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Conventional and Metaheuristic Optimization Algorithms for Solving Short Term Hydrothermal Scheduling Problem: A Review

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ABSTRACT Short term hydrothermal scheduling (STHTS) is a non-linear, multi-modal and very complex constrained optimization problem which has been solved using several conventional and modern metaheuristic optimization algorithms. A number of research articles have been published addressing STHTS using different techniques. This article presents a comprehensive review of research published for solving the STHTS problem in the last four decades.

INDEX TERMS Short term hydrothermal scheduling, conventional algorithms, meta-heuristic algorithms, no free lunch theorem.

I. INTRODUCTION

Short-term hydrothermal scheduling STHTS is a non-linear and multi-modal optimization problem, which can be presented in cascaded or non-cascaded form. The STHTS problem is generally presented as given by equations (1) to (9).

$$min(f) = \sum_{m=1}^{N} n_m F_m \tag{1}$$

The main objective function of STHTS problem is to minimize the cost of energy generation from the thermal generators, which is a function of the fuel costs, subjected to equation (2).

$$\sum_{i=1}^{N_s} P_{th_{i,m}} + \sum_{j=1}^{N_s} P_{hyd_{j,m}} = P_{Demand} + P_{losses} \tag{2}$$

where,

$$P_{hyd_{j,m}} = f(V_{hyd_{j,m}}, Q_{hyd_{j,m}}) \tag{3}$$

Generator limits

$$P_{hyd_j}^{min} \leq P_{hyd_{j,m}} \leq P_{hyd_j}^{max} \tag{4}$$

$$P_{th_i}^{min} \leq P_{th_{i,m}} \leq P_{th_i}^{max} \tag{5}$$

The equation (2) is an equality constraint that makes sure that the power produced by the hydro and thermal power plants is equal to the sum of power demand and the transmission losses in a power system. Equation (3) tells that hydel power at scheduling interval *m* of reservoir *j* is the function of the volume of j^{th} reservoir and the j^{th} interval's value of water discharge rate. Inequalities (4) and (5) give respectively the minimum and maximum limits of the hydel and Thermal powers of unit *j* and *i* at the scheduling interval *m*.

Hydraulic network constraints

$$V_{hyd_j}^{min} \leq V_{hyd_{j,m}} \leq V_{hyd_j}^{max} \tag{6}$$

$$Q_{hyd_j}^{min} \leq Q_{hyd_{j,m}} \leq Q_{hyd_j}^{max} \tag{7}$$

$$\sum_{m=1}^{N} Q_{j,m} = Q_{j,total} \tag{8}$$

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The inequalities (6) and (7) and are related to the operation of the water reservoir, whereas equation (8) gives the allowed value of the water discharged by the j^{th} reservoir for total time of N intervals. The reservoir's volume and the discharges are balanced by the continuity equation (9) which is given as:

$$V_{hyd_{j,(m+1)}} = V_{hyd_{j,m}} + I_{hyd_{j,m}} - Q_{hyd_{j,m}} - S_{hyd_{j,m}} + \sum_{i=1}^{R_{u,j}} (Q_{hyd_{m-t_{(i,j)}}} + S_{hyd_{m-t_{(i,j)}}}) \quad (9)$$

where, m is equal to the number of scheduling hours and j is the number of reservoirs. $R_{u,j}$ is the number of upstream reservoirs of the j^{th} reservoir.

Equation (1), is the main objective of the STHTS problem, i.e. to minimize the cost of the scheduling of hydro and thermal generators. The cost F_j is the function of the power of thermal power generator which is in fact the function of the fuel cost. This relation of cost and thermal power is given by equation (10) as;

$$F_m = a + bP_{th_m} + cP_{th_m}^2 \quad (10)$$

Which is a quadratic function of thermal power at m_{th} scheduling interval and a, b and c are coefficients of scheduling equation. Depending on the thermal generator, this equation can be of higher orders as well which increase the non-linearity of the objective function. Moreover, since the scheduling problem has many scheduling intervals, the STHTS problem becomes a multi-dimensional optimization problem, where each scheduling interval is considered as one dimension of the problem. The multi-dimensional function makes STHTS problem highly multi-model, i.e. a problem with objective function having multiple peaks.

There are different types of STHTS problem, however, most of the main problems can be completely defined by the model presented in equations (1) to (9). Different definitions of STHTS problems which have been specifically solved by using metaheuristic optimization algorithms as presented in [1] and in many other literature references, are being presented for the interest of the readers.

The non-cascaded short-term hydrothermal scheduling problem (NCSTHTS), deals with the economic dispatch of one water reservoir based hydel power plant and an equivalent or composite of many thermal power plants. Mathematically, the NCSTHTS can be defined by the above equations and inequalities, if $j = 1$.

The *cascaded short-term hydrothermal scheduling (CSTHTS) problem* deals with the combined economic operation of a chain of multiple reservoirs present on the same stream in series, i.e. one reservoir-based power plant is downhill the other reservoir-based power plant. In such problems, there can also be several thermal generating units, but are usually presented as individual units, or as an equivalent thermal unit. Mathematically, the CSTHTS can be defined by the above equations and inequalities, if $j > 1$.

The multi-objective short-term hydro-thermal scheduling problem (MOSTHTS) problem is a type of STHTS problem in which two or more objectives may be considered simultaneously. The first objective is to reduce the cost of operation, called economic dispatch problem, whereas, the other objective is usually to minimize the CO_x, NO_x, and SO_x emissions from the thermal power plants. Most of the literature concerning MOSTHTS problems, as discussed in the following sections will consider the cascaded reservoir STHTS problems. In MOSTHTS problem, the other objective function, which is conflicting to equation (1), can be defined by equation (11) as

$$min(F^{emission}) = \sum_{m=1}^{N} n_m F_m^{emission} \quad (11)$$

where,

$$F_m^{emission} = d + eP_{th_m} + gP_{th_m}^2 \quad (12)$$

where d, e and g are coefficients of the objective function equation.

In non-cascaded as well cascaded STHTS problems, the generation cost of thermal power plants is the function of fuel cost, which may be a linear, quadratic or sinusoidal function (if valve point loading of thermal power plants is considered). The valve point loading in thermal power units is represented by equation (13) as given below;

$$F_m = a + bP_{th_m} + cP_{th_m}^2 + f(\sin P_{th_m}) \quad (13)$$

where, $f(\sin P_{th_m})$ represent a function of sinusoidal of thermal power P_{th_m} at scheduling interval m.

Depending upon the non-linearity of the cost function, the optimization problem can be multi-modal, i.e. the objective function can have multiple peaks (minima), including the local minima and global minimum. In all optimization problems, global optimum solution is found by multiple iterations to ensure the lowest operating cost, for scheduling of hydro-thermal plants operation.

The STHTS problems can also be of pumped storage type, in which the water stored in the upstream reservoir is first discharged to the downstream reservoir through the hydro-power generators to produce electricity and then the discharged water accumulated in the downstream reservoirs is pumped back to the upstream reservoir to keep the water available for electricity generation for other periods. The other possible type of STHTS problem deals with transmission line losses, which are usually the function of the hydro-power generation because the hydro-power units are usually present far away from the load centres, and therefore transmission line losses are usually related to hydro-power units only. It is a common practice to represent the transmission line losses in the form of hydro-power generation. STHTS problems also vary based on types of head. There can be fixed head based and variable head based STHTS problems. This paper gives a review on most of these types of STHTS problems.

The STHTS problem, as already mentioned, is a constrained optimization problem. A lot of work has been done and is still going on in finding good approximates to the global optimum solutions of these types of the STHTS problems. Due to highly non-linear and multi-modal and multidimensional nature of STHTS problems, it is very difficult to find out the exact solutions in many cases and an approximate optimized solution do the needful. Many conventional and modern optimization algorithms have already been applied to solve STHTS problems and researchers are still trying to find robustly performing algorithms. Following sections present a comprehensive review of most of the literature available on STHTS problem and its solutions.

STHTS is a very complex, multi-modal, non-convex and non-linear optimization problem for which it is very difficult to exactly find the global optimum solution. Therefore, several numerical methods have been opted in the literature to find the closest possible solution, i.e. the nearest approximation of the global optimum solution. Reference [2], presents the review of the 123 articles, relevant to the STHTS problem and the algorithms applied on different types of STHTS problems, till the year 2009. This article summarizes the review presented in [2] and extends discussion with the review of conventional and modern optimization algorithms applied on STHTS problems after the year 2009 till date to establish a state of art comparison of meta-heuristic algorithms. The focus of discussion has been limited to the solution methodologies and algorithms to solve STHTS problems only, while excluding the solutions of mid-range and long-range hydrothermal scheduling problems. The review is based on two important points on the basis of which the algorithms were implemented to solve the STHTS problems as presented in there respective articles, though generically.

1) The minimization of cost of STHTS that was achieved by the different optimization algorithms. For MOSTHTS problem, the algorithms also tried to achieve minimization of pollutants like CO2, along with the minimization of the fuel cost.
2) The achievement of the minimum cost with fast convergence rate, i.e. short computation time.

Both these points improve the the energy utilization while achieving the dispatch of the thermal amd hydel power plants.

II. CONVENTIONAL OPTIMIZATION METHODS APPLIED ON STHTS PROBLEM

This section discusses conventional optimization methods many of those are gradient based. These are mostly deterministic in nature and use a single path while proceeding to find optimal solutions. For multi-modal cases, these algorithms may stuck to local optima, being deterministic in nature.

A. LAGRANGIAN RELAXATION AND BENDERS DECOMPOSITION-BASED METHODS APPLIED ON STHTS PROBLEM

The deterministic optimization algorithms were applied to STHTS problems in first decade of this century [2]. These deterministic algorithms usually utilize the concepts of gradients/derivatives and utilize hessian matrices [3], in repetitive attempts for finding the best solution. The trajectories of the procedure can be easily traced with repetition if the starting point of the algorithms is exactly known and same. The major disadvantage of these algorithms is that they stuck in the local minimum solutions as these are deterministic in finding the solution. On the other hand, metaheuristic optimization algorithms are stochastic in nature and are population-based and due to the randomness in the procedure, the trajectories of the procedure are mostly non-repetitive. These metaheuristic algorithms are derivative-free algorithms which also, mostly, let them get rid of sticking to local optimum solutions. Reference [2] presents, Lagrangian relaxation and Benders decomposition methods which are deterministic optimization methods, which in their canonical form, and their variants were applied to STHTS problems

References [4], [5] have presented the convergence behaviour of Lagrangian based formulation of CSTHTS problems and a relaxation coefficient was presented to assure the convergence of algorithm towards good approximate of the global optimum solution. Reference [6], has solved the CSTHTS problem by first dividing the main problem into two sub-problems and then applied a blend of Lagrangian relaxation method and dynamic programming to solve it. The authors of reference [6], have solved pumped storage CSTHTS problem using Lagrangian relaxation and dynamic programming and presented it in reference [7]. In references [8]–[10], network flow programming was used while considering hydro dominated power systems. In reference [6], augmented Lagrangian decomposition and coordination method, a variant of Lagrangian relaxation method, was implemented.

References [11], [12], incorporated a hybrid of Lagrangian relaxation method and dynamic programming. Reference [13], solved the CSTHTS problem considering the composite of several cascaded reservoirs and discrete hydro constraints, by using the Lagrangian relaxation-based algorithm and presented a good approximate of a global optimum. Reference [14], solved the pumped storage CSTHTS problem while keeping the focus on river catchment sub-problem on the cascaded reservoir system by using a novel relaxation algorithm. Although, the near approximate to a global solution was promised, however, the convergence behaviour was not good. Reference [15], used the Lagrangian relaxation algorithm to solve an integrated problem of hydrothermal scheduling and its biding in the energy market. The problem was divided into several sub-problems and Markov chains were used to model the market pricing while considering the scheduling requirements. The dynamic programming based algorithms were also incorporated to solve some of the sub-problems. Reference [16], adopted the augmented Lagrangian algorithm to solve pumped storage CSTHTS problem on an IEEE 24 bus system for finding the near-global while considering transmission line power losses and pumped storage hydel power system. Reference [17], used variable splitting based Lagrangian relaxation algorithm to solve the real CSTHTS problem on Brazilian power system that was having large scale predominantly hydro electrical systems.

In reference [18], security-constrained CSTHTS problem was solved by using a multistage Benders decomposition method while considering transmission line power losses. The problem considered many constraints of the hydro system like cascaded- reservoirs without ignoring the water spillage constraint.

References [19], solved the NCSTHTS problem while considering the DC transmission losses and the AC power flow, by using the Benders decomposition method. The system considered was an actual 9-bus power system and the method considered the model of the transmission system by incorporating the AC power flow. The convergence rate was slow and to increase the convergence rate, and accelerating variant of Benders technique was implemented on the same problem in reference [20].

