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A New Approach to Cell Formation in Group Technology with Alternative Solutions

Mohammad Raafat A. Abou-zeid[a]*, Amer A. Boushaala[b], Haneya J. Madi[c]

[a, b, c] *I &MSE Dept, University of Benghazi, Benghazi, Libya.*
[*]*Corresponding author: Tel.: +218-770-4902; e-mail: mrabouzeid@uob.edu.ly.*

ABSTRACT

The concept of group technology (GT) in design of manufacturing systems is explained. Achieving the highly appreciated benefits of applying GT mainly depends on proper design of manufacturing cells within a manufacturing system. As the ideal design of manufacturing cells is practically unattainable, research work aims at optimizing this process within a number of objectives. This paper categorizes and briefly introduces some of the previously published research work. Then, a proposed approach for design of manufacturing cells is introduced with the objective of minimizing the number of exceptional elements, needing processing in more than one cell, thus reducing the material handling needs between cells which reduces efficiency and increases costs. The mathematical model for this approach, based on the 0-1 incidence matrix of parts/machines, is explained. Five performance measures for the approaches of design of cells are applied to the proposed approach. Twelve previously published bench mark problems with eighty eight different solutions, based upon different approaches from literature, were used in the comparison and evaluation of the performance of the proposed approach/ model. The result of comparison indicated that the proposed approach gave better solutions in forty nine percent of the cases, with equal performance in the remaining cases. Thus, the proposed approach is a highly valued addition to the available approaches.

Keywords: *Group technology, Formation of manufacturing cells, Mathematical programming, Exceptional elements.*

1. Introduction

The group technology (GT) concept evolved to face growing competition in industry and the need to successfully and economically meet the current trend towards low volume production of a variety of products. This is achieved through following the principle that similar things should be done similarly. Therefore, GT is a tool for organizing and using information about component similarities to improve the production efficiency of a manufacturing firm. Component similarities form the basis for creating families of components to be produced by all machines needed, in a manufacturing cell. This leads to form a number of cells for to manufacture all components / parts.

The ideal, mostly, un attainable, configuration for a manufacturing firm is where components and machines are grouped in a diagonal form as depicted in Figure1 for three cells. However, in practice, some parts may need processing in more than one cell. These are called "exceptional parts" and machines processing them are "bottleneck machines". The intercellular moves of parts can be eliminated by duplicating sufficient number of bottleneck machines. However, this involves additional costs and should be kept at a minimum such as not to offset the advantages of GT.

Implementation of GT resulted in significant benefits for all the functional areas of manufacturing, e.g., design manufacturing, manufacturing engineering, production control quality [8,10].

	1	2	3	4	5	6	7	8	9	10	11	12
A	1	1	1	1								
B	1		1	1	1	1						
C			1	1	1	1						
D							1	1	1	1		
E							1	1	1	1		
F							1	1		1		
G											1	1
H											1	1

Figure 1: The ideal solution for components and machines.

2. Strategies for manufacturing cells formation

Strategies for manufacturing cells formation depend on where to start from, either from machines, parts, or concurrently considering machine cells and part families.

3. Performance measures for methods of forming manufacturing cells

The performance measures consider, for purpose of evaluation of methods, the number of ones and zeros in the diagonal blocks and in the off diagonal blocks, as well as voids in the diagonal blocks. The mostly used measures are grouping efficiency η_3 [31], grouping efficacy η [8], weighted grouping efficacy ω [31], modified grouping efficacy τ_2 [30], grouping index GI [29], grouping capability index GCI [31], and number of exceptional elements e_0. For example, weighted grouping efficacy ω is calculated by placing a weight q on each entry inside the diagonal blocks and a weight 1-q on the exceptional elements.

4. Approaches for formation manufacturing cells, an overview

Relevant literature may be classified into four categories. These are similarity coefficients based methods [13, 32, 38, 41], mathematical programming techniques [2, 4, 6, 12, 21, 33, 36, 42], heuristic methods [14, 18, 24, 28, 37, 40], and genetic algorithms based methods [10, 43].

Kusiak [22], considered basically the matrix approach for forming cells of a specified number. Then, Visvanathan [38], developed on Kusiak's model to relieve its limit and to find the optimal number of cells.

The objectives of the mathematical programming formulations varied among a number of researchers. Examples of such objectives are minimizing number of exceptional elements [5], minimizing intercellular part movements [23], minimizing dissimilarity between parts in each cell [4], finding optimal labor assignment and groupings [36], and increasing productivity while maximizing cell independency [42].

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In heuristic methods, considerations were given, for example, to operations sequence [34], operation sequence and number of cells [24], sequence based material flow [37], balanced workload [40], and increasing total profits of the system [14].

The genetic algorithm's based approaches considered reducing setup times and work-in- process [10], parts volume and processing time [43], operations times [26], layout design to minimize material handling costs [20], among other objectives.

5. A proposed approach for formation of manufacturing cell

The proposed approach [25], is based on Won and Lee's approach [42], with a modification to give the designer the ability to control cell sizes while beingable to use the basic commercial integer linear programming software available. Moreover, number of alternatives are produced for the same number of cells. This gives flexibility to the system's designer.

The objective function and constraints are as follow:

$$Z=\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}\left(\sum_{k=1}^{p}\left|X_{ik}-Y_{jk}\right|\right)/2 \tag{1}$$

The objective function Z can be linearized in the following manner as treated by Boctor [5], by introducing two sets of non-negative variables u_{ikj} and v_{ikