Cell formation problem with alternative process plans and alternative routes considering defect rate

Hamed Rafiei, Masoud Rabbani, Hossein Dashti, Abtin Nourmohammadzadeh

Abstract—This paper presents cell formation (CF) problem in dynamic condition with multiple alternative process plans and a set of alternative routes for each of process plans. Previous models paid attention to just one of the terms of process plans and routes and also they have not reflected the notion of defect rate after operations. Therefore, this paper also addresses defect rate. The proposed model seeks to minimize cell formation costs as well as the costs associated with production, while dynamic conditions, alternative routing, machine capacity limitation, cell size constraints, and outsourcing are also taken into account. The proposed model is solved in small, medium and large sizes to which a hybrid meta-heuristic approach is developed to cope. The developed algorithm consists of Simulated Annealing (SA) and Particle Swarm Optimization (PSO) to solve the problem in large scale due to high level of computational complexity. In the developed algorithm, the SA algorithm is applied to generate initial solution for the PSO. The comparison between results of exact and meta-heuristic methods for both small and medium scale problems confirms efficiency of the developed hybrid meta-heuristic approach.

Index Terms— Alternative process plans, Alternative routes, Cellular manufacturing system, Particle Swarm Optimization, Simulated Annealing.

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1 INTRODUCTION

Cellular manufacturing has been one of the most successful ways that companies have utilized in order to deal with challenges of today's global competitive environment. The approaches has been applied in a variety of industries over the three past decades, such as machinery and tools, aerospace and defense, Automotive, and electrical [1]. The Cell Formation (CF) is a part of cellular manufacturing system (CMS) that is actually the implementation of Group Technology (GP) in manufacturing and production systems with the goal of classifying parts in a way that the physical or operational similarities of the parts are used in different aspects of design and production of parts [2]. This method includes grouping of parts with similar design features or processing requirements into part families and machines into machine cells. This approach has found extensive use in just in time (JIT) production and in flexible manufacturing (FMS) [1].Some the advantageous of CF which have been established through simulation studies, analytical studies, surveys and actual implementation are:

1. Setup time is reduced.
2. Lot sizes are reduced.
3. Work-in-Process (WIP) and finished product inventories are reduced.
4. Throughput time is reduced.
5. Working flexibility improved. [2]

The first one refers to the traditional cellular manufacturing system where no changes in demand are taken into account, whereas the second one examines cases where part demand volume and part mix changes reflecting fluctuating market requirements.[3]

A majority of models assume a single process route possibility for each part [4]. But a few authors improved flexibilities offered by taking multiple process routes into account at the design phase, several benefits can be realized, such as allowing for the smaller number of machines, higher machine utilization, a reduced interdependence between cells, and an improved system throughput rate [4]. It should be noticed that there is an important difference between a *process plan* and a *process route*. A *process plan* refers to a list of the operations required in order to transform row materials into some finished products, not the precedence relationship between those operations. On the other hand, a *process route* refers to a sequence of specific machines or work centers in which a part follows them through to complete its processing, as required by the process plan. Hence, for a given process plan, multiple process routes would exist if one or more of the operations required for a part can be performed on alternative machines (either different type or identical processors) which are physically located at different places. Thus, in general, a process route implies a specific movement within the manufacturing facility, whereas a process plan does not have any such direct implication [5]. Modeling a problem with alternative routing and alternative process planning entails defining some new variables and including them in the mathematical model. As best of our knowledge, only a few papers reflected the two alternative terms simultaneously. Hence it can be more considerable for future researches and is the subject of this survey. In a survey conducted by Nsakada et al [5] which is the nearest to this study, alternative routing and alternative process

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planning are taken into account in the mathematical model. Also outsourcing is allowed and machines have limited capacities. Remainder of the paper is structured as follows. Next section Reviews body of literature briefly, while the dynamic CF problem with alternative routes and process plans with defect rate is elaborated in Section 3. Section 4 describes the developed meta-heuristic algorithm with the designed problem set. Finally, conclusion and future research directions are provided in Section 5.