Reference [21] proposed a combination of augmented Lagrange Hop-field network method and improved merit order method to solved pumped storage CSTHTS problem on IEEE 24 bus network while considering transmission line power losses and pumped storage hydel power system on 32 power units. Reference [22], has utilized a Lagrangian Relaxation scheme that works on a variable splitting technique that divides the CSTHTS coordination problem of a real system into sub-problems which use the bundle method to get solved. This work analyzes the decomposition strategy and the quality of the solutions produced by the Lagrangian relaxation method and the pseudo-primal point, which is calculated by active cuts found by implementing the Bundle method. In Reference [23] A dual dynamic programming technique known as Multistage Benders decomposition (MSBD), is applied to solve hydrothermal scheduling problems, on a predominantly hydro system. It is shown that there is an "optimal aggregation factor," which finds the trade-off between solving a "larger number of shorter sub-problems" and solving a "smaller number of larger sub-problems". While utilizing the decomposition approach to solve the real CSTHTS problem on Brazilian power system.

Reference [24] has solved the CSTHTS problem by using a decomposition approach. A Lagrangian Relaxation (LR) and an Inexact Augmented Lagrangian based on variable splitting are applied in which the resulting dual problem is solved by a Bundle method. The inexact Augmented Lagrangian method is used to improve the quality of the solution supplied by the LR. Reference [25] implemented an augmented Lagrange Hop-field network (ALHN) based method, to solve MOSTHTS problem, which is a combination of augmented Lagrange relaxation and continuous Hopfield neural network, in which the augmented Lagrange function is taken as the energy function of the network. Fuzzy set theory was applied to find the best solution among the Pareto optimal fronts.

Reference [26] presented the application of the multi-stage Benders decomposition method to solve the real CSTHTS problem on Brazilian power system with a smart definition of stages of the main CSTHTS problem and utilized multiple processors in parallel to solve different sub-problems to increase the speed of solving. Reference [27] implemented a simplified Lagrangian multiplier-based algorithm to solve both NCSTHTS and CSTHTS problem in which water discharge rate was modelled as a quadratic function of hydro-power generation and fuel cost was modelled as a quadratic function of thermal power generation. The NCSTHTS problem was solved in reference [28] using Lagrange function for a fixed head problem. Figure 1 gives the year wise distribution of the number of articles published on STHTS using variants of Lagrangian relaxation and Benders decomposition. Table 1 summarizes the implementation of Lagrangian multiplier and its variants on STHTS.

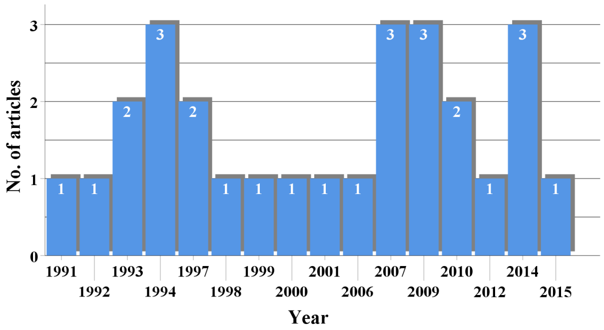

FIGURE 1. Year wise distribution of articles published on STHTS using variants of Lagrangian relaxation and Benders decomposition.

B. MIXED-INTEGER PROGRAMMING APPLIED ON STHTS PROBLEM

According to reference [2], branch and bound and cutting plane are the most widely implemented methods of mixed-integer programming and STHTS is widely solved by using mixed-integer programming methods in much commercial software. In reference [29], A convex function of hydrothermal scheduling problem was solved by mixed-integer programming solvers by improving the convexity issues of the algorithm. This involved the linearization of non-linear and mixed integer and multi-modal CSTHTS problem. In reference [30], an algorithm based on mixed-integer programming was implemented to solve the unit commitment problem along with the implementation of the linear programming algorithm to solve the CSTHTS problem. The hydro units, in the problem, were presented by linear models and water head was considered fixed. To improve the slow convergence rate of the implementations of reference [30], a variant algorithm of the branch and bound search method was used in reference [31], that considered an initial feasible integer solution that helped the branch and bound algorithm to approach towards optimal solution of the hydrothermal scheduling problem. Reference [32] solved CSTHTS problem using mixed-integer linear programming while considering DC network flows of power. Prohibited discharge zones of hydro reservoirs were also taken into consideration as system constraints. Reference [33] has addressed the self-scheduling hydrothermal scheduling problem in day-ahead energy and reserves markets while considering the prohibited operating zones of hydro plants.

TABLE 1. Summary of lagrangian and bender's decomposition for different types of STHTS problems.

Optimization Algorithm	Variants of the Algorithm	General Overview of Performance
Lagrangian relaxation and benders decomposition	Canonical version with relaxation coefficient [4], [5], [13]–[15], [27], [28] Hybrid with dynamic programming [6], [7], [11], [12] Augmented Lagrangian decomposition [6], [16] Hybrid with Markov chains [15] Variable splitting based Lagrangian relaxation [12], [17] Multi-stage benders decomposition (MSBD) [18], [19], [23], [26] Accelerating variant of benders technique [20] Augmented Lagrangian Hopfield network method [21], [25] Hybrid with pseudo primal point MSBD with optimal aggregation factor [23] Inexact augmented Lagrangian method [24]	Robust solutions achieved though the. later metaheuristic implementations helped achieving good approximates to global optimum solution . Premature convergences to local optima were also observed while implementing these algorithms. Convergence rate is usually slow, but variants helped improving convergence, though not better than heuristic algorithms. Due to premature convergences to local optima, the algorithm approached to their best possible solutions in many number of iterations

A binary i.e. 0/1 mixed-integer linear formulation method is applied, which allows realistic modelling of the unit's operating phases like synchronization, soaking, dispatching and desynchronization.

Reference [34] has solved the real system CSTHTS problem using a new method, based on mixed-integer nonlinear programming (MINLP). The main contribution of this work is that discharge ramping constraints and start/stop of units are also considered, which make hydro-power as a nonlinear function of water discharge and the head. Reference [35] has solved the CSTHTS problem by applying a variant of mixed-integer quadratic programming approach while considering head-dependency, discontinuous operating regions of hydro and thermal generators and ramping discharge rate constraints. Reference [36] has solved the CSTHTS problem by applying a variant of mixed-integer non-linear programming approach while considering head-dependency, discontinuous operating regions of hydro and thermal generators and ramping discharge rate constraints. Reference [37] has proposed Mixed-integer linear programming (MILP) for modeling the MOSTHTS problem in the day-ahead energy and reserve markets while considering the prohibited working zones, dynamic ramp rate constraints and operating services of thermal generating units and the characteristics of multi-head power discharge for hydro generating units and reservoirs' spillage. Reference [38] discussed the implementation of a parallelized stochastic mixed-integer linear program (SMILP) to solve the CSTHTS problem. A scenario-based decomposition approach based on the progressive hedging (PH) algorithm is implemented to decrease simulation time while using multi-core processing. Reference [39] implemented Stochastic Mixed-Integer Linear Programming (SMILP) algorithm to solve CSTHTS problem under uncertainty on Chilean Central Interconnected system while using Progressive Hedging Algorithm (PHA) with which each sub-problem is solved in parallel. Reference [40] has implemented a mixed-integer linear programming (MILP) methodology, using the branch and bound & cut (BB&C) algorithm, to solve CSTHTS problem. In reference [41], a logarithmic size mixed-integer linear programming (MILP) method was proposed for the CSTHTS problem, that takes only a logarithmic number of binary variables and constraints to piece-wise linearize the nonlinear functions of CSTHTS problem. Figure 2 gives the year wise distribution of the number of articles published on STHTS using variants of mixed-integer programming. Table 2 summarizes the implementation of mixed integer programming and its variants on STHTS.

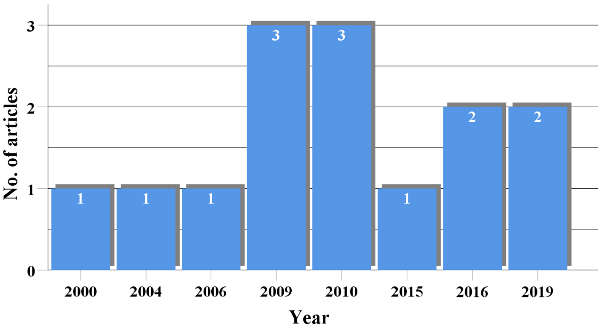

FIGURE 2. Year wise distribution of articles published on STHTS using variants of mixed-integer programming.

TABLE 2. Summary of mixed integer programming for different types of STHTS problems.

Optimization Algorithm	Variants of the Algorithm	General Overview of Performance
Mixed integer programming	Canonical Function and Branch and bound method [29]–[32], [40] Cutting plane method [40] Mixed integer linear programming [37] 0/1 mixed integer linear programming [33] Mixed integer non-linear programming [34], [36] Mixed integer quadratic programming [35] Parallelized Stochastic mixed integer linear programming [38] Stochastic mixed integer linear programming [39] Logarithmic sized mixed integer linear programming [41]	Robust solutions achieved but not better than metaheuristic algorithms. Though the algorithms show better performance in terms of avoiding premature convergence to local optimum than Lagrangian and bender's decomposition methods. Convergence rate is usually slow, but variants helped improving convergence, though not better than heuristic algorithms.

C. DYNAMIC PROGRAMMING APPLIED ON STHTS PROBLEM

According to reference [2], despite the limitation of dynamic programming to solve large dimensional and large-sized problems, a lot of variant of dynamic programming had been applied to STHTS problem because dynamic programming can deal with non-convexity and non-linearity of STHTS problem. Reference [42], has implemented a multi-pass dynamic programming method, a variant of the original dynamic programming algorithm, on realistic CSTHTS problem. In reference [43], authored by the researchers of reference [42], same multi-pass dynamic programming approach was utilized to solve the pumped storage CSTHTS problem, and the technique was further applied in reference [44], to solve the pumped storage CSTHTS problem on Taiwan power system while considering the battery energy storage system. References [45], [46], presented the solution of a sub-problem of NCSTHTS and CSTHTS hydrothermal scheduling respectively and the primal problem, using multi-pass dynamic programming.

In reference [47], a dynamic programming algorithm was used to solve the sub-problem of the thermal units whereas the hydro units sub-problem was solved by implementing the state space approximation within the multi-pass dynamic programming. A good near-optimal solution in less convergence time was possible in this implementation. In reference [48], a hybrid of multi-pass dynamic programming and evolutionary programming to improve the NCSTHTS and CSTHTS problem's solution on Taiwan power system already presented in references [45], [46]. In reference [49], a combination of mixed extended differential dynamic programming and mixed coordination method was used to solve CSTHTS problem. Reference [50], presented the solution of unit commitment part of the CSTHTS problem by using priority-list-based dynamic programming, which is one of the successive approximation methods. Reference [51] has solved the CSTHTS problem using dynamic non-linear programming while considering power transmission losses and valve point loading of thermal generators. Reference [23] has applied a dual dynamic programming technique known as Multistage Benders decomposition to solve CSTHTS problems on Brazilian power system. An "optimal aggregation factor", was found which searched for the trade-off between solving a "larger number of shorter sub-problems" and solving a "smaller number of larger sub-problems". Reference [51] has solved the CSTHTS problem using dynamic non-linear programming while considering power transmission losses and valve point loading of thermal generators.

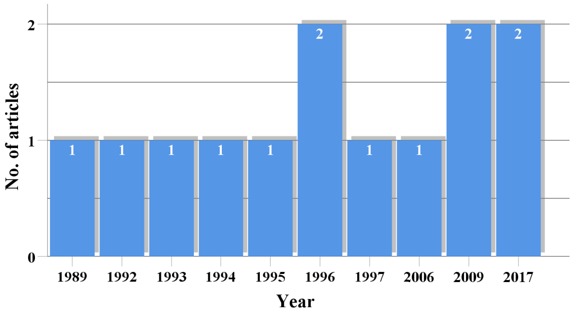

FIGURE 3. Year wise distribution of articles published on STHTS using variants of dynamic programming.

Figure 3 gives the year wise distribution of the number of articles published on STHTS using variants of dynamic programming. Table 3 summarizes the implementation of dynamic programming and its variants on STHTS.

D. INTERIOR POINT (IP) ALGORITHMS APPLIED ON STHTS PROBLEM

According to [2], reference [52], implemented the primal-dual IP algorithm to solve the CSTHTS problem on Brazilian

TABLE 3. Summary of dynamic programming for different types of STHTS problems.

Optimization Algorithm	Variants of the Algorithm	General Overview of Performance
Dynamic programming	Multi-pass DP [42]–[47] Hybrid of EP and multi-pass DP [48] Mixed extended differential DP [49] Priority-list-based DP [50] Non-linear DP [51] Dual DP [23]	Robust solutions achieved. Better. performance than Lagrangian and benders decomposition and mixed integer programming. Though performance in multidimensional problems like CSTHTS was lower than metaheuristic algorithm. Convergence rate is usually slow, but Variants helped improving convergence, though not better than heuristic algorithms. Low convergence for multi-dimensional STHTS problems

TABLE 4. Summary of variants of interior point method for different types of STHTS problems.

Optimization Algorithm	Variants of the Algorithm	General Overview of Performance
Interior point algorithms	Primal dual IP [52], [53], [55], [56] Predator corrector IP method [54] Homogeneous IP method [58]	Robust solutions achieved in most. of the cases. Efforts were made to find near global optimum, but heuristic algorithms succeeded. The convergence rate is usually slow but amazingly better than many genetic algorithm variants, specially the canonical version of genetic algorithm

power system while considering the effect of bilateral contracts and spot market on optimal dispatch. Reference [53], combined primal-dual IP algorithm with a genetic algorithm to solve CSTHTS problem. The on and off state of thermal generators was set by the genetic algorithm whereas, the economic scheduling of thermal plants was done using the primal-dual IP method to solve CSTHTS problem. Reference [54], predictor-corrector IP method was implemented on the CSTHTS problem on Brazilian power system and was compared with the implementation of the primal-dual IP method on the same CSTHTS problem and the results of both implementations were compared.

In reference [55], primal-dual IP algorithm was utilized to meet the objective of minimizing the difference between the cost of generation and consumer benefit while considering the dynamic consumer energy constraints, in an STHTS problem. Reference [56], utilized the primal-dual IP algorithm to solve the individual hydro and thermal sub-problems and utilized the bundle method for the dual CSTHTS problem while considering transmission line power losses. Reference [57], solved NCSTHTS problem on Spanish power system by genetic algorithm and compared its results with implementations of IP method. It was found that the convergence was accelerated in IP method implementations as compared to genetic algorithm implementations.

Reference [58], also presented a homogeneous IP method to further improve the convergence rate of CSTHTS problems. Figure 4 gives the year wise distribution of the number of articles published on STHTS using variants of interior point algorithm.Table 4 summarizes the implementation of interior point method and its variants on STHTS.

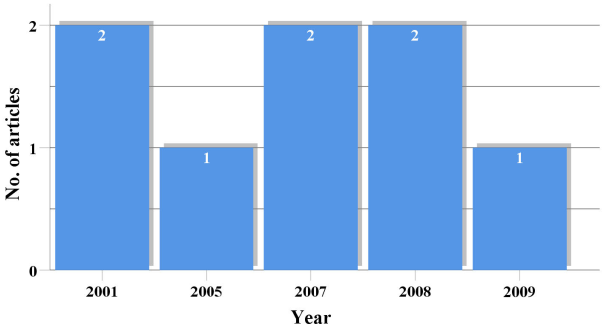

FIGURE 4. Year wise distribution of articles published on STHTS using variants of interior point algorithm.

E. CONVENTIONAL OPTIMIZATION ALGORITHMS APPLIED ON STHTS PROBLEM

Reference [59], has applied a direct method optimization algorithm to solve the CSTHTS problem. Reference [60], has applied a non-linear optimization algorithm called the conjugate gradient method, which is a classical numerical method, to solve the CSTHTS problem. Reference [61], has used a decomposition approach in combination with linear programming to solve the CSTHTS problem. Reference [62], has applied the combination of first-order gradient technique and non-linear programming to solve CSTHTS problem.

TABLE 5. Summary of other conventional algorithms for different types of STHTS problems.

Optimization Algorithm	Variants of the Algorithm	General Overview of Performance
Other conventional algorithms	Direct method optimization [59]	Efforts made to find near global. optimum, but heuristic algorithms succeeded. The convergence rate is usually slow and mostly the algorithms based on gradients show poor convergence rate as they stick to local optima and sometimes also show premature convergence
	Conjugate gradient method [60]	
	Decomposition approach with linear programming [61]	
	First order gradient technique with non-linear programming [62]	
	Sequential quadratic programming [63]	
	Lexicographic order and ϵ-constraint method [65], [66]	
	Normal boundary intersection method [66]	
	Modified sub-gradient algorithm based on feasible values (F-MSG) [67], [69]	
	Two-stage linear programing with special ordered sets algorithm (TLPSOS) [68]	

In reference [63] Sequential quadratic programming method is used for solving the CSTHTS problem by deploying a multi-objective optimization technique. An index called water consumption per unit output value is introduced in this paper. A multi-objective function is fuzzed by finding the membership function of each objective and transformed into a single objective problem with fuzzy satisfaction degree maximization method. Reference [64] has presented different ways of representing line flow limits constraints and linear approximations for transmission line losses in the CSTHTS problem on Brazilian power system with a dc model of the electrical network. Reference [65] presents a method based on lexicographic order and ϵ-constraint method to solve the MOSTHTS problem on a cascaded reservoir system while considering the valve point loading effects of thermal generators. the most preferred solution out of the Pareto front is determined using a fuzzy satisfying method. The thermal plants are considered with valve point effect and emission level function. Reference [66] has solved and found the Pareto optimal fronts of the MOSTHTS problem using lexicographic optimization and Normal Boundary Intersection (NBI) method. The advantage of which was that it avoids the selection of arbitrary parameters and produces a set of evenly distributed points regardless of the objectives scales. The best solution among all Pareto solutions was then selected utilizing a fuzzy satisfying method. In reference [67], the modified sub-gradient algorithm based on feasible values (F-MSG) was implemented to solve CSTHTS problem by considering additional constraints like off-nominal tap ratio constraints, SVAR system susceptances constraints on 16-bus test-system. Reference [68] solved the CSTHTS problem by implementing the two-stage linear programming with special ordered sets algorithm (TLPSOS) which works by modelling the nonlinear thermal cost functions and hydro-power output functions using the special ordered sets. The two stages were to solve the linearized model first and a second stage, eliminate the linearization errors. Stability of results was guaranteed on multiple trials.

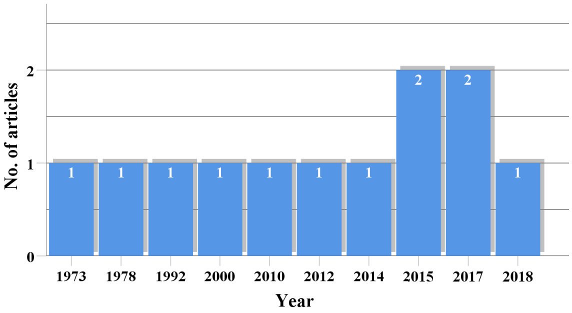

FIGURE 5. Year wise distribution of articles published on STHTS using variants of other conventional optimization algorithms.

Reference [69] has applied modified sub-gradient algorithm based on feasible values (F-MSG) CSTHTS problem while considering several power system constraints, especially, transmission line capacity constraints, bus voltage magnitude constraints, off-nominal tap ratio constraints, SVAR system susceptances constraints. Reference [70] has implemented a robust stochastic algorithm to solve STHTS problem considering the market price and demand uncertainties. Figure 5 gives the year wise distribution of the number of articles published on STHTS using variants of other conventional optimization algorithms. Table 5 summarizes the implementation of the mentioned conventional algorithms on STHTS.

F. NEURAL NETWORKS (NN) AND FUZZY LOGIC-BASED ALGORITHMS APPLIED ON STHTS PROBLEM

According to [2], despite their huge importance in power systems optimization, NN and Fuzzy logic-based algorithms

TABLE 6. Summary of neural network and fuzzy logic for different types of STHTS problems.

Optimization Algorithm	Variants of the Algorithm	General Overview of Performance
Neural networks and fuzzy logic	Two phase NN [71]	Robust solutions achieved mostly for. multi-dimensional problems and near global optimum solutions achieved usually for problems of small dimensionality. Convergence speed better than conventional methods like Kirchmayer's method. However, in multidimensional STHTS problems, due to enhanced neurons, and complex fuzzification, convergence speed compromised as compared to Metaheuristic algorithms
	Hopfield NN [72]	
	Improved Lagrange Hopfield NN [73]	
	Combination of fuzzy set with GA and SA [74], [75]	
	Interactive fuzzy satisfying method [77]	
	Fuzzy decision-making algorithm [76]	
	Back propagation NN [78]	
	Recurrent NN [79]	

have not been utilized much to solve STHTS problems. Reference [71], implemented an algorithm based on two-phase neural networks to solve STHTS problem. Reference [72], utilized Hopfield neural networks to solve CSTHTS problem considering fixed water head and a piece-wise linear function of electric power with water discharge rate. Reference [73], implemented improved Lagrange Hopfield neural network to solve the pumped storage STHTS problem. Reference [74], presented a combination of the fuzzy set algorithm with genetic algorithm and with simulated annealing algorithm to solve CSTHTS problem while considering the valve point loading effect of thermal generators. Reference [75], also presented a combination of fuzzy logic and genetic algorithm to solve CSTHTS problem. Reference [76], implemented a fuzzy decision-making algorithm to solve multi-objective STHTS problem while considering the fixed water head. Reference [77], utilized interactive fuzzy satisfying method to solve the combined economic/emission dispatch of MOSTHTS problem.

Reference [78] has applied conventional and slow Kirchmayer's method to solve NCSTHTS problem and then applied Back Propagation Neural Network (BPNN) method also to solve NCSTHTS problem to overcome the disadvantage in the Kirchmayer's method. The result shows the effectiveness of the proposed method compared to the conventional in terms of speed and accuracy. Reference [79] applied the recurrent neural network technique to solve CSTHTS problem. Given below are the details of the works on short term hydrothermal scheduling problem using metaheuristic optimization algorithms. The following sections are presented in terms of the types of STHTS problem and for each type, the implementations of metaheuristic algorithms, as present in literature, is presented. Figure 6 gives the year wise distribution of the number of articles published on STHTS using variants of neural networks and fuzzy logic-based algorithms. Table 6 summarizes the implementation of neural network and its variants on STHTS.

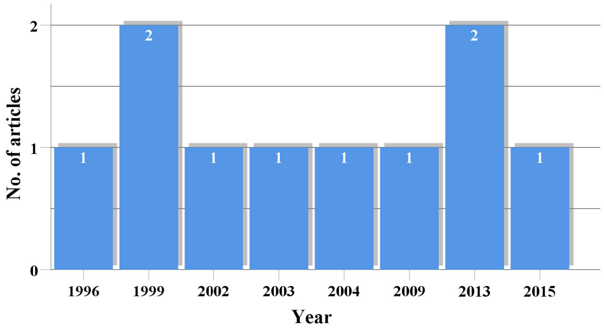

FIGURE 6. Year wise distribution of articles published on STHTS using variants of neural networks and fuzzy logic-based algorithms.

G. OPTIMAL CONTROL THEORY AND OTHER RELATED METHODS APPLIED ON STHTS PROBLEM

Reference [80] introduced for the first time the differential equations based analytical optimization method called optimal control theory that identified the paths of control and state variables to optimize the cost function. Reference [81] solved the STHTS problem while considering the ramp rate constraint of the thermal unit, although the objective was not the same as that of the conventional STHTS problem.

Reference [82] implemented the Pontryagin's maximum principle to solve the STHTS problem while giving a cost value to the water used in the scheduling process and adding the cost of water used in the thermal cost to make an objective function. Reference [83] solved the CSTHTS problem using a non-linear network flow model, without decomposing the problem into thermal and hydro sub-problems, while considering the network constraints along with the coupling constraints of the local and spinning reserves.

Reference [2], has given some details on the mentioned articles, of which the summary is mentioned in this section. However, since these methods do not exactly discuss the objective function of interest of conventional STHTS, the details on the matter have been avoided in this paper. Figure 7 gives the year wise distribution of the number of articles published on STHTS using variants of optimal control theory and other related methods.

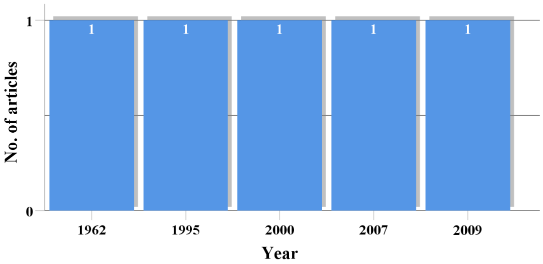

FIGURE 7. Year wise distribution of articles published on STHTS using variants of optimal control theory and other related methods.

III. METAHEURISTIC OPTIMIZATION ALGORITHMS APPLIED ON STHTS

Metaheuristic optimization algorithms are relatively latest types of optimization algorithms which use both stochastic and deterministic approach to find good approximates of a global optimum solution of an optimization problem. These algorithms are usually inspired from some of the other phenomena of nature, e.g. food search behaviour of birds, fish, the evolution process of living beings, the attraction and repulsion behaviours of species within their kind, the genetic mutation process, the water cycling process of nature and many more natural phenomena. Genetic algorithms, evolutionary algorithms, swarm algorithms, all fall under the category of metaheuristic optimization algorithms.

According to reference [3], In every metaheuristic algorithm, two main components will be randomization and selection of the best solution for proceeding towards the next iteration of the iterative search process. The selection of best solution within an iteration ensures that ultimately, after the completion of the iterative process, the solutions will converge to a good approximate of global optimum solution whereas the randomization process hinders the solutions to stick to any local optimum of the solution space and increase the diversity of solutions [3].

Metaheuristic algorithms can be further classified into two major types. Trajectory based, like simulated annealing algorithms starts with the generation of only one solution that follows some rules and protocols to update its position to make a trajectory to ultimately reach towards a global optimum. On the other hand, the type is population-based, like particle swarm optimization, in which several solutions are randomly generated which follow an iterative procedure of updating position to ultimately converge to a global optimum solution [3]. Given below is the literature review of the implementations of metaheuristic algorithms on different forms of STHTS problem.

