problem. The objectives were to minimize total cost of purchasing items, setup of each product in each factory, production, and inventory cost items including the cost of raw material, final product in factory and distribution centres and delivery times of products for customers. [165] applied Non-dominated Sorting PSO (NSPSO) for tanker synthesis model. They obtained uniformly distributed pareto front using proposed model. [177] worked on implementation of MOPSO algorithm in SC network optimization. They formulated and analyzed a strategic plant location-allocation model for single product two-echelon distribution network. [195] optimized the SC network using discrete MOPSO by minimizing the SC cost and demand fulfilment lead time and maximizing the volume flexibility. [199] proposed MOPSO based on the development of an experiment-based optimization system for the process parameter optimization of MIMO plastic injection molding process. The experiment contained Taguchis parameter design method, Neural Networks based on PSO (PSONN model) and MOPSO algorithm. [200] used MOPSO for the maintenance of deteriorating bridges and keeping a balance between the performance obtained and the incurred cost. [201] presented the study of three Gorges cascade hydropower system during low-flow period. They compared three strategies to improve the performance of the Hierarchy PSO (HPSO) algorithm: Adaptive Inertia Weight Algorithm (AWA), Mutative Scale Local Search Algorithm (MSLSA) and hybridization of PSO with MSLSA.

5.13. **Mechanical Engineering.** [186] considered MOPSO for sheet metal forming process which aims to improve the quality and reduce cost. For solving the common problems like metal shrinking and cracking a drawbead design was adopted. [209] used MOPSO with Random Weighted Aggregation (RWA) technique. It maintained the suitable pareto-optimal solution in design problem of alloy steel to determine the optimal heat treatment regime and the composite weight percentage for the required mechanical properties of steel. [112] designed a brushless permanent magnet considering minimum thrust ripple and maximum thrust density using MOPSO as the optimization technique. [121] used parallel asynchronous MOPSO for Optimization Based Mechanism Synthesis (OBMS) of four bar and five bar mechanism synthesis. The method for synthesising the grashof mechanism was effective at locating the pareto front, so the designer can choose a preferred solution from competing optimizing solution after optimization process. [127] applied MOPSO to water distribution optimization problem. Certain modifications were made regarding the way the particle chooses its best position, the selection of leader and the particles ability to clone themselves to increase the density in pareto front. [52] optimized the diesel engine control parameters using MOPSO for the problem like brake specific fuel consumption, exhaust gas emission and soot. [171] implemented MOPSO for optimization of a benchmark cogeneration system in which exergetic, exergoeconomic, environmental objectives were considered. In optimization the exergetic efficiency as exergetic objective was maximized while the unit cost of the system and cost of environmental impact namely exergoeconomic and environmental objectives were minimized respectively. [202] handled the machining parameters to have more control on machining process. MOPSO was applied for minimizing the production time and cost and for maximizing the profit. [205] proposed MOPSO for vehicle crashworthiness to ensure passengers safety and reduce cost in vehicle cost in the early design stage of vehicle design. The aim was to produce an optimized structure that can absorb crash energy while maintaining enough space for passengers compartment. [96] tried to improve the global convergence and uniform distribution of MOPSO. Proposed algorithm with elitism strategy performed efficiently for the optimization of single-stage air compressor for two and three objectives. [128] optimized a Gas Turbine Engine (GTE) fuel control system. They simulated a single spool turbojet engine for evaluation of the objective function and investigation of the effectiveness of the approach. [166] worked on selecting warship combat system during the period of warship alternatives conceptual design. After computing the overall measure of performance and risk the design variables representing equipment alternatives were chosen using discrete PSO. [[182]182] worked on the microstructural and mechanical properties of the Friction Stir Welding (FSW) of AA7075-O to AA5083-O aluminium alloys and applied Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) for determining the best compromised solution.

5.14. **Neural Network.** [84] developed a procedure with the combination of neural network modelling with MOPSO to formulate and solve optimization problem for multiple and conflicting objectives for finish hard turning process. [77] worked on optimizing the motion trajectory of the space robots using MOPSO which includes some parameters like motion time, dynamic disturbance and jerk etc. It is helpful for the space robots to maintain and repair the space station and satellites efficiently. [151];[152];[153] applied MOPSO and Adaptive MOPSO (AMOPSO) to develop generalization and classification accuracy for Radial Basis Function (RBF) network called as RBF-MOPSO and RBF-AMOPSO respectively. RBF network shows good result on MOP which are based on evaluation of approximation ability and structure complexity. [154] introduced Time Variant MOPSO (TVMOPSO) which was used in RBF networks to optimize the accuracy and connections of the network. The proposed work was used in medical diagnosis and provided better results. [146] applied the concept of Fuzzy RBF Neural Networks with Information Granulation (IG-FRBFNN) with their optimization by MOPSO. They applied MOPSO with Crowding Distance (MOPSO-CD) for structural and parametric optimization of the model with simultaneous minimization of complexity and maximization of accuracy.

5.15. **Robotics.** [117] employed PSO and Probabilistic Roadmap Method (PRM) for presenting robot motion planning which handles two objectives together, shortest path and the smoothest path. PSO was used for global path planning while PRM was used for obstacle avoidance. [61] presented modified MOPSO to solve the multi-robot co-operative box pushing problem. The objective was minimization of energy and time. The objectives are conflicting because for minimum time, the forces applied on the box should be maximized but for the minimum energy consumption, forces applied by the robots should be minimized. [160] solved problem in ascending and descending gait planning of a 7-dof Biped Robot using PSO and GA. The staircase had been modeled as a MOP.

