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CELL FORMATION IN GROUP TECHNOLOGY: REVIEW, EVALUATION AND DIRECTIONS FOR FUTURE RESEARCH*

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Abstract—This paper discusses and reviews a fundamental issue in cellular manufacturing—cell formation. This problem is of strategic and operational importance in that it affects the fundamental structure and the overall layout of a cellular manufacturing system. We first provide a comprehensive mathematical formulation of the cell formation problem and then propose a methodology-based classification of prior research. This classification is used in reviewing the most recent literature on the cell formation problem. Based on a comparison and critical evaluation, we highlight the shortcomings of current approaches and also outline directions for future research. © 1998 Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

Group Technology (GT) is an approach to manufacturing and engineering management that helps manage diversity by capitalizing on underlying similarities in products and activities. Within the manufacturing context, GT can be defined as a manufacturing philosophy identifying similar parts and grouping them together into families to take advantage of their similarities in manufacturing and design. One application of the GT philosophy in manufacturing is cellular manufacturing (CM). CM is concerned with the creation and operation of manufacturing cells which are dedicated to the production of a set of part families.

In order to introduce CM, it is necessary first to identify parts and machine types to be considered in the cellular configuration. This process differs with respect to whether cells are created by rearranging existing equipment on the factory floor or whether new equipment is acquired for the cells. Cells using existing equipment are typically manned and operators have major responsibilities for setup, processing, materials handling, and inspection. Cells may be designed to operate with completely new equipment often incorporating various forms of flexible automation (e.g., flexible manufacturing systems (FMS)). Such cells are typically unmanned and the role of humans in the operation of the cells is restricted to loading and unloading parts, tool changing, maintenance, and inspection [1]. Irrespective of the type of cell, however, one of the first problems faced in implementing CM is cell formation (CF).

CF deals with the identification of the family of parts and the group of machines on which these parts are to be processed. The CF problem may be defined as: "If the number, types, and capacities of production machines, the number and types of parts to be manufactured, and the routing plans and machine standards for each part are known, which machines and their associated parts should be grouped together to form cells?" [2]. In some cells the problem definition is expanded to allow choice of processing operations to achieve specific features. During the past two decades, a considerable amount of research has been directed at this problem. Comprehensive reviews of cell formation procedures have previously been provided [3–6, 1].

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Table 1. Notation used for model development

	Indices:
c	Index for cells ($c = 1,\ldots,C$)
j	Index for operation types ($j = 1,\ldots,J$)
t	Index for tool types ($t = 1,\ldots,T$)
m	Index for machine types ($m = 1,\ldots,M$)
p	Index for parts ($p = 1,\ldots,P$)
w	Index for workers ($w = 1,\ldots,W$)
	Parameters:
a_{mw}	1 if worker w can operate machine type m; 0 otherwise
A_m	proportion of time a machine of type m is available
c_m	variable cost per unit time to operate a machine of type m
D_p	average demand for part p (in units) per period
F_m	amortized cost per period to procure one machine of type m
G_m	proportion of operator attention required while a machine of type m is operating
h	handling cost per intercell move
R_m	cost to train a worker to operate a type m machine
s_t	cost per period to stock tool type t
$d_{j_p m}$	unit processing time to perform operation j_p on machine type m
U	total shop time per period
S_c	maximum number of machines allowable in cell c
Q_w	availability of worker w in each period
	Decision variables:
T_{mc}	number of workers trained to operate type m machines in cell c
Y_{mc}	number of machines of type m assigned to cell c
W_{wc}	1 if worker w is assigned to cell c; 0 otherwise
$X_{j_p c}$	1 if operation j on part p is assigned to cell c; 0 otherwise
Z_{tc}	1 if tool t is used in cell c; 0 otherwise
$y^+_{j_p c}$	1 if part p's jth operation is performed in a different cell than the preceding operation
k_{mwc}	the amount of time worker k is assigned to type m machines in cell c

CF assumes that a set of parts is identified as suitable for manufacture on a specified group of specific machines or machine types. To do this there must exist a basic relationship between a part and a set of machines (e.g., a part routing). Parts can then be assigned to families such that all parts in the family are processed on the same group of machines, and similarly machines can be grouped into cells if they process the same set of parts. Most procedures for CF rely on this type of relationship to establish part families and machine cells. Once the part and machine populations for CM have been identified, the CF problem can be reduced to three major decisions: (a) identification of part families; (b) identification of machine cells; and (c) allocation of the families to cells or vice versa. These three decisions are interrelated and compose subproblems of the CF problem.

The main objectives of the paper are to: (i) present a comprehensive mathematical formulation of the CF problem; (ii) review prior research on CF using a solution-method based taxonomy; and (iii) provide directions for future research. The remainder of this paper is organized as follows. In Section 2, we present our comprehensive mathematical formulation for CF. This is followed by a review of prior research which is classified based on the solution-methodology employed in Section 3. In Section 4, we present a comparison of mathematical programming formulations for CF as well as an overall comparison of recent contributions in the area (in terms of type of procedure, objectives considered, features/constraints incorporated, solution approach, etc.). This is followed by a critical evaluation with a view to formulating guidelines for future research in Section 5.

GENERAL CELL FORMATION MODEL

Given size limits on cells based on organizational considerations, cell formation is concerned with assigning workers, part types, machines and tooling to specific cells. The following model captures all these features and is described for completeness (and to lay a foundation for the subsequent discussion), but the master problem is far beyond current solution capabilities. In general, the static, part–machine cell formation problem may be described as follows. We assume we are given a set of current part types and machines. For each part, we are given a set of operation types required, and setup time and unit processing time for each operation.

Tooling is identified with operation types. Operation sequences may or may not have precedence constraints. In this model it is assumed that setup is determined by the operation type and parts sharing operations may share a setup. Each part type has a planning demand rate. A set of available machine types is also provided. For each machine type we assume knowledge of annual fixed cost, operating cost rate, available time per year and the set of operations which can be performed. Other constraints include limits on the number of machines in a cell and possible limits on the number of machines allowed for one or more types.

The cell solution consists of a specification of cells consisting of specific machines and routing of each part type to those machines subject to the constraints mentioned above and machine availability. Cell specification includes the relative layout of machines within the cell and the location of tooling for each part type. Our objective is to determine the minimal cost assignment of part operations, machines, workers and tooling to cells. The notation used in developing our model is shown in Table 1.

A mathematical program representing the general cell formation problem (GCFP) is then as follows:

$$\text{Minimize } Z = \sum_{m=1}^{M}\sum_{c=1}^{c} F_m Y_{mc} + \sum_{m=1}^{M} c_m \sum_{c=1}^{C} Y_{mc} \sum_{p=1}^{P}\sum_{j=1}^{J} D_p d_{j_p m} X_{j_p c}$$

$$+\sum_{t=1}^{T} s_t \sum_{c=1}^{C} Z_{tc} + h\sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{c=1}^{C} D_p v^{+}_{j_p c} + \sum_{m=1}^{M}\sum_{c=1}^{C} R_m T_{mc} \tag{1}$$

subject to

$$\sum_{c=1}^{C} X_{j_p c} = 1 \quad \forall j,p \tag{2}$$

$$\sum_{p=1}^{P}\sum_{j=1}^{J} D_p d_{j_p m} X_{j_p c} \le A_m U Y_{mc} \quad \forall m \text{ and } c \tag{3}$$

$$\sum_{O_{pj}=t} X_{j_p c} \le T Z_{tc} \quad \forall i,t,c \tag{4}$$

$$X_{j_p c} - X_{j_p - 1,c} = v^{+}_{j_p c} - v_{j_p c} \quad \forall j_p > 1, p \text{ and } c \tag{5}$$

$$\sum_{m=1}^{M} Y_{mc} \le S_c \quad \forall_c \tag{6}$$

$$T_{mc} + \sum_{w=1}^{W} a_{mw} W_{wc} \ge \theta Y_{mc} \quad \forall m \text{ and } c \tag{7}$$

$$\sum_{c=1}^{C} W_{wc} = 1 \quad \forall w \tag{8}$$

$$\sum_{w=1}^{W} Q_w W_{wc} \ge \sum_{m=1}^{M} G_m \sum_{p=1}^{P}\sum_{j=1}^{J} D_p d_{j_p m} X_{j_p c} \quad \forall c \tag{9}$$

$$Z_{tc}, W_{wc}, X_{j_p c} \epsilon \{0,1\}, \qquad Y_{mc} \text{ integer} \tag{10}$$

The objective function minimizes the sum of costs for purchasing machines (fixed cost such as depreciation, opportunity cost and time-based maintenance), variable cost of using machines, tooling cost, material handling cost and amortized worker training cost per period. Tooling cost need only be considered if tools are associated with operations and tooling will be kept in each cell which performs that operation. Material handling cost assumes an incremental charge for moving a load between cells and accumulates this cost for all intercell moves. We could integrate the machine layout problem within cells (so as to minimize intra-cell materials handling costs) into our formulation, but, since the object of cell formation is to create independent cells, this should not be necessary. After cells are formed conceptually, our contention is that the within cell layout can be handled using traditional layout approaches.

Constraints (2) force each operation of each part to be assigned to a unique cell. Constraints (3) ensure that each cell has an adequate allocation of machines of each type to perform its assigned workload. The left hand side accumulates total workload for machines of type m in the cell and the right hand side gives the time available on these machines each period based on machine assignments. Constraints (4) simply serve to indicate which operations are performed in each cell. If tooling costs are not dependent on this information, these constraints can be eliminated along with the Z_{tc} binary variables. Constraints (5) pick out the intercell moves. The $v^{+}_{j_pc}$ variables will be 1 if part p's jth operation is performed in a different cell than the preceding operation. If this occurs, the objective function is charged a cost h for each load of part p moved per period. If operation sequences are not fixed, this constraint set can be replaced by one that counts the number of cells to which part type p is assigned for one or more operations and the objective can be modified accordingly. Constraints (6)limit the number of machines in each cell. Without this constraint, the optimal solution to the cell formation subproblem is to use a single cell since the model assumes within cell moves are free.

While the cell formation problem has been previously given in several forms by various researchers, we are unaware of any existing mathematical statements of the worker assignment problem. Several approaches are possible. The approach used in the formulation above resembles a covering problem given the machine assignments. Constraints (7) ensure that at least θ workers are trained with the skills to operate each machine in each cell. Values of θ greater than one allow for worker sharing, a key aspect of successful Just-in-time systems. Cross-training to allow such flexibility is a key aspect of group operations. Constraints (7) also tie together the cell formation variables with worker assignments. Constraints (8) assign each worker to exactly one group. Lastly, constraints (9) ensure adequate workforce in each cell to meet total workload. It should be noted that this model does not guarantee feasibility at the operation level. To be assured that a feasible assignment of workers to machines exists we must incorporate individual worker skills into this latter set of constraints. We could add constraints of the form

$$\sum_{w=1}^{W} k_{mwc} \geq \sum_{m=1}^{M} G_m \sum_{p=1}^{P} \sum_{j=1}^{J} D_p d_{j_p m} X_{j_p c} \quad \forall m \text{ and } c \tag{11}$$

We would also have to constrain the k_{mwc} to agree with the binary W_{wc} variables.

Dynamic and stochastic versions of the problem incorporate changing and probabilistic demand respectively. Capacity constraints could be formulated for each period of the season or foreseeable horizon. The formulation above assumes knowledge of the machine type to be used for each operation. If machines are flexible, the X_{j_pc} variables can be expanded to include a machine index and the model may select machines. The d_{j_pm} parameters in this case would represent conditional times. Flexibility presents another challenge to cell formation. Process layouts are insensitive to the mix of product demand and changes in product design do not generally cause major disruption. This holds provided total demand for a process does not vary. However, with cells, each product represents a greater proportion of the cell capacity, thus machines may be overloaded in one cell and idle in another. The effect is similar to that in queuing theory where it is well known that pooling of servers with a common queue is more effective than separate queues. The idea behind cellular manufacturing however is that by cleverly segmenting the queue, efficiencies in processing, scheduling and transport accrue which dominate

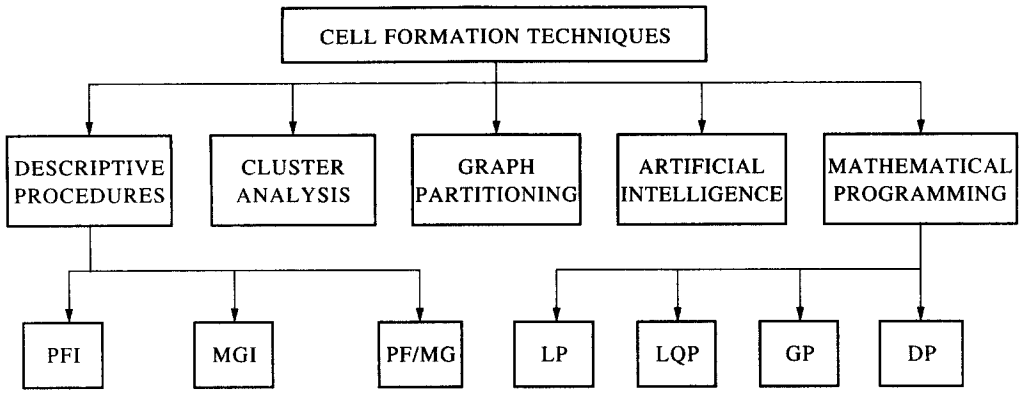

Fig. 1. Classification of the CF methods.

the loss in efficiency. Unpredictable demand, lessens our ability to intelligently segment the product lines. The final model should enable an evaluation of flexibility to changes in demand level, product mix, product design and routing.

Part families often contain setup sharing potential. A turret lathe may hold all the cutting tools necessary to make all parts in a family. Parts with similar shapes may fit in a generic fixture with only individual part inserts needed for adjustment. In machining furniture components, changeover time may be eliminated if the next part shares common dimensions and tool with the previous part. The model formulated above does not explicitly consider such advantages when assigning parts to cells. One possible addition would be to define a setup time per period for each operation code assigned to a cell. A setup time factor could also be added to constraints (3) and (9). Thus, if all parts using an operation were assigned to a cell, this cost would only be incurred once. With this approach the cost factor could be included in s_t. However, it may be preferable to define a part based setup factor instead of this operation based factor.

Finally, note that the CF model presented in this section is combinatorially complex and will not be solvable for any real problem. However, smaller models (which incorporate a some of the objectives and constraints) have been proposed by several prior researchers and these are compared in Section 4 of the paper. We now present a general classification of CF procedures based on the methodology employed.

CF SOLUTION METHODS

Classification of methods of CF have been proposed by several researchers. To facilitate our review, a classification based on the type of general solution methodology is developed and shown in Fig. 1. In the next five subsections, we briefly review procedures based on this classification.

Descriptive procedures

In general, descriptive procedures can be classified into three major classes [1]. The first class, which is referred to as part families identification (PFI), begins the cell formation process by identifying the families of parts first and then allocates machines to the families. The second class, which is referred to as machine groups identification (MGI), follows the reversal of the first class' steps. The third class of the descriptive procedures, which is referred to as part families/machine grouping (PF/MG), identifies the part families and machine groups simultaneously.

