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ORIGINAL RESEARCH

Development of a cell formation heuristic by considering realistic data using principal component analysis and Taguchi's method

Shailendra Kumar · Rajiv Kumar Sharma

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Abstract Over the last four decades of research, numerous cell formation algorithms have been developed and tested, still this research remains of interest to this day. Appropriate manufacturing cells formation is the first step in designing a cellular manufacturing system. In cellular manufacturing, consideration to manufacturing flexibility and production-related data is vital for cell formation. The consideration to this realistic data makes cell formation problem very complex and tedious. It leads to the invention and implementation of highly advanced and complex cell formation methods. In this paper an effort has been made to develop a simple and easy to understand/implement manufacturing cell formation heuristic procedure with considerations to the number of production and manufacturing flexibility-related parameters. The heuristic minimizes inter-cellular movement cost/time. Further, the proposed heuristic is modified for the application of principal component analysis and Taguchi's method. Numerical example is explained to illustrate the approach. A refinement in the results is observed with adoption of principal component analysis and Taguchi's method.

Keywords Cellular manufacturing · Cell formation · Manufacturing flexibility · Production data · Principal component analysis · Taguchi's method

Introduction

In the present era, cut-throat competition, fluctuating demands, customization of product, very high initial investment and ever increasing manpower cost, are severely affecting the profit margins of manufacturing industry. The concept of cellular manufacturing is placed at high level on the agenda of manufacturing industries, not only to overcome but to excel in this situation. Cellular manufacturing is a well-mixed blend of manufacturing flexibility and production efficiency. It has the ability to deal with frequent changes in product mix and fluctuations in production volume. Due to its superior performance, it is considered as a feasible approach to realise mass customization philosophy (Lian et al. 2013). Cell formation (CF), group layout (GL) and group scheduling (GS) are the three major steps in cellular manufacturing (Fardis et al. 2013; Kia et al. 2013). Amongst these, CF is the foremost (Doulabi et al. 2009; Kumar and Sharma 2014) and key step (Krushinsky and Goldengorin 2012) in any cellular manufacturing problem. Cell formation deals with the identification of the part families with similar process requirements and allocating them to the machine cells for processing (Boutsinas 2013; Fardis et al. 2013; Kumar and Sharma 2014; Sarker 1996). Ideally manufacturing cell is to be formed in such a fashion that each manufacturing cell should act as an independent manufacturing unit. The essence of CF approaches is to eliminate/minimize the inter-cellular movement cost of parts (Arkat and Farahani 2012; Kumar and Sharma 2014; Lian et al. 2013; Selim et al. 1998). It can simply be achieved by duplicating the machines but duplication of machine involves large capital investment which ultimately adds to the product cost. Therefore, a manufacturing CF approach should provide an optimisation amongst these, without much complexity in approach. The cell formation approaches developed so far can be categorised as (Boutsinas 2013; Lian et al. 2013; Papaioannou and Wilson 2010; Kumar and Sharma 2014; Yasuda et al. 2005; Yin and Yasuda 2006) (i) Similarity

S. Kumar (✉) · R. K. Sharma
Mechanical Engineering Department, National Institute of Technology, Hamirpur 177005, HP, India
e-mail: tyagi_sk@yahoo.com

coefficient-based methods (ii) Mathematical programming-based methods (iii) Artificial intelligence-based approaches (iv) Heuristics/meta-heuristics/hybrid meta-heuristics, (v) Any combination of these. Amongst CF techniques similarity coefficient-based methods are more flexible and easy to implement (Yin and Yasuda 2006). A large number of cell CF approaches have been developed so far, majority of them do not consider production-related data (Boutsinas 2013; Won and Lee 2001). Susanto et al. (2009) revealed that 80 % of manufacturing CF approaches are focussed on the arrangement of binary part-machine incidence matrix, whereas more realistic and effective approaches could be developed by considering the various manufacturing flexibility and production-related data (Kumar and Sharma 2014). A little work is observed on CF considering any such data in a simple manner and some of them are summarised in Table 1, whilst on the other hand a large number of literature is available on binary matrix-based cell formation techniques. A statistical review of literature can be found in Reisman et al. (1997). The focus of researchers is shifting towards the development of meta-heuristic techniques of CF. Study of metaheuristic techniques of CF can be found in Nourie et al. (2013) and Saeedi et al. (2010). The literature reflects the need for efforts to incorporate production and manufacturing flexibility-related data (realistic data) in CF procedures in a simple manner. Thus, to abridge this gap, in present study effort has been made to develop a simple CF heuristic approach with considerations to manufacturing flexibility and production-related parameters, namely production volume, operation sequence, inter-cell movement cost/time, alternate process plans (routing flexibility), identical machines and operation sequence for a part (operation flexibility). Further considerations to machine capacity and machine reliability are also given. In proposed heuristic, considerations to inter-cell movement time/cost has given precedence over part processing cost/time as part processing cost does not much affect the inter-cellular movement. The proposed heuristic approach cannot be limited to any particular similarity coefficient-based or other clustering approach. It can work well with any clustering approach with some modifications. Its ability to adopt modern statistical tools like principal component analysis (PCA), and Taguchi's method, with little modifications is demonstrated.

The outline of rest of the paper is as follows: "Methodology" explains the methodology and proposed heuristic for solving the CF problem. "Implementation and illustration" illustrates implementation of proposed heuristic through a numerical problem. In discussion and analysis part i.e. "Discussion and analysis", results of clustering algorithm used, are compared with some well-known CF algorithms. Further in this section, proposed algorithm is modified for the implementation of PCA and Taguchi's method, whilst conclusions are drawn in "Conclusions".

Methodology

The proposed heuristic is a development in the work of Kumar and Sharma (2014). The simple logic used for consideration to operation sequence is that a machine could add maximum one inter-cell move per part if it is either at starting or at ending position of the operation sequence of a particular part, otherwise it could add maximum two inter-cell moves (Won and Lee 2001). Taking inspiration of Leem and Chen (1996) the concept of part-operation incidence (POI) matrix is used in proposed CF procedure. Albadawi et al. (2005), Hachicha et al. (2006, 2008a) highlighted the application of PCA in solving CF problems. Hachicha et al. (2008b) used Taguchi's method along with PCA in route selection of CF problems. Applications of PCA and Taguchi's method are introduced in modification of proposed heuristic.

