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Particle SWARM optimization for natural grouping in context for group technology application

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Abstract— The Cell-formation problem (CFP) addresses the issue of creation of part families based on similarity in processing requirements and the grouping of machines into groups, based on their ability to process those specific part families. The CFP is combinatorial in nature and due to difficulty faced in solving related mathematical programming problems, efforts have been made to use evolutionary approaches. Literature highlights that there are many advantages of converting batch type manufacturing system (BTMS) in cellular manufacturing system (CMS). In this paper, mathematical model has been proposed for groups to be emerged naturally. As this mathematical model of CFP becomes NP- complete in nature, researchers advocated the use of meta-heuristics. Over the years, many different meta-heuristic methods have been used to solve the CFP in group technology application. In the present paper, evolutionary population based method known as Particle swarm optimization (PSO) hybridized with assignment algorithm is used to solve cell formation problems. Due to these proposed changes, efficiencies of cell formed are significantly increased in comparison to the result available in the literature. Proposed hybrid algorithm is applied to solve 30 different types of randomly generated and 10 standard CFP comprising of large verity in terms of number of machine, number of parts and number of machines required by parts. For this algorithm, optimal values of parameter were found with the use of Taguchi method. It is found that the proposed changes in algorithm and parameters obtained significantly impact the results in terms of efficiency values.

Keywords—Cell Formation Problem(CFP), Group Technology (GT), Cellular Manufacturing (CM), Particle Swarm Optimization(PSO)

I. Introduction

Changing scenario of market with decreased product life cycle and increased competition led the researchers to exploit most of the known benefits of mass production system in batch type production system (BTPS). According to a survey done by [1], BTPS constitutes 50–75% of world manufacturing. This encouraged the development of new manufacturing approaches over the time such as Cellular Manufacturing (CM) that involves Group Technology (GT) in organizing and manufacturing for managing diversity by capitalizing on underlying similarities in products and activities.

The idea of GT leading to CM was first proposed by Flanders [2]. Reference [3] and Reference [4] were among the early researchers to demonstrate the concept of GT on various issues. Some benefits of GT as highlighted by [5], [6] and [7] were reduction in material handling, reduction in setup, increased utilization of resources, reduction in lead time, better space utilization, reduced cost of production, etc.

For forming the cells in CM, parts are grouped into part families and machines into cells based on the processing requirements of parts. In other words, all the parts in a family should find machines in the same group. Thus, the whole manufacturing system is decomposed into independent and small subsystems. In this process, a Part Machine Incidence Matrix (PMIM) is generally used to portray machine requirements of various parts to be manufactured. Grouping exercise is to find least interacting cells. This is ensured by minimizing the inter-cellular movements and maximizing the utilization of machines within the cell.

Various methods have been proposed by the researchers for solving cell formation problem (CFP). A broad classification of these methods was presented by [7] and [8]. Reference [9] and [10] presented Production flow analysis for factory-flow and department flow analysis that later were subdivided into group and line analysis. Reference [11] used Similarity Coefficient Based methods. It was further improved by [12] and the method was termed as Average Linkage Clustering. This method has also been used by [13], [14], [15] and [16]. Reference [17] suggested a graph partitioning approach that uses cliques of machine graphs as a means of grouping machines.

Rank Order Clustering (ROC) methodology, proposed by [18], is the most popular array based method for CFP. The idea was further studied and improved version of the same as MODROC was proposed by [19]. Chandrasekharan Rajagopalan [19] have, after identification of some short comings of ROC, used MODROC (the ROC algorithm in conjunction with a block and slice method) to obtain a set of intersecting machine cells and non-intersecting part families. In the same year, Reference [20] proposed non-hierarchical clustering algorithms which were modified form of McQueen's method[21]. Integer programming formulation with additional constraint has been proposed by [22] and [23]. Reference [24] proposed network flow models for the GT problem.