PFI methods can be sub-classified as those based on informal systems (e.g., rules of thumb, visual examination or other criteria) and those based on formal coding and classification systems. Most of the literature discussing informal approaches to identify part families describes actual experiences of firms that have implemented cells [7, 8]. The role of group technology (GT) codes in the context of cellular manufacturing is primarily as an aid in identifying the part

families to which production cells should be dedicated. Further analysis is required before a family of parts to be manufactured in a cell, and the machines which will comprise that cell, can be specified. The reader interested in an overview of coding and classification systems is referred to Askin and Vakharia [9].

MGI procedures consider the CF problem as a two-stage process where in the first stage of their analysis, machines are grouped based on information available in part routings and then in the second stage, parts are allocated to machine groups [10, 11].

When a CF approach attempts to group parts into part families and machines into machine groups simultaneously, then such an approach can be classified as PF/MG. Burbidge [12–14] proposed one of the earliest PF/MG descriptive approaches for the CF problem which is referred to as Production Flow Analysis (PFA). PFA is a technique which analyses the information given in route cards to form cells. A manual method for CF called "Nuclear Synthesis" is proposed where manufacturing cells are created around "key machines". El-Essawy [15, 16] proposed a method called Component Flow Analysis (CFA) at about the same time. In some respects, the methodology of CFA does differ from that of Burbidge's PFA procedure since the latter first partitions the problem, whereas the former does not.

Procedures based on cluster analysis

Cluster analysis is composed of many diverse techniques for recognizing structure in a complex data set. The main objective of this statistical tool is to group either objects or entities or their attributes into clusters such that individual elements within a cluster have a high degree of "natural association" among themselves and that there is very little "natural association" between clusters. Clustering procedures can be classified as: 1) array-based clustering techniques, 2) hierarchical clustering techniques, and 3) non-hierarchical clustering techniques.

In array based clustering, the processing requirements of components on machines can be represented by an incidence matrix. This is referred to as the machine–component matrix $\tilde{A}$. The machine–component matrix has zero and one entries (a_{ij}). A "1" entry in row i and column j ($a_{ij}=1$) of the matrix indicates that component j has an operation on machine i, whereas a "0" entry indicates that it does not. The array based techniques try to allocate machines to groups and components to associated families by appropriately rearranging the order of rows and columns to find a block diagonal form of the $a_{ij}=1$ entries in the machine–component matrix.

The literature yields at least eight array-based clustering algorithms, namely, Bond Energy Analysis by McCormick *et al.* [17], Rank Order Clustering by King [18, 19] and King and Nakornchai [4], Modified Rank Order Clustering by Chandrasekharan and Rajagopalan [20], Direct Clustering Analysis by Chan and Milner [21], Occupancy Value method by Khator and Irani [22], Cluster Identification method by Kusiak and Chow [23], and the Hamiltonian Path Heuristic by Askin *et al.* [24].

In hierarchical clustering, the data in the machine–component matrix are not partitioned into groups or cells in one step. Rather they are first separated into a few broad cells, each of which is further divided into smaller groups, and each of these further partitioned, and so on until terminal groups are generated which cannot be subdivided. Essentially hierarchical techniques may be subdivided into agglomerative methods which proceed by a series of successive fusions of the M machines or the P parts into groups, and divisive methods which partition the set of M machines (P parts) successively into finer groups. All the agglomerative hierarchical techniques ultimately reduce the data to a single cluster containing all the machines (parts), and divisive techniques will finally split the entire set of machines (parts) into M (P) cells each containing a single machine (part). Hierarchical classifications may be represented by inverted tree structures or dendrograms, which are two-dimensional diagrams illustrating the fusions or divisions which have been made at each successive stage of the analysis.

In the context of CF, only agglomerative clustering techniques have been used. The most widely used technique is single linkage. More recently, the problem of "chaining" due to the use of single linkage has been investigated and hence, the average linkage algorithms have been recommended for CF [25, 26]. A new hierarchical clustering algorithm for CF referred to as the Set Merging algorithm has also been proposed by Vakharia and Wemmerlöv [26]. Fusions are based on similarities between machines or parts. Machine similarity measures have been pro-

posed in [27], [28], [29], [30], [31], [32], and [33]. Part similarity measures based on common machine requirements are discussed in [34], [5], and [6] and based on operation sequences in [35], [36], [37], [38], and [26]. Recently, Shafer and Rogers [39, 40] overviewed the similarity and dissimilarity measures applicable to cellular manufacturing.

Non-hierarchical clustering methods are iterative methods and they begin with either an initial partition of the data set or the choice of a few seed points. In either case, one has to decide the number of clusters in advance. Arbitrariness in the choice of seed points (or initial partition of data) could lead to unsatisfactory results. Non-hierarchical procedures have been developed by Chandrasekharan and Rajagopalan [41], Lemoine and Mutel [42], and Srinivasan and Narendran [43].

Graph partitioning approaches

Graph partitioning methods treat the machines and/or parts as vertices and the processing of parts as arcs connecting these nodes. These models aim at obtaining disconnected subgraphs from a machine–machine or machine–part graph to identify manufacturing cells. Rajagopalan and Batra [44] suggest the use of Jaccard's similarity coefficients and graph theory to form machine groups. Each vertex in the graph represents a machine type and the edge connecting vertices j and k is introduced in the graph only if the "similarity" between the machine types is greater than a prespecified threshold value. After all allowable edges have been introduced, cliques are formed. These cliques are then merged to create cells so that intercell moves are minimized. An upper limit on cell size constrains the number of machines in each partition. During the process high and balanced machine utilization are strived for and machine loads are used to determine the number of machines of a given type needed for each cell.