2 LITERATURE REVIEW

Mathematical programming formulations for CF can be nonlinear or linear integer programming problem. They have been applied in a number of circumstances offering the distinct advantageous of being able to incorporate ordered sequence of operations, alternative resource plan, non-consecutive part operations on the same machines, setup and processing time, the use of identical machines as well as outsourcing of parts, multiple process planning and multiple routing. Due to NP-hard nature of CF problem, heuristic and meta-heuristic approaches have been successfully used. Several type of integer programming have been proposed over the last three decades by a number of researchers such as: Kusiak [6], Shtubt [7], Choobineh [8], Wei and Gaither [9], Boctor [10]. Most of these researches are discussed in a paper written by Selim et al [11] with the objective of minimizing simultaneously cost assignment of part operations, machines, workers, and tooling to cell [2]. Due to complexity of the problems, the author proposed a method in which the whole problem was divided to sub-problems, which had fewer variables and constraints.

A modified p-median approach for efficient Group Technology (GT) cell formation was proposed by Won and Lee [12] with the objective of maximizing the sum of similarities between machines in the same cell. The authors commented that when the original p-median formulation [6] was applied in practice, was severely restricted because of two factors: the size of problem and the type of software. Foulds et al [13] extended a mixed-integer mathematical programming model in which unlike the previous studies, the machine modification was included as a key factor. In cell formation problem it's very significant to reassign machine from one cell to anther in order to avoid duplication which has much expenses. They proposed machine modification to reduce the intercellular travel of parts. The objective was sum of modification cost and intercellular movement cost.

Heuristic algorithms are useful for solving a problem with large scale that cannot be solved in appropriate time by normal methods. Although using heuristic algorithms gives no guarantee to obtain the optimal solution, they can find an acceptable solution in a reasonable time. Mukattash et al [14] proposed three heuristic methods. These methods find a solution to CF problem with presence of alternative process plans, multiple alternative machines and processing times. Chan et al [15] developed a heuristic method pertaining to problems of machine allocation in cellular manufacturing only in case of intra-cell material flow. Kim et al [16] considered a more comprehensive multi-objective CF problem. The objective was minimization of the total sum of inter-cellular part movement and maximization of machine workload imbalance. The problem was solved with a two-phase heuristic algorithm.

Over the past two decades the meta-heuristic approaches have been mainly proposed to solve NP-hard problems. The CF problem is considered to be a complex and difficult optimization problem. Many researchers applied meta-heuristic approaches in order to gain more benefits from the CF problem. The important meta-heuristics are: simulated annealing (SA), tabu search (TS), genetic algorithm (GAs), ant colony optimization (ACO) and particle swarm optimization (PSO) [4].

The following table summarizes the main features in this study in comparison to other related studies.

TABLE 1
FEATURES IN THIS STUDY IN COMPARISON TO THE OTHERS

Author	Dynamic	Process Plans	Routes	Defect	Batch	Outsourcing	Inventory	Cell Size	Machine Capacity
Nsakada [5]		√	√		√		√		
Caux [17]		√							
Vin [18]			√		√				
Rafiee [19]	√		√			√	√	√	√
Saxena [20]	√	√	√		√	√	√	√	√
Gravel [4]			√						
Safaei [3]	√	√			√				
Deljoo [2]	√				√				
This paper	√	√	√	√	√	√	√	√	√

3 PROBLEM DEFINITION AND FORMULATION

As it is clarified in previous sections, it is attempted to employ some new assumptions like route sets (part of assumption 3) which clearly represent the definition and application of alternative routes in cell formation better than other surveys, bringing the fact of having defect rate after each step or operation to the model (assumption 4), considering the inventory cost per batch (assumption11) and including various limitations such as investigation in machines (assumption 8) and the total sum of the outsourced parts (assumption 11). By doing so, an appropriate quantity should be chosen as the upper bound in order to avoid making an unfeasible model. Other assumptions are also taken into account from papers which were not about this subject like batch size and inventory (assumptions 9 and 11). At the end of this part, it is worth mentioning that assumptions which are used to shape this mathematical model are discussed to be practical after reviewing most of related cell formation papers.