The methodology adopted is discussed under four subtitles namely proposed CF heuristic procedure, commonality score/similarity coefficient-based clustering algorithm, PCA and Taguchi's method.

Proposed CF heuristic procedure

The proposed CF heuristic procedure is explained with the help of a self-explanatory flow chart presented in Fig. 1. The essence of proposed heuristic procedure is to minimize the inter-cellular movement time or cost

Commonality score-based clustering algorithm

Though any similarity score-based clustering algorithm can be used with the proposed procedure, the commonality score-based clustering algorithm used is discussed in illustration in this section. The commonality score is used to deduce similarity matrix amongst all possible machine pairs.

Step 1: Compute the similarity coefficient amongst all possible machine pairs from the data matrix by using a variant of Jaccard's similarity coefficient, proposed by Kumar and Sharma (2014), is reproduced in Eq. 1.

$$\text{Commonality score} = a/(a+b+c), \qquad (1)$$

where a is the sum of elements common to both machines in concerned machine pair (in this case, maximum possible inter-cell movement cost of parts visiting both machines) $a = \sum_{k=1}^{k=n} a_{(\mathrm{ij})k}$, $a_{(\mathrm{ij})k}$ is the elements common to both machines M_i and M_j, for $k = 1$ to $k = \mathrm{n}$ parts. b is the sum

Table 1 Summary of work observed on cell formation using production or manufacturing flexibility-related data

Author and year	Parameter considered	Approach/remarks
Kumar and Sharma (2014)	Operation sequence, production volume, inter-cell movement cost, part processing cost, alternate process plans	Proposed similarity coefficient-based heuristic
Lian et al. (2013)	Multiple identical machines, processing time, set-up time, machine capacity, production volume, cell size, alternative routes	Proposed genetic algorithm (GA)-based procedure
Gupta et al. (2012)	Operation sequence	Similarity coefficient, principal component analysis (PCA), K-means algorithm
Kumar and Jain (2010)	Operation sequence, operation time, production volume, machine capacity	Proposed a PCA-based concurrent algorithm "APMOSTVC"
Ahi et al. (2009)	Operational time, operation sequence	TOPSIS and SAW
Pandian and Mahapatra (2009)	Operation sequence, operation time	Adaptive resonance theory, neural network
Paydar and Sahebjamnia (2009)	Operation sequence	Proposed a linear mathematical programming model
Susanto et al. (2009)	Sequence of operations, part-volume, alternative routes	C-means clustering algorithm, Hungarian (assignment) algorithm, linear programming model
Garbie et al. (2008)	Alternative routings, processing time, machine capacity (reliability), machine capability (flexibility), production volume, part demand, number of operations done on each machine	Proposed similarity coefficient-based heuristic
Muruganandam et al. (2008)	Demand of parts in different period, routing sequences, processing time, machine capacities	Proposed a GA based heuristic "PRABHA"
Kumar and Jain (2008)	Operation sequence, operation time, production volume, inter-cellular travel loss	Proposed an algorithm "APOSTVUIT" based on average void values and PCA
Masmoudi et al. (2008)	Alternative routes	Combined axiomatic design principles with experimental design technique, and PCA
Kim et al. (2004)	Machine sequence of part routes, alternative routes, machine work load imbalance	Proposed a two phased heuristic algorithm-based on dissimilarity measure
Mahesh and Srinivasan (2002)	Processing time, alternative routes	Branch and bound technique, a heuristic based multistage programming approach
Mukattash et al. (2002)	Multiple parallel machines, processing time, alternative routes	Proposed three heuristics
Won and Lee (2001)	Operation sequence and production volume, with extension for inter-cell material handling cost and processing times	Mathematical model that seeks to minimize the actual inter-cell flows
Sofianopoulou (1999)	Operation sequence	Proposed simulated annealing-based algorithm
Wicks and Reasor (1999)	Operation sequence, production volume	Proposed genetic algorithm-based procedure
Nair and Narendran 1998	Operation sequence	Proposed measures of similarity and performance are incorporated in a non-hierarchical clustering algorithm: "CASE"
Beaulieu et al. (1997)	Machines and material handling costs, machine utilization, alternative routeings, Inter-cell movement	Presented algorithm has two main resolution phases: formation of independent cells then introduction of inter-cell movements
Beaulieu et al. (1993)	Work load balance, machine flexibility, routing flexibility	Developed heuristic
Ahmed et al. (1991)	Production volume, material handling cost	Proposed heuristic for minimization of total material handling cost

of values of elements concerned to only first machine in pair (in this case, maximum possible inter-cell movement cost of parts visiting only first machine) $b = \sum_{k=1}^{k=n} b_{(\mathrm{i})k}$, $b_{(\mathrm{i})k}$ is the elements concerned to machine M_{i} but not machine M_{j}, for $k = 1$ to $k = \mathrm{n}$ parts. c is the sum of values of elements concerned to only second machine in pair (in other terms, maximum possible inter-cell movement cost of parts visiting only second machine) $c = \sum_{k=1}^{k=n} c_{(\mathrm{j})k}$, $c_{(\mathrm{j})k}$ is the elements concerned to machine M_{j} but not machine M_{i}, for $k = 1$ to $k = \mathrm{n}$ parts.

Step 2: Group machine pair having highest value of commonality score, and transform this machine pair into a machine unit M_{r} having elements $\mathrm{M}_{(\mathrm{i,j})\mathrm{r}}$ (Kumar and Sharma 2014).