A. SIMULATED ANNEALING ALGORITHMS APPLIED ON STHTS PROBLEM

According to reference [2], simulated annealing technique, introduced by reference [84], while having a simple approach of optimizing, can solve combinatorial optimization problems and can be utilized in different areas of optimization. However, according to reference [85], simulated annealing has one disadvantage that it is unable to detect the final optimal solution, due to repeated annealing, unless some other method is utilized along with it. Reference [86] has solved the NCSTHTS problem using simulated annealing algorithm which is a single trajectory-based metaheuristic optimization algorithm. Reference [86], presented a sequential simulated annealing algorithm to solve the NCSTHTS problem without considering ramp rates constraints. Although simulated annealing helped find the robust solution of the NCSTHTS problem, it also required high computational time. To overcome the issue of high computational time, the authors of [86], successfully implemented a variant of simulated annealing, known as coarse-grained parallel simulated annealing to solve the same test case of the NCSTHTS while achieving lowering of computational time, and presented their work in reference [87]. Reference [88], applied simulated annealing on the thermal sub-problem and solved the hydro subproblem using peak shaving method to solve the CSTHTS problem on Greek power system. Figure 8 gives the year wise distribution of the number of articles published on STHTS using variants of simulated annealing algorithms. Table 7 summarizes the implementation of simulated annealing and its variants on STHTS.

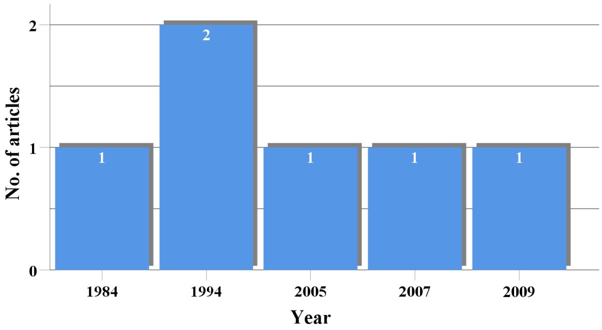

FIGURE 8. Year wise distribution of articles published on STHTS using variants of simulated annealing algorithm.

B. PARTICLE SWARM OPTIMIZATION ALGORITHMS APPLIED ON STHTS PROBLEM

Particle Swarm Optimization, introduced in [89] and based on the behaviour of swarms like fish and birds in search of food, has gained a lot of popularity among the meta-heuristic optimization algorithms and many of the variants of the canonical version have been implemented on different types of STHTS problems. Reference [90] implemented for the first time the canonical PSO algorithm on NCSTHTS problem and showed that results were very encouraging as compared to previously implemented algorithms.

Reference [91] presented four variants of canonical PSO in terms of particles' update equations and in terms of the neighbourhood topologies of the particles to solve CSTHTS problem while considering an equivalent thermal

TABLE 7. Summary of simulated annealing for different types of STHTS problems.

Optimization Algorithm	Variants of the Algorithm	General Overview of Performance
Simulated annealing	Canonical SA [88] Sequential SA [86] Coarse-grained parallel SA [87]	Robust solutions achieved, but. poorest performance among the metaheuristic algorithms. High computational time with canonical SA. However, coarse-grained parallel SA achieved fast convergence

unit. In reference [92] PSO in its canonical form was applied to the CSTHTS problem while considering valve point loading effect of thermal units and taking into consideration the economic dispatch of three individual thermal units. In reference [93] pumped storage NCSTHTS problem was solved using the combination of evolutionary algorithm and PSO. Reference [94], has used improved particle swarm optimization algorithm, which is a variant of canonical particle swarm optimization to solve the NCSTHTS problem. The improvement is in terms of the acceleration of particles updating process by modifying the acceleration coefficients of the velocity update equations in the canonical version of Particle swarm optimization.

Reference [95], has used another modification in the canonical particle swarm optimization algorithm to find the solution of same NCSTHTS problem, however, [95] has performed the solution by considering alternatively one of the four variables of the optimization problem to be an independent variable and the remaining three variables as dependent variables. [95] has shown that if the volume of the reservoir is taken as an independent variable, there is more chance to reach a good approximate to the global optimum solution. References [96] and [97], implemented improved quantum behaved PSO algorithm, a variant of canonical PSO algorithm, which is probabilistic and is inspired from some of the phenomena of quantum mechanics, to solve MOSTHTS problem. In reference [98] Modified Adaptive Particle Swarm Optimization (MAPSO) was applied to solve six test cases of CSTHTS problem. The inertia weight and acceleration coefficients of the PSO were updated adaptively in every iteration in the MAPSO while using tree neighbourhood topology. Reference [99] has solved the CSTHTS problem using a variant of canonical PSO, known as self-organizing hierarchical particle swarm optimization in which the acceleration coefficients of the particles update equation in the canonical PSO are updated at every iteration adaptively. Reference [100] presented a variant of PSO called self-organizing hierarchical PSO which has time-varying acceleration coefficients during the particles update process for CSTHTS problem. Reference [101] has solved a real operated CSTHTS problem by utilizing Time-Varying Acceleration coefficients PSO (TVAC_PSO). Reference [102] has solved the CSTHTS problem by implementing improved PSO that works by maintaining a high diversity of the swarm during the optimization process to help to prevent premature convergence. Reference [103] has implemented canonical PSO to solved the fixed head CSTHTS problem. Reference [104] has solved the CSTHTS problem by using a variant of PSO that works by updating the inertia weight of the particle update equation in a self-adaptive way. Reference [105] has solved the MOSTHTS problem using a variant of PSO known as Efficient PSO in which instead of initializing the particle randomly, particles are generated on a fixed map utilizing the star neighbourhood topology. Reference [106] has used a small population-based PSO, a variant of canonical PSO to solve the CSTHTS problem. In this variant of PSO, the concept of genetic mutation of the genetic algorithm is used to update the particles in the iterative process.

Reference [107] has used an improved version of PSO is implemented, to solve CSTHTS problem, which deals with modifying the parameters of particle update equation to avoid premature convergence to local optima. Reference [108] has implemented the PSO algorithm on CSTHTS problem while considering the prohibited operating zones of hydro reservoirs as system constraint. Reference [94] has solved NCSTHTS problem is solved using weight adaptive variant of PSO algorithm. Reference [109] solved a real CSTHTS problem using a mixed-binary evolutionary particle swarm optimization algorithm. Moreover, heuristic operators were used to modelling the hydro and thermal constraints. Reference [110] has applied canonical PSO technique to solve the MOSTHTS. Reference [111] solved the CSTHTS problem using variants of PSO algorithm that modify the constriction factor and inertia weight during the particles update process. The valve point loading behaviour of thermal units was also considered. Reference [112] presented Dynamically Controlled Particle Swarm Optimization (DCPSO) to solve MOSTHTS problem. Exponential functions were introduced in the update equations to modify the social and cognitive behaviour of PSO for better exploration and exploitation of the search space. Preceding and aggregate experience of particles was presented to make PSO highly efficient.

Reference [113] presented the particle swarm optimization technique with constriction factor to solve CSTHTS problem with non-smooth fuel cost objective functions. The computational time was reduced to achieve robust solutions. Reference [114] has solved the STHTS problems using a combination of differential evolution and PSO algorithms to accelerate the canonical PSO algorithm. This combination of PSO and differential algorithms also promised good local and global search abilities. Reference [115] presented, the particle swarm optimization technique with constriction factor to solve CSTHTS problem with non-smooth fuel cost objective functions and compared the performance with the performance of the genetic algorithm on the same problems. The computational time was reduced to achieve robust solutions by using constriction factor based PSO.

Reference [116] has solved the CSTHTS problem using a hybrid of PSO and direct search method. Direct search method was used to select the local best of each particle in every iteration to improve the local search behaviour of canonical PSO. Reference [117] gives a review of the variants of PSO algorithm implemented on NCSTHTS problem. Reference [118] implemented an enhanced PSO algorithm to solve CSTHTS problem considering valve point loading effects of thermal units. The modification in canonical PSO was done using exponential functions in the particles update process which improves both the exploration and exploitation. Reference [119] combined the PSO and differential evolution algorithm to solve the MOSTHTS problem while adopting the penalty factor approach to combine the two objectives into a single objective. Reference [120] solved CSTHTS problem while considering the valve point loading of thermal units by using PSO algorithm that updates the acceleration coefficients, inertia weight and constriction coefficients iteration to iteration. Reference [121] solved CSTHTS problem using modified dynamic neighbourhood learning-based PSO. The neighbourhood memberships were changed at defined iterations that causes an information exchange between all particles in the swarm to improve both exploration and exploitation abilities in comparison with the conventional PSO.

Reference [122] proposed an incremental cost-based algorithm for MOSTHTS problem using Particle Swarm Optimization (PSO). While using the penalty factor approach to make multiple objectives as a single objective. Reference [123] solved the CSTHTS problem using dynamically controlled PSO algorithm which enhances the exploration and exploitation capability by modifying the controlling parameters of the update equation at each iteration. Reference [124] implemented several variants of PSO on several types of STHTS problems and found that the constriction factor based PSO considering the local best neighbourhood topology works best among all the variants.

Reference [125] has introduced chaotic maps in the update process of the quantum behaved PSO algorithm to solve CSTHTS problems. The chaotic maps help in maintaining a good diversity in population to avoid pre-mature convergences. Reference [126] implemented the PSO algorithm to solve an CSTHTS problem on a Sudanese national grid. Reference [127] implemented constriction factor and inertia weight-based PSO algorithm on CSTHTS problem. Reference [128] has implemented a local neighbourhood topology-based variant of PSO algorithm that sets neighbourhood of two particles randomly at each iteration, to solve the CSTHTS problem. The searchability was proved to be improved. Reference [129] has taken the actual online data for solving the CSTHTS problem claiming that the already predicted data of STHTS is static and might be inaccurate, and then applied auxiliary search based PSO algorithm, which is based on the concept of iterative-lengthening and auxiliary search, to solve CSTHTS problem.

Reference [130] has solved a valve point loading of thermal generators based CSTHTS problem using a combination of gravitational search algorithm and particle swarm optimization based on krill herd algorithm to improve the local and global search in the algorithms' update process. Reference [131] has solved the STHTS problem using variants of PSO algorithm and compared the results with the implementations of Genetic algorithm. Reference [132] has reviewed the performance of flower pollination algorithm and PSO algorithms on the thermal scheduling problem on the 33 buses Brazilian power system considering the interconnected transmission lines and AC power flows.

Reference [133], has presented implementation of fully informed PSO (FIPSO), a variant of canonical PSO, to solve NCSTHTS problems. The paper discussed the local and global neighbourhood variants of FIPSO to solve the problem. References [134] and [135] discussed the implementation of metaheuristic optimization algorithms, i.e. two variants of Accelerated Particle Swarm Optimization algorithm and a variant of firefly algorithm on NCSTHTS problems. In reference [134], a comparison of simple APSO algorithm and dynamic search space squeezing based APSO was made statistically using independent sample t-test. Reference in solving NCSTHTS problem. Reference [135], solve the solar-hydro-thermal scheduling problem using firefly and APSO algorithms. The comparison was statistically made between the performances of the two algorithms using independent sample t-test.

Figure 9 gives the year wise distribution of the number of articles published on STHTS using variants of particle swarm optimization algorithm. Table 8 summarizes implementation of PSO and its variants for STHTS.

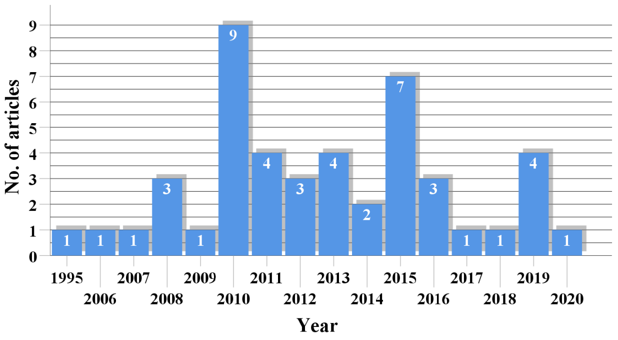

FIGURE 9. Year wise distribution of articles published on STHTS using variants of particle swarm optimization algorithms.

TABLE 8. Summary of PSO and its variants for different types of STHTS problems.

Optimization Algorithm	Variants of the Algorithm	General Overview of Performance
Particle Swarm optimization	Canonical PSO [90], [92], [95], [103], [108], [110], [122], [126], [132] With different neighborhood topologies [90], [121], [128] Constriction factor PSO [111], [113], [115], [127] Hybrid of PSO and Evolutionary programming [93] Updating Inertia weights PSO [104] Quantum behaved PSO [96], [97], [125] Modified adaptive PSO [98] Self-organizing hierarchical PSO [99], [100] Time varying acceleration coefficients PSO [101], [120] Improved PSO [94], [102], [107] Efficient PSO [105] Mixed-binary evolutionary PSO [109] Dynamically controlled PSO [112], [123] Hybrid of PSO and DE [114], [119] Hybrid of PSO and direct search method [116] Enhanced PSO [118] Auxiliary search based PSO [129] Hybrid of PSO and GSA [130] Fully informed PSO [133] Accelerated PSO [134], [135]	Near global optimum solutions. achieved in most implementations and robust solutions in remaining implementations. Performed well in both low dimension and high dimension STHTS problems. High convergence rate in canonical version, which improved further in other variants specially APSO, quantum behaved PSO, and dynamic search space squeezed PSO give very fast convergence speeds. The exploration and exploitation variables like alpha and beta in the update process would be improved to make variants explore the search space to avoid premature convergence to local optima

C. EVOLUTIONARY PROGRAMMING ALGORITHMS APPLIED ON STHTS PROBLEM

In reference [136], evolutionary algorithms were introduced. Since then, many implementations of various types of evolutionary algorithms were applied to CSTHTS problem. Reference [137] solved the pumped storage NCSTHTS problem along with STHTS problem while considering rum-off river hydro plants. Reference [138], has applied the differential evolution optimization algorithm to solve CSTHTS problem by considering valve point loading effect of thermal generators. Reference [139], has applied fast evolutionary programming-based optimization technique, in which evolutionary programming algorithm is combined with Gaussian and other mutation techniques, to solve the CSTHTS problem, while considering the prohibited operating zones of the hydro plants. References [140] and [141] solved the NCSTHTS problems using evolutionary programming algorithms and compared the performance with the performances of simulated annealing and conventional gradient search method. Reference [142] applied several evolutionary programming-based algorithms to solve MOSTHTS problem while considering ramp rates of thermal units and transmission line losses. Reference [143] solved an NCSTHTS problem while ignoring many reservoir and thermal constraints, using hybrid evolutionary programming.

