MANUFACTURING CELL FORMATION USING SIMILARITY COEFFICIENTS AND PAIR-WISE INTERCHANGE: FORMULATION AND COMPARISON

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Abstract

Many algorithms have been proposed to form manufacturing cells from component routings. Most of these methods require specialized algorithms for implementation. Some others use well-known procedures such as Integer Programming. But these may be difficult for practising managers to comprehend. In this study we propose a simple method that can be implemented using spreadsheet software and an inexpensive layout package such as CRAFT. In addition, we also compare our procedure with many existing procedures using eight well-known problems from the literature.

The results show that the proposed procedure compares well with the existing procedures using three evaluation measures. Therefore, this procedure may be useful to practitioners and researchers.

Keywords: Cellular Manufacturing Algorithms, CRAFT, Similarity Coefficients, Spreadsheets.

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1.0 INTRODUCTION

In order to be successful in today's competitive manufacturing environment, managers are seeking new approaches. One such approach is Group Technology (GT). The GT concept has existed for decades. However,it has only recently become popular in North America. GT is based on the principle of grouping similar parts into families and this can lead to economies throughout the manufacturing cycle (Suresh and Meredith, 1985). These part families may be formed on the basis of either design characteristics or manufacturing characteristics. Design characteristics may include size, shape and function. Manufacturing characteristics include the type and sequence of operations required.

This paper discusses one aspect of forming part-families based on manufacturing characteristics. This aspect is called Cellular Manufacturing (CM) and it is an important part of GT. CM concentrates on the formation of cells or groups of machines that process one or more part-families. Benefits of GT are many (Suresh and Meredith). Various approaches have been suggested for forming manufacturing cells. Many of them may be too complicated for practising managers to comprehend. A recent survey by Wemmerlov and Hyer (1989) suggests that managers are interested in simple cell formation procedures. In this paper, a procedure called SC-CRAFT is developed. It forms manufacturing cells effectively, and is easy to understand and implement.

2.0 BACKGROUND

For an extensive review of cell formation procedures, see Wemmerlov and Hyer (1986). A more recent review of the algorithms, measures of performance and widely used problems can be found in Chu (1989). Some of the more relevant and recent research is briefly discussed here. Three of the more popular approaches are the Bond Energy Algorithm or BEA (McCormick et al., 1972); the Rank Order Clustering Algorithm or ROC (King, 1980); and the ROC2 (King and Nakornchai, 1982). These algorithms identify machine groups and part groups simultaneously. More recently, Askin et al. (1991) identify a Hamiltonian Path Heuristic (HPH) approach to machine grouping. They report results superior to the ROC2 approach. Wei and Gaither (1990) use a 0-1 Binary Programming (BP) approach for an optimal solution. This method is quite flexible since it can incorporate many different types of constraints. Kaparthi and Suresh (1992) report successful results using neural networks to solve the problem. They managed to solve a 10000 part, 100 machine problem, which is relatively very large. Shafer and Meredith (1990) compare six different cell formation algorithms using real data and computer simulation. They found that no algorithm was best for all situations. Miltenburg and Zhang (1991) compare nine well-known algorithms including the ROC2, BEA and algorithms with similarity coefficients using popular problems from the literature and an experimental data set. Based on their results, they suggest the ISNC algorithm of Chandrasekharan and Rajagopalan (1986a) as a good general approach for forming cells. In order to investigate a variety of factors about CM, Wemmerlov and Hyer (1989) surveyed companies that had been using manufacturing cells. Some of their relevant results are: (1) companies preferred simple techniques in order to form cells, (2) over one third of the companies had used formal algorithms, (3) many companies also performed manual analyses such as modifying part routings.

The SC-CRAFT procedure proposed here is similar to the ones described above. But it has the advantage of being simple and allowing for the decision maker to manually perform some analysis. Thus, based on the results of Wemmerlov and Hyer, this procedure may be useful to practitioners.