5.16. **Software Engineering.** [47] tested the MOPSO for fault prediction of software class or module. By exploring the pareto dominance concept the method allows the creation of classifiers with specific properties. [31] demonstrated the different unconventional method using PSO for the design of disk type RF windows. The concept of MOPSO was used to achieve the optimal trade off between the objectives of desired resonant frequency and minimizing the reflection around the resonant frequency. [124] considered MOPSO for solving the optimization problem which is a standard problem in bank by selecting the percentage of each asset in such a way that the profit is maximized and risk is minimized. [48] introduced a fault prediction model for reducing testing cost and efforts. This model reduces the disadvantages of the machine language like difficult interpretation and pre-process approach for obtaining a balanced datasheets. [67] proposed a skill to time model for software development process using MOPSO in which the task processing time varies according to the skill of personnel as per the task. [21] studied the stock traders problem as they have to consider several objectives in making decision. The problem was solved by using MOPSO which provide an optimal trade-off among different objective by using the end of the day historical market data. [115] used MOPSO with different velocity for calculation of free parameters in the active control. A fuzzy control system was proposed which was assumed be suitable to control the systematic development of non linear activities and be fined tuned for no experience or complicated structures. [51] worked on minimization of tracking error, and liquidity enhancement by the reduction of transaction costs and market impact. For the purpose they hybridised two variants of MOPSO. [64] worked on implementation of MOPSO-CD, a variant of MOPSO for Environment for Modeling, Simulation and Optimization (EMSO). EMPSO is a Brazilian equation-oriented process simulator. [123] combined MOPSO and Meta-Learning (ML) to the problem of Support Vector Machine (SVM) parameter selection. The initial solution adapted was the congurations of parameters suggested by ML. [125] combined NSGA-II and MOPSO to the portfolio optimization problem using Markowitz mean variance model. For the prediction of return a low complexity single layer neural network was used. [184] used MOPSO for optimization of motion segmentation for better representation and processing of the standard image in video sequence. The objective was to minimize the number of parameters of final labelling in a data cost, measuring the similarity and dissimilarity of moving target at the minimum error rate, minimizing the connect component labelling and minimizing overestimating number of regions. [190] proposed video coding technique in dual tree discrete wavelet transform solved using MOPSO.

6. Discussion and Conclusions

Multi-objective optimization has become an inevitable part of various fields of Engineering, Industries, Biology, Management, Environment, and many other disciplines. Nowadays, PSO has become a very popular approach for optimization and hence PSO for MOP is gaining recognition and being widely used. After having a careful look at the papers we reviewed, it is concluded that there has been notably a lot of work done and remains much more scopes and areas to work on the algorithmic and application aspects of MOPSO. The studies of the publications related to MOPSO in terms of application areas, the purpose, objectives and variant applied/developed regarding each paper is presented in table 2. Figure 4 shows the year wise increasing applicability of MOPSO. In 2009 it has more number of application based publications, which decreased in 2010, followed by decrement in

2011 which has notably increased and arrived at maximum in 2012 at number 69. Figure 4 enhances the increasing popularity of MOPSO for engineering and real life problem solving. Figure 5 shows the type of MOPSO algorithm/variant applied, which is divided in 7 sections as shown in table 1. This table contains the category wise division along with the number of papers, from the category corresponding variant belongs to. Each MOPSO variants category regarding each application is also described in table 2 third column. As clear from categories of table 1, some MOPSO variants are newly developed, some are applied after a few basic changes, some are hybridized, some are previously developed and some changed the problem to single objective, and then solved using proposed PSO algorithm. The detailed algorithms of newly developed and hybridized variants are not discussed here due to space limitation. They all are discussed in our next article (in pipeline) on MOPSO variants developed till date. As it can be observed from figure 5 the newly developed variants (category A) have the maximum frequency and it is increasing year wise as compare to other categories. Hence, the trend is moving towards developing specific variant for specific problem, since no variant is suited for all type of MOPs. Still, there are a number of areas where the problem nature is MO and MOPSO can give very efficient results, particularly for Bioinformatics Applications, Computational Biology and Data mining. The applications may include the MOPs like Sequence Alignment, Structure Alignment, Interaction Prediction, Structure Prediction, optimization of Biochemical process and system, Combinatorial drug design, Classification problems, Gene regulatory networks, Phylogenetic tree inference etc. Also, there is not much work done on mathematical analysis and other theoretical aspects of the algorithm. Due to the large applicability of MOP and suitability of PSO for solving it, a new era is defined towards solving practical MOPs by applying/developing suitable MOPSO algorithm.

Table 1. **Variants Categorized**

Variant Type	**Number of times applied**	**Category**
New variant developed	56	A
Hybrid of MOPSO with other techniques	20	B
Converted MOP to single objective, then applied newly developed variant	6	C
Converted MOP to single objective, then applied existing variant	16	D
Applied existing MOPSO variant	19	E
Applied MOPSO with modifications	32	F
Applied MOPSO directly / Basic modifications	41	G

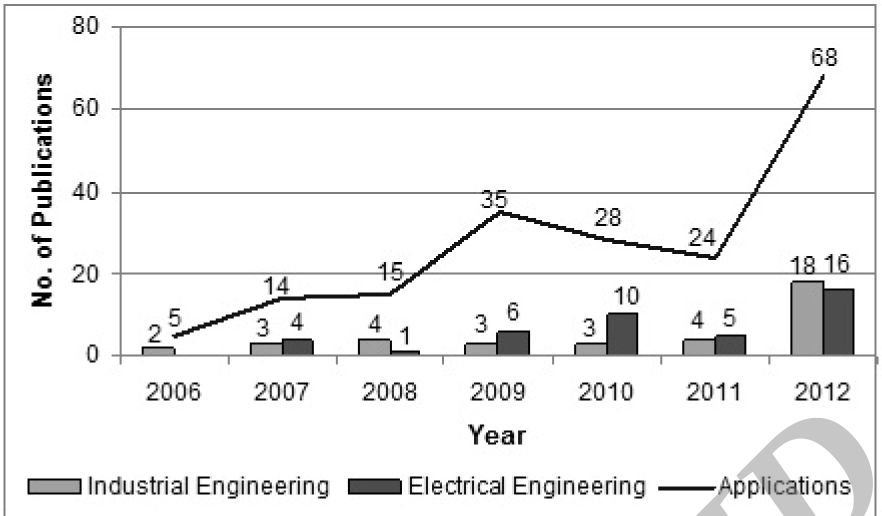

Figure 4. **Year wise publications on MOPSO**

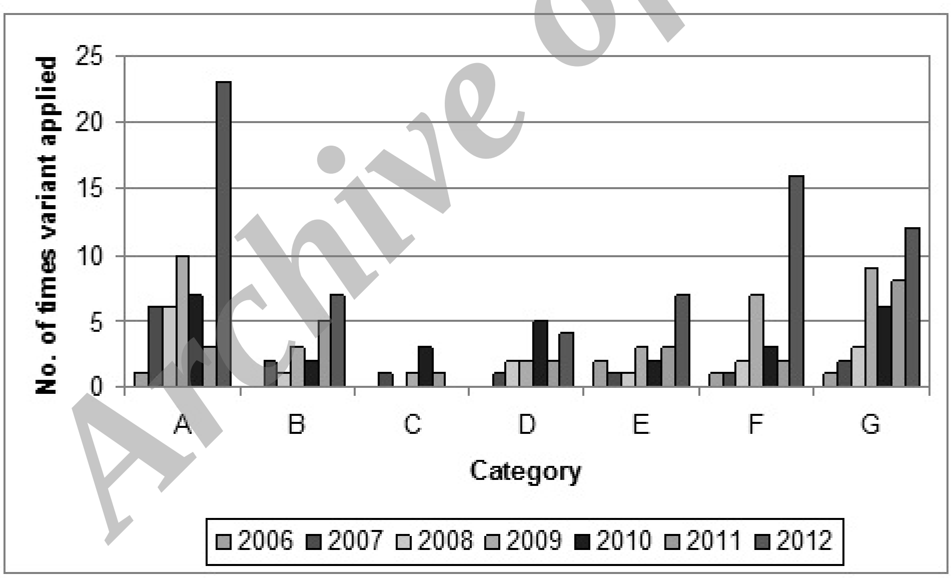

Figure 5. **Category wise publications on MOPSO**

Table 2: **Publications on application areas of MOPSO**

Area	Reference	Group	Type of MOPSO Variant (If used / developed)	Application	Objectives
Aerospace Engineering	Blasi et al. (2012)	G	*	Flight path optimization	Minimization of total flight path length; maximization of trajectory length covered over specified target areas
	Guo et al. (2012)	**A**	Elitist Vector Evaluated PSO (EVEPSO)	Multi-mode resource leveling	Minimization of project duration, resource requirements and resource variance
	Omkar et al. (2012)	**A**	Hybridization of Vector Evaluated PSO (VEPSO) proposed in Parsopoulos and Vrahatis (2002) with message passing interface	Design optimization of laminated composite plates	Minimization of weight and cost
	Yang et al. (2012)	**A**	Crowding Distance based Fuzzy MOPSO (CD-FMOPSO)	Economic-statistical optimization design of $\bar{X}$ and S charts	Minimization of expected costs and losses per hour and out-of-control average time to signal; maximization of in-control average time to signal between false alarms

Biological Sciences	Janson et al. (2007)	**A**	Clustering based Multi-objective PSO (ClustMPSO)	Molecular docking	Optimization of intra-molecular energies occurring between atoms of flexible ligand and inter-molecular energies between ligand and macro-molecule
	Liu et al. (2008)	**A**	MOPSO Biclustering (MOPSOB)	Mine coherent patterns from microarray data	Minimization of mean squared residue; maximization of volume and row variance
	Liu et al. (2008)	**A**	Crowding distance based MOPSO Biclustering (CMOPSOB)	Biclustering of microarray data	Minimization of mean squared residue; maximization of volume and gene-dimensional variance
	Cai et al. (2009)	**B**	Hybrid algorithm of genetic programming and MOPSO	Structure and parameters finding of a gene regulatory network	Minimization of error in prediction of: bolting date and gene expression data for one unspecified gene present in network
	Lashkargir et al. (2009)	**B**	Hybrid adaptive MOPSO	Discovering biclusters in gene expression	Maximization of bicluster size and variance; minimization of mean squared residue and overlapping among biclusters

Biological Sciences	Moubayed et al. (2011)	**E**	Smart MOPSO using Decomposition (SDMOPSO) proposed in Moubayed et al. (2010)	Cancer chemotherapy optimization	Minimization of number of tumor cells and total amount of toxic anti-cancer drugs in blood plasma
	Mandal and Mukhopadhyay (2012)	**F**	MOPSO with modifications	Identification of non-redundant gene markers from microarray gene expression data	Maximization of specificity and sensitivity
Chemical Engineering	Rao et al. (2008)	**D**	***	Electrochemical machining process parameter optimization	Optimization of dimensional accuracy, tool life, and material removal rate
	Rajulapati and Narasu M (2011)	**G**	*	α-Amylase and ethanol production from spoiled starch rich vegetables	Two objectives: Regression equation between Activity and Protein separately (as dependent variable) with: time, potential of Hydrogen (pH), temperature, starch concentration and inoculum size
Civil Engineering	Baltar and Fontane (2006)	**E**	MOPSO variant proposed in Coello Coello et al. (2004)	Selective withdrawal from thermally stratified reservoirs	Minimization of deviations from outflow water quality targets of: temperature, dissolved oxygen, total dissolved solids and pH

Civil Engineering	Gill et al. (2006)	**G**	*	Parameter estimation of conceptual rainfall-runoff model and calibrating sacramento soil moisture	Minimization of root-mean-square error and bias
	Reddy and Kumar (2007)	**A**	Elitist-Mutation operator with MOPSO (EM-MOPSO)	Reservoir operation problem	Minimization of sum of squared deviations for irrigation; maximization of hydropower production and satisfaction level of river water quality
	Liu (2008)	**B**	Multi-objective hybrid algorithm using Non-dominated Sorting PSO (NSPSO)	Automatic calibration of a rainfall-runoff model	Minimization of average root mean squared-error of peak and low flow events
	Reddy and Kumar (2009)	**A**	Elitist-Mutated MOPSO (EM-MOPSO)	Water resource management	Maximization of hydropower production; minimization of annual sum of squared decits of irrigation release from demands
	Azadnia and Zahraie (2010)	**B**	MOPSO with non-domination sorting and crowding distance approaches	Operation management of reservoirs with sedimentation problems	Optimization of water supply to downstream demand points and sediment removal from reservoir