Faber and Carter [45] developed a graph theoretic algorithm for grouping machines and parts into manufacturing cells by converting the machine similarity matrix into a cluster network. The cluster network is partitioned into cells by solving a minimum cost flow problem. Kumar *et al.* [46] developed a 0–1 quadratic programming with linear constraints to solve the part grouping problem. The quadratic model has been converted to two linear problems and dealt with the k-decomposition problem.

Askin and Chiu [47] proposed a cost-based mathematical formulation and heuristic solution for the CF problem. The Kernighan and Lin [48] graph partitioning method was adapted and applied in a two phase partitioning algorithm. The first phase assigns parts to specific machines. The second phase groups machines into cells. Vohra *et al.* [49] proposed a network-based algorithm to minimize the amount of machining times performed outside the part primary cells. Wu and Salvendy [2] developed a network model to partition the machine–machine graph into cells by considering operation sequences.

Artificial intelligence approaches

Elmaghraby and Gu [50] presented an approach for using domain specific knowledge rules and a prototype feature based modeling system to automate the process of identifying parts attributes and assigning the parts to the most appropriate manufacturing cell. The expert assignment system is based on the geometric features of the parts, characteristics of formed manufacturing cells, parts functional characteristics and attributes, as well as domain specific manufacturing knowledge. Kusiak [51] developed a pattern recognition based parts grouping which is similar to the grouping in GT. The basic difference between these two approaches is in the degree of automation. Application of artificial neural networks to CF problems has been proposed by Rao and GU [52] and Karapathi and Suresh [53].

Mathematical programming approaches

Mathematical programming methods can be further classified into four major groups based on the type of formulation: 1) linear programming (LP), 2) linear and quadratic integer programming (LQP), 3) dynamic programming (DP), and 4) goal programming (GP). LP based CF methods have been proposed by Purcheck [8, 54–56] and Olivia-Lopez and Purcheck [57]. They essentially apply the technique of combinatorial grouping and LP to the CF problem. LQP models have been proposed by Ballakur [3], Kumar *et al.* [19], Kusiak [46], Kusiak and

Table 2. Mathematical programming approaches

Reference	Form	Obj.	Number of constraints	Number of variables		Solution technique(s)
				Integer	Continuous	
Ballakur [3]	LQP	1	$4(MPC)+M+P+C$	$C(F+P+M)$		LINDO
	QP	1	$M+P+C$	$C(M+P)$		NONE
Boctor [12]	LQP	1	$M+P+2CD$	$C(M+P)+2CD$		LINDO & SIMUL. ANNEAL.
Choobineh [59]	LQP	4, 10	$F(1+PC)+MC+1$	$C(F+P+M)$		NONE
Co & Araar [65]	LQP	6	$3M$	M^2		LINDO
Dahel & Smith [66]	LQP	1	$CM+\sum_{p=1}^{P} m_p(PC+1)+M+C$	$PC+OPC+MC$		LINDO
Damodaran *et al.* [67]	LQP	10	$P+M+MP(1+O+MO)$	M^2PO	$PM+M^2PO$	NONE
Elzinga *et al.* [60]	LQP	2, 9	$PM+MC+C$	$>PC+C$		NONE
Gunasingh & Lashkari [68]	LQP	1, 5	$C+M$	CM		SAS/OR
Kasilingam & Bhole [53]	LQP	10	$C(1+P+M)+T+P$	$PMCT+PC+T+MC$		LINDO
Kumar *et al.* [19]	QP	1	$P+C$	PC		k-Decomp (QAP)
Kusiak [46]	LQP	11	P-MED: P^2+P+1 GN-MED: $(\sum_{p=1}^{P} K_p)^2+P+1$	P^2 $(\sum_{p=1}^{P} K_p)^2$		IP CODE LINDO
Kusiak & Heragu [58]	LQP	11	P-MED: P^2+P+1 GN-MED: $(\sum_{p=1}^{P} K_p)^2+P+1$	P^2 $(\sum_{p=1}^{P} K_p)^2$		IP CODE LINDO
	DP		$P+F$	PF		NONE
Lashkari & Gunasingh [5]	LQP	11	$M+C$	MC		LAGRANG. RELAX.
Logendran [69]	LQP	2	$P+M+OP+OPC$	$C(P+OP+M)$		NONE
Ferreira *et al.* [45]	LQP	2, 5, 11	$P+M$	PM		B&B
Rajamani *et al.* [70, 71]	LQP	5	$2P+(1+CM)\sum_{p=1}^{P}\sum_{k=1}^{K_p} o_{kp}+C(P+M+1)+1$ $CM+\sum_{p=1}^{P} K_p+M\sum_{p=1}^{P}\sum_{k=1}^{K_p} o_{kp}$	$CM\sum_{p=1}^{P}\sum_{k=1}^{K_p} o_{kp}$	LINDO	
Sankaran [52]	GP	10	$4F+M+2$	$PF(1+F)+MF$		LINDO
	LQP	10	$F(5+2M+2P+2P^2)+P$	$PF(1+F)+MF$		NONE
Sankaran & Kasilingam [72]	LQP	5, 10	$P+C+M+CM\sum_{p=1}^{P} R_p$	$MC+C\sum_{p=1}^{P} R_p$		LINDO
Shafer & Rogers [37]	GP	2, 9, 12	NEW: $4+4F+3P^2F+3P+MF(3+P)$	$2P^2F+6MF+2PMF$	$4+PF+2MF$	NONE
			EXIST: $M+1$	$2P^2F+4MF+2PMF$	$2+PF+2MF$	NONE
			MIX: $M+1$	$2P^2F+6MF+2PMF+M$	$4+PF+2MF$	NONE