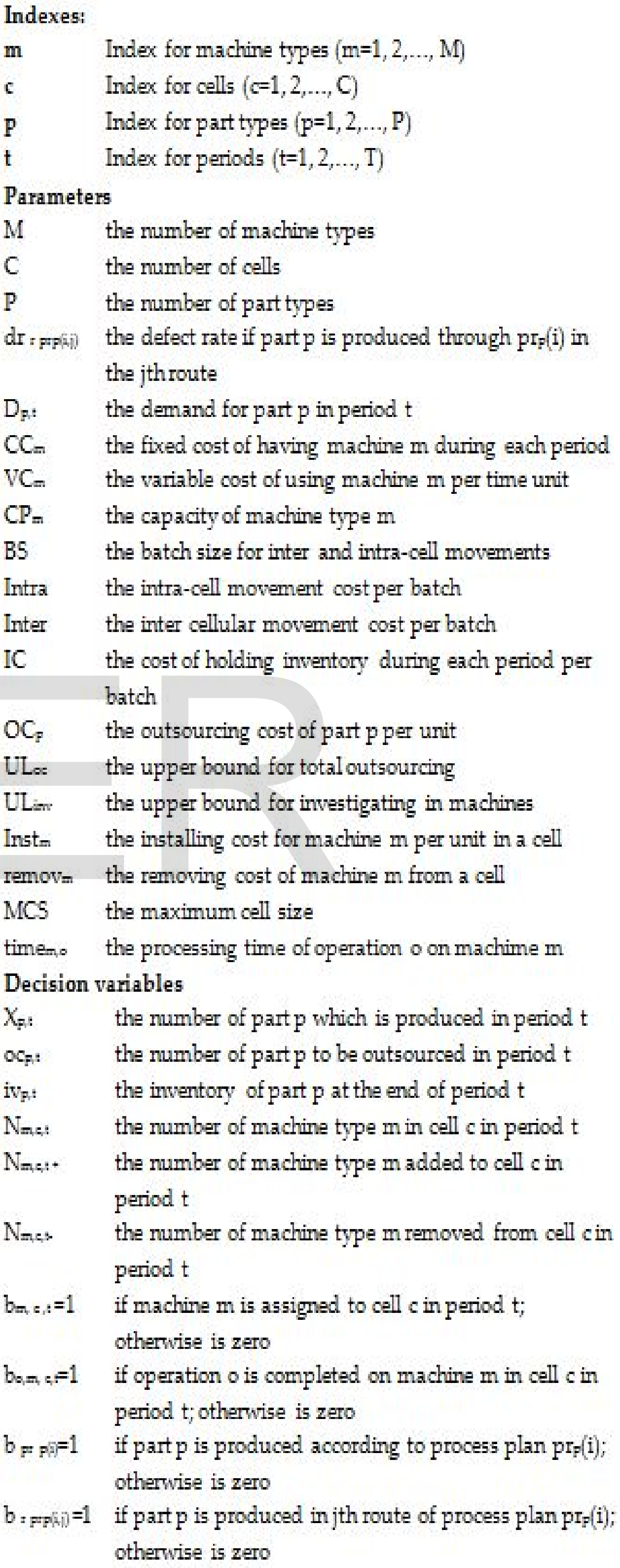
3.1 Problem assumptions and notations

The main assumptions and characteristics used in this problem formulation are as follows:

1. A dynamic cell formation problem is under consideration.

2. There are a set of process plans for each part to be produced.
3. For each process plan, a set of routes are considered, which is due to the fact that different operations can be done in each machine with different operational times and it creates alternative routes for each part to be produced.
4. A defect rate is considered for each operation on each specific machine. It means the in-flow and out-flow of machine are not equal and there is a defect rate that cannot continue with.
5. The processing time of each operation on each machine is known, deterministic and independent of time periods.
6. A fixed cost is considered for each machine type which is used during one period and is independent of time.
7. A variable cost is considered for machine which depends on the time of working machine during a period.
8. A constraint is considered for total sum of fixed and variable machine costs which is called investigation constraint.
9. Movement within and between cells are through batches, the batch size is known and is equal for inter or intra-cell moves.
10. The unit cost for inter or intra-cell movements per batch is known and for simplifying the problem, it is independent of traveled distance. The unit cost for inter-cellular movement is much higher than intra-cellular movement due to the fact that the goal of cell formation is to produce each part family in specific cell as much as possible.
11. Outsourcing is allowed but there is a constraint for maximum number of total outsourced parts. It is because of the fact that purchasing parts from other producers, which are often firm's rivals, are sometimes a threat to the company's reputation and it is also occasionally impossible.
12. The demand for each part in each period is known, deterministic and must be satisfied.
13. Over-stock is allowed at the end of periods.
14. The inventory cost during one period per batch is known and in order to simplifying the problem, a fixed cost is considered for all part types.
15. The demand for each part can be satisfied by the production, inventory from previous periods and outsourcing.
16. Relocation cost is considered for each machine. There is a cost for removing a specific machine from one cell and additional cost for installing it in another cell.
17. Maximum number of machines in cells is known and considered as a constraint and there is no minimum limitation.
18. The capacity of each machine is known and must be considered.

The indexes, sets, parameters and decision variables used to formulate the problem mathematically are as follows:



Indexes:

m	Index for machine types (m=1, 2,…, M)
c	Index for cells (c=1, 2,…, C)
p	Index for part types (p=1, 2,…, P)
t	Index for periods (t=1, 2,…, T)

Parameters

M	the number of machine types
C	the number of cells
P	the number of part types
$dr_{r\,pr_p(i,j)}$	the defect rate if part p is produced through $pr_p(i)$ in the jth route
$D_{p,t}$	the demand for part p in period t
CC_m	the fixed cost of having machine m during each period
VC_m	the variable cost of using machine m per time unit
CP_m	the capacity of machine type m
BS	the batch size for inter and intra-cell movements
Intra	the intra-cell movement cost per batch
Inter	the inter cellular movement cost per batch
IC	the cost of holding inventory during each period per batch
OC_p	the outsourcing cost of part p per unit
UL_{oc}	the upper bound for total outsourcing
UL_{inv}	the upper bound for investigating in machines
$Inst_m$	the installing cost for machine m per unit in a cell
$remov_m$	the removing cost of machine m from a cell
MCS	the maximum cell size
$time_{m,o}$	the processing time of operation o on machime m

Decision variables

$X_{p,t}$	the number of part p which is produced in period t
$oc_{p,t}$	the number of part p to be outsourced in period t
$iv_{p,t}$	the inventory of part p at the end of period t
$N_{m,c,t}$	the number of machine type m in cell c in period t
$N_{m,c,t+}$	the number of machine type m added to cell c in period t
$N_{m,c,t-}$	the number of machine type m removed from cell c in period t
$b_{m,c,t}=1$	if machine m is assigned to cell c in period t; otherwise is zero
$b_{o,m,c,t}=1$	if operation o is completed on machine m in cell c in period t; otherwise is zero
$b_{pr_p(i)}=1$	if part p is produced according to process plan $pr_p(i)$; otherwise is zero
$b_{r\,pr_p(i,j)}=1$	if part p is produced in jth route of process plan $pr_p(i)$; otherwise is zero

3.2. Proposed mathematical model

Objective function:

$$\begin{aligned}
&\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{c=1}^{C} CC_m \; N_{m,c,h} \cdot \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{pr_p(i)\in pr_p}\;\sum_{prp(i,j)\in pr_p(i)}\;\sum_{O\in prp(i,j)} VC_m x_{p,t} b_{prp(i,j)} time_{m,o} \cdot \\
&\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{pr_p(i)\in pr_p}\;\sum_{prp(i,j)\in pr_p(i)}\;\sum_{O\in prp(i,j)} Inter\left|b_{o,m,c,t}-b_{o+1,m,c,t}\right|\left\lceil\frac{x_{p,t}}{BS}\right\rceil+ \\
&\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{pr_p(i)\in pr_p}\;\sum_{prp(i,j)\in pr_p(i)}\;\sum_{O\in prp(i,j)} Intra(b_{o,m,c,t} * b_{o+1,m,c,t})\left\lceil\frac{x_{p,t}}{BS}\right\rceil+ \\
&\sum_{t=1}^{T}\sum_{p=1}^{P}(OC_p * oc_{p,t})+\left\lceil\sum_{t=1}^{T}\sum_{p=1}^{P}(iv_{p,t-1}+\sum_{c=1}^{C}\sum_{m=1}^{M}(b_{m,c,t} * x_{p,t}-D_{p,t})/Bs\right\rceil IC+ \\
&\sum_{t=1}^{T}\sum_{c=1}^{C} N_{m,c,t}+ {}^{*}inst_m+\sum_{t=1}^{T}\sum_{c=1}^{C} N_{m,c,t}- {}^{*}remov_m
\end{aligned} \tag{1}$$

Constraints:

$$\sum_{pr_p(i)\in pr_p} b_{pr_p(i)} = 1 \qquad \forall p \tag{2}$$

$$\sum_{pr_p(i)\in pr_p}\;\sum_{r_{prp}(i,j)\in pr_p(i)} b_{r_{prp}(i,j)} = 1 \qquad \forall p \tag{3}$$

$$x_{p,t} = \sum_{pr_p(i)\in pr_p}\;\sum_{r_{prp}(i,j)\in pr_p(i)} b_{r_{prp}(i,j)} x_{p,t} \; dr_{r\,prp(i,j)} \qquad \forall t,p,m \tag{4}$$

$$\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{c=1}^{C} CC_m . N_{m,c,t}+\sum_{t=1}^{T}\sum_{m=1}^{M}\;\sum_{pr_p(i)\in pr_p}\;\sum_{r_{prp}(i,j)\in pr_p(i)} VC_m x_{p,t} b_{r_{prp(i,j)}} \leq UL_{inv} \tag{5}$$

$$\sum_{t=1}^{T}\sum_{p=1}^{P} oc_{p,t} \leq UL_{oc} \tag{6}$$

$$D_{p,t}+iv_{p,t} = x_{p,t}+oc_{p,t}+iv_{p,(t-1)} \qquad \forall p,t \tag{7}$$

$$\sum_{c=1}^{C} b_{m,c,t} = 1 \qquad \forall t,c \tag{8}$$

$$\sum_{m=1}^{M} b_{m,c,t} \leq MCS \qquad \forall t,c \tag{9}$$

$$\sum_{p=1}^{P}\;\sum_{pr_p(i)\in pr_p}\;\sum_{r_{prp}(i,j)\in pr_p(i)} b_{r_{prp}(i,j)} * b_{m,o,c,t} \leq CP_m \qquad \forall t,m \tag{10}$$

$$N_{m,c,t} = N_{m,c,t-1}+N_{m,c,t^{+}}+N_{m,c,t^{-}} \qquad \forall c,t \tag{11}$$

$$X_{p,t}, oc_{p,t}, iv_{p,t}, N_{m,c,t}, N_{m,c,t^{+}}, N_{m,c,t^{-}} \geq 0 \text{ and integer} \qquad \forall m,c,t,p \tag{12}$$

$$b_{m,c,t}, b_{o,m,c,t}, b_{pr\,p(i)}, b_{r\,prp(i,j)} \in \{0,1\}$$

The objective function seeks to minimize the sum of total costs including machine fixed cost, machine variable cost, inter cellular movement cost, intra-cell movement cost, outsourcing cost, inventory cost, installing and removing cost of machines.

Equation (2) ensures that only one process plan must be chosen for producing part p, whilst (3) shows part p must be assigned to only one route. After each operation on each specific machine, there is a defect rate which cannot flow through the next operations; this assumption is entered to model by (4). Constraint (5) is one of the contributions of this survey and shows that the total sum of investigation on machines must be less than determined amount. It should be noticed that considering an inappropriate upper bound can lead to an unfeasible model. Constraint (6) ensures that the total sum of outsourced parts must be equal or less than its limit because of aforementioned reasons. The inventory balance constraint is (7). Constraint (8) forces each machine to be assigned to only one cell. The maximum cell size limitation is considered by (9). Also the machine capacity limitation is shown by (10). Constraint (11) confirms that number of machines in each cell in each period is equal to sum of added machines and removed machines in beginning of that period plus number of machines in the previous period. Finally, constraint (12) is the logical binary and non-negativity requirements on the variables.