Reference [144] solved MOSTHTS problem using a differential evolutionary algorithm and was compared with the implementation of an evolutionary programming algorithm on the same problem. Valve point loading of thermal units was considered. References [145] and [146] presented the implementation of the hybrid evolutionary algorithm on NCSTHTS problem and the comparison was given with previous implementations of other algorithms on the same problem. high convergence rate was promised by evolutionary algorithms as compared to the other algorithms. Reference [77], presents the implementation of interactive fuzzy satisfying evolutionary programming algorithm to solve the MOSTHTS problem, to find the Pareto solution set that gives the non-inferior solution to both the objectives. Reference [147], the MOSTHTS problem using variant of differential evolution algorithm which considers three different chaotic sequences/maps in the update process of solution space, iteratively, which enhances the search space dynamically at each iteration to increase the probability of finding better evolution's of solutions. Both these references have considered the MOSTHTS of cascaded STHTS problems.

In the reference [112] CSTHTS problems are solved using adaptive chaotic differential evolution algorithm (ACDE) in which an adaptive dynamic parameter adjusting strategy is adopted to obtain the parameter settings in differential evolution algorithm (DE) while considering valve point loading of thermal units. Moreover, chaotic local search (CLS) operation is integrated with DE that helps to avoid premature convergence and sticking to local optima. A Constraint handling method is also deployed that does not utilize the penalty factor approach. Reference [148] has implemented different variants of an evolutionary algorithm to solve MOSTHTS problem. Reference [149] has implemented a differential evolutionary algorithm to solve MOSTHTS problem while considering cascaded reservoir case.

Reference [150] has solved the optimization problem by utilizing a decomposition-based Multi-objective evolutionary algorithm by introducing a relaxed constraint on the reservoir end volume and then considering this relaxed constraint as the second objective of the CSTHTS problem. Reference [151] has solved the MOSTHTS problem using differential algorithm while handling the water reservoir constraints using randomization/heuristic approaches and the heuristic rules dependent upon the priority list approaches are deployed to handle the active power balance constraints. Reference [152] modifies the differential evolution algorithm by modifying its operators to make it suitable for MOSTHTS problem while improving its performance by avoiding premature convergence, using adaptive Cauchy mutation that increases the diversity of the population. Thermal power units are considered to operate with valve point loading. Reference [153] has implemented a differential evolution algorithm to solve short-term scheduling optimization of hydro-thermal power systems and an adaptive hybrid differential evolution is proposed. This reference has introduced a variant of differential algorithm to solve the STHTS problem. The algorithm updates the cross operator adaptively during the iterations to enhance the diversity of the population to increase the global search capability while utilizing the simulated annealing algorithm to remedy the defect of premature convergence of DE algorithm. Reference [154] proposed a combination of differential evolution (DE) as a global optimizer and sequential quadratic programming (SQP) as a local optimizer for solving CSTHTS problem considering non-convex fuel cost function. Reference [155] has applied the quadratic approximation based differential evolution technique to solve the MOSTHTS problem. Reference [156] solves NCSTHTS problem using fast evolutionary programming, a variant of evolutionary programming. The conventional EP method updates the offspring by using stochastic approaches like Gauss and Cauchy mutations, the fast EP method, on the other hand, updates the offspring's using deterministic approaches to ensure fast convergence rates to find good solutions.

Reference [157] applied differential real-coded quantum-inspired evolutionary algorithm (DRQEA) to solve CSTHTS problem. The algorithm ensured global searching ability by adapting adaptive mutation and crossover operation. Reference [158] presents the integration of Clonal operator and Cauchy mutation, in the quantum-inspired evolutionary algorithm, to help to avoid premature convergence, to solve CSTHTS problem. Reference [159] has solved the CSTHTS problem while considering the transmission line losses and ramp-rate limits of thermal generators, by using an improved differential algorithm. The search efficiency of conventional differential algorithm gets impaired during the solution process with fast descending diversity of the population. The solution to this problem was the introduction of a Gaussian random variable instead of scaling factor which improved search efficiency.

Reference [160] has combined three chaotic maps in the update equations of the differential evolution algorithm to solve the MOSTHTS problem. The chaotic maps improve the searchability by reducing the chances of premature convergences. Reference [161] integrated a modified multi-objective differential evolutionary algorithm into the culture algorithm (CA) while using a chaotic factor in the update equations to solve MOSTHTS problem. The chaotic factor helped to avoid premature convergence. Reference [162] presents the implementation of the differential evolution algorithm for solving STHTS problem. Reference [163] has implemented a modified chaotic differential evolution algorithm to solve CSTHTS problem. A constraint handling mechanism based on the simultaneous application of a repair strategy and selection operation was introduced into the MCDE. The purpose of this modification was to avoid the flaws of the penalty factor approach of constraint handling.

Reference [164] has solved the CSTHTS problem using an improved chaotic hybrid differential evolution algorithm. Chaos theory is used to implement a self-adjusted parameter setting in differential evolution (DE) to help prevent it from premature convergence. Valve point loading of thermal units and prohibited discharge zones of water reservoirs were also considered. Reference [165] has implemented the small population-based parallel differential evolution algorithm to solve the CSTHTS problem while considering power flow constraints. A large population is divided into several subpopulations each with small population size and several parallels running processes of one or more CPUs are performed synchronously each evolving a certain subpopulation and searching for the optimal solution independently so that the computational resources are not wasted. Reference [166] has implemented improved chaotic hybrid differential algorithm to solve MOSTHTS problem. in this algorithm, self-adjusted parameter setting in Differential Evolution is obtained by using chaotic maps which helps to improve the search space.

Reference [167] has solved the MOSTHTS problem using gradient descent-based multi-objective cultural differential evolution algorithm while considering the integration of wind and solar photovoltaic power units. The gradient descent adds the deterministic approach in the stochastic cultural-based differential evolution algorithm to find near-global solutions. Reference [168] has introduced a method to find the weights of the combined objective function of MOSTHTS problem when implementing a weighted sum approach.

Reference [169] implemented differential evolution (DE)-based optimization technique for solving MOSTHTS problem while considering valve point loading behaviour of thermal units and transmission line losses. Reference [170] has embedded the potentialities of the Differential Evolution algorithm in Krill herd algorithm to improve the convergence speed and robustness of finding the near-optimal solution of CSTHTS problem.

Reference [171] has implemented a modified version of the evolutionary programming algorithm to solve CSTHTS problem. the modified evolutionary algorithm proved to be faster in convergence rate as compared to the conventional evolutionary algorithm. The transmission line power losses had also been taken into consideration.

Reference [172], has solved the pumped storage NCSTHTS problem using evolutionary programming. In a pumped storage NCSTHTS problem, the water that is discharged from the water reservoir can be pumped back to the reservoir by using power generated by the thermal power plant. Reference [140], has utilized an evolutionary programming algorithm to solve NCSTHTS problem without considering the pumped storage and power transmission losses constraints to find robust solutions.

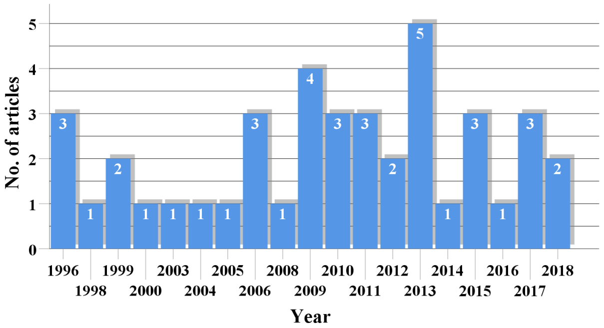

FIGURE 10. **Year wise distribution of articles published on STHTS using variants of evolutionary programming algorithms.**

Reference [139], has implemented fast evolutionary programming technique, on the same problem that was presented in [140], which utilized Gaussian and Cauchy mutation methods along with original evolutionary programming algorithm to solve the NCSTHTS problem, in fast convergence time to find good approximates of a globally optimal solution. Figure 10 gives the year wise distribution of the number of articles published on STHTS using variants of evolutionary programming algorithms. Table 9 summarizes the implementation of EP and its variants for STHTS.

D. CUCKOO SEARCH OPTIMIZATION ALGORITHM APPLIED ON STHTS PROBLEM

Cuckoos search is a very promising and swarm intelligence-based metaheuristic optimization algorithm, inspired from the brood parasitism of cuckoo species and uses Levy flights to create randomization in the update process, which was developed by the authors of reference [173]. Reference [174], implemented one rank cuckoos search algorithm on NCSTHTS problem. Levy based distribution and Cauchy distributions are embedded in the original Cuckoos search algorithm to form the improved version i.e. one rank cuckoos search algorithm. Reference [174], has also proposed the bound by best solution mechanism to handle the constraints of NCSTHTS problem to accelerate the convergence. This constraint handling approach, used by reference [174], is another type of dynamic search space squeezing approach.

Reference [175], has incorporated the CS optimization algorithm, which is another swarm intelligence based meta-heuristic algorithm, to solve the CSTHTS problem, while considering the power losses in the transmission lines and also the valve point loading behaviour of the thermal generators. Reference [176], has applied the Effective Adaptive Selective Cuckoos Search algorithm, a variant of canonical CS algorithm in which solution space, i.e. cuckoos is updated using adaptively selective randomization in the Levy flights, to solve the CSTHTS problem.

References [177], [178] have incorporated variants of canonical CS algorithms by making modifications in the Levy flights update to enhance the searchability of the conventional CS algorithm, to solve the MOSTHTS problem. Several test cases of MOSTHTS problems, considering, quadratic fuel cost functions/quadratic while considering power losses in the transmission system. Reference [179] presented the application of Cuckoos search algorithm on the CSTHTS problem while considering the transmission line losses. The algorithm proved to give a promising and robust solution with fast convergence. Reference [180] utilized three distributions including Lévy distribution, Gaussian distribution and Cauchy distribution to generate and update the Cuckoos in the Cuckoos search algorithm to solve the CSTHTS problem. The methods promised robust solutions. Reference [181] implemented a modified Cuckoos search algorithm to solve different test cases of CSTHTS problem while considering the valve point loading behaviour of thermal units. The proposed method is the modification in terms of enhancement of the searchability of the conventional cuckoo search algorithm. Reference [182] used a cuckoo search algorithm (CSA) for solving CSTHTS problem considering transmission line losses and valve point loading effects of thermal units.

Reference [183] has implemented three distributions including Lévy distribution, Gaussian distribution and Cauchy distribution in the update equations of the Cuckoos search algorithm to solve CSTHTS problem. Reference [177] has implemented two distributions based Lévy distribution,

TABLE 9. Summary of EP and its variants for different types of short term hydrothermal scheduling problem.

Optimization Algorithm	Variants of the Algorithm	General Overview of Performance
Evolutionary programming algorithms	Differential evolution [138], [144], [149], [151], [153], [162], [169]	Robust solutions mostly and near global optimum solutions for other implementations. Good convergence rate, especially in variants. Chaotic sequencing and helped in avoiding pre-mature convergences that usually exist in canonical versions
	Fast evolutionary programming [139], [156]	
	Canonical Evolutionary programming [140]–[142], [148], [172]	
	Hybrid evolutionary programming [143], [145], [146]	
	Interactive fuzzy satisfying EP [77]	
	Chaotic sequence-based DE [147], [160]	
	Adaptive chaotic DE [112]	
	Decomposition based multi-objective EP [150]	
	DE with Cauchy mutation [152]	
	Hybrid of DE and SQP [154]	
	Quadratic approximation based [155]	
	Differential real coded quantum inspired EP algorithm [157]	
	Clonal operator and cauchy mutation with quantum inspired EP algorithm [158]	
	Improved DE [159]	
	Hybrid of DE and Cultural algorithm [161]	
	Modified chaotic DE [163]	
	Multi-objective DE	
	Improved chaotic hybrid DE [164]	

in the update equations of the Cuckoos search algorithm to solve CSTHTS problem. In this modified method, the nests in the update process are classified into two groups i.e. a top group with better quality eggs and an abandoned group with worse quality eggs to improve the movements of Cuckoos using quality influences.