Shafer *et al.* [73]	LQP	2, 4	$1 + E + CM$	$P + PM + CM$	LINDO
Singh *et al.* [74]	LQP	10	$P + M$	CP	Multi-obj
Song & Hitomi [75]	QP	1	$C + M$	CM	B&B
Ballakur & Steudel [76]	QP	11	NONE	M	HELD & KARP TSP DP
Vakharia *et al.* [38]	LQP	1, 5	$O + C(1 + M + O)$	$C(M + O)$	ZOOM
Vakharia & Kaku [62]	LQP	2, 5	$O + C(M + O)$	$PCM + CM$	ZOOM
Venugopal & Narendran [77, 78]	LQP	7	$C + M$	CM	NONE
Wei & Gaither [63]	LQP	3	$2M + C + P(C + 2)$	$P(M + 2) + MC$	ZOOM

Notes:
(A) The objectives considered by the different models shown in column (3) are as follows:
Minimization of the number of exceptional parts (EPs) defined below.
Minimization of the number, cost, or weighted distance of intercell moves of EPs.
Minimization of the opportunity costs of EPs.
Minimization of the cost of duplicate machines.
Minimization of the machine allocation costs.
Minimization of the inter-cell capacity imbalance.
Minimization of the load imbalance within cells.
Maximization of the capacity utilization.
Minimization of the conversion costs.
Minimization of the total operating costs.
Maximization of the sum of similarities.
Minimization of the setup time.

(B) Exceptional parts are those which have operations carried out in multiple cells.

(C) C = number of cells;
D = number of 1's in the part–machine matrix;
E = number of EP's;
F = number of part families;
K_p = number of plans for part p;
M = number of machines;
m_p = number of machines required by part p;
O = number of operations;
o_{kp} = number of operations for the kth plan of part p;
P = number of parts;
R_p = number of routes for part p;
T = number of tools.

Table 3. Comparison of the CF methods

	Type			Objectives				Features/constraints				Solution approach					
Reference	A	B	C	E	G	K	P	F	L	N	O	H	I	J	Q	M	D
Askin and Chiu [47]			•		•	•	•				•		•			N	92 × 362
Askin and Subramanian [79]	•					•								•		N	14 × 24
Askin *et al.* [HPH] [24]			•											•	•	Y	16 × 43
Balasubramanian and Panneerselvam [80]			•			•						•		•		N	16 × 21
Ballakur [3]			•	•	•		•	•								N	4 × 6
Ballakur and Steudel [WUBC] [76]			•	•	•		•							•	•	N	15 × 10
Ben-Arieh and Triantaphyllou [81]	•													•		N	
Boctor [12]			•	•	•			•							•	Y	16 × 43
Burbidge [PFA] [13, 82, 14, 83–85, 34]	•				•		•				•					N	16 × 43
Carrie [86]	•											•		•		N	20 × 35
Chan and Milner [DCA] [21]			•											•		N	16 × 43
Chandrasekharan and Rajagopalan [87]			•		•								•	•		N	8 × 20
Chandrasekharan and Rajagopalan [MODROC] [87]			•									•		•		N	8 × 20
Chandrasekharan and Rajagopalan [ZODIAC] [20, 41]			•		•							•		•		Y	40 × 100
Choobineh [59]	•					•	•				•	•			•	N	– × 10
Chu [88]			•											•		Y	40 × 100
Dahel and Smith [66]			•	•			•	•							•	N	14 × 24
Damodaran *et al.* [67]			•			•	•								•	N	5 × 2
Faber and Carter [89]	•											•	•			N	16 × –
Ferreira *et al.* [45]	•			•	•		•		•	•	•				•	Y	43 × 20
Frazier and Gaither [90]		•				•	•							•		Y	30 × 41
Gongaware and Ham [91]	•								•			•		•		N	
Gunnasingh and Lashkari [68]			•	•	•	•		•			•	•			•	N	10 × 25
Gupta [92]		•					•		•			•				N	15 × –
Han and Ham [28]	•											•		•		N	
Harhalakis *et al.* [93]		•		•	•	•								•		N	86 × 1186
Irani *et al.* [94]		•											•		•	N	
Kang and Wemmerlöv [95]	•						•		•	•	•	•		•		N	12 × 25
Kasilingam and Bhole [53]			•			•	•	•							•	N	5 × 10
Khator and Irani [OV] [22]			•											•		N	16 × 43
King [ROC] [48, 96]			•											•		N	16 × 43
King and Nakornchai [ROC2] [18]			•											•		N	54 × 90
Kumar *et al.* [19]			•		•								•			N	20 × 23
Kusiak [*p*-MED] [46]	•											•			•	N	– × 12
Kusiak and Chow [51]			•			•								•		N	100 × 200
Kusiak and Heragu [58]	•											•			•	N	– × 12
Lashkari and Gunnasingh [5]		•		•							•	•			•	N	500 × 2000
Logendran [23]		•		•	•		•							•		Y	7 × 14
Logendran [69]		•		•	•		•		•					•		Y	7 × 14
Logendran [29]		•		•	•		•					•		•		Y	7 × 14
Logendran and West [97, 98]		•		•	•		•							•		N	16 × 43
McCormick *et al.* [BEA] [30]			•											•		N	37 × 53
Nagi *et al.* [99]		•		•	•	•			•					•		N	20 × 20
Okogbaa *et al.* [100]		•		•										•		N	16 × 43
Rajagopalan and Batra [101]		•					•		•		•	•	•			N	40 × 100
Rajamani *et al.* [70, 71]			•	•		•	•	•		•					•	N	3 × 4
Sankaran [52]	•					•	•	•			•	•			•	N	10 × 6
Sankaran and Kasilingam [72]			•			•		•	•	•	•				•	N	6 × 10

Shafer *et al.* [73]					•	•	•	•									•	N	9 × 10
Shafer and Rogers [37]	•			•	•	•	•		•		•						•	N	12 × 12
Sheu and Krajewski [102]	•					•	•						•		•	•	•	N	
Shiko [103]	•								•				•		•			N	
Shtub [104]	•					•				•			•				•	N	4 × 5
Singh *et al.* [74]		•				•					•						•	N	4 × 5
Song and Hitomi [75]		•		•	•			•						•			•	N	16 × –
Srinivasan and Narendran [GRAFICS] [43]		•			•								•		•			Y	76 × 468
Srinivasan *et al.* [105]			•										•				•	N	40 × 100
Stanfel [106]				•	•												•	N	11 × 14
Vakharia and Chang [107]			•		•	•	•											N	78 × 325
Vakharia and Kaku [62]			•	•		•	•	•			•		•				•	N	40 × 100
Vakharia and Wemmerlöv [108]	•			•	•		•				•		•		•			N	12 × 19
Vannelli and Hall [109]			•	•	•	•	•							•				N	30 × 90
Venugopal and Narendran [77]		•					•										•	N	
Vohra *et al.* [110]			•		•									•				N	7 × 7
Waghodekar and Sahu [MACE] [111]		•											•					Y	36 × 90
Wei and Gaither [ODCC] [63]	•			•		•	•	•									•	N	30 × 41
Wu and Salvendy [2]		•			•					•				•				N	15 × 25

Notes:
A = PFI.
B = MGI.
C = PF/MG.
D = maximum solved problem size (machines × parts).
E = cell size limit.
F = provides optimal solution.
G = maximizing cell independence (minimizing intercell moves).
H = using similarity/dissimilarity measures.
I = using graph partitioning.
J = using clustering analysis.
K = considering costs.
L = considering operations precedence.
M = compared to other methods (Y = yes and N = no).
N = considering multiple process plans.
O = considering availability of multiple machines of the same type.
P = considering machine load/utilization.
Q = using mathematical programming.

Heragu [58], Choobineh [59], Elzinga *et al.* [60], Kasilingam and Bhole [53], Vakharia and Chang [61], Vakharia *et al.* [38], Vakharia and Kaku [62], Wei and Gaither [63], and Boctor [12]. DP models have been developed by Ballakur [3] while GP models have been proposed by Sankaran [52] and Shafer and Rogers [37].

COMPARISONS AND CRITICAL EVALUATIONS OF CF METHODS

As seen in the previous section, there are a large number of methods which have been developed for cell formation. The emphasis seems to have been on developing "new" techniques rather than on evaluating the current contributions. Further, comparisons made between methods to date are directed towards their performance when applied to sets of data rather than on the features of the methods, *per se* [64, 26]. In this section we compare evaluate in two ways.

The first evaluation focuses on the mathematical programming formulations developed to identify cellular configurations. These are evaluated in terms of: (i) type of mathematical formulation, (ii) objectives incorporated, (iii) problem size (in terms of number of constraints and number of integer/continuous decision variables), and (iv) solution technique developed. A comparison of all these formulations is shown in Table 2. The table indicates that:

- Most of the formulations attempt to create "independent" cells by minimizing the number of parts requiring processing in multiple cells. Other formulations focus on minimizing the costs of duplicating machines while a few try to create cells such that capacity is balanced between

and within cells. However, none of them incorporate *all* the objectives/constraints shown in the comprehensive CF model shown in Section 2.

- Given that these formulations are incomplete, their usefulness is limited in an industrial setting. Further, all the models are computationally complex and although several researchers have used existing software to illustrate them, it is unlikely that they can provide solutions to large-scale problems.

The second comparison of CF methods shown in Table 3 focuses on the: (i) method type (PFI, MGI, or PF/MG), (ii) major objectives considered, (iii) features/constraints incorporated, (iv) solution approach, (v) comparisons to other methods, and (vi) maximum problem size solved. This table indicates that:

- Most of the solution methods create part families and machine groups simultaneously (of type PF/MG).
- Most of the methods are not compared to other methods in order to evaluate the performance.
- Most of the data sets used in testing the CF solution methods are not industry data. This means that the solution methods do not deal with real and practical systems.

These comparisons and evaluations lead us to the following critical evaluation of prior research:

1. The descriptive heuristics for CF use a subjective evaluation in order to identify part families and/or machine groups. Thus, the performance and the solution quality of these methods is not automatically quantified nor is the objective clearly stated.
2. Most of the clustering techniques focus on manipulating the machine–component matrix in one way or another. Some methods use array-based techniques and the others use some similarity or distance measures to identify the clusters. The performance guarantee of these methods is not known. The limited number of comparisons published to date indicates that solutions differ depending upon the algorithm used. Thus, there is a need for comprehensive comparisons to screen the applicability of the vast varieties of techniques. Recently, objectives for clustering in a CM context have been discussed by Vakharia and Wemmerlöv [26]; the measures combine cell density maximization and minimization of exceptional (off-diagonal) elements.
3. Most of the similarity coefficients available in the literature on CF focus on a single criteria. However, given that CF is typically a multi-criteria problem, there is a need to develop better similarity measures to deal with these multiple objectives.
4. Although there are numerous mathematical programming formulations for CF which have been developed to date, these are hard to implement due to computational limitations for large, practical problems.
5. In general, the major shortcomings with prior research are as follows. First, several cell formation procedures proposed consider only a single objective in identifying cells. This ignores the fact that the CF problem, by structure, contains multiple objectives and limitations. For example the array-based methods only focus on the single objective of cell independence, which could make the final configuration unsuitable for implementation since factors such as machine loadings, and the availability of multiple machines of the same type, are not considered when identifying such configurations. Second, other CF methods which focus on minimizing total costs do consider multiple factors but are typically based on heuristic approaches. These methods either consider the multiple objectives in a predetermined hierarchical fashion or require the user to develop a ranking of the objectives in order of importance. Third, there are very few comparison studies in the literature to compare the solution quality of all the methods. This issue is compounded by the fact that the objectives considered, and information requirements of the methods differ. Fourth, very little attention has been paid to the process of converting from existing process arrangements to cells and the corresponding effect on workers training and cost.
6. Very little attention has been paid to the incorporation and measurement of manufacturing flexibility in cellular manufacturing systems. In fact, no method explicitly incorporates this

objective in CF and few, if any, measures to assess flexibility in cellular configurations have been developed to date.

Based on this evaluation, we now proceed to describe several potential directions for future research in the area.

CONCLUSIONS AND SUGGESTIONS FOR A FUTURE RESEARCH AGENDA

In this paper we introduced a comprehensive mathematical formulation of the cell formation (CF) problem. This formulation includes two additional dimensions of the CF problem. The first dimension is grouping workers and the second deals with tooling. Employing a solution-methodology approach we classified, evaluated, and compared the current literature of the CF problem. Based on this critical evaluation, we propose six directions for future research in the CF field.

The primary focus of CF research to date has been grouping parts into part families and machines into machine groups in order to create manufacturing cells such that one or more criteria is optimized. To achieve the goal of creating efficient manufacturing cells it is imperative that we go beyond just grouping parts and machines. This can be achieved by adding workers and tools as third and fourth dimensions to parts and machines in the cell formation process. The CF model presented in Section 2 shows one way of incorporating workers and tools in the CF process.

Simulation studies such as Flynn and Jacobs [112, 113], Steudel [114], and Shafer and Meredith [115] have indicated the importance of workload balancing and machine utilization in determining the advantage of cells. However, many of the better known clustering techniques do not include machine utilization nor consider multiple machines of the same type. To be complete, we believe these methods must be extended and embedded in larger solution schemes that will include such considerations.

Burbidge [85] noted the importance of being able to reassign operations to different machine types in order to obtain good cellular configurations in real problems. This general cell formation problem (GCFP), where we are provided with machines with operation processing capabilities and parts with operation requirements, has received only limited attention [116]. More attention should be given to utilizing the operational flexibility of modern general purpose machines.

Only limited work has been done to address the important issue of incorporating manufacturing flexibility in the CF process [117]. The current CF research deals with manufacturing flexibility from a local point of view (e.g. routing flexibility). There is a need to deal with "cellular" manufacturing flexibility as a strategic and operational competitive weapon and further, flexibility should be used as a design parameter in the CF process.

There are a large number of different CF approaches (see Tables 1 and 2). There is a need to evaluate and compare these approaches based on their applicability, availability, and practicability. These approaches should be tested to evaluate their performance in practical situations including realistic problem sizes and organizational considerations.

The current CF approaches all focus on reorganizing the current shop into a complete cellular shop. However, in certain situations (such as unstable demand environments), virtual cells may be preferred over completely dedicated cells. Although this seems to be implemented in practice, there is a need for researchers to develop approaches by which virtual cells may be identified (i.e., which machines in the current process groups are dedicated to which part sets). This could also facilitate the comparison of a "virtual cell design" to a "cellular design" before implementation.

The applicability of current CF approaches in an industrial context is also limited by the unavailability of interactive software programs supporting such an application. Hence, future research on CF methods should include documented and tested supporting software in order to facilitate industrial applications.

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