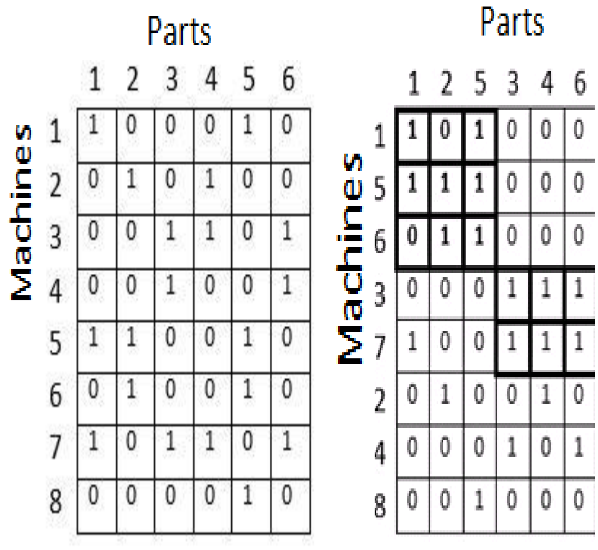
Since solving mathematical programming formulations do not provide solutions efficiently in reasonable time, number of heuristic approaches, including those developed using metaheuristic framework, have been developed and applied for CFP by many researchers. Metaheuristics as evolutionary methods have been applied for GT problem using framework of simulated annealing (SA), genetic algorithm (GA), tabu search (TS), ant colony optimization (ACO), particle swarm optimization (PSO) etc.

SA and TS are among the earliest methods for solving NP-hard combinatorial optimisation problems. Reference [25] proposed SA for GT application and reported that it was not affected by disposition of 1's and 0's in the initial part-machine incidence matrix and possessed capability of solving large and complex problems in computationally efficient way. TS approach for GT application was proposed by [26] for machine-cell formation and part-families are determined thereafter. GA is a biologically inspired approach based on Darwin's theory of evolution- survival of the fittest [27]. Reference [28] reported a new GA for solving Generalized Grouping Problem (GGP). ACO is inspired by the behaviour of real ant colonies and was first introduced by [29]. Reference [30] represented grouping problem as an artificial ant system. A better solution was found by semi-blind ants by way of communication supported random search process.

In the mathematical model due to [31], [32], [33] and [34], groups are formed with the objective of minimizing intercellular movement with the constraint on cell size in terms of number of machines. The objective function proposed by them will not help to form the groups in case the cell-size restriction is not included in their proposed formulations. In other words, the groups do not evolve naturally but because of the constraint on the cell-size. SA approach by [31] or PSO approaches by [32], [33] and [34] try to identify the groups based on cell-size restriction. Their proposed heuristics result grouping in hierarchical manner and have the characteristic of forming machine cells without any group assigned to it. For example, following the PSO approach by [32] for a grouping problem, shown in Fig. 1(a), the resultant block diagonal matrices denoting groups were found as shown in Fig. 1(b). From the two figures, it can be noted that machine cell with machines M2, M4 and M8 does not find any part allocated to it.

In the present paper, a different formulation of grouping problem has been proposed that results groups in a more natural way by identifying the closeness between various parts in an objective manner acknowledging concern both for the number of exceptional elements and voids[35] and [36]. Exceptional elements appear as 1's outside the block diagonalized matrices and voids as 0's within them. In Fig. 1(b), the exceptional element can be seen as '1' corresponding to a part 1 and machine 7 whereas void as '0' corresponding to part 1 and machine 6. PSO based proposed approach is different from that of [32]in the sense that

1) the groups do not emerge because of cell-size restriction but rather by striking an optimal balance between number of exceptional elements and voids, and
2) no machine cells without any part assigned to it will be formed in the optimal solution.



(a) A grouping problem (b) Grouping solution

Fig. 1: A grouping problem with grouping solution from PSO based approach of Andres and Lozano (2006).

The paper is organized in the following manner. Section II describes the problem statement and Section III explains the

PSO for GT application. In section IV, optimal values for parameters of the proposed PSO are determined and discussed. In section V, a study has been carried out to determine comparative advantage to be gained in use of determined optimal parameter values reported in this paper over that [32]. Besides, comparative performance of PSO is also analyzed with ACO and GA.

II. The Problem

The problem considered here is a simple grouping problem [37] for which the input is taken in the form of a part-machine incidence matrix A = [a_{ij}] that consists of elements as '0' and '1'. The appearance of '1' in matrix shows the requirement of the associated machine by the corresponding part and that of '0' otherwise.

The notations used in the formulation of the problem are described below.

1) *Indices*

i: a machine
j: a part
k: a group

2) *Parameters*

C = number of cells
M = number of machines
P = number of parts

3) *Decision variables*

$y_{i,k}$ = 1 if machine i assigned to cell k otherwise 0

$z_{j,k}$ = 1 if machine j assigned to cell k otherwise 0

The objective function stating minimization of the total number of exceptional elements and voids is stated as

$$\text{Minimize} \sum_{k=1}^{C} \sum_{i=1}^{M} \sum_{j=1}^{P} (a_{ij} z_{jk} (1 - y_{ik}) + (1 - a_{ij}) z_{jk} y_{ik}) \quad (1)$$

Subject to

$$\sum_{k=1}^{C} y_{ik} = 1 \ \forall i, \quad (2)$$

$$\sum_{k=1}^{C} z_{jk} = 1 \ \forall j, \quad (3)$$

$$y_{ik}, z_{jk} \, \varepsilon \, \{0,1\} \ \forall i \ \forall j \ \forall k \quad (4)$$

First and second terms of the objective function respectively represent the number of exceptional elements and voids. Naturally the groups are to be formed in a manner to minimize the total of number of exceptional elements and voids. Constraint (2) will ensure that a machine is definitely assigned to a group and similarly constraint (3) for part assignment. Constraint (4) in the formulation represents binary nature of decision variables.

The above formulation is basically a mathematical programming formulation. Determining solution from this is not an easy task. Therefore, PSO based heuristic is being proposed in the next section.

III. PSO Based Heuristic

The framework of the PSO as proposed by [32] is being taken as such with velocity and location of particles given by the following expressions

$$V_{i,t+1} \leftarrow C_1(\text{rand}_{i,t} - X_{i,t}) + C_2(P_{i,t} - X_{i,t}) + C_3(G_{best,t} - X_{i,t}) + C_4(\text{ref}_{i,t} - X_{i,t}) \quad (5)$$

$$X_{i,t+1} \leftarrow X_{i,t} + V_{i,t+1} \quad (6)$$

where $V_{i,t+1}$ and $X_{i,t+1}$ respectively represent the velocity and position of the i^{th} particle in the $t+1^{th}$ iteration, $G_{best,t}$ is the best value obtained by swarm so far, $P_{i,t}$ is the best value obtained in respect of i^{th} particle till t^{th} iteration. C_1, C_2, C_3 and C_4 are positive constants called confidence coefficients [38]. Values of confidence coefficients vary in the range [0, 1].

Expression (5) calculates a new velocity for each particle considering also its previous velocity, the particle's position at which the best possible fitness has been achieved so far, and the global best position achieved. The last term in expression (5) is taken as such as considered by [32] with the same meaning and context. Expression (6) updates each particle's position in the solution space.

PSO based heuristic by [32] does not reveal as how the cell size restrictions are to be incorporated for group formation. The framework for forming solution is given in the form of a flowchart in Fig. 2.

In the flowchart of Fig. 2, each particle in the swarm is taken to represent a grouping solution in terms of machine-cells only. A complete grouping solution in terms of machine cells and part-families comes from blocks 2 and 3 of the flowchart. Reference sets, as mentioned in block 5 are updated by replacing the reference solutions with low grouping efficiency values with those with higher values that are obtained corresponding to current positions of the swarm. P-best value corresponding to a particle in the swarm is modified if the current location points to a better location measured in terms of higher grouping efficiency. G-best is to be updated in a similar way on overall basis considering all particles in the swarm. Grouping efficiency referred to here is taken as

$$\eta = [1 - k((qE + (1-q)V)/G) * (1/mn)] \quad (7)$$

where E is number of exceptional elements, V is number of voids, m and n are number of machines and parts respectively, and G is the number of groups formed. Values of k and q have been taken as 2.0 and 0.8 respectively as proposed by [37].

From the elaboration made above and also from Fig. 2, it can be observed that the PSO methodology proposed here is different from that of [32], as the quality of the grouping is viewed not only in terms of exceptional elements but in terms of numbers of voids as well. In addition, it does away with the constitution of machine cells without any parts assigned to them.

IV. IDENTIFICATION OF OPTIMAL VALUES FOR PARAMETERS OF PROPOSED PSO

The optimal values of these parameters had been identified by working with 10 problems from the literature [37] and other randomly generated 30 problems with number of machines varying in the range of five to forty and number of parts to be in the range of nine to forty. These 30 problems are generated in a manner such that first 10 problems have 20% density of 1's in the corresponding part-machine matrix, another 10 problems with 30% density, and remaining 10 problems with 40% density. For determination of optimal values of C_1, C_2, C_3 and C_4, (different levels are shown in Table 1), design of experiment methodology, as proposed by Taguchi [39] in terms of orthogonal array is shown in Table 2, is followed. For the purpose of statistical analysis and related graph plot reported here or in the next section, STATISTICA 12 has been used.

Table 2 shows orthogonal array for four parameters each with three levels. Taguchi approach helps to reduce number of experiments in comparison to performing full factorial experimentation. Each experiment was conducted for all the 40 problems. Each time, a record of maximum grouping efficiency achieved was recorded. The result of the experiments is shown in concise and compiled form in Fig. 3.

In Fig. 3, vertical lines show the spread of values around their mean for each experiment for 95% confidence. The mean values are shown connected by lines. It is evident from the figure that experiment 4 gives the optimal values of parameters as C_1 = 0.2, C_2 = 0.4, C_3 = 0.7 and C_4 = 0.6 for criterion as maximum efficiency with C_2 and C_4 values being the extreme values of their levels considered. It is quite possible that optimal values of these two parameters may lie beyond these extreme values. So, new sets of experiments have been performed with values of C_2 and C_4 beyond these extremes. Table 3 shows new sets of experiments. Results of these new sets of experiments are added to the old ones and shown in Fig. 4 for maximum efficiency. From this figure, it can be seen the experiment 4 still governs in terms of quality of grouping solution on an average. Corresponding to this experiment the optimal parameters as C_1 = 0.2, C_2 = 0.4, C_3 = 0.7 and C_4 = 0.6 can be taken.

In order to compare parameters that were found optimal in the present work and parameters that were reported optimal by [32], grouping efficiency due to [19] was used for the purpose of maximizing it for CFP. For this comparison, the 30 randomly generated problems were once again solved with proposed PSO and also using PSO due to Andres and Lozano (2006) with their respective optimal parameter values (C_1= 0.2, C_2= 0.4, C_3= 0.6, C_4= 0.7 *for proposed PSO , and* C_1= 0.1, C_2= 0.5, C_3= 0.7 and C_4= 0.5 *for PSO due to* [32]. Based on the results shown in Fig. 5, it is clear that proposed optimal values of parameters give better results than the values suggested by [32].

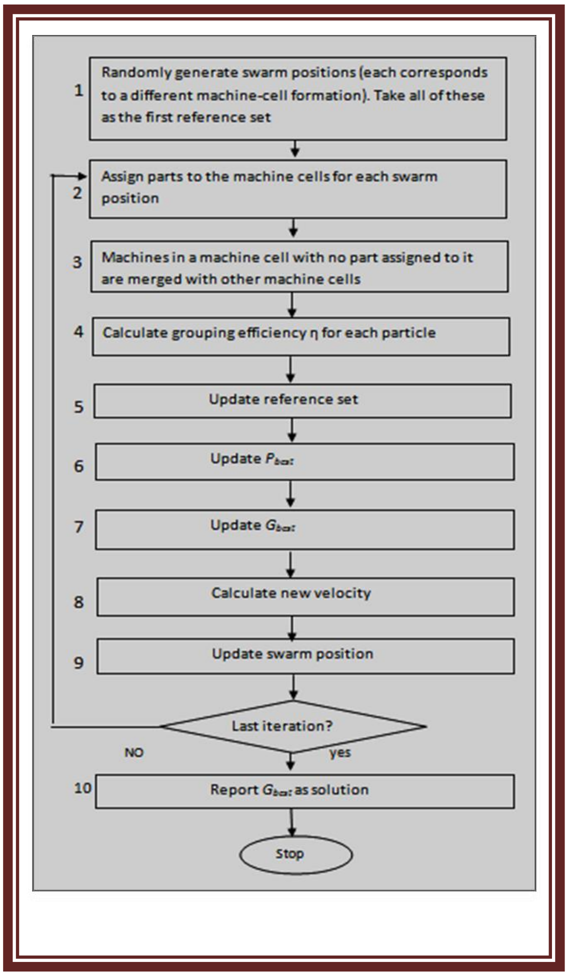


Fig. 2: Flowchart describing framework of proposed PSO based approach for grouping.

Table 1: Levels of PSO parameter

Parameters	**Levels**		
	1	**2**	**3**
***C*₁**	0.10	0.20	0.30
***C*₂**	0.40	0.50	0.60
***C*₃**	0.60	0.70	0.80
***C*₄**	0.40	0.50	0.60

Table 2: Design of experiment with values at each level

Experiment No.	Levels for parameter			
	C1	*C2*	*C3*	*C4*
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

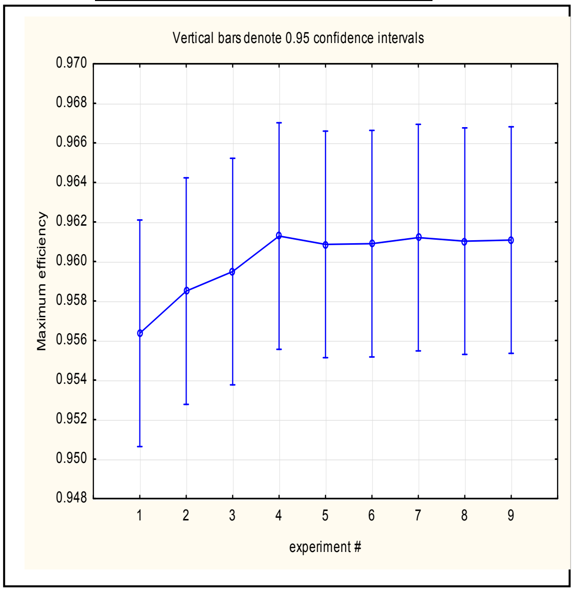


Figure 3: "all effect" graph for maximum efficiency

Table 3: Parameters values for additional experiments

Experiment No.	*C1*	*C2*	*C3*	*C4*
10	0.10	0.40	0.60	0.80
11	0.10	0.20	0.80	0.60
12	0.20	0.50	0.80	0.80
13	0.20	0.20	0.60	0.50
14	0.30	0.20	0.70	0.80

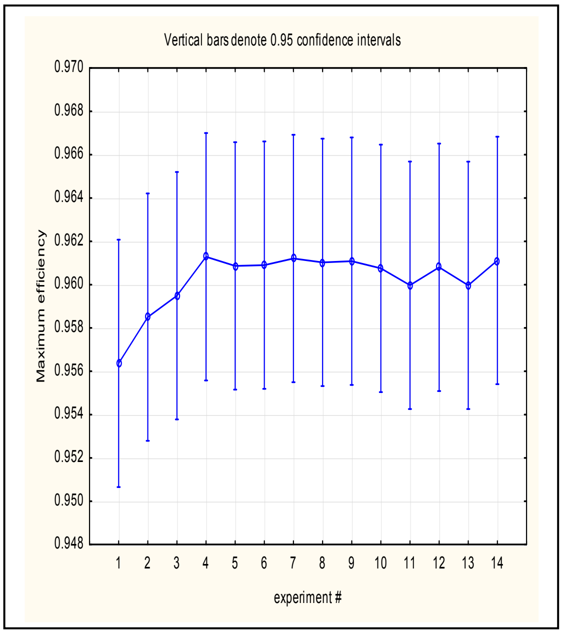


Figure 4: "all-effect" graph for maximum efficiency with added number of experiments

A Wilcoxon signed rank test was also performed using SPSS software to analyze the significance of inferior performance of PSO parameter values due to [32] compared to the ones proposed here. This was done based on the maximizing efficiency achieved using optimal parameter values of the two approaches. The rank test was carried out by subtracting the efficiency value achieved by the use of reported values from those using values due to [32]. 28 cases of negative rank (favourable to our reported values), 1 case of tie and 1 case of positive rank (against our reported values) were found. Our reported values were found to be better for $p = 0.00$. Thus, the parameter values as reported here be used in application of PSO for group technology.

V. Comparison of PSO with ACO and GA

Many metaheuristics like PSO, ACO and GA are being used for the purpose of solving CFP. To know which metaheuristic is better and suitable for CFP, an effort has been made here to determine comparative performance of ACO, PSO and GA. ACO with Tabu search (ACO-TS) framework due to [40] was reported to be the best amongst various variations of ACO for solving CFP and hence is used here. GA due to [41] has been picked for the same purpose. The three approaches are used to solve all the 40 problems mentioned earlier. Fig. 6 shows the result for the maximum average efficiency in the form of box plot. It is evident from the figure that ACO-TS is marginally better to PSO while GA has performed poorly in comparison of both with ACO-TS and PSO. Wilcoxon signed rank test was performed to analyze the comparative performance of the three approaches. In case of ACO and PSO, 27 cases of positive ranks (in favour of ACO), with 11 ties and 2 negative ranks (against ACO) were found.ACO was found to be better than PSO at $p = 0.00$. Comparing performance of GA and PSO, 28 cases of negative ranks (in favour of PSO), with 10 ties and 2 positive ranks (against PSO) were found. Here also PSO was found to be better than GA at $p = 0.00$. From the above, it is evident that PSO is better to GA and ACO is the best among all.

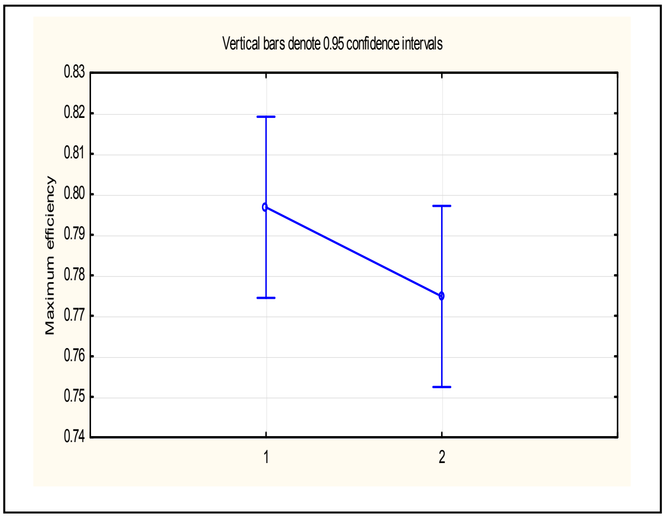


Figure 5: Comparison between parameters developed by Andres and Lozano [9] and proposed one.

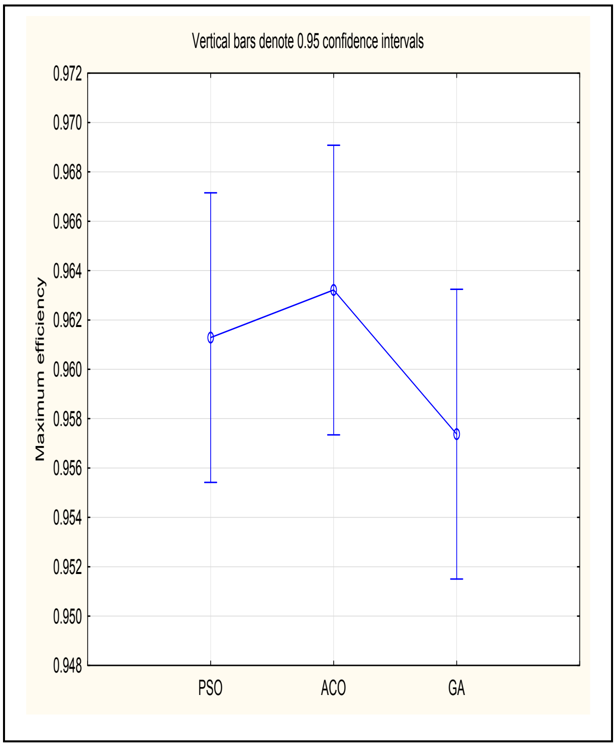


Fig. 6 Comparison between PSO, ACO and GA based on maximum efficiency achieved.

VI. Conclusion

In this paper, a mathematical formulation is proposed for groups to be emerged naturally for a CFP. As this model was NP-complete in nature, A meta-heuristic method, namely PSO, was used to solve CFP. A significant improvement in the efficiency of CFP has been observed with the proposed algorithm. It was noted that the results are better in comparison to reported solution. Further, an effort was made to find optimal parameter values for proposed PSO. Taguchi method was used to design the experiments. The parameter values that were found to be optimal are as $C_1 = 0.2$, $C_2 = 0.4$, $C_3 = 0.7$ and $C_4 = 0.6$ for the performance criterion as maximum efficiency. The performance of these parameters are then compared with the optimal parameters due to Andres and Lozano (2006)[32], and it was found through Wilcoxon signed rank test , a statistical analysis, that proposed optimal parameters superior to be used in the case of solving CFP by PSO. A comparison is also made among three metaheuristics PSO, ACO and GA. To compare these algorithms, Wilcoxon signed rank test was again performed. It was found that ACO performed better than PSO, where as PSO can be preferred over GA. By the study of results obtained, it can be concluded that to solve CFP, PSO and ACO-TS are more suitable in comparison to GA.

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