Reference [184] applied three versions of Cuckoo Search Algorithm (CSA) i.e. conventional Cuckoo Search Algorithm (CSA), modified CSA (MCSA) and adaptive CSA (ACSA) to solve fixed head STHTS problem while considering the transmission line losses. Reference [185] implemented a modified cuckoo search algorithm (MCSA) for solving CSTHTS problem. Reference [186] has solved the MOSTHTS problem using a variant of the Cuckoos search algorithm.

Reference [187] implemented the Cuckoos search algorithm to solve the fixed head MOSTHTS problem. Reference [188] has implemented the fast convergence rate based effectively enhanced Cuckoos search algorithm to solve the variable head CSTHTS problem. Reference [189] has modified the conventional cuckoos search algorithm by using Levy flights concept to solve the MOSTHTS problem. Reference [176] has modified the conventional cuckoos search algorithm that adaptively improves the search space of the conventional cuckoos search update process based on two new techniques including the new ratio of the difference between the fitness function values and the integration of solutions into one group, to solve the CSTHTS problems in less number of iterations. Reference [190] has solved MOSTHTS problem using penalty factor approach by applying the Cuckoos search optimization algorithm. Figure 11 gives the year wise distribution of the number of articles published on STHTS using variants of cuckoo search algorithms.

Table 10 summarizes the implementation of CSA and its variants for STHTS.

E. GRAVITATIONAL SEARCH ALGORITHM APPLIED ON STHTS PROBLEM

Reference [191], introduced for the first time the gravitational search algorithm which was mathematically inspired by the law of gravity among the heavenly bodies. Although it is inspired by the law of gravitation, yet it is quite

TABLE 10. Summary of CSA and its variants for different types of STHTS problems.

Optimization Algorithm	Variants of the Algorithm	General Overview of Performance
Cuckoo search algorithm	Canonical CSA [175], [179], [182], [184], [187], [190] One rank CS [174] Effective adaptive selective CS [176] Adaptive CS [176], [184] Variants of CS with modification in Levy flights updates [177], [178], [180], [183], [189] Modified CS [181], [184]–[186] Fast convergence rate based effectively enhanced CS [188]	Good approximates to near. global optimum solution achieved. Mostly promised fast convergences but many variants of PSO performed better in convergence

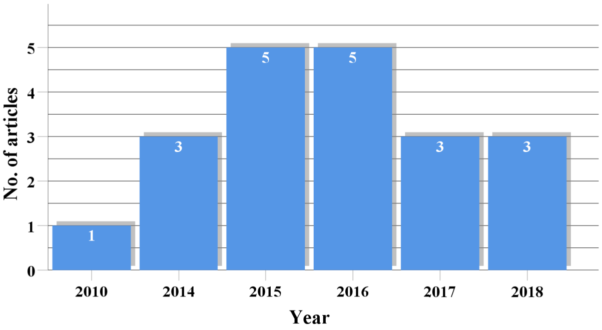

FIGURE 11. Year wise distribution of articles published on STHTS using variants of cuckoo search algorithms.

close in form to the swarm intelligence-based algorithms. Reference [192] has solved NCSTHTS problems using gravitational search algorithm which is a swarm intelligence-based metaheuristic optimization algorithm. Reference [193] proposed a non-dominated sorting gravitational search algorithm with chaotic mutation (NSGSA-CM) to solve MOSTHTS problem. To improve the performance of NSGSA-CM, particle memory character and population social information in velocity update process were introduced. Moreover, a chaotic mutation was applied to prevent premature convergence.

Reference [194] has solved the CSTHTS problem using disruption based gravitational search algorithm while considering the valve point loading behaviour of thermal units. A disruption operator which is inspired by astrophysics was included into gravitational search algorithm to enhance its performance both in terms of exploration and exploitation capabilities of the searching process. Reference [195] introduced an improved multi-objective variant of the gravitational search algorithm to solve MOSTHTS problem. The wight of the objective is redefined by multiple objectives to make it suitable for a multi-objective optimization problem. For balancing exploration and exploitation, a neighbourhood searching mechanism was also suggested to that incorporated chaotic mutations.

Reference [180] introduced an improved multi-objective variant of the gravitational search algorithm to solve MOSTHTS problem. The wight of the objective is redefined by multiple objectives to make it suitable for a multi-objective optimization problem. For balancing exploration and exploitation, a neighbourhood searching mechanism was also suggested to that incorporated chaotic mutations. Moreover, particle memory character and population social information is used to update velocity in the update equations. In reference [196], Quasi-oppositional based learning approach is combined with Gravitational search algorithm to efficiently control the local and global search, while solving the CSTHTS problem. Premature convergence was avoided using this approach.

Reference [197] implements a combination of gravitational search algorithm and sequential quadratic programming to solve the CSTHTS problem. gravitational algorithm gave promising results for global search whereas the sequential quadratic programming worked for enhancing the local search. Reference [198] has implemented a fuzzy logic-based variant of gravitational search algorithm known as non-dominated sorting gravitational search algorithm with disruption operator to solve four objectives based MOSTHTS problem. Reference [199] presented a non-dominated sorting disruption-based gravitational search algorithm with the mutation to solve fixed-head and variable-head MOSTHTS problem while considering valve point loading of thermal units and transmission line losses as well. Reference [200] implemented an opposition-based learning concept in a gravitational search algorithm to improve the update of the current population towards global optimal solutions along with the introduction of a disruption operator to accelerate the convergence behaviour of the algorithm to solve CSTHTS problem. Reference [201] has solved the MOSTHTS problem using non-dominated sorting-based disruption in the oppositional gravitational algorithm. Opposition-based learning perception when embedded in a gravitational search algorithm helped to explore the excellence of the present population and disruption operator was integrated to accelerate the convergence of solutions. Reference [202] has solved two cases of variable head CSTHTS problem using a modified incremental gravitation search algorithm. One case did not

TABLE 11. Summary of GSA and its variants for different types of short term hydrothermal scheduling problem.

Optimization Algorithm	Variants of the Algorithm	General Overview of Performance
Gravitational search algorithm	Canonical GSA [192] Non-dominated sorting GSA with chaotic mutation [193] Disruption based GSA [194] Improved multi-objective GSA [180], [195] Hybrid of quasi-oppositional-based learning approach and GSA [196] Hybrid of GSA and SQP [197] Fuzzy logic-based GSA [198] Non-dominated sorting disruption-based GSA with mutation [199], [201] Opposition based learning concept with GSA [200] Modified incremental GSA [202]	Near global optimum solutions. achieved mostly and robust solutions otherwise. Good convergence rate was promised especially with variants of chaotic mutations. the structure of algorithms matches PSO variants and the performances were comparable to PSO variants in most of the implementations

consider the transmission line losses whereas the other case considered the transmission line losses found using Newton Raphson method. Figure 12 gives the year wise distribution of the number of articles published on STHTS using variants of gravitational search algorithms. Table 11 summarizes the implementation of GSA and its variants for STHTS.

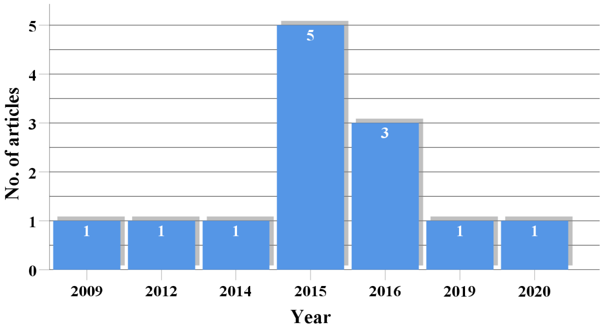

FIGURE 12. Year wise distribution of articles published on STHTS using variants of gravitational search algorithms.

F. GENETIC ALGORITHM APPLIED ON STHTS PROBLEM

Genetic algorithms are renowned and immensely implemented metaheuristic optimization algorithm, which were first introduced in its canonical form in 1975 in reference [203]. Since its birth, the genetic algorithm has been implemented on my power systems optimization problems. Reference [204] implemented the genetic algorithm for the first time on CSTHTS problem. Reference [205] implemented a genetic algorithm on the same problem with one modification of applying multiple-step and single-step genetic algorithms. Water transport delays among the cascaded reservoirs on the same stream were taken into consideration. It was found that using the penalty factor approach for constraint handling, the genetic algorithm worked very well in achieving a near-global optimum solution.

Reference [206] implemented variants of the genetic algorithm on realistic CSTHTS problem, based on diploid genotype and its performance was compared with haploid genotype-based genetic algorithm. In reference [207], CSTHTS problem was divided into thermal and hydro subproblems and hydro subproblem was solved using an enhanced genetic algorithm while considering several practical constraints of a real CSTHTS problem. Reference [208] divided the scheduling of generators problem into three subproblems; unit commitment, economic dispatch and CSTHTS. Constraints like volume and discharge rate limits while not ignoring the spinning reserves and transmission losses. The subproblems were solved using a genetic algorithm. In reference [209], the cultural algorithm was implemented on CSTHTS problem and results were compared with genetic algorithm implementations. Though cultural algorithm was proven better than the genetic algorithm in terms of finding near-global optimum solutions and in less convergence time. Reference [210] improved the canonical genetic algorithm into the binary-coded genetic algorithm to achieve a fast rate of convergence and applied it to CSTHTS problem. Reference [57] solved CSTHTS problems using genetic algorithm while finding the on/off state of the hydro and thermal units while considering the ramp rate characteristics of the thermal units.

Reference [211] applies optimal gamma-based scheduling algorithm for fixed head hydrothermal scheduling problems using genetic algorithm. Reference [212] has solved the CSTHTS problem by applying a combination of three algorithms while using the decomposition approach. The hydro subproblem is optimized by using discharge proportional to demand approach whereas, the conventional lambda iteration method is applied to economically dispatch the thermal units. The AC power flows are then calculated using the genetic algorithm, of a 9-bus power system. Fast Non-dominated sorting genetic algorithm (NSGA-II) [213], a new multi-objective genetic algorithm, was applied to the optimal scheduling model while applying a multi-objective model to solve the MOSTHTS problem. Reference [214] has solved the MOSTHTS problem by utilizing search space squeezed multi-objective genetic algorithm. An additional constraint on the coal-fired thermal power plant is taken into consideration i.e. the limited coal supply restricts the power production of the thermal units. The genetic algorithm works in duality by first finding the proper weight for the two objectives and then solves the weighted sum multi-objective problem.

Reference [215] has solved a 9-bus power system with several hydro plants and several thermal plants by using a decomposition approach. The hydro subproblem was solved using GA and the thermal subproblem was solved using lambda iteration method. It was claimed that the convergence rate was high. Reference [216] presents fast genetic algorithm by introducing the concept of search space squeezing iteratively to solve the CSTHTS problem in small convergence time.

Reference [217] utilized the Real coded genetic algorithm (RCGA) to achieve global search, whereas, Artificial fish swarm algorithm (AFSA) was used for local search to improve the exploitation capability of the algorithm to solve the CSTHTS problem. Moreover, a method other than the penalty factor method was used to deal with the equality constraints of water reservoir. Reference [218] applied the genetic algorithm to solve CSTHTS problem of an Indian power system. Reference [219] introduced the chaotic maps in the update equations of real coded genetic algorithm (ACRCGA) to solve CSTHTS problem which helped to improve the local search ability of the real coded genetic algorithm. Reference [220] has divided the CSTHTS problem into thermal power dispatch and hydropower dispatch subproblems rand solved each independently using the combination of genetic algorithm and conventional Tabu search method. Prohibited discharge zones of hydro reservoirs were considered.

Reference [221] has solved MOSTHTS problem using a parallel multi-objective genetic algorithm that works on the Fork/Join parallel framework that divides the whole population of individuals into several subpopulations which evolve in different cores in parallel so that the computational resources are not wasted. A set of robust solutions was generated. Reference [222] implemented twelve real-coded genetic algorithms with an improved Mühlenbein mutation (RCGA-IMM) to solve several large-sized CSTHTS problems considering fifteen constraints. Figure 13 gives the year wise distribution of the number of articles published on STHTS using variants of genetic algorithms. Table 12 summarizes the implementation of GA and its variants for STHTS.

G. OTHER METAHEURISTIC ALGORITHM APPLIED ON STHTS PROBLEM

There are many metaheuristic algorithms, other than the previously mentioned famous metaheuristic algorithms that have been applied to STHTS problems. This section gives a comprehensive review of those implementations.

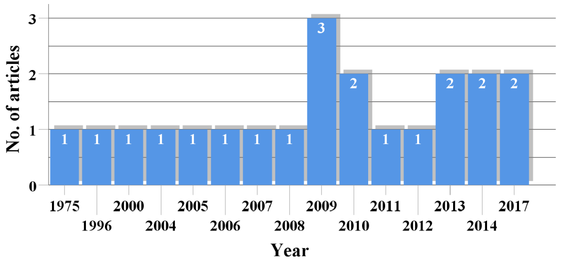

FIGURE 13. Year wise distribution of articles published on STHTS using variants of genetic algorithms.