Civil Engineering	Shuai et al. (2012)	**F**	MOPSO with modifications	Dispatch problem of reservoir flood control	Minimization of highest water level before dam, releasing peak discharge, difference of water level after flood season and flood control level
Data Mining	de Carvalho and Pozo (2008)	**E**	MOPSO-N proposed in de Carvalho et al. (2008)	Non-ordered data mining	Maximization of sensitivity and specificity
	Alatas and Akin (2009)	**A**	Chaotic PSO based multi-objective rule mining	Modeling of classification rule mining	Maximization of predictive accuracy and comprehensibility
	de Carvalho and Pozo (2009)	**A**	MOPSO-P	Mining rules from large datasets	Maximization of sensitivity and specificity
	Zahiri and Seyedin (2009)	**G**	*	Designing novel classifiers	-
	Zhang and Chau (2009)	**A**	Multi-Sub-Swarm PSO (MSSPSO)	Multilayer ensemble pruning	Maximization of generalization performance of multi-classifiers ensemble system
Electrical Engineering	Wang and Singh (2006)	**A**	Fuzzified MOPSO (FMOPSO)	Dispatch of electric power at economic and environmental issues	Minimization of total fuel cost and total emission impact
	Abido (2007)	**G**	*	Environmental /Economic dispatch (EED) problem	Minimization of fuel cost and emission

Electrical Engineering	Bouktir et al. (2007)	**D**	***	Power flow problem	Minimization of total fuel cost of generation and environmental pollution
	Hazra and Sinha (2007)	**G**	*	Congestion problem in power system	Minimization of cost of operation and congestion
	Agrawal et al. (2008)	**A**	Fuzzy Clustering-based PSO (FCPSO)	EED problem	Minimization of total generation cost and classical economic dispatch including NOx emission
	Baguda et al. (2009)	**G**	*	Wireless video support	Minimization of delay, rate and distortion
	Cai et al. (2009)	**A**	MO Chaotic PSO (MOCPSO)	EED problems	Minimization of fuel cost and emission
	Duan et al. (2009)	**D**	***	Design of surface mount permanent magnet motors	Minimization of weighted sum of volume, weight, efficiency, weight of magnets and torque per ampere at rated condition
	El-Gammal and El-Samahy (2009)	**G**	*	Tuning of Proportional-Integral-Derivative (PID) speed controller	Minimization of maximum overshoot, rise time, speed tracking error, steady state error and settling time
	Gong et al. (2009)	**B**	Hybrid algorithm of PSO and differential evolution	Highly constrained EED problem	Minimization of fuel cost and emission

Electrical Engineering	Sharaf and El-Gammal (2009)	**A**	MO multi-stage PSO	Optimal capacitor sizing	Minimization of feeder current for feeder loss reduction, voltage deviation at each bus of distribution system, and feeder capacity release
	Abido (2010)	**G**	*	Power flow problem	Minimization of fuel cost and enhancement of voltage stability
	Ajami and Armaghan (2010)	**D**	**	Power system stability enhancement	Optimization of damping factor and damping ratio
	Chen and Wang (2010)	**A**	Pareto Archive Multi-objective PSO (PAMPSO)	EED problems	Minimization of fuel cost and emission
	Coelho et al. (2010)	**A**	Enhanced MOPSO (EMOPSO)	Brushless DC wheel motor design	Minimization of mass; maximization of efficiency
	Ganguly et al. (2010)	**F**	MOPSO with modifications	Electrical distribution system planning	Minimization of total installation and operational cost; maximization of network reliability
	Kornelakis (2010)	**G**	*	Photovoltaic grid connected system design	Maximization of lifetime, systems total net profit and environmental benefit

Electrical Engineering	Liu et al. (2010)	**A**	MO Adaptive PSO (MOAPSO)	Reactive power optimization and voltage control	Minimization of active power loss of transmission lines, total sum of each load bus voltage deviation and voltage stability margin
	Ming et al. (2010)	**D**	***	Energy-saving power generation scheduling	Minimization of coal consumption rates, NOx emissions and operating cost
	Niknam et al. (2010)	**C**	Multi-objective Fuzzy Adaptive Chaotic PSO (MFACPSO)***	Operation management of fuel cell power plants	Minimization of total electrical energy losses, electrical energy cost and pollutant emission
	Niknam et al. (2010)	**C**	Multi-objective Fuzzy Self Adaptive Hybrid PSO (MFSAHPSO)***	Operation management of fuel cell power plants	Minimization of total electrical energy losses, electrical energy cost and pollutant emission
	Arivoli and Chidambaram (2011)	**G**	*	Proportional plus Integral (PI) controllers design	Maximization of tie-line power in area 1 and area 2
	Green II et al. (2011)	**G**	*	Intelligent state space pruning	Minimization of total load curtailment and load curtailment in each state
	Sen et al. (2011)	**G**	*	Contingency surveillance	Minimization of congestion cost, load curtailment and generation cost

Electrical Engineering	Lu et al (2012)	**B**	Hybrid of Priority-List method and MOPSO (PL-MOPSO)	Scheduling optimization problem of wind power integrated system	Minimization of generation cost and pollution
	Zhao et al. (2011)	**E**	Two lbests MOPSO (2LB-MOPSO) proposed in Zhao and Suganthan (2011)	PID controllers design	Minimization of integral squared error and balanced robust performance criterion
	Baghaee et al. (2012)	**G**	*	Designing of Wind/Photovoltaic /hydrogen/fuel cell generation system	Minimization of annualized cost of system, loss of load expected and loss of energy expected
	Baghaee et al. (2012)	**A**	m-objective PSO method	Allocation of multi-type flexible alternating current transmission system devices	-
	Bahmanifirouzi et al. (2012)	**A**	Fuzzy adaptive modified theta PSO	Dynamic EED (DEED) problem	Minimization of total fuel cost and total emission
	Bilil et al. (2012)	**A**	Accelerated MOPSO (AMOPSO)	Reactive power dispatch	Minimization of compensation devices cost, voltage deviation and real power loss
	Chang (2012)	**E**	Fitness sharing MOPSO proposed in Maximino and Jonathan (2005)	Static Var Compensator (SVC) installation for power system loading margin improvement	Maximization of system loading margin; minimization of SVC installation cost