4 NUMERICAL EXPERIMENTS

In this section, three categories of test problems are utilized to validate feasibility and applicability of the developed model as well as quality of the developed hybrid meta-heuristic algorithm. In order to cope with computational complexity of the proposed mathematical model and find a near optimal solution for the large-size problem instances, a hybrid algorithm is adopted from [21]. In the adopted algorithm, SA is applied so as to initiate the solution generation procedure. The generated initial solutions enter developed PSO algorithm to improve quality of the solutions. Pseudo-code of the hybrid meta-heuristic algorithm is presented in Fig. 1. In this regard, two sample problems with small and medium sizes are taken into account, whose parameter data are generated randomly. For the first problem instance (small-size), characteristics of the problem are as the ones in Table 2.

TABLE 2
PROBLEM PARAMETERS FOR THE SMALL-SIZE TEST PROBLEM

Spec.	Part no.	Machine types	Cell no.	Cell size	Process plan	Route no.	Period no.
Value	5	4	2	3	5	2	2

Moreover, it is considered that there are five process plans each of which includes two process routes as followings:

pr_{p1}= {pr_{p1} (1), pr_{p1} (2)}
pr_{p2}= {pr_{p2} (1), pr_{p2} (2), pr_{p2} (3)}
pr_{p3}= {pr_{p3} (1), pr_{p3} (2)}
pr_{p4}= {pr_{p4} (1)}
pr_{p5}= {pr_{p5} (1), pr_{p5} (2)}

and the considered process routes for each process plan:

r1= {M1, M2, M3, M4}
r2= {M3, M1, M2, M4}

Optimal solution of the small-size problem is as the solution presented in Table 3.

TABLE 3
RESULTS OF A SMALL SIZE EXAMPLE OBTAINED FROM GAMS SOFTWARE (NUMBERS IN PARENTHESES INDICATE PROCESS PLANS AND ROUTES, RESPECTIVELY)

	C1	C2
T1	P1(1,1), P4(1,2)	P2(1,2), P3(2,2), P5(2,1)
T2	P1(1,1), P2(3,1), P4(1,2)	P3(1,1), P5(2,1)

Next, the medium size problem is solved, whose features are as listed in Table 4.

TABLE 4
PROBLEM PARAMETERS FOR THE SMALL-SIZE TEST PROBLEM

Specification	No. of parts	No. of machine types	No. of cells	Max cell size	No. of process plans	No. of routes	No. of periods
Value	10	10	5	3	10	2	5

The considered process plans and their corresponding process routes are as:

pr_{p1}= {pr_{p1} (1), pr_{p1} (2)}
pr_{p2}= {pr_{p2} (1), pr_{p2} (2), pr_{p2} (3)}
pr_{p3}= {pr_{p3} (1), pr_{p3} (2)}
pr_{p4}= {pr_{p4} (1)}
pr_{p5}= {pr_{p5} (1), pr_{p5} (2)}
pr_{p6}= {pr_{p6} (1), pr_{p6} (2), pr_{p6} (3)}
pr_{p7}= {pr_{p7} (1), pr_{p7} (2)}
pr_{p8}= {pr_{p8} (1)}
pr_{p9}= {pr_{p9} (1), pr_{p9} (2)}
pr_{p10}= {pr_{p10} (1), pr_{p10} (2)}.

Once more there are two routes for each process plan:

r1= {M1, M2, M3, M4, M5}
r2= {M6, M7, M8, M9, M10}

This test problem is solved using GAMS and the developed algorithm in 4.67 and one seconds with 219539 and 227004, respectively. Table 5 summarizes results of the medium-size test problem.