Reference [223] first introduced the bacterial foraging algorithm which was inspired by the foraging behaviour of e-Coli bacteria. This algorithm has some variants as well and they have been applied on different problems of the power system as mentioned in reference [224]. The canonical bacterial foraging algorithm (BFA) shows poor convergence properties while solving large-scale problems such as the STHTS problem. To tackle this complex STHTS problem, considering its high-dimension search space, reference [225] presented critical improvements in the canonical BFA to solve NCSTHTS problem. Reference [226] has solved the CSTHTS problem using a modified bacterial foraging algorithm (MBFA) which is one of the evolutionary optimization techniques. The modifications in canonical BFA were made to improve its convergence behaviour. Reference [227] implemented bacterial foraging algorithm on a real Indian power system to solve the CSTHTS problem.

Reference [228] introduced the cultural algorithm for the first time which belong to the class of evolutionary algorithms and they work by using knowledge of the domain that is extracted during the process of evolution and thus improve the performance of search engine. CSTHTS problem was solved by reference [229] by implementing a hybrid of differential algorithm and cultural algorithm. In reference [230] CSTHTS problem while incorporating the water transport delay, was solved using the cultural algorithm. Equality constraints were handled without incorporating the penalty factor approach. Reference [231] introduced for the first time the stochastic electromagnetism-like optimization algorithm which works by mimicking the mechanism of repulsion and attraction of charges in electromagnetic fields. In reference [232], a stochastic Multi-objective variant called electromagnetism-like mechanism (ELM) was applied to solve the CSTHTS problem with complex constraints efficiently. The algorithm also utilizes Space reduction while proceeding through the iterations, along with self-adaptive steps and mutation strategy for improving the algorithm convergence rate.

Reference [233] has implemented a hybrid of Data envelopment analysis and electromagnetism-like magnetism to solve MOSTHTS problem. The system considered had eight cascaded hydroelectric plants and six coal-fired plants to show that the hybrid method was computationally efficient and fast. Reference [234], introduced the predator-prey optimization algorithm as a multi-objective optimization

TABLE 12. Summary of GA and its variants for different types of short term hydrothermal scheduling problem.

Optimization Algorithm	Variants of the Algorithm	General Overview of Performance
Genetic algorithm	Canonical GA [57], [204], [208], [209], [212], [215], [218]	Robust and near global optimum. solutions achieved but requires large number of iterations as compared to other metaheuristic algorithms. Canonical version is very slow in convergence, however, the variants performed well in achieving fast convergence rate, specially the search space squeezed variants improve the convergence speed a lot
	Multi step and single step GA [205]	
	Diploid genotype and haploid genotype-based GA [206]	
	Enhanced GA [207]	
	Binary coded GA [210]	
	Optimal gamma-based GA [211]	
	Non dominated sorting GA [213]	
	Search space squeezed multi-objective GA [214]	
	Fast GA [216]	
	Real coded GA [217]	
	Real coded GA with chaotic maps [219]	
	Hybrid of GA and tabu search [220]	
	Parallel multi-objective GA [221]	
	Real coded GA with improved Muhlenbein mutation [222]	

evolutionary algorithm that helps to improve the search space of particles by utilizing the concepts of predation and prey. the influence of predator function improves the search process of the swarm by not letting the particles getting influence from unhealthy particles in the update process. Reference [235] presented the heuristic Predator-prey optimization based on the particle swarm optimization while having an additional predator effect that helps to improve the searchability of the algorithm, to solve CSTHTS problem. Reference [236] has applied the swarm intelligence-based predator-prey optimization algorithm to solve CSTHTS problem.

Reference [237] presented predator-prey-based optimization (PPO) technique to solve CSTHTS problem for both fixed head and variable head reservoirs. Reference [238] implemented a swarm intelligence based improved predator influenced civilized swarm optimization algorithm to solve CSTHTS problem. In reference [239] CSTHTS is solved using clonal selections algorithm. Reference [240], introduced for the first time the biogeography-based optimization algorithm that is inspired from the geographical distribution of biological species and was a mathematical mimicry of the immigration and emigration processes of different species from one locality to other.

In reference [241], CSTHTS problem was solved using biogeography-based optimization. Reference [242] solved the CSTHTS problem by using quadratic migration model of biogeography-based optimization (QBBO) which is inspired by the phenomenon of species' survival from one habitat to another habitat and their annihilation. The robust solution both in terms of finding near-global optimum and in terms of fast convergence rate was promised. Reference [243] has also applied the Biogeography Based Optimization approach to solving some cases of CSTHTS problem. Reference [244] implemented a real coded chemical reaction based (RCCRO) algorithm to solve the CSTHTS problem. Robust solutions proved the capability of the algorithm to solve highly non-linear and multimodal optimization problems. Reference [245] implemented an oppositional real coded chemical reaction based (RCCRO) algorithm to solve the CSTHTS problem. The oppositional real coded variant of chemical reaction algorithm promised a fast convergence rate.

Reference [246] implemented a hybrid of chemical reaction-based algorithm and differential evolution algorithm to solve the MOSTHTS problem. Valve point loading of thermal units was considered. Robust solutions proved the capability of the algorithm to solve highly non-linear and multimodal optimization problems. Reference [247] implemented a chemical reaction based (CRO) algorithm, to solve CSTHTS problem, which imitates the inter-collision between molecules during a chemical reaction to reach a lower energy stable state. Reference [248] introduced the memetic and metaheuristic, swarm intelligence based shuffled frog leaping algorithm for the first time. This algorithm has both local and global search abilities and it gets strength by having interaction among particles (frogs) in a cultural or memetic way. It has particle swarm optimization-based local search ability and it uses shuffled complex evolution-based technique for global search. Reference [249] has solved the CSTHTS problem using modified shuffled frog leaping algorithm in which a threshold judging strategy is used in the local evolution process to improve the searchability and convergence accuracy of an original shuffled frog leaping algorithm. Reference [250] solved the MOSTHTS problem by utilizing the penalty factor approach to combine the economic and environmental objectives as one objective function. Reference [251] proposed a blend of several optimization algorithms like Newton-Raphson, genetic algorithm, random search method and fuzzification of weights to solve the MOSTHTS problem. A coal-constrained thermal unit was also introduced to make the scheduling problem more universal. Reference [252] presented a modified seeker optimization algorithm to solve the CSTHTS problem. The seeker optimization algorithm is a gradient-based, metaheuristic algorithm that is inspired by the random process of the human search strategy and was first presented by reference [253]. Valve-point loading of thermal units and prohibited operating zones of hydro reservoirs were considered in the optimization problem.

Reference [254] introduced the honey bee mating algorithm for the first time and it was a mathematical imitation of the mating process of honey, and it is one of the swarm-based optimization approaches. Reference [255] has applied a variant of honeybee mating algorithm known as improved honeybee mating algorithm to CSTHTS problem. The improvement was in term of achieving fast convergence rate to a near-optimal solution. Reference [256] has implemented harmony search algorithm, on MOSTHTS problem, which is a metaheuristic optimization algorithm, inspired from the process of making music in the perfect state of harmony, on a real Indian 9 bus power system having 11 transmission lines. Reference [257] has implemented an improved harmony search algorithm to solve CSTHTS problem while considering valve point loading behaviour of thermal units and transmission line losses. Reference [258] has solved the CSTHTS problem using a hybrid stochastic algorithm which is a combination of random search technique and genetic algorithm. The level of customer service was modelled as an equation to be added as a constraint in the conventional CSTHTS problem. Reference [259] introduced the metaheuristic teaching-learning based optimization algorithm for the first time that mathematically imitates the influence of a teacher on its students during the learning process and is also close to the swarm intelligence-based algorithms. Reference [260] has solved the CSTHTS problem by using swarm intelligence-based teaching-learning optimization algorithm while considering the valve point loading behaviour of the thermal units and incorporated the prohibited discharge zones of operation of the hydro units. The algorithms gave promising results both in terms of finding near-global optimum and in terms of fast convergence rate. Reference [261] has implemented an improved variant of teaching learning-based optimization algorithm to solve CSTHTS problem. Reference [262] has presented a constructive framework based on an intelligent technique to make a stochastic multi-objective model for the flexible scheduling of hydrothermal plants with valve-point loading effects of thermal units. A non-dominating sorting-based teaching-learning optimization algorithm. A non-dominated sorting-based teaching-learning algorithm was presented, to solve MOSTHTS problem, that found a pair of non-dominated solutions and then the fuzzy-based method was implemented to choose the best solution.

Reference [263] introduced the artificial bee colony algorithm for the first time that mimics the communication phenomenon of bees with their neighbour bees to complete their tasks. Reference [264] added a chaotic factor in the update equations of the artificial bee colony (ABC) algorithm to solve the STHTS problem in fast convergence time while avoiding the premature convergence. This reference [265] has solved the CSTHTS problem using Artificial bee colony optimization algorithm. Prohibited operating zones of hydro units and thermal units with valve point loading with ramp-rate limits were considered. Reference [266] presented the multi-objective artificial bee colony algorithm to solve the MOSTHTS problem. In this algorithm, select operator of artificial bee colony algorithm was modified to adapt the multi-objective problem optimization, and employed bee phase and probability calculation of onlooker bee phase was changed to avoid local optima. Progressive optimality algorithm-based method was also adopted to enhance the local search ability of the multi-objective ABC algorithm. Reference [267] implemented an artificial bee colony algorithm for solving valve point loading based pumped storage CSTHTS problem. Reference [268] implemented the artificial bee colony algorithm to solve CSTHTS problems. Reference [269] has implemented the hybrid algorithm that was a combination of Artificial Bee Colony (ABC) and the BAT algorithm to solve CSTHTS problem on a Chilean power system. Reference [270] introduced the flower pollination algorithm for the first time that is inspired by the natural phenomenon of pollination of flowers and it is a swarm intelligence-based algorithm. Reference [271] has implemented the improved version of flower pollination algorithm (IFPA) to solve the CSTHTS problem while considering valve point loading of thermal units and the prohibited discharge zones of hydro units. IFPA works by controlling the local pollination process of FPA by introducing a scaling factor and an additional intensive exploitation phase is added to tune and improve the global best solution. Reference [272] introduced the grey wolf optimization algorithm for the first time and it mimicked mathematically hunting phenomenon and hierarchy of leadership of grey wolves. the Reference [273] implemented the Grey Wolf Optimization (GWO) algorithm to solve two large cases of STHTS problem. GWO algorithm can increase the diversity in solutions and thus the searching capability. Moreover, good convergence rate was achieved in this implementation. Reference [274] has solved the wind-solar-hydrothermal scheduling problem using a combination of grey wolf and cuckoos search optimization algorithms to solve the emission CSTHTS problem. Reference [275] has implemented the hybrid of chaotic grey wolf optimization and dragonfly optimization algorithms to solve the CSTHTS problem. Moreover, two constraint handling methods were also presented. Reference [276] solved the STHTS problem using the grey wolf optimization algorithm which is inspired by the hunting methods adopted by the grey wolfs.

Reference [277] introduced for the first time the water cycle optimization algorithm which was a mathematical inspiration from the natural water cycle process that helps streams and rivers to flow in the world. Reference [278] has implemented an evaporation rate-based water cycle algorithm (ERWCA). ERWCA is a nature-inspired metaheuristic algorithm based on the four steps of the natural water cycle to solve CSTHTS problem. Reference [279] has implemented improved water cycle algorithm to solve MOSTHTS problem. Reference [280] introduced for the first time the symbiotic organisms search algorithm which is inspired by the natural process of symbiosis among organisms that deals with mutualism, commensalism and parasitism. Reference [281] has implemented the metaheuristic Symbiotic Organisms Search (SOS) algorithm to solve CSTHTS problem. Reference [282] has implemented the symbiotic organisms search algorithm to solve three test cases of CSTHTS problem. Reference [283] has implemented quasi-reflected symbiotic organisms search algorithm to solve three test cases of CSTHTS problem.The quasi-reflected scheme was incorporated into symbiotic organisms search to improve the searching performance of the algorithm.

The whale optimization algorithm is inspired by the hunting methods of whales was first introduced by reference [284]. Reference [285] presented the implementation of metaheuristic whale optimization algorithm to solve CSTHTS problem in the presence of solar panel-based power generation. Reference [286] has solved wind power integrated STHTS problem using metaheuristic Ant Lion optimization algorithm which is inspired from the six stepped hunting model of lions and ants and was first presented by reference [287]. Reference [288] introduced for the first-time swarm-intelligence-based group search algorithm which is inspired by the searching behaviour of animals. Reference [289] implemented the group search optimization algorithm to solve CSTHTS problem. Reference [290] introduced the sine cosine optimization algorithm for the first time which like swarm algorithms initialize a set of solutions and then update them in a fluctuated way towards the global optimum using the sine and cosine functions. Reference [291] has implemented the metaheuristic sine-cosine algorithm to solve CSTHTS problem while considering valve point loading behaviour of thermal units and transmission line losses. Reference [292] introduced the ions-motion optimization algorithm which works on imitating the principle that opposite charges attract each other and same charges repel each other.

Reference [293] implemented quasi-reflected ions motion optimization algorithm, to solve seven test cases of CSTHTS problem. The quasi-reflected variant of ion motion algorithm has fast convergence speed as compared to the original ions motion algorithm in finding the near-global optimum solution. Reference [294] has solved the NCSTHTS problem using epsilon greedy algorithm-based, reinforcement learning algorithm which in its stochastic form was first introduced by reference [295].

Reference [296] has implemented the Differential Evolution Method, Newton-Raphson Method and Heuristic Search Method on different NCSTHTS problems. Reference [297] introduced the social group optimization algorithm which is inspired by the ability of human beings to interact socially to solve a complex problem.