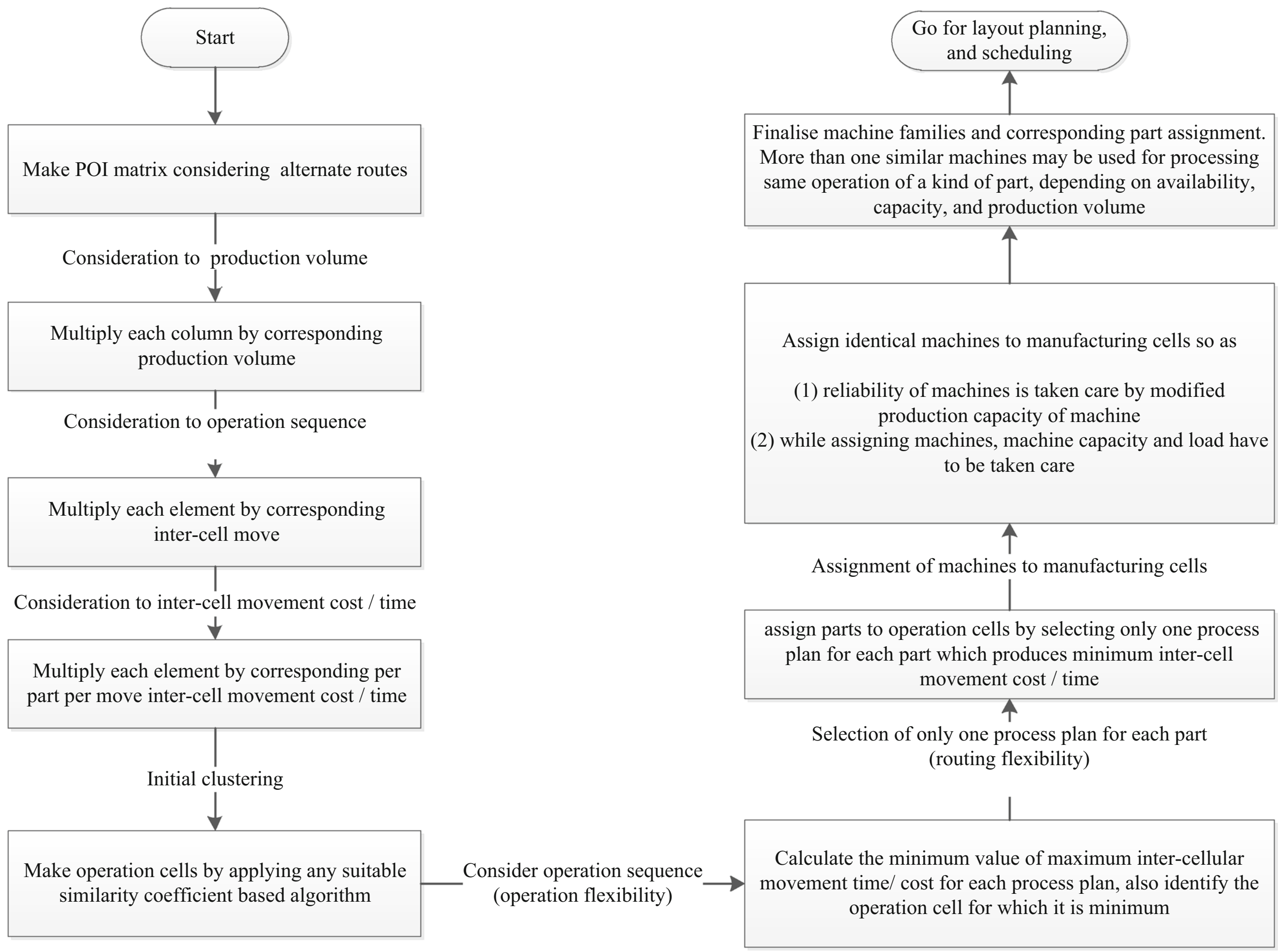

Fig. 1 Flow chart for proposed cell formation heuristic procedure

$$M_{(i,\ j)r} = \begin{cases} a_{i(r)}, & \text{if } a_{i(r)} \geq a_{j(r)} \\ a_{j(r)}, & \text{if } a_{i(r)} < a_{j(r)} \end{cases}$$

where $M_{(i,\ j)r}$ is the corresponding elements of machine unit M_r, obtained after transformation of machine M_i and machine M_j into a single machine unit, $a_{i(r)}$ and $a_{j(r)}$ is the corresponding elements of machine M_i and M_j, respectively.

Taguchi's method

This is a powerful statistical method for improving the performance of the design, process and product by optimizing process parameters. It looks for a mean performance characteristic value close to target value rather than a value within a certain range (Eşme 2009). It is made up of following three design procedures:

- System design: to find the suitable working levels of the design factors.
- Parameter design: to determine the factor levels for the optimum performance of the product or process.
- Tolerance design: to refine the results of parameter design by narrowing the tolerance levels of factors that have significant effects on the product or process under study.

Special design of orthogonal arrays (OAs) are utilized in parameter design for minimising the time, cost and number of experiments. Analyses of variance (ANOVA) and the signal-to-noise (S/N) ratio are used to analyse the experimental data and find the optimal parameter combination. A good amount of literature (Eşme 2009; Ghosh and Dan 2011; Hachicha et al. 2008b; Hadighi et al. 2013; Kamaruddin et al. 2004; Seenivasan et al. 2014; Unal and Dean 1991, and others) is available on Taguchi's method and its implementation. The procedure includes the following three steps:

1. Planning experiment
   - Determination of the control factors, noise factors and quality or performance measure responses of the product or process.

- Determination of the levels of each factor.
- Selection of a most suitable OA table. It depends on the number of factors and interactions, and the number of levels for the factors.

2. Implementing experiment.
3. Analysing and examining result.

- Determination of the parameters signification (ANOVA).
- Conduct a main effect plot analysis to determine the optimal level of the control factors.
- Execute a factor contribution rate analysis.
- Confirm experiment and plan future application.

The intended use of Taguchi's method is in the selection of best part routings for each part type. The essence of proposed CF procedure is to minimize the inter-cell movement time/cost, which cannot be used as a response measure for Taguchi's method due to large dimensions of variables. To overcome this situation, PCA, a dimension-reduction technique is employed.