Electrical Engineering	Ganguly et al. (2012)	**F**	MOPSO with heuristic selection and assignment of leaders or guides	Planning of electrical distribution systems	Minimization of total installation and operational cost and risk factor
	Liang et al. (2012)	**A**	Dynamic Multi-Swarm MO PSO (DMS-MO-PSO)	EED problems	Minimization of total fuel cost and total emission
	Lin et al. (2012)	**A**	MOPSO based on Pheromone sharing Mechanism (PM-MOPSO)	Electric Arc Furnace steelmaking process	Minimization of electric power consumption, smelting time, electrode consumption; maximization of lining life
	Moslemi et al. (2012)	**F**	MOPSO with modifications	Congestion management	Minimization of congestion cost; maximization of corrected transient stability margins
	Sahoo et al. (2012)	**F**	MOPSO based on pareto-optimality principle	Planning of electrical distribution systems	Minimization of total installation and operational cost and risk factor
	Shayeghi and Ghasemi (2012)	**F**	MOPSO with modifications	Dynamic Economic Load Dispatch (DELD)	Minimization of overall cost of generation units, which is a quadratic function for interval T
	Soundarrajan et al. (2012)	**G**	Enhanced PSO, MOPSO and Stochastic PSO	Voltage and frequency control in power generating system	Optimization of gains PID controller

Electrical Engineering	Teng et al. (2012)	**F**	CMOPSO with external species, adaptive mutation and adaptive grid method	Cognitive radio decision engine	Optimization of radio parameters
	Veeramachaneni et al. (2012)	**F**	MOPSO with modifications	Design of a wind farm	Maximization of energy output; minimization of cost of turbines and land area used for wind farm
	Zhang et al. (2012)	**A**	Bare-Bones MOPSO (BB-MOPSO)	EED problems	Minimization of total fuel cost and total emission
	Zhou and Sun (2012)	**D**	**	Configuration optimization of wind-PV hybrid power system	Optimization of number of PV modules, wind generators, batteries and maintenance cost
Electromagnetic Engineering	Goudos and Sahalos (2006)	**F**	MOPSO with small modifications	Designing of microwave absorbers	Minimization of total thickness of absorber and maximum reflection coefficient at first layer over desired frequency and angle range
	Chamaani et al. (2007)	**F**	MOPSO with small modifications	Designing of planar multilayered Electromagnetic (EM) absorbers	Minimization of thickness of each layer and maximum of logarithm of reflection coefficient of multilayer structure

Electromagnetic Engineering	Goudos et al. (2009)	**E**	MOPSO with fitness sharing (MOPSO-fs) proposed in Goudos et al. (2007)	Design of dual-band base station antennas	Minimization of average among all elements return losses and side lobe levels; maximization of gains
	Lu et al. (2009)	**G**	*	Risk management for virtual enterprise	Optimization of multiple members in constructional distributed decision making model
	Martin et al. (2009)	**G**	*	Designing Ultra-Wide Band (UWB) planar antennas	Optimization of gain, beamwidth and vector of results
	Chamaani et al. (2010)	**G**	*	UWB antenna array design	Minimization of sidelobe level and beamwidth
	Mussetta et al. (2010)	**D**	Meta-PSO***	Different EM optimization problems solution	As par the taken problem (taken different case studies)
	Ashabani and Mohamed (2011)	**D**	***	Cogging torque minimization	Minimization of cogging torque; maximization of machine developed output torque
	Bastos-Filho et al. (2011)	**E**	MOPSO with Crowding Distance and Roulette Wheel (MOPSO-CDR) proposed in Santana et al. (2009)	Designing of the configuration of pumping lasers of Raman amplifiers	Minimization of ripple and maximization of average on-off gain

Electromagnetic Engineering	Chamaani et al. (2011)	**G**	*	Design of an antipodal Vivaldi antenna for UWB	Minimization of transient distortion, reflection coefficient and cross polarization level
	Coelho et al. (2012)	**A**	MOPSO based on Exponential distribution probability operator (MOPSO-E)	Hysteresis model parameter identification	Minimization of mean squared error and linear error between calculated and measured curves
	Goudos (2012)	**G**	MOPSO with fitness sharing (MOPSO-fs)	Antenna and microwave design problem	-
	Pham et al. (2012)	**A**	MOPSO with Multi-Guider and Cross-searching techniques (MGC-MOPSO)	Benchmark TEAM 22 EM problems	Different for different-different functions
	Scriven et al. (2012)	**A**	Peer-to-Peer MOPSO (P2P-MOPSO)	Designing of EM Compatibility shielding enclosures	Maximization of thermal performance and EM shielding effectiveness of enclosure
Electronics Engineering	Latiff et al. (2008)	**A**	Dynamic Clustering approach using Binary MOPSO (DC-BMPSO)	Wireless Sensor Networks (WSN)	Minimization of energy expenditure in a cluster based network topology and intra-cluster distance
	Chen et al. (2009)	**G**	*	VLSI floorplanning	Optimization of wire length and area

Electronics Engineering	Pradhan et al. (2009)	**F**	MOPSO with modifications	Layout for a WSN	Maximization of coverage and life time
	Sharaf and El-Gammal (2009)	**A**	Discrete MOPSO	Hybrid power filter compensator with the design of C-type filter and fixed capacitor bank	Minimization of change in fundamental frequency load bus voltage, feeder current, fundamental frequency utilization feeder active, reactive power losses, dominant harmonic current penetration, harmonic voltage distortion; maximization of harmonic current absorption
	Sharaf and El-Gammal (2009)	**A**	MO multi-stage PSO	Power system shunt filter design	Minimization of harmonic current penetration and harmonic voltage distortion; maximization of harmonic current absorption
	Chi et al. (2011)	**A**	Comprehensive Learning MOPSO (CLMOPSO)	Crossing way-points location in air route network	Minimization of airline cost and flight conflict
	Ali et al. (2012)	**F**	MOPSO with modifications	Energy-efficient clustering in mobile ad-hoc networks	Optimization of degree difference and energy consumption
	Ali et al. (2012)	**F**	MOPSO with modifications	Energy-efficient clustering in WSN	Optimization of number of clusters