TABLE 5
RESULTS OBTAINED FROM SOLVING A MEDIUM SIZE EXAMPLE WITH GAMS SOFTWARE (NUMBERS IN PARENTHESES INDICATE PROCESS PLANS AND ROUTES, RESPECTIVELY)

	C1	C2	C3	C4	C5
T1	P3(1,1),P7(1,2)	P1(1,1),P6(2,1)	P4(1,1)	P2(3,1),P8(1,1),P9(2,2)	P5(1,1),P7(1,2),P10(2,2)
T2	P3(1,1),P7(1,2)	P1(1,1),P6(2,1),P4(1,2)	-	P2(3,1),P8(1,1),P9(2,2)	P5(1,1),P7(1,2),P10(2,2)
T3	P3(2,1),P7(1,2)	P1(1,1,),P6(2,1)	P4(1,1)	P2(3,1),P8(1,1),p9(1,2)	P5(1,1),P7(1,2),P10(2,2)
T4	P3(2,1),P1(1,2)	P6(2,1),P4(2,2)	P6(1,2)	P2(3,1),P8(1,1),p9(1,2)	P5(1,1),P7(1,2),P10(2,2)
T5	P3(2,1),P1(1,2)	P6(2,1),P4(2,2)	P6(1,2)	P2(3,1) P5(1,1),P8(1,1)	P7(1,2), p9(1,2)P10(2,2)

Optimality gap of the developed hybrid algorithm with the optimization software package indicate a gap less than two and four percent in the case of small-size and medium-size test problems, respectively. Therefore, it is showed that the developed algorithm is robust enough to cope with the large-size sample problems whose results are reported next. In this regard, different problems of different sizes are generated randomly in order to assess validity of the developed algorithm. Table 6 presents optimal results of the generated sample problems as well as its elapsed time towards optimality.