Principal component analysis

Principal component analysis is the most widely used dimension-reduction statistical technique. It investigates the largely widespread data in many areas of science and industry. It provides a condensed description (Hachicha et al. 2008a; Kumar and Jain 2010), in order to model the total variance of the original data set, through new uncorrelated variables known as principal components. These components recover as much variability in the data as possible and account for near total variance of the data. Principal component analysis is recommended for large sample sizes (Gupta et al. 2012; Hachicha et al. 2008a; Mehrjoo and Bashiri 2013).The usual progression of PCA starts with the eigenvalues and eigenvector of semi-definite matrix. A brief description on implementation of PCA is as follows:

Let, the initial matrix (A) be a semi-definite matrix, in which rows and columns stand for part (P) and machines (M) respectively, having the information like part-machine incidence, operation sequence, production volume and inter-cell movement time/cost. Since CF problem is a dimension-reduction problem in which a number of inter-related machines and parts are to be grouped into a smaller set of independent cells, the application of principal components analysis can give a very good solution as mentioned by (Albadawi et al. 2005; Gupta et al. 2012; Hachicha et al. 2006, 2008b) quickly.

The eigenvector equation where the terms $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_n$ are the nonnegative real roots of the determinant polynomial equation of degree m, given as:

$$\det(S - \lambda I) = 0;\ \mathrm{i} \in (1, M)$$

$$\text{Covariance matrix } (S) = B^{\mathrm{T}}B/P$$

B is the standardization matrix of the initial matrix A, B^{T} is the transpose matrix of matrix B

To obtain a model with the first and the second principal components the principal components analysis was performed on the mean centred data, this model explained the recovered cumulated percentage (CP) of the variance in the data as follows:

$$\mathrm{CP} = \frac{\lambda_1 + \lambda_2}{\sum_{k=1}^{m} \lambda_k} = \frac{\lambda_1 + \lambda_2}{M}$$

For more details of PCA method, and its application in cell formation relevant literature such as (Albadawi et al. 2005; Chattopadhyay et al. 2012; Gupta et al. 2012; Hachicha et al. 2006, 2008a, b; Llin et al. 2010; Kumar and Jain 2010; Mehrjoo and Bashiri 2013; Min et al. 2014) and others can be referred.

In this work, PCA finds its application in two ways, first in reduction of variability for implementation of Taguchi's method in selection of alternate route, second in the making of operation and part families through graphical analysis.

Implementation and illustration

The proposed heuristic CF procedure is implemented on an arbitrarily designed CF problem illustrated in "Illustrative problem".

Illustrative problem

For illustration purpose, a cell formation problem of five operation and five different parts with random data has been developed and given in Table 2. Operation 'O1' can be performed either on machine 'M1' or 'M2'. Reliability of machine 'M1' and 'M2' is 0.9 and 0.8, respectively. The operation time (processing time of any part for operation 'O1') is 10 units. Part 'P1' can be made by two alternate process plans either through 'O1 → O3 → O2 → O5' or 'O2 → O4 → O1'. Production volume required for part 'P1' is 100 units. Per move inter-cell movement time for part 'P1' is 1 unit. In the operation sequence (alternate process plans) of part 'P1' the order of operation 'O1' and operation 'O3' can be interchanged. Rest of the data can be explained in similar manner.

Step 1: It is dedicated to the deduction of POI matrix from the problem data. If a particular operation is required for procession of a particular part by a particular process plan, put '1', otherwise '0' in corresponding cell of POI

Table 2 Initial data for cell formation illustrative problem

Operation	Machine	Reliability	Operation time	Part	Alternate process plans (routings)	Interchangeability of operation	Production volume	Inter-cell movement time
O1	M1	0.9	10	P1	O1 → O3 → O2 → O5	O1 ↔ O3	100	1
	M2	0.8	10		O2 → O4 → O1	O4 ↔ O2		
O2	M3	0.9	15	P2	O1 → O2 → O5	Nil	50	4
	M4	1.0	15		O3 → O1 → O2 → O4	O3 ↔ O1		
O3	M5	0.7	25	P3	O4 → O2 → O1 → O5	O2 ↔ O1	70	3
O4	M6	0.9	20	P4	O4 → O3 → O2 → O3 → O1	O4 ↔ O2	65	2
O5	M7	1.0	15	P5	O1 → O5 → O4	Nil	75	2
	M8	0.85	15		O3 → O4 → O5 → O4	Nil		

Table 3 POI matrix for illustration

Part	P1		P2		P3	P4	P5	
Process plan	1	2	3	4	5	6	7	8
O1	1	1	1	1	1	1	1	0
O2	1	1	1	1	1	1	0	0
O3	1	0	0	1	0	1	0	1
O4	0	1	0	1	1	1	1	1
O5	1	0	1	0	1	0	1	1

Table 4 POI matrix after consideration to production volume

Part	P1		P2		P3	P4	P5	
Process plan	1	2	3	4	5	6	7	8
O1	100	100	50	50	70	65	75	0
O2	100	100	50	50	70	65	0	0
O3	100	0	0	50	0	65	0	75
O4	0	100	0	50	70	65	75	75
O5	100	0	50	0	70	0	75	75

Table 5 Maximum possible inter-cell moves matrix

Part	P1		P2		P3	P4	P5	
Process Plan	1	2	3	4	5	6	7	8
O1	100	100	50	100	140	65	75	0
O2	200	100	100	100	140	130	0	0
O3	200	0	0	50	0	260	0	75
O4	0	200	0	50	70	65	75	210
O5	100	0	50	0	70	0	150	150

Table 6 Maximum possible inter-cell movement time matrix

Part	P1		P2		P3	P4	P5	
Process plan	1	2	3	4	5	6	7	8
O1	100	100	200	400	420	130	150	0
O2	200	100	400	400	420	260	0	0
O3	200	0	0	200	0	520	0	150
O4	0	200	0	200	210	130	150	420
O5	100	0	200	0	210	0	300	300

matrix. Thus obtained POI matrix with alternative process plans is presented in Table 3.

Step 2: For consideration of production volume, multiply the elements of POI matrix (Table 3) with the corresponding production volume. Thus, modified POI matrix is given in Table 4.

Step 3: Operation sequence is considered by introducing maximum inter-cell moves that could be generated by a machine according to its position in operation sequence. For these elements of matrix in Table 4, are multiplied by the maximum inter-cell moves that can be generated by corresponding operation as per its position in operation sequence of particular part. Thus, modified matrix accounts for production volume and operation sequence. This matrix is called maximum possible inter-cell moves matrix and presented in Table 5.