Electronics Engineering	Chen et al. (2012)	**A**	Coevolutionary MOPSO (CMOPSO)	VLSI floorplanning	Minimization of layout area and total interconnection wire length
	Gao et al. (2012)	**A**	Velocity-free MOPSO with centroid	Optimization of WSN	Maximization of network coverage and lifetime
	Ozkaya and Gunes (2012)	**F**	Modified PSO	Field-Effect Transistor modeling	Maximization of operation bandwidth; minimization of losses by maximizing transducer power gain
Environmental Sciences	Liu et al. (2012)	**A**	MOPSO with Constriction factor and Crossover and Mutation operator (MOPSO-CCM)	Land use zoning	Maximization of attribute difference, spatial compactness, spatial harmony and ecological benefits of land-use zones
	Liu et al. (2012)	**A**	Parallelized MOPSO (PMOPSO)	Designing of soil sampling network	Minimization of mean kriging variance and survey budget
	Masoomi et al. (2012)	**E**	MOPSO variant developed by Coello Coello and Lamont (2004)	Land management	Maximization of compatibility, dependency, suitability and compactness of land uses

Environmental Sciences	Wang et al. (2012)	**A**	Multiple Objective Chaos PSO (MOCPSO)	Water saving crop planning	Maximization of total net output, total grain yield, ecological efficiency and water production profit
Flowshop & Jobshop Schedulling Problem	Chandrasekaran et al. (2007)	**C**	*** Solved by small modifications in PSO	Flowshop scheduling problem	Minimization of makespan, total flow time and completion time variance
	Liu et al. (2007)	**A**	Variable Neighborhood PSO (VNPSO)	Flexible job shop scheduling problem	Minimization of flow time and make-span
	Rahimi-Vahed and Mirghorbani (2007)	**A**	MO Particle Swarm (MOPS)	Flowshop scheduling problem	Minimization of weighted mean completion and weighted mean tardiness
	Lei (2008)	**A**	Pareto Archive PSO (PAPSO)	Job shop scheduling problem	Minimization of agreement index; maximization of fuzzy completion time and mean fuzzy completion time
	Pan et al. (2008)	**F**	MOPSO with modifications	No-wait scheduling problem	Minimization of makespan; maximization of tardiness
	Liu et al. (2009)	**A**	Multi PSO (MPSO)	Flexible job shop scheduling problem	Minimization of sum of flowtime and maximum makespan

Flowshop & Jobshop Schedulling Problem	Sha and Lin (2009)	**F**	MOPSO with modifications	Job shop scheduling problem	Minimization of makespan, total tardiness and total machine idle time
	Sha and Lin (2009)	**F**	MOPSO with modifications	Flowshop scheduling problem	Minimization of makespan, mean flow, and machine idle time
	Li et al. (2010)	**B**	Combination of PSO and improved ant colony algorithm	Flexible job shop scheduling problem	Minimization of makespan, total workload and critical machine workload
	Lin (2010)	**F**	MOPSO with modifications	Open shop scheduling problem	Minimization of makespan, total flow time and machine idle time
	Moslehi and Mahnam (2010)	**F**	MOPSO with local search	Flexible job shop scheduling problem	Minimization of makespan, total workload of machines and critical machine workload
	Nai-ping and Pei-li (2010)	**C**	*** Applied random and uniform design method to produce weight coefficient	Flexible job shop scheduling problem	Minimization of completion time, total machine workload and biggest machine workload
	Tavakkoli-Moghaddam et al. (2011)	**B**	Hybrid of MO pareto archive PSO and genetic operators	Job shop scheduling problem	Minimization of weighted mean flow time and total penalties of tardiness&earliness

Flowshop & Jobshop Schedulling Problem	Tavakkoli-Moghaddam et al. (2011)	**B**	Combination of PSO with genetic operators	Job shop scheduling problem	Minimization of weighted mean flow time and total penalties of tardiness & earliness
	Wang et al. (2012)	**A**	MOPSO based on crowding distance with Baldwinian Learning mechanism (Mopsocd_BL)	Flowshop scheduling problem	Minimization of makespan and total idle time of machines
Image Processing	Kwok et al. (2009)	**F**	MOPSO with modifications	Contrast enhancement of gray-level digital images	Maximization of enhancement of contrast and preservation of intensity
	Paoli et al. (2009)	**F**	MOPSO with modifications	Clustering hyper-spectral images	Maximization of log-likelihood function and Bhattacharyya statistical distance between classes
	Niu et al. (2010)	**A**	MO Constriction PSO (MOCPSO)	Pixel-level image fusion	Optimization of fusion parameters
	Saeedi and Faez (2011)	**G**	*	Panchromatic (Pan) sharpening of a multispectral image	Minimization of relative dimensionless global error in synthesis and relative average spectral error; maximization of correlation coefficient

Image Processing	Ma and Zhang (2012)	**E**	Cultural-based MOPSO model proposed in Daneshyari and Yen (2011)	Image compression quality assessment	Compression ratio and mean squared error
Industrial Engineering	Heo et al. (2006)	**E**	PSO, Hybrid PSO and EPSO for optimizing deviation	Optimal power plant operation	Minimization of maximum deviation of objective functions: load tracking error, fuel usage, and throttling losses in main steam
	Yapicioglu et al. (2006)	**A**	Bi-objective PSO	Semi-obnoxious facility location problem	Minimization of transportation costs and undesirable effects
	Li et al. (2007)	**B**	Hybrid model of MOPSO and Artificial Neural Network (ANN)	Industrial cracking furnace	Maximization of ethylene and propylene production
	Liu et al. (2007)	**A**	Multiobjective Evolutionary PSO (MOEPSO)	Bin packing problem	Minimization of number of bins used and average deviation of Center of Gravity (CG) from idealized CG of bins
	Rahimi-Vahed et al. (2007)	**B**	Hybrid MO algorithm based on PSO and Tabu search	Mixed model assembly line sequencing problem	Minimization of total utility work, total production rate variation and total setup cost
	Jia and Gong (2008)	**G**	*	Multi-criteria human resource allocation	Maximization of benefit; minimization of cost