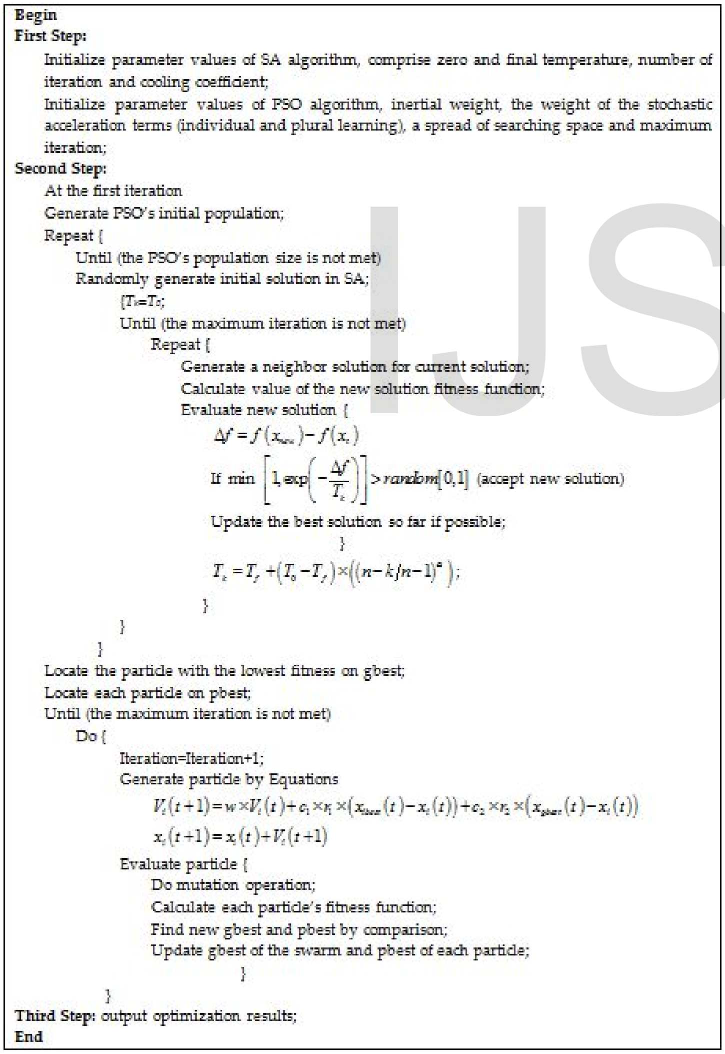
TABLE 6
RESULTS OF THE RANDOMLY GENERATED SAMPLES FOR LARGE-SIZE PROBLEMS

No.	No. of parts	No. of machine types	No. of cells	Max cell size	No. of process plans	No. of routes	No. of periods	Best objective function	Elapsed time (sec)
1	15	10	5	3	10	2	5	240916	1.43
2	20	10	5	4	10	2	5	260127	1.89
3	20	15	6	4	13	2	5	281034	3.18
4	27	17	6	4	13	2	6	381893	6.05
5	30	17	6	3	13	2	7	521912	17.93
6	35	18	7	3	13	3	7	583192	19.68
7	38	18	7	4	13	3	7	600912	23.48
8	40	18	8	4	15	3	7	615913	30.71
9	40	19	8	5	15	4	8	671091	69.07
10	73	25	12	7	17	6	15	3019812	2528.21

5 CONCLUSION AND DIRECTIONS FOR FUTURE RESEARCH

Cell formation problem is one of the most appealing research interests in the field of operations management with which some approaches have been developed to cope. Among the adopted approaches, mathematical programming has been one of the most prevailing ones. In this regard, this paper addressed cell formation problem in which each part has different alternative process plans and for each process plan there is set of machines or different alternative routes. One of the significant contributions of this paper is consideration of both features of process plan and process routes, which have not been considered in the body of literature so far. The developed mathematical model was solved by GAMS software package, whilst a hybrid SA-PSO meta-heuristic was developed in order to cope with complexity of the large-size sample problems. Hence, two small and medium size sample problems were solved by both GAMS and the developed hybrid algorithm whose best objective functions indicate low level of optimality gap for the developed hybrid algorithm.

Moreover, future research directions are twofold in order to continue research direction of this paper. First, developing indeterministic models towards CF problem might be of great interest, since it bears more realistic assumptions than those of the deterministic ones. Also, it is highly recommended to add reliability measures to the developed mathematical model in order to study the considered system from this point of view.



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Begin
First Step:
    Initialize parameter values of SA algorithm, comprise zero and final temperature, number of iteration and cooling coefficient;
    Initialize parameter values of PSO algorithm, inertial weight, the weight of the stochastic acceleration terms (individual and plural learning), a spread of searching space and maximum iteration;
Second Step:
    At the first iteration
    Generate PSO's initial population;
    Repeat {
        Until (the PSO's population size is not met)
        Randomly generate initial solution in SA;
            {$T_k=T_0$;
            Until (the maximum iteration is not met)
                Repeat {
                    Generate a neighbor solution for current solution;
                    Calculate value of the new solution fitness function;
                    Evaluate new solution {
                        $\Delta f = f(x_{new}) - f(x_c)$
                        If min $\left[1, \exp\left(-\frac{\Delta f}{T_k}\right)\right] > random[0,1]$ (accept new solution)
                        Update the best solution so far if possible;
                                            }
                        $T_k = T_f + (T_0 - T_f) \times ((n-k/n-1)^a)$;
                    }
            }
        }
    Locate the particle with the lowest fitness on gbest;
    Locate each particle on pbest;
    Until (the maximum iteration is not met)
        Do {
            Iteration=Iteration+1;
            Generate particle by Equations
                $V_i(t+1) = w \times V_i(t) + c_1 \times r_1 \times (x_{pbest}(t) - x_i(t)) + c_2 \times r_2 \times (x_{gbest}(t) - x_i(t))$
                $x_i(t+1) = x_i(t) + V_i(t+1)$
            Evaluate particle {
                Do mutation operation;
                Calculate each particle's fitness function;
                Find new gbest and pbest by comparison;
                Update gbest of the swarm and pbest of each particle;
                            }
        }
Third Step: output optimization results;
End
```

Fig. 1. Pseudo-code of the developed ACO-GA algorithm.

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