Step 4: For consideration of inter-cell movement time, multiply each element of the matrix presented in Table 5 with corresponding per part per move inter-cell movement time. Thus the obtained maximum possible inter-cell movement time matrix is presented in Table 6. As explained in Fig. 1, the inter-cell movement cost may be considered on the same line as inter-cell movement time.

Step 5: For formation of operation cells, any clustering algorithm is to be applied in the matrix given in Table 6. In this case, the similarity-based algorithm discussed in "Commonality score-based clustering algorithm" is applied. The matrix after application of clustering algorithm is given in Table 7. In this case operation 'O1' and 'O2' are clubbed in an operation cell whilst operation 'O3', 'O4' and 'O5' are clubbed into another operation cell. Minimum value of maximum possible inter-cellular

Table 7 Matrix after clustering of operation cells

Part	P1		P2		P3	P4	P5	
Process plan	1	2	3	4	5	6	7	8
Operation cell 1								
O1	100	100	200	400	420	130	150	0
O2	200	100	400	400	420	260	0	0
Operation cell 2								
O3	200	0	0	200	0	520	0	150
O4	0	200	0	200	210	130	150	420
O5	100	0	200	0	210	0	300	300
Max. Inter-cellular movement time (min value)	300	200	200	400	420	390	150	0
Part in operation cell	Any	Any	1	1	1	2	2	2

Table 8 Matrix after clustering of operation cells and operation flexibility

Part	P1		P2		P3	P4	P5	
Process plan	1	2	3	4	5	6	7	8
Operation cell 1								
O1	200	100	200	200	420	130	0	0
O2	200	200	400	400	420	130	150	0
Operation cell 2								
O3	100	0	0	400	0	520	0	150
O4	0	100	0	200	210	260	150	420
O5	100	0	200	0	210	0	300	300
Max. inter-cellular movement time (min. value)	200	100	200	600	420	260	150	0
Part in operation cell	1	1	1	any	1	2	2	2

movement time is calculated for each process plan. The operation cell in which the part is producing this minimum value of maximum possible inter-cell movement is also noted in the last column of Table 7.

Step 6: The use of interchangeability of operation i.e. operation flexibility for a particular part is made here. After its consideration, minimum value of maximum possible inter-cellular movement time is calculated for each part. Further, for this minimum value the operation cell to which the corresponding part should be assigned is also noted and presented in Table 8.

Step 7: At this stage selection of process plan and operation cell of a particular part is made by the comparison of Tables 7 and 8. The conditions for selection of process plan and operation cell are only one process plan for a particular part, and minimum inter-cellular movement time. Process plans 2, 3 and 8 are selected for parts 'P1', 'P2' and 'P5', respectively. Part 'P3' and 'P4' each has only one process plan. The selected process plan and corresponding operation cells are highlighted in Table 9.

At this stage, total inter-cell moves and inter-cell movement cost for required production volume are 1,210 and 585 units, respectively.

Step 8: Assignment of machines to operation cells on the basis of their production capacity and reliability is to be made at this stage. If processing time of a part is 10 min on a reliable machine, it would be 10/0.8 = 12.5 min for 80 % reliable machine. For this illustrative problem, 8 h production capacity after reliability considerations for each machine 'M1', 'M2', 'M3', 'M4', 'M5', 'M6', 'M7', 'M8' is found to be 129.6, 115.2, 86.4, 96 and 81.6 parts, respectively. Further, it is observed that operation 'O5' can be performed on two machines 'M7' and 'M8' with 8 h production capacity of 96 and 81.6 parts, respectively. It is observed that the processing requirement of operation 'O5' for parts assigned to its operation cell (operation cell 2) is 75 whilst for parts assigned to another operation cell is 120. It is advisable to assign machine 'M8' and 'M7' to 'operation cell 2' and 'operation cell 1' respectively, based on their production capacity and processing requirement. Final manufacturing cell is shown in Table 10.

Thus, total inter-cell moves and inter-cell movement cost for required production volume are 300 and 570 units, respectively.

Discussion and analysis

The discussion and analysis is performed in two subsections. In first subsection results from clustering algorithm used, are compared with the results of some well-established binary matrix-based CF methods. In second subsection, the modified proposed CF procedure for adoption PCA and Taguchi's method is presented.

Comparison of results of clustering algorithm used

Results from clustering algorithm used, are compared with the results of some well-established binary matrix-based CF methods. These methods were compared and found better than several other methods in the studies made by their respective authors. The comparison of results is summarized in Table 11. The comparison establishes that clustering algorithm used in proposed procedure, is comparable to other contemporary algorithms. The abbreviations used in Table 11 are explained as *EE* → number of exceptional elements: The number of machine-part cells that remain outside the diagonal blocks. These off-diagonal non-zero entries are called exceptional elements (Albadawi et al. 2005; Murugan and Selladurai 2011).

Table 9 Operation cell after selection of process plan and part assignment

Part		P1	P2	P3	P4	P5
Process plan		**2**	**3**	**5**	**6**	**8**
Operation cell 1	**O1**	100	200	420	130	0
	O2	100	400	420	260	0
Operation cell 2	**O3**	0	0	0	520	150
	O4	200	0	210	130	420
	O5	0	200	210	0	300
Inter-cell movement time		200	200	420	390	0
Inter-cell moves		200	50	140	195	0

Table 10 Final clustered matrix containing manufacturing cell with assigned machines and parts

Process plan			2	3	5	6	8
Part		**Machine**	**P1**	**P2**	**P3**	**P4**	**P5**
Operation cell 1	**O1**	**M1,M2**	100	200	420	130	0
	O2	**M3,M4**	200	400	420	130	0
	O5	**M7**	0	200	210	0	0
Operation cell 2	**O3**	**M5**	0	0	0	520	150
	O4	**M6**	100	0	210	260	420
	O5	**M8**	0	0	0	0	300
Inter-cell movement time			100	0	210	260	0
Inter-cell moves			100	0	70	130	0