Industrial Engineering	Padhye (2008)	**F**	MOPSO with small modifications	Topology optimization of compliant mechanism	Minimization of strain energy and normalized volume
	Rahimi and Iranmanesh (2008)	**G**	*	Project management	Minimization of cost and time; maximization of total quality of project
	Tsai and Yeh (2008)	**D**	**	Inventory classification	Minimization of cost; maximization of inventory turnover ratio and inventory correlation
	Castro et al. (2009)	**G**	*	Vehicle routing problem	Minimization of number of vehicles, total distance, waiting time and elapsed time
	Forouraghi (2009)	**C**	*** applied modified PSO	Tolerance allocation	Minimization of total cost function for assembly within feasible region and assembly response variance; maximization of total root sum squares tolerance
	Rabbani et al. (2009)	**A**	MOPSO with new selection regimes for global best and personal bes	Project selection problem	Maximization of total benefit; minimization of cost and total risk

Industrial Engineering	Coelho et al. (2010)	**A**	MOPSO with updating of velocity vector using Gaussian distribution (MGPSO)	Multi-loop proportional integral controller tuning	Optimization of tuning parameters
	Pawar et al. (2010)	**D**	***	Grinding process	Minimization of production cost and surface roughness; maximization of production rate
	Zhang and Xing (2010)	**A**	Fuzzy MOPSO	Time-cost-quality tradeoff problem	Minimization of cost and time; maximization of quality
	Mo (2011)	**D**	***	Cylindrical helical gear design	Optimization of designing parameters
	Norouzi et al. (2011)	**G**	*	Open vehicle routing problem	Minimization of travel cost; maximization of obtained sales; optimization of goods distributed to vehicles according to their capacities
	Rongwei and Zhenghong (2011)	**B**	Hybrid of simulated annealing algorithm in MOPSO	Airofoil aerodynamic optimization design	Optimization of share function
	Venkatesan and Kumanan (2011)	**A**	MO Binary PSO (MOBPSO)	Supply chain sourcing strategy design	Minimization of total cost; maximization of supplier delivery reliability

Industrial Engineering	Chen et al. (2012)	**F**	*	Selective assembly problem with multiple characteristics	Minimization of clearance variation in selective assembly
	Escamilla-Salazar et al. (2012)	**D**	**	Machining optimization in titanium (6Al4V) alloy	Minimization of temperature and roughness
	Farmani et al. (2012)	**F**	MOPSO with modifications	Multidisciplinary design optimization	-
	Gonzlez et al. (2012)	**D**	***	Refining process in oil industry	Optimization of flow, concentration of sulfur species, total acid number, temperature and chromium content
	Haeri and Tavakkoli-Moghaddam (2012)	**A**	Intelligent MOPSO (IMOPSO)	Traveling salesman problem	Optimization of five standard problems with bi-objectives
	Javanshir et al. (2012)	**E**	MOPSO variant proposed in Coello Coello et al. (2004)	Supply chain problem	Minimization of total cost of supply chain and delays in serving customers
	Jia et al. (2012)	**F**	MOPSO with modifications	Control for batch processes	Basic: Maximization of amount of final product while reducing the amount of by-product (different for different case studies)

Industrial Engineering	Jolai et al. (2012)	**G**	*	Unequal sized dynamic facility layout problem	Minimization of material handling and rearrangement costs and maximization of total adjacency and distance requests
	Kusiak and Wei (2012)	**G**	*	Optimization of activated sludge process	Optimization of air flow rate, carbonaceous biochemical oxygen demand and total suspended solids of effluent
	Kusiak and Xu (2012)	**A**	** MO Constant Inertia Weight PSO (MO-CIWPSO), MO Decreasing Inertia Weight PSO (MO-DIWPSO), and MO Constricted PSO (MO-CPSO)	Optimization of heating, ventilating and air conditioning system	Minimization of energy consumed (electricity and natural gas)
	Liu et al. (2012)	**B**	MOPSO based on Grey relational analysis with entropy weight	Location-routing network optimization in reverse logistics	Minimization of cost and vehicles
	Pourrousta et al. (2012)	**G**	*	Integrated supply chain	Optimization of total cost, setup of each product, production, inventory cost, final product in factory&distribution centers and delivery time

Industrial Engineering	Ren et al. (2012)	**E**	Non-dominated Sorting PSO (NSPSO) proposed by Li (2003)	Tanker conceptual design	Maximization of effectiveness; minimization of production cost
	Shankar et al. (2012)	**B**	Hybridization of basic PSO with binary PSO	Decisions of facility location and allocation	Minimization of total supply chain cost; maximization of fill rate
	Venkatesan and Kumanan (2012)	**A**	MO Discrete Particle Swarm Algorithm (MODPSA)	Supply chain network	Minimization of supply chain cost and demand fulfillment lead time; maximization of volume flexibility
	Xu et al. (2012)	**G**	*	Plastic injection molding industry	Minimization of product weight, volumetric shrinkage and flash
	Yang (2012)	**A**, B	Hierarchy PSO (HPSO) and hybridization of PSO with Mutative Scale Local Search Algorithm (MSLSA)	Daily generation scheduling for hydropower stations	Maximization of peak-energy capacity benefits and power generation
	Yang et al. (2012)	**G**	*	Maintenance planning of deteriorating bridges	Optimization of expected values of life-cycle maintenance cost and performance measures
Mechanical Engineering	Sun et al. (2009)	**G**	*	Drawbead design in sheet metal forming	Minimization of rupture and wrinkling