3 USING SIMILARITY COEFFICIENTS AND THE CRAFT ALGORITHM IN CELL FORMATION: THE SC-CRAFT PROCEDURE

3.1 Determining Similarity Coefficients

Similarity coefficients (SCs) define relationships between pairs of machines or parts. The closer the relationship is, the higher the SC. The SCs are determined for both parts and machines from the part machine incidence matrix. One such matrix is shown in Appendix 4. A '1' in a cell in the matrix indicates that the part is processed on the machine. The two SCs used here are the ones by McAuley (1972) for machines and by Carrie (1973) for parts. Studies by Vakharia and Wemmerlov (1988) and Mosier (1989) respectively compare different similarity coefficients and report that McAuley's and Carrie's SCs performed quite well. McAuley's SC for machines is as follows:

$$m_{kl} = \frac{n_{kl}}{x_k + y_l + n_{kl}}$$

m_{kl} *Similarity coefficient between machines k and l*

n_{kl} *Number of parts processed on both k and l*

x_k *Number of parts processed on machine k but not on l*

y_l *Number of parts processed on machine l but not on k*

An m_{kl} is determined for all possible pairs of machines. Carrie's SC is very similar to that of McAuley's and is given by:

$$p_{ij} = \frac{n_{ij}}{x_i + y_j + n_{ij}}$$

p_{ij}	*Similarity coefficient between parts i and j*
n_{ij}	*Number of machines processing both i and j*
x_i	*Number of machines processing part i but not part j*
y_j	*Number of machines processing part j but not part i*

A p_{ij} is computed for all possible pairs of parts. A method of calculating SCs for a part machine matrix using LOTUS 1–2–3 is shown in Appendix 4.

3.2 Using the Similarity Coefficients in the CRAFT algorithm

CRAFT stands for **C**omputerized **R**elative **A**ssignment of **F**acilities **T**echnique (Buffa et al., 1964) and provides heuristic solutions for the facility layout problem. Given a set of departments such as work areas, in a layout such as an office, the objective is to minimize the total cost of material handling between departments. For example, two departments which interact highly with each other would be placed close to each other so that cost of material handling between them (which depends on the distance and amount of interaction between the two) is reduced. For an extensive overview of the facility layout problem and the various algorithms available to solve it, see Kusiak and Heragu (1987). CRAFT is a popular layout algorithm because it is simple and effective. Descriptions of it can be found in most introductory operations management textbooks and inexpensive CRAFT computer codes are readily available. The CRAFT module in STORM (Emmons et al.,1992), a multi-purpose computer package, was used in this paper. This CRAFT module can handle up to 50 departments.

CRAFT requires three inputs: 1) the material handling flow between every pair of departments; 2) the transportation cost per unit of material flow per unit distance; and 3) the initial layout. In the proposed procedure where parts or machines are analogous to departments, the similarity coefficient between each pair of machines or parts forms the first input. The intention is to have machines with high similarity, a surrogate for material handling flow, placed close to each other. For parts, although they are not placed close to each other in a physical sense, those parts with high similarity should be grouped together. The groupings for the parts and machines form two different CRAFT problems. The second input, the transportation cost, is $1/unit flow/unit distance in all cases. The distance between the centres of adjacent departments is unity. The final input is the initial layout. The shape of the layout for the seven parts in the example problem (Appendix 4) is shown in Figure 1. CRAFT will rearrange the sequence of parts so that similar parts are close to each other in the final sequence. The initial layout for the machines is similar except that the layout is vertical. The initial layout for the machines in the example problem is shown in Figure 2.

---Insert figure 1---

---Insert figure 2---

3.3 Obtaining Part and Machine Sequences using CRAFT

CRAFT operates by considering switching the positions of pairs of departments. Given the initial layout, it takes the first department in the layout and considers switching its position with each of the other departments. Given 'n' departments, this requires (n-1) evaluations. This is repeated for each of the 'n' departments. The switch that reduces the total cost of material handling flow the most is implemented. This procedure is repeated until costs cannot be reduced. The layout at that point is the final layout. In the example problem, CRAFT provided the final part and machine sequences shown in Figure 3. Filling in the '1's gives the final part machine matrix.

---Insert figure 3---

Machines 2 and 4 form the first cell, machines 1 and 7 form the second cell, and machines 3, 6 and 5 form the third cell. The processing of part 4 on machine 3 is the only operation that is not assigned to a machine cell. This results in an inter-cell transfer and is known as an exceptional element.

3.4 Visual Analysis of the CRAFT Solutions

The final layout using CRAFT is sensitive to the initial layout. For example, if two different initial machine sequences are used, the final machine sequences could be different. To ensure a good solution, five random different initial layouts generated by STORM for the parts and machines were used in the test problems. This gave 5*5 or 25 different final part-machine incidence matrices. These were then visually analyzed to determine the cells. Figure 3 shows the cells identified in one of the 25 final matrices for the example problem.