GE → grouping efficiency: It incorporates both machine utilization and inter-cell movement. It is defined as the sum of two weighted functions, one for machine utilization and other for inter-cell movement with a weight factor; recommendation is in favour of equal weight for both functions (Chandrasekharan and Rajagopalan 1986; Nair and Narendran 1998; Sarker 1996; Wang 2003). *GEF* → grouping efficacy, $GEF = \frac{N_1 - N_1^{out}}{N1 - N_0^{in}}$, where, N_1 is the Total number of 1 s in the clustered machine-part incidence matrix, N_1^{out} → Total number of 1 s outside the diagonal block in clustered matrix, N_0^{in} is the Total number of 0 s inside the diagonal block of clustered matrix (Albadawi et al. 2005; Nair and Narendran 1998; Sarker 1996; Wang 2003). *GI* → Grouping Capability Index: $GI = 1 - \frac{e}{o}$, where, e → number of exceptional elements, o → total number of 1 s (i.e. number of operations) in the matrix (Yin and Yasuda 2006). *GM* → grouping Measure: It is the difference between the measure of utilization of machines and measure of inter-cell movement i.e. {(ratio of the number of 1 s to the number of total elements in the diagonal block) – (ratio of the number exceptional elements to the total number of 1 s in the matrix)} (Miltenburg and Zhang 1991; Yin and Yasuda 2006).

Modified proposed heuristic

Few modifications are incorporated in proposed heuristic for the application of PCA and Taguchi's method. The modified CF heuristic is presented in a self-explanatory flow chart shown in Fig. 2.

Route selection through PCA, and Taguchi's method

In the modified proposed methodology, route selection is performed on the basis of data available in maximum possible inter-cell movement time matrix (Table 6). In this section route/process plan selection is made on the application of PCA ad Taguchi's method and rest of the work is done as per the method explained in "Proposed CF heuristic procedure" and illustration in "Implementation and

Table 11 Performance comparison of clustering algorithm used against some established binary matrix-based CF methods

Source of problem	Size of problem (part × machine)	Performance measure									
		Procedure used					Source author's method				
		EE	GE	GEF	GI	GM	EE	GE	GEF	GI	GM
Elbenani and Ferland (2012)	8 × 6	6	88.89	67.44	74.54	68.35	6	88.89	67.44	74.54	68.35
Gupta et al. (2012)	11 × 7	1	80.3	62.5	70.3	54.29	1	80.3	62.5	70.3	54.29
Ghosh and Dan (2011)	7 × 5	3	54.3	69.6	85	75.6	3	54.3	69.6	85	75.6
Doulabi S H et al. (2009)	8 × 6	2	87.06	76.92	77.78	74.24	2	87.06	76.92	77.78	74.24
Hachicha et al. (2006)	11 × 7	2	86.1	70.37	72.41	66.47	2	86.1	70.37	72.41	66.47
Albadawi et al. (2005)	20 × 8	9	95.8	85.2	85.2	1	9	95.8	85.2	85.2	1

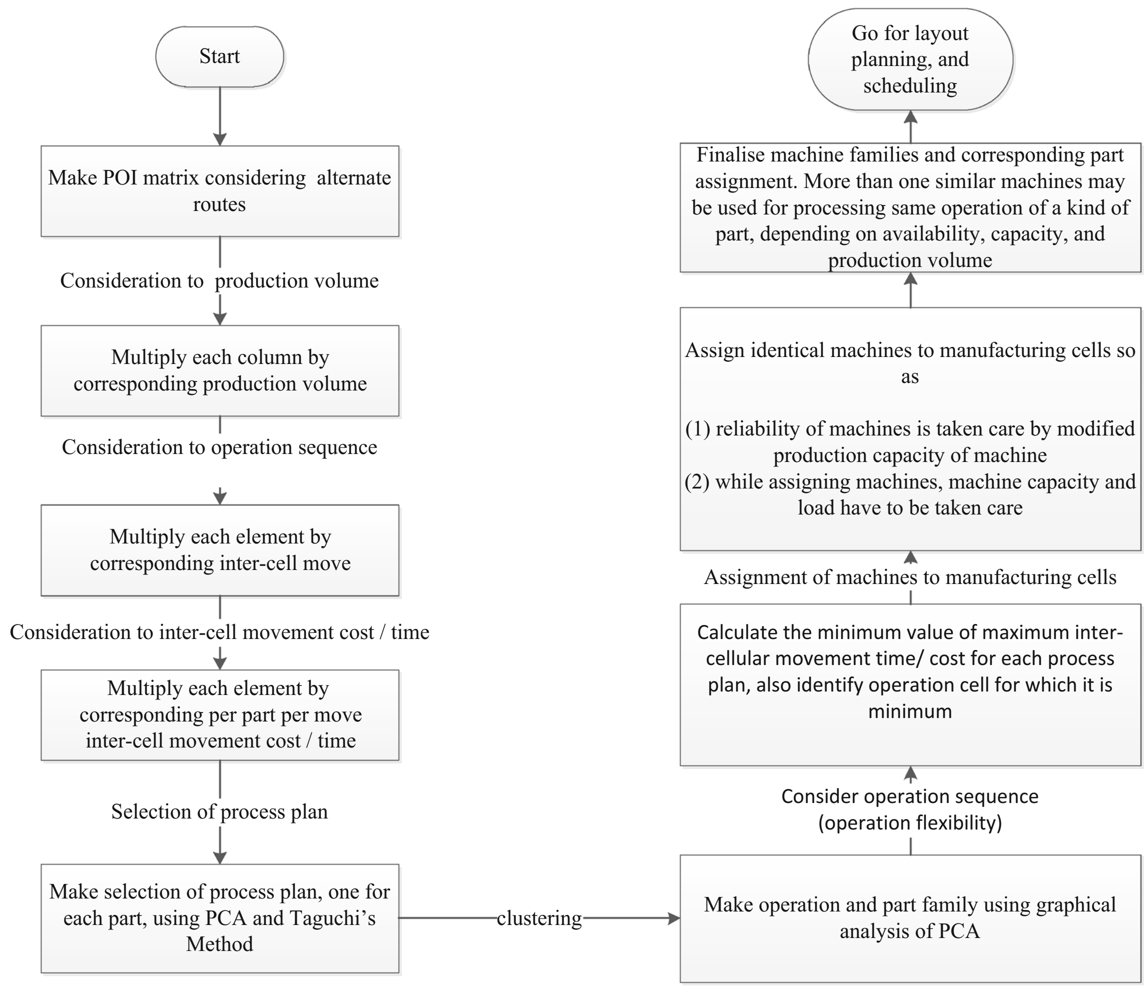

Fig. 2 Flow chart for modified proposed CF heuristic for the use of PCA and Taguchi's method