Mechanical Engineering	Zhang and Mahfouf (2009)	**D**	nPSO ***	Design problem of alloy steels	Minimization of ultimate tensile strength and reduction of area
	Lucas et al. (2010)	**G**	*	Designing of a brushless permanent magnet motor	Minimization of thrust ripple; maximization of thrust density
	McDougall and Nokleby (2010)	**E**	Parallel Asynchronous MOPSO (MOPAPSO) proposed in McDougall and Nokleby (2009)	Grashof mechanisms	Minimizing deviation from specied precision points and deviation from optimal transmission angle
	Montalvo et al. (2010)	**G**	*	Water distribution systems design	Minimization of initial investment cost and lack of pressure at every consumption node and one additional objective for reliability assessment of network
	Dongmei et al. (2011)	**B**	MOPSO as the integration of PSO and crossover approach	Diesel engine control parameter optimization	Optimization of brake specific fuel consumption, exhaust gas emission, and soot
	Sayyaadi et al. (2011)	**G**	*	Design of a benchmark cogeneration system i.e. CGAM cogeneration system	Maximization of exergetic efficiency; minimization of unit cost of system product and cost of the environmental impact

Mechanical Engineering	Yang et al. (2011)	**A**	Fuzzy global and personal best-mechanism-based MOPSO (F-MOPSO)	Optimization of multi-pass face milling	Minimization of production time and cost; maximization of profit rate
	Yildiz and Solanki (2011)	**C**	*** Hybrid of PSO and receptor editing property of an immune system	Vehicle crashworthiness	Minimization of intrusion, distances and mass
	Li et al. (2012)	**A**	Distance ranking-based MOPSO (DMOPSO)	Air compressor design	-
	Montazeri-Gh et al. (2012)	**D**	**	Gain tuning of gas turbine engine fuel controller	Minimization of response time during engine acceleration and deceleration and engine fuel consumption
	Ren et al. (2012)	-	Discrete MOPSO (DMOPSO)	Warship combat system design	-
	Shojaeefard et al. (2012)	**B**	Hybrid of MOPSO and TOPSIS	Friction stir welding butt joints	Maximization of hardness and tensile shear force
Neural Network	Karpat and Ozel (2007)	**E**	Dynamic Neighborhood PSO (DN-PSO) proposed in Hu and Eberhart (2002)	Advanced turning process	Minimization of machining induced stresses on surface and surface roughness; maximization of productivity, tool life and material removal rate
	Huang et al. (2008)	**G**	*	Trajectory planning	Minimization of disturbances, mechanical energy of actuators and traveling time

Neural Network	Qasem and Shamsuddin (2009)	**F**	MOPSO with modifications	Radial Basis Function (RBF) network training	Minimization of Mean Square Error (MSE) and sum of square weights
	Qasem and Shamsuddin (2009)	**E**	Adaptive MOPSO (AMOPSO) proposed in Tripathi et al. (2007)	RBF network training	Minimization of MSE and sum of square weights
	Qasem and Shamsuddin (2009)	**F**	MOPSO with modifications	RBF network training	Minimization of MSE and sum of square weights
	Qasem and Shamsuddin (2010)	**A**	Time Variant MOPSO (TV-MOPSO)	RBF network training	Minimization of MSE and sum of square weights
	Park et al. (2012)	**E**	MOPSO with Crowding Distance (MOPSO-CD)	Fuzzy RBF neural network design with Information granulation	Minimization of complexity; maximization of accuracy
Robotics	Masehian and Sedighizadeh (2010)	**D**	**Solved by small modifications in PSO	Robot motion planning	Minimization of path length; maximization of smoothness
	Ghosh et al. (2012)	**F**	Modified MOPSO	Multi-robot co-operative box pushing problem	Minimization of energy and time
	Rajendra and Pratihar (2012)	**B**	MOPSO with neuro-fuzzy inference system	Gait planning of biped robot	Minimization of power consumption; maximization of dynamic balance margin
Software Engineering	de Carvalho et al. (2008)	**A**	MOPSO-N	Software testing for fault-prediction	Optimization of sensitivity, specificity, support and confidence

Software Engineering	Chauhan et al. (2009)	**E**	Crowding distance based MOPSO proposed in Raquel and Naval (2005)	Computer-aided design of RF windows	Maximization of match of frequency response at desired frequency; minimization of reflections around resonant frequency
	Mishra et al. (2009)	**G**	*	Portfolio optimization	Maximization of profit; minimization of risk
	de Carvalho et al. (2010)	**E**	MOPSO-N proposed in Carvalho et al. (2008) with few aspects	Software testing for fault-prediction	Optimization of sensitivity, specificity, support and confidence
	Gonsalves and Itoh (2010)	**G**	*	Software development	Minimization of project development cost and processing time
	Briza and Naval Jr (2011)	**F**	MOPSO with modifications	Stock traders problem	Optimization of percent profit and sharpe ratio
	Marinaki et al. (2011)	**F**	MOPSO with modifications	Vibration suppression of smart structures	Minimization of error functions for nodal displacements and rotations array and corresponding velocities array

Software Engineering	Fernndez et al. (2012)	**B**	Hybrid of Vector Evaluated PSO (VEPSO) and Quantum-behaved VEPSO (VEQPSO)	Construction of emerging markets exchange traded funds	Minimization of standard deviation of difference between returns from benchmark & constructed exchange traded fund and sum of transaction costs and market impact
	Gonales et al. (2012)	**E**	Crowding distance based MOPSO proposed in Raquel and Naval (2005)	Implementation for software: environment for modeling, simulation and optimization	Maximization of ammonia production; minimization of power consumption
	Miranda et al. (2012)	**B**	Hybrid MOPSO (HMOPSO)	Support vector machine parameter selection	Minimization of complexity; maximization of success rate on classication
	Mishra et al. (2012)	**G**	*	Portfolio optimization with functional link ANN	Maximization of portfolio expected return; minimization of portfolio risk

Software Engineering	Sjarif et al. (2012)	**G**	*	Motion segmentation problem	Different objectives for different test problems. Basic objectives: Maximization of number of elements of pareto optimal set found and spread solutions found; minimization of distance of pareto front
	Thamarai and Shanmugalakshmi (2012)	**F**	MOPSO with modifications	Video coding	Maximization of compression ratio; minimization of MSE

*: Applied MOPSO directly/with basic modifications,
**: Converting the problem in single objective using normalization then applied PSO,
***: Single objective formulation using weighted approach, and then applied PSO.

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