Reference [298] has solved the CSTHTS problem using a modified social group algorithm in which the acquiring phase of the original social group optimization algorithm was modified to get improved convergence behaviour. Reference [299] introduced for the first time the metaheuristic lightening attachment optimization algorithm which mathematically mimics the upward and downward leader movements of lightning arcs. Reference [300], has implemented lightning attachment procedure Optimization (LAPO) algorithm CSTHTS problem considering the valve point loading effects of thermal generators and the power transmission losses.

Reference [301] introduced the Crisscross optimization algorithm for the first time that applies two distinctive search operators, i.e., horizontal crossover and vertical crossover. The horizontal crossover is used as a global optimizer that works on a cross-border search strategy. The vertical crossover addresses the premature convergence by applying a unique dimensional crossover mechanism. Reference [302] has solved the CSTHTS problems using a crisscross optimization algorithm.

Reference [302] has given a very short review of the implementations of nature-inspired algorithms on the CSTHTS problems solved in the last two decades. Figure 14 gives the year wise distribution of the number of articles published on STHTS using variants of other metaheuristic algorithms. Figure 15 shows the distribution of the number of papers on STHTS for different years. Figure 16 shows the distribution of algorithms for the STHTS problem. Table 13 shows the summary of other metaheuristic algorithms for STHTS.

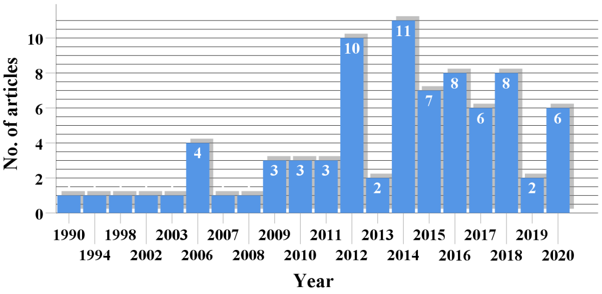

FIGURE 14. Year wise distribution of articles published on STHTS using variants of other metaheuristic algorithms.

IV. NO FREE LUNCH THEOREM AND IMPORTANCE OF STATISTICAL TESTS FOR STHTS PROBLEM

According to reference [3] the "No Free Lunch Theorems" state that every algorithm gives the same performance for all

TABLE 13. Summary of other meta heuristic algorithms for different types of short term hydrothermal scheduling problem.

Optimization Algorithm	Variants of the Algorithm	General Overview of Performance
Other metaheuristic algorithms	Bacterial Foraging algorithm and its variants [225]–[227] Cultural algorithm and its variants [204], [229] Electromagnetism like optimization algorithm and its variants [232], [233] Predator-prey optimization algorithm and its variants [235]–[238] Clonal selection algorithm [239] Bio-geography-based algorithm and its variants [241]–[243] Chemical reaction-based algorithm and its variants [244]–[247] Modified shuffled frog leaping algorithm [249] Modified seeker's optimization algorithm [252] Honeybee mating algorithm and its variant [255] Harmony search algorithm and its variants [256], [257] Artificial bee colony algorithm and its variants and combination with Bat algorithm [264]–[269] Flower pollination algorithm and its variant [271] Grey wolf algorithm and its variants [273]–[276] Water cycle algorithm and its variants [278], [279] Symbiotic search algorithm and its variants [281]–[283] Whale optimization [284], [285] Ant-Lion optimization algorithm [286], [287] Group search algorithm [288], [289] Sine-cosine algorithm [290], [291] Ions-motion algorithm and its variant [292], [293] Reinforcement learning algorithm [294], [295] Differential evolution method [296] Social group optimization algorithm [297], [298] Lightning attachment algorithm [299], [300] Criss-cross algorithm [301], [302]	Very good performances in find-. ing near global optimum solutions. Their structure is usually like the PSO variants as they are mostly swarm intelligence-based algorithms, and their performances were comparable and sometimes better than PSO variants. Fast in convergence rates. Mostly the variants performed better in terms of convergence rate. Though, harmony search and biogeography-based algorithms were slowly converging.

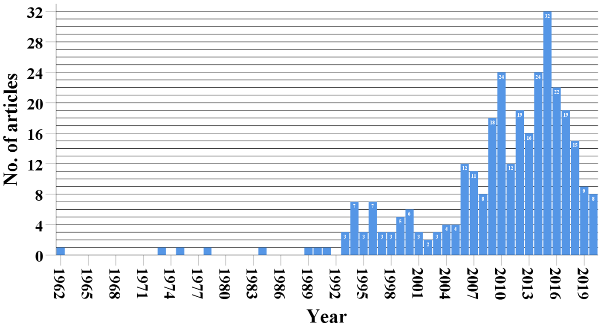

FIGURE 15. Summary of the number of papers on STHTS for different years.

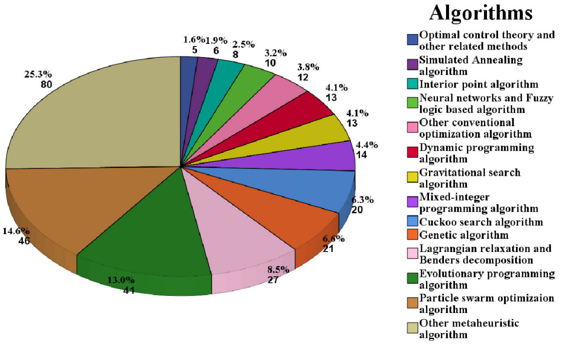

FIGURE 16. Summary of the implementation of algorithms for different types of STHTS problem.

types of optimization problems if taken on average. It can be further explained as; if an algorithm gives good performance for one type of problem, it does not guarantee good performance for some other type of optimization problem. Keeping these arguments in view, there is a need for establishing the superiority of one algorithm over other algorithms for the solution of STHTS problems by utilizing parametric or non-parametric statistical tests. Due to the stochastic nature of metaheuristic and heuristic optimization algorithms, to establish the superiority of one type of algorithm over the other type of algorithm, some proper statistical tests are needed. Reference [303], has presented the significance of non-parametric statistical tests as a procedure to compare the evolutionary and swarm intelligence-based optimization algorithms for different types of optimization

TABLE 14. List of references according to the conventional algorithm applied and the type of STHTS problem solved.

Type of STHTS problem	References cited						
	Lagrangian relaxation and Benders decomposition	Mixed integer programming	Dynamic programming	Interior point algorithm	Conventional optimization algorithm	Neural network and Fuzzy logic	Optimal control and other related methods
NCSTHTS	[19], [27]	X	[45], [46], [48]	[57]	X	[78]	X
CSTHTS	[4]–[6], [13], [14] [16]–[18], [21], [22] [23], [24], [26], [27]	[29], [30], [32] [34]–[36], [38] [39]–[41]	[23], [42]–[46] [48]–[51]	[52]–[54] [56], [58]	[59]–[64] [67]–[69]	[72], [74] [75], [79]	[83]
MOSTHTS	[25]	[37]	X	X	[65], [66]	[77]	X

TABLE 15. List of references according to the metaheuristic algorithm applied and the type of STHTS problem solved.

Type of STHTS problem	References cited						
	Simulated annealing algorithm	Particle swarm optimization algorithm	Evolutionary programming algorithm	Cuckoo search optimization algorithm	Gravitational search algorithm	Genetic algorithm	Other metaheuristic algorithm
NCSTHTS	[86], [87]	[90], [93]–[95] [117], [134], [135]	[137], [140], [141] [143], [145], [146] [140], [156], [172]	[174]	[192]	X	[225], [294], [296]
CSTHTS	[88]	[91], [92], [98]–[104] [106]–[109], [111], [113] [115]–[117], [120], [121] [123], [125]–[130]	[112], [136], [138], [139] [150], [154], [157]–[159] [163]–[165], [170], [171]	[175], [176], [179] [177], [180]–[183] [176], [185], [188]	[194], [196], [197] [200], [202]	[204], [206]–[209] [57], [210], [212] [216]–[220], [222]	[226]–[228], [230], [232], [235]–[239] [241]–[245], [247], [249], [252], [255] [257], [258], [260], [261], [265], [267] [268], [269], [271], [274], [275], [278] [281]–[283], [285], [289], [291], [293] [298], [300], [302]
MOSTHTS	X	[96], [97], [105] [110], [112], [119] [122]	[77], [142], [144], [147] [148], [149], [151], [152] [155], [160], [161], [166] [167]–[169]	[177], [178], [186] [187], [189], [190]	[180], [193], [195] [198], [199], [201]	[213], [214], [221]	[233], [246], [250], [251] [256], [262], [266], [279]

problems. Reference [304], has also signified the importance of a statistical test known as T-test, to establish the superiority of digital pheromones based PSO algorithm over canonical PSO algorithms, by comparing data sets of the performances of both algorithms on five different nonlinear and multi-modal optimization problems. Research articles, that have been discussed in previous sections have all proposed solutions to different types of STHTS problems. However, due to the stochastic nature of the metaheuristic algorithms that are utilized in the solution of STHTS need a proper statistical test to establish the superiority of one type of algorithm over the other algorithm. References [134] and [135] discussed the implementation of metaheuristic optimization algorithms, i.e. two variants of Accelerated Particle Swarm Optimization algorithm and a variant of firefly algorithm on NCSTHTS problems. In these articles, to establish the superiority of one algorithm over the other, the concept of deploying true statistical test, especially independent sample T-test was presented to compare a hundred trials, each of the two algorithms is compared on the same problem to check if the results for hundred trials of both the algorithms are statistically different or not, by comparing the mean values of the results. There can be other statistical tests also as suggested in reference [303] which can be incorporated for comparing such implementations of metaheuristic optimization algorithms, which have not been taken into consideration in most of the research articles published on STHTS problem. Table 14 gives the list of references according to the conventional algorithm applied and the type of STHTS problem solved. Table 15 gives the list of references according to the metaheuristic algorithm applied and the type of STHTS problem solved.

V. DISCUSSION AND ANALYSIS

1) The STHTS problems are highly non-linear, multi-modal and non-convex optimization problems with many constraints.
2) STHTS problems are highly multi-dimensional problems, i.e. each scheduling hour or period is one dimension in that multidimensional problem.
3) Conventional optimization algorithms are mostly gradient based and therefore they stick to the local optima (in highly multimodal problems like STHTS) and therefore they do lead to premature convergences to local optima and take high convergence time in attempt to reach global optima.
4) To solve STHTS problems, metaheuristic algorithms mostly solve the issue of premature convergences, however, in their canonical versions, the exploration and exploitation factors in the update process are weak and therefore the canonical versions are usually slow in reaching toward robust or near global optimum solutions. The variants of the most of the metaheursitic algorithms provided better explorations and exploitations and thus achieved better solutions and in faster convergence times as compared to the canonical versions.
5) It has been observed that Swarm intelligence framed metaheuristic optimization algorithms have performed the best in finding good approximates to global optimum solution in very fast convergence time. At least, they are mostly able to reach to robust (acceptable) solutions in small time. Although, particle swarm optimization algorithm and its variants are one class of swarm intelligence algorithms, but many modern metaheuristic algorithms like flower pollination algorithm, Cuckoo search algorithm, teaching learning based algorithms, gravitational search algorithms frog leaping algorithm, honey bee algorithms, ant colony algorithms are quite similar in the form to the particle swarm optimization algorithm and may be rendered as swarm intelligence algorithms. These algorithms, along with the specific PSO algorithms have better results for most of the test cases of STHTS problems available in literature, in finding good approximates of global optimum solutions and also in fast convergence time.
6) Due to high dimensionality, STHTS problems are still open to solve problems and the No free lunch theorems also establish that despite so much work on STHTS problems, there is still a big chance to make new metaheuristic optimization algorithms to solve the different cases of STHTS problems to find even better approximates of global optimum solutions in faster convergence rate.
7) Due to random nature of STHTS problems and also due to the theory of no free lunch theorems, there is a need to establish a superiority of one type of algorithm over other type of algorithms by performing true hypothetical statistical tests (parametric or non-parametric). Most of the references have tried to establish the superiority of one type of algorithm over the other type of algorithm by just comparing the optimum solutions achieved by them as compared to the previous literature. However, the stochastic nature of metaheuristic algorithms require that the comparison among the results of algorithms on STHTS problems be made on the basis of statistical tests like parametric and non parametric tests.

There are many new metaheuristic optimization algorithms and their variants that had been applied to solve many different types of STHTS problems, as already reviewed and cited in the previous sections. A new researcher of the domain may find it helpful to have foundation level codes of these algorithms to solves some benchmark or other easy optimization problems. Reference [305], has given many such codes written on MATLAB. Interested researcher is encouraged to take advantage of these computer programs.

VI. CONCLUSION

This article presents a comprehensive review of most of the implementations of conventional and metaheuristic optimization algorithms for solving STHTS problems. The pros and cons of different algorithms were comprehensively and critically presented in solving the STHTS problem.

This article will provide a quick and effective overview of the literature published on STHTS and will also let them find niches in the very research area considering the above-mentioned observations.

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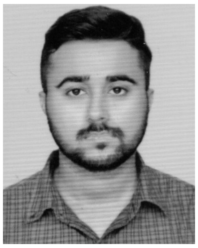

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