illustration". Part 'P1', 'P2' and 'P5' each has two possible process plans, whilst parts 'P3' and 'P4' have no choice in process plans. For application of Taguchi's method, only parts 'P1', 'P2' and 'P5' are considered with two level each namely '1' and '2' for 'P1', '3' and '4' for 'P2', '7' and '8' for 'P8'. For application and analysis of Taguchi's method a software package "MINITAB 16" is used. Value of cumulative percentage of variance is calculated through PCA, with the help of "MATLAB 13a. The OA and CP measure is presented in Table 12. Cumulated percentage measure is calculated separately for each serial number by making a matrix having routes according to Table 12, and data of Table 6. The optimum route (level) for each part (factor) is the level having the highest value of CP measure

Table 12 The L_8 orthogonal array and CP measure

S. no.	P1	P2	P5	CP
1	1	3	7	91.36
2	1	3	8	92.4
3	1	4	7	92.58
4	1	4	8	97.13
5	2	3	7	71.34
6	2	3	8	88.63
7	2	4	7	91.36
8	2	4	8	99.58

Table 13 Maximum possible inter-cell movement time matrix after route selection

Part Process plan	P1 1	P2 4	P3 5	P4 6	P5 8
O1	100	400	420	130	0
O2	200	400	420	260	0
O3	200	200	0	520	150
O4	0	200	210	130	420
O5	100	0	210	0	300

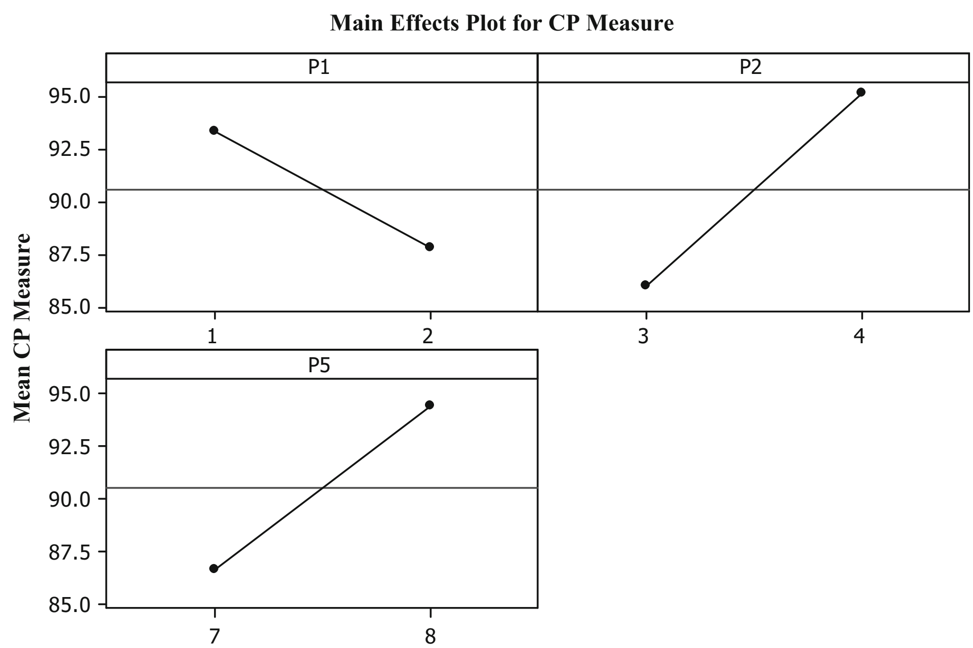

Fig. 3 Effect plot for CP measure response

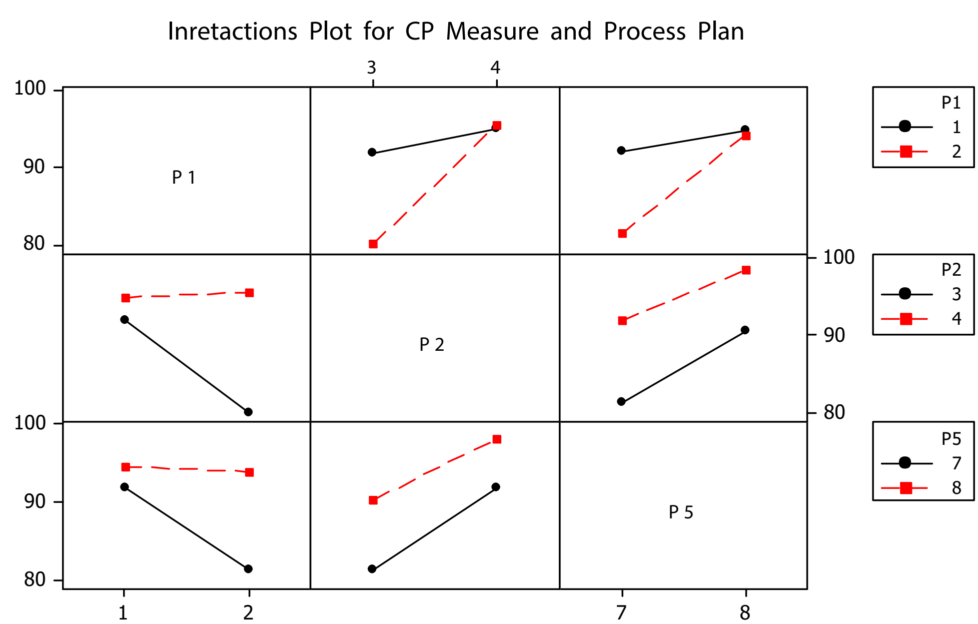

Fig. 4 Interactions plot for CP measure and process plans

Table 14 Clustered Matrix before machine assignment and operation flexibility

Part	P1	P2	P4	P5	P3
Process plan	1	4	6	8	5
O1	100	400	130	0	420
O2	200	400	260	0	420
O3	200	200	520	150	0
O4	0	200	130	420	210
O5	100	0	0	300	210
Inter-cell move time	100	200	130	150	420
Inter-cell moves	100	50	65	75	140