Since cell formation is a design issue, computation time was not considered important. STORM does not record the CPU time for solution. But it does record the elapsed time. The maximum elapsed time was 4 minutes, for a 43 part problem on an IBM PS/2 Model 77 personal computer.

4 COMPARISON WITH OTHER ALGORITHMS

4.1 Problem Set

To test the effectiveness of the SC-CRAFT procedure, eight problems from the literature were solved. Table 1 shows the different problems and their characteristics.

---Insert Table 1 ---

Problems 1, 3, 4, 5 and 6 were solved by Miltenburg and Zhang using nine different algorithms. In these problems, the SC-CRAFT procedure results are compared to their results. In addition, problems 2, 3 and 4 were solved by Askin et al. using the HPH method. They reported better results than the ROC2 algorithm. So the SC-CRAFT results from these problems are also compared to the HPH method results. Finally, problems 7 and 8 were solved optimally by Wei and Gaither using Marsten's (1987) XMP mathematical programming package. The optimal solutions to these two problems serve as benchmarks to evaluate the SC-CRAFT performance.

4.2 Performance Measures for Cell Formation Solutions

The results are presented as part-machine incidence matrices which by itself cannot convey the quality of the solution. Therefore, measures are needed to compare these matrices. The three measures used by Miltenburg and Zhang are used here. They are: (1) The Grouping Measure; (2) The Bond Energy Measure; and (3) The Clustering Measure. These measures were chosen because together they measure the within cell utilization, inter-cell movement, the ability to convert a random matrix into a diagonal form, and the ability to cluster the '1's together. Thus they are comprehensive in their evaluation of cell formation. The first measure is the primary measure, while the other two are secondary measures.

4.2.1 The Grouping Efficiency Measure

Let n_1 denote the number of '1's in the diagonal blocks (which form the cells) in the matrix. P_i and Q_i represent the number of parts and machines in each cell i respectively. Then

$$e_1 = \frac{n_1}{\sum_{i=1}^{K} P_i Q_i}$$

where K is the number of cells in the matrix and e_1 is an indicator of the within cell density of a cell. Higher values of e_1 indicate greater similarity between the parts or machines in this cell. Ideally, we would want the whole cell filled with '1's. Also

$$e_2 = 1 - \frac{n_1}{n_1 + n_0}$$

where n_0 is the number of '1's outside the cells or inter-cell transfers. Lower values of n_0 and thus lower values of e_2 indicate fewer inter-cell transfers and better solutions. The grouping efficiency, 'e' is then given by

$$e = e_1 - e_2 \qquad -1 \le e \le 1$$

In Figure 3, e_1 is 17/17 or 1 and e_2 is equal to (1- (17/(17+1))) or 0.056 leading to a grouping efficiency (e) of 0.944.

4.2.2 The Bond Energy Measure

When algorithms form clusters, the '1's are placed close to each other. The strength of the clustering can be computed by 'b', the normalized bond energy measure of a matrix where

$$b = \frac{\sum_{i=1}^{M} \sum_{j=1}^{N-1} a_{ij} a_{i(j+1)} + \sum_{i=1}^{M-1} \sum_{j=1}^{N} a_{ij} a_{(i+1)j}}{\sum_{i=1}^{M} \sum_{j=1}^{N} a_{ij}}$$

The more closely linked the '1's are, the higher the total bond energy measure will be and in turn the higher and better the 'b' will be. In the example in Figure 3, 'b' is 1.17.

4.2.3 The Clustering Measure

Cell formation algorithms cluster '1's from a random matrix along the diagonal as shown in Figure 3 so that it becomes easier to identify the cells. In addition the further the distance of a '1' from the diagonal, the more likely it is that inter-cell travel will result. So the normalized clustering measure of a matrix, 'c' calculates the average distance of a '1' from the diagonal.

$$c = \frac{\sum_{all\ a_{ij}=1} \sqrt{(h_{a_{ij}})^2 + (v_{a_{ij}})^2}}{\sum_{i=1}^{M} \sum_{j=1}^{N} a_{ij}} \quad where$$

$h_{a_{ij}}$ - *horizontal distance between a non-zero* a_{ij} *and the diagonal.*

$$= i - \frac{j(M-1)}{N-1} - \frac{N-M}{N-1}$$

$v_{a_{ij}}$ - *vertical distance between a non-zero* a_{ij} *and the diagonal.*

$$= j - \frac{i(N-1)}{M-1} + \frac{N-M}{M-1}$$

The closer a '1' is to the diagonal, the less is the Euclidean distance to the diagonal, and the lower and better 'c' is. In Figure 3, 'c' is 1.10. Note that this measure is based on the north-west to south-east diagonal. If the cells are formed along a south-west to north-east diagonal for example, the rearranged matrix will have a poor clustering measure. This can be rectified by rearranging the cells along the north-west to south-east diagonal.

5.0 RESULTS

The results presented here are based on the visual analysis of the solutions provided by the SC-CRAFT procedure. Out of the twenty-five candidate solutions, the one in which the cells could be most clearly identified was selected. Often, more than one solution had clearly identifiable cells. The results are discussed in Table 2 where the SC-CRAFT results are compared to the SC-Seed of Miltenburg and Zhang, the HPH method, and 0-1 Programming. Not all of the four procedures solved all eight problems as shown in the numerical results table in Appendix 1. In the Miltenburg and Zhang study, with respect to the five problems included here, the SC-Seed performed best. The 'nine' in Table 2 refers to the nine algorithms compared by Miltenburg and Zhang. The actual cells formed are shown in Appendix 3. The results show that SC-CRAFT performed quite well. In addition, by generating multiple solutions, the decision maker is presented with different solutions, some of which may be better than the others under different situations.

The SC-CRAFT performed well even when compared to the 0-1 Programming algorithm of Wei and Gaither. The comparison was made between the unconstrained versions of Wei and Gaither and SC-CRAFT. SC-CRAFT has the advantage of taking much less computer time and thus may be preferable for large problems. But 0-1 Programming is more flexible than SC-CRAFT because different types of constraints can be incorporated.

---Insert Table 2 ---

6.0 CONCLUSION

The tests conducted indicate that the SC/CRAFT procedure is an effective one regardless of matrix density. In seven out of the eight problems, it performed well on the primary measure of the quality of the solution, the grouping measure. In addition, SC-CRAFT performed extremely well on the two secondary measures in all the problems. The two secondary measures indicate the ability of an algorithm to rearrange random part-machine incidence matrices such that it becomes easy to identify cells. As reported by Wemmerlov and Hyer (1989), many companies performed manual analysis. The ability to form diagonal matrices will ensure that decision maker has good starting solutions. Based on these, manual analysis can be performed to form cells that suit the particular environment. This manual analysis may include factors such as the capacity of the machines and the capabilities of the employees. Thus, performing well on the two secondary measures may be as important as doing well on the primary measure. In addition, since multiple solutions are generated, the decision maker now has the flexibility of choosing from many solutions so that the best solution for a particular situation can be selected. For example, as seen in Appendix 1, the three-cell solution for Problem 2 has higher within cell utilization than the two-cell solution, but has more inter-cell movement. If parts can be rerouted or machines duplicated, the inter-cell movement can be reduced and the three-cell solution may be preferable. If part re-routing or machine duplication is expensive, or inter-cell movement will cause significant problems, the two-cell solution may be preferable. So it is important to have multiple solutions to choose from. Another advantage of the SC-CRAFT procedure is its simplicity. Many cell formation algorithms would be difficult for practitioners to comprehend. The SC-CRAFT procedure is relatively easy to understand and simple to implement. Wemmerlov and Hyer (1989) report that simplicity was a characteristic of methods used by companies. The SC-CRAFT has been implemented using LOTUS 1-2-3 and since this software is widely used, it is likely that the decision maker is familiar with it. The second software required, CRAFT, is also easy to acquire and a 50-department version along with various other operations management\management science applications costs only about $25.

In summary, the effectiveness of the SC-CRAFT approach, along with its simplicity, and the low cost of implementation of the procedure, should make it useful for practising managers and researchers alike. Further research could involve using an expert system along with this procedure for analyses such as modifying part routings, duplicating machines or subcontracting.

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Appendix 1
Numerical Results

		SC-CRAFT					SC-Seed			HPH Method			0-1 Programming		
	No. of cells	e_1	e_2	e	c	b	e	c	b	e	c	b	e	c	b
1	3	0.92	0.0	0.92	2.06	1.41	0.93	2.13	1.37	-	-	-	-	-	-
2	2	0.57	0.12	0.45	3.78	1.27	-	-	-	-	-	-	-	-	-
	3	0.65	0.31	0.34	3.78	1.29	-	-	-	0.37	4.69	1.29	-	-	-
3	4	1	0.15	0.85	3.99	1.33	0.85	4.26	1.31	0.85	3.87	1.38	-	-	-
4	4	0.59	0.23	0.36	7.7	1.14	0.45[1]	8.24	1.02	0.42[1]	8.44	1.11	-	-	-
5	4	0.78	0.02	0.76	2.94	1.56	0.76	3.83	1.40	-	-	-	-	-	-
6	1	0.57	0	0.57	5.16	1.33	0.57	6.20	1.21	-	-	-	-	-	-
	2	0.79	0.31	0.48	5.16	1.33	-	-	-	-	-	-	-	-	-
7	4	0.37	0.06	0.31	9.31	1.09	-	-	-	-	-	-	0.16[2]	3.83	0.91
8	2	0.33	0	0.33	3.01	1.24	-	-	-	-	-	-	0.33	2.91	1.08
	4	0.66	0.03	0.66	3.01	1.24	-	-	-	-	-	-	0.66	2.91	1.08

NOTE: [1] Five cell solution
[2] Two cell solution

Appendix 2
Multiple Solutions for Problem 2

	Parts																		
Machines	12	18	19	11	9	17	16	10	15	14	5	1	4	7	13	6	8	2	3
5		1	1																
3	1	1	1																
2			1			1	1												
4	1	1	1	1	1	1	1	1											
8	1	1	1	1	1	1	1		1										
9		1	1	1	1	1		1	1	1									
6	1	1	1	1			1		1	1	1	1							
1					1	1	1	1		1									
7						1	1	1	1	1	1		1	1	1	1	1		
10									1	1	1		1	1	1			1	
11														1	1	1	1	1	1
12												1			1	1	1		1

Three cell solution for problem 2

	Parts																		
Machines	12	18	19	11	9	17	16	10	15	14	5	1	4	7	13	6	8	2	3
5		1	1																
3	1	1	1																
2			1			1	1												
4	1	1	1	1	1	1	1	1											
8	1	1	1	1	1	1	1		1										
9		1	1	1	1	1		1	1	1									
6	1	1	1	1			1		1	1	1	1							
1					1	1	1	1		1									
7						1	1	1	1	1	1		1	1	1	1	1		
10									1	1	1		1	1	1			1	
11														1	1	1	1	1	1
12												1			1	1	1		1

Two cell solution for problem 2

Appendix 3
Cells Formed by SC-CRAFT

PROBLEM		CELL 1	CELL 2	CELL 3	CELL 4
1	Parts	8 5 2	9 6 3 4	1 7 10	
	Machines	8 5 3 15 13	4 14 9 6 1	7 2 10 11 12	
2	Parts	12 18 19 11 9 17 16	10 15 14 5 1 4	7 13 6 8 2 3	
	Machines	5 3 2 4 8 9	6 1	7 10 11 12	
	Parts	12 18 19 11 9 17 16 10 15 14	5 1 4 7 13 6 8 2 3		
	Machines	5 3 2 4 8 9 6 1	7 10 11 12		
3	Parts	7 18 4 20 6 3	10 12 15 1 5	9 17 11 14 13 19 8 2 16	
	Machines	2 8 4 7	5 6	1 3	
4	Parts	31 26 25 22 35 13 39 17 6 34	4 7 18 10 40 32 42 37 2 38 28	1 12 36 8 33 43 23 14 19 41 21 5 15 29 9 16	11 20 27 3 24 30
	Machines	7 10 14 3	1 16 9 2 6	8 5 15 4	11 12 13
5	Parts	34 16 8 14 19 26 22	12 24 13 2 27 7 10 18 31	29 17 5 15 1 3 23 25 20	35 32 28 30 9 11 4 21 6 33
	Machines	5 6 10 9 20	13 4 14 2 18	3 17 8 7 1	19 11 16 15 12
6	Parts	6 11 12 20 7 5 8 13 17 19 16	2 1 10 15 14 3 18 9 4		
	Machines	7 3 5 6	8 1 4 2		
7	Parts	27 16 34 36 17 5 37 4 26 18	22 21 3 1 30 13 9	41 33 10 32 31 39 12 40 23 11 2 20 14 29 8 19	6 38 24 25 7 35 28 15
	Machines	15 5 26 7 17 18 14 25	11 1 2 21 22 3 23 10 12 27 28 8	29 19 20 30 9	4 6 16 13 24
8	Parts	19 20 17 2 1 23	7 6 18 8	24 3 4 21	11 14 22 16 10 12 9 15 5 13
	Machines	4 5 7	13 12 1	10 11 3 2	14 9 8 6
	Parts	19 20 17 21 23 7 6 18 8 24	3 4 21 11 14 22 16 10 12 9 15 5 3		
	Machines	4 5 7 13 12 1	10 11 3 2 14 9 8 6		

Appendix 4

Procedure for Determining SC's using LOTUS 1-2-3

Step 1: Enter the part machine incidence matrix A

	A	B	C	D	E	F	G	H	I	J
						Part Machine Incidence Matrix				
						Part				
			1	2	3	4	5	6	7	
										TOTAL
5	Machine	1	1	0	0	1	0	0	0	2
6		2	0	1	0	0	0	0	1	2
7		3	0	0	1	1	1	1	0	4
8		4	0	1	0	0	0	0	1	2
9		5	0	0	1	0	1	1	0	3
10		6	0	0	1	0	1	1	0	3
11		7	1	0	0	1	0	0	0	2
12	TOTAL		2	2	3	3	3	3	2	

Step 2: Determine the transpose of A, A^T
Command: /Range Transpose (define ranges)

Part Machine Incidence Matrix

			Machine							
			1	2	3	4	5	6	7	TOTAL
25	Part	1	1	0	0	0	0	0	1	2
26		2	0	1	0	1	0	0	0	2
27		3	0	0	1	0	1	1	0	3
28		4	1	0	1	0	0	0	1	3
29		5	0	0	1	0	1	1	0	3
30		6	0	0	1	0	1	1	0	3
31		7	0	1	0	1	0	0	0	2
32	TOTAL		2	2	4	2	3	3	2	

Step 3: Determine AA^T

Command: /Data Matrix Multiply (define ranges)

	A	B	C	D	E	F	G	H	I	J
						Machine Commonality				
						Machine				
			1	2	3	4	5	6	7	
45	Machine	1	2	0	1	0	0	0	2	
46		2	0	2	0	2	0	0	0	
47		3	1	0	4	0	3	3	1	
48		4	0	2	0	2	0	0	0	
49		5	0	0	3	0	3	3	0	
50		6	0	0	3	0	3	3	0	
51		7	2	0	1	0	0	0	2	

Step 4: Determine A^TA
Command: /Data Matrix Multiply (define range)

Part Commonality

Part

			1	2	3	4	5	6	7
65	Part	1	2	0	0	2	0	0	0
66		2	0	2	0	0	0	0	2
67		3	0	0	3	1	3	3	0
68		4	2	0	1	3	1	1	0
69		5	0	0	3	1	3	3	0
70		6	0	0	3	1	3	3	0
71		7	0	2	0	0	0	0	2

Step 5: Determine SC for machines for cell C85 and copy.
C85: C45/(C$32+$J5-C45)
Command: /Copy Range (C85..I91)

	A	B	C	D	E	F	G	H	I	J
					Similarity Coefficient: Machines					
						Machine				
			1	2	3	4	5	6	7	
85	Machine	1	1.00	0.00	0.20	0.00	0.00	0.00	1.00	
86		2	0.00	1.00	0.00	1.00	0.00	0.00	0.00	
87		3	0.20	0.00	1.00	0.00	0.75	0.75	0.20	
88		4	0.00	1.00	0.00	1.00	0.00	0.00	0.00	
89		5	0.00	0.00	0.75	0.00	1.00	1.00	0.00	
90		6	0.00	0.00	0.75	0.00	1.00	1.00	0.00	
91		7	1.00	0.00	0.20	0.00	0.00	0.00	1.00	

Step 5: Determine SC for parts for cell C101 and copy.
C105: C65/(C$12+$J25-C65)
Command: /Copy Range (C101..I111)

Similarity Coefficient: Parts

			Part						
			1	2	3	4	5	6	7
105	Part	1	1.00	0.00	0.00	0.67	0.00	0.00	0.00
106		2	0.00	1.00	0.00	0.00	0.00	0.00	1.00
107		3	0.00	0.00	1.00	0.20	1.00	1.00	0.00
108		4	0.67	0.00	0.20	1.00	0.20	0.20	0.00
109		5	0.00	0.00	1.00	0.20	1.00	1.00	0.00
110		6	0.00	0.00	1.00	0.20	1.00	1.00	0.00
111		7	0.00	1.00	0.00	0.00	0.00	0.00	1.00

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Number	Problem	Parts (N)	Machines (M)	Matrix Density[1]
1	Chan & Milner (1982)	10	15	0.31
2	De Witte (1980)	19	12	0.33
3	Chandrasekharan and Rajagopalan (1986a)	20	8	0.38
4	Burbidge (1975)	43	16	0.18
5	Carrie (1973)	35	20	0.19
6	Chandrasekharan and Rajagopalan (1986b)	20	8	0.57
7	King (1980)	24	14	0.175
8	Kumar and Vanelli (1987)	41	30	0.105

[1] The matrix density is given by $\dfrac{\sum_{i}^{M} \sum_{j}^{N} a_{ij}}{M x N}$ where $a_{ij} = (0,1)$, one element in the part machine matrix.

Test Problem Characteristics

Table 1

Problem	Cells	e*	c	b	Comments
1	3	SC–CRAFT very close to SC–Seed	SC–CRAFT better than SC-SEED	SC–CRAFT better than SC-SEED	'b' for SC–CRAFT is even better than BEA which maximizes bond energy. Only one of the nine algorithms is better than SC-CRAFT for 'c'.
2	2	Solution obtained only by SC-CRAFT and was not obtained by HPH . The 2- and 3-cell solutions are shown in Appendix 2.			The 2-cell solution has less exceptional elements than the 3-cell solution. If machines cannot be duplicated, part routings cannot be modified or inter-cell movement is expensive, this solution may be better than the 3-cell solution.
	3	HPH slightly better than SC–CRAFT	HPH better than SC–CRAFT	HPH, SC-CRAFT are same	
3	4	HPH, SC–Seed, SC–CRAFT same	HPH better than SC–Seed, SC–CRAFT	HPH better than SC-CRAFT, SC-SEED	In b, SC–CRAFT better than any of the nine algorithms. Only two of the nine are better for 'c'.
4	4	SC–Seed better than HPH and SC–CRAFT	SC–CRAFT better than HPH, SC-SEED	SC–CRAFT better than HPH, SC-SEED	HPH and SC–CRAFT have same number of exceptional elements. Only one algorithm from the nine is better than SC-CRAFT for 'b', 'c'.
5	4	SC–CRAFT and SC–Seed are same	SC–CRAFT better than SC-SEED	SC–CRAFT better than SC-SEED.	SC-CRAFT is the best of nine algorithms for 'b' and 'c'.
6	1	SC–CRAFT and SC–Seed the same	SC–CRAFT is better than SC-SEED	SC–CRAFT is better than SC–Seed	SC-CRAFT is the best of all nine algorithms for 'b' and 'c'.
	2	Not obtained by the other algorithms			Has better within cell utilization but more exceptional elements than 1-cell solution. If exception elements can be reduced by routing changes, this will be a better solution than the 1-cell solution.
7	4	SC–CRAFT is better than Wei & Gaither	Wei & Gaither better than SC–CRAFT	SC–CRAFT is better than Wei & Gaither	Wei & Gaither obtain two cell solution.
8	2,4	SC–CRAFT and Wei & Gaither obtain same cells	Wei & Gaither is better than SC–CRAFT	SC–CRAFT better than Wei & Gaither	SCFA and Wei & Gaither obtain 2- and 4-cell solutions.

* In all five problems, SC-SEED had the best grouping efficiency out of the nine algorithms tested by Miltenburg and Zhang.

Comparative Performance of SC-CRAFT
Table 2

Figures

1) Figure 1 - Initial part layout

2) Figure 2 - Initial machine layout

3) Figure 3 - Final part and machine layout

1	2	3	4	5	6	7

(1)

1
2
3
4
5
6
7

	2	7	4	1	6	3	5
2	1	1					
4	1	1					
1			1	1			
7			1	1			
3			1		1	1	1
6					1	1	1
5					1	1	1

(3)

Biographical Sketch

JAYDEEP BALAKRISHNAN is currently assistant professor of Operations Management in the Faculty of Management at the University of Calgary. He has a PhD from Indiana University and an MBA from the University of Georgia, both in Operations Management. His undergraduate degree is in Mechanical Engineering from Nagpur University in India. He has also worked for the automobile industry in India. Dr. Balakrishnan's research interests include facility layout and cellular manufacturing. He has published in **Management Science, The European Journal of Operational Research** and **The Production and Inventory Management Journal**. He has also presented papers at various international conferences.