Table 15 Final clustered matrix after route selection through PCA and Taguchi's method

Process plan			**1**	**4**	**6**	**5**	**8**
Part		**Machine**	**P1**	**P2**	**P4**	**P3**	**P5**
Operation cell 1	**O1**	**M1,M2**	100	400	130	420	0
	O2	**M3,M4**	200	400	260	420	0
	O3	**M5**	0	200	520		0
Operation cell 2	**O3**	**M7**	0	0	0	0	150
	O4	**M6**	0	200	130	210	420
	O5	**M8**	100	0	0	210	300
Inter-cell movement time			100	200	130	210	0
Inter-cell moves			100	50	65	70	0

in the experimental region. Based on the main effect plot, shown in Fig. 3, the optimal route of each part is 1, 4, 8 for parts P1, P2, P5. respectively. The route selection through Taguchi's method is also verified by interactions plot between CP measure and process plan drawn through ANOVA analysis using "MINITAB 16" and presented in Fig. 4.

After route selection though PCA and Taguchi's method, the maximum possible inter-cell movement time matrix of Table 6 is reduced to maximum possible inter-cell movement time matrix after route selection presented in Table 13. The clustered matrix before machine assignment and operation flexibility, and final clustered matrix is shown in Tables 14 and 15, respectively.

Thus, total inter-cell moves and inter-cell movement cost for required production volume are 285 and 640 units, respectively.

In comparing the two solutions of same illustrative problem presented in Tables 10 and 15 (route selection through PCA and Taguchi's method), it is observed that the implementation of PCA and Taguchi's method only in route selection decreases the total inter-cell moves whilst a slight increase in total inter-cell movement cost is also there.

Clustering of operations with PCA-based graphical analysis

In this section the objective is clustering of operations into groups. After route selection in "Route selection through PCA, and Taguchi's method", clustering of operations are performed on maximum possible inter-cell movement time matrix after route selection (Table 13) by the application of PCA in the lines of Hachicha et al. (2008a) with the help commercially available package XLSTAT 2014. Any other statistical package like SPSS, S-PLUS, SAS, SPAD, etc. may also be used. Two principal components are sufficient to analyse correlation between elements (operations and

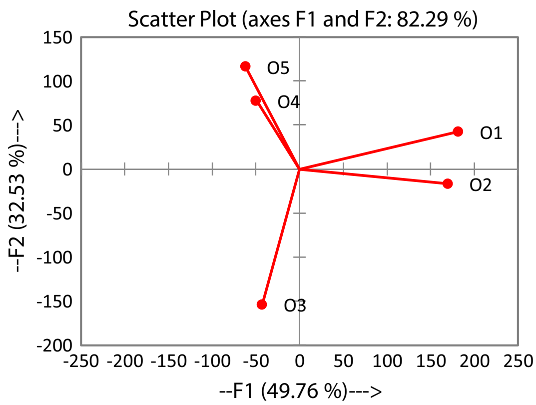

Fig. 5 Scatter plot for Illustrative problem

parts).The use of graphical analysis is based on a two-dimensional scatter plot (Fig. 5) where each machine is represented by a line from the origin and the axis are two eigenvalues contributing maximum amount of variance. Following four principal situations for the classification of machines are possible:

- Two neighbouring operations with a small angle distance measure → Operations belong to the same cell. (‘O4’ and ‘O5’, ‘O1’ and ‘O2’ in Fig. 5).
- Two operations with angle distance measurement between them is almost 180°. → Operations may not belong to the same cell.
- Two operations for which the angle distance measurement between them is almost 90°. → Operations are independent and do not belong to the same cell (‘O2’ and O3 in Fig. 5).
- If none of the above three cases are verified, the operation is not affected to any cell. → An exceptional operation. Since the objective is to group operations with minimum angle distance, Operation Oi, which has the smallest angle distance with O*k*, is assigned to the operation group containing O_i and O_k.

For illustrative problem two operation cells are identified having facility for operation ‘O1’, ‘O2’ and ‘O3’, ‘O4’, ‘O5’. The final clustered matrix would be same as Table 15. Further on the similar lines of Hachicha et al. (2008a) part may also be assigned through PCA.

Conclusions

In the availability of large number of highly complex and sophisticated manufacturing cell formation heuristics, the paper successfully proposed a simple and easy way to implement heuristic procedure having the ability to handle a large number of production and flexibility-related parameters namely production volume, operation sequence, inter-cell movement cost/time, alternate process plans (routing flexibility), identical machines and operation sequence for a part (operation flexibility) with considerations to machine capacity and machine reliability. The proposed procedure is producing good results compared to highly sophisticated methods. Further, the modified proposed CF procedure shows its ability to go with modern statistical tools like PCA and Taguchi’s method. Following salient features may be observed in proposed CF procedure:

- It is computationally very simple and conceptually easy to understand.
- It has the ability to consider a number of production and manufacturing flexibility-related data.
- The relationship between the machines are found on the basis of commonality score.
- The proposed CF procedure can also be implemented with any other compatible clustering algorithm.
- It can be used for both cases, binary and non-binary.
- It minimizes the inter-cellular movement cost/time
- It is adaptable for more sophisticated techniques like PCA, Taguchi’s method and others
- Use of modern statistical and computational tools extend the applicability of proposed heuristic from mid to large size flexible manufacturing system.

Scope for further work, one hand lies in considerations to other/more production and manufacturing flexibility parameters like decisions on number of manufacturing cells and size, work imbalance, machine flexibility, etc. for the development of more realistic, efficient and effective simple CF procedure; on the other hand, in the development of simple procedures for simultaneous assignments of machine groups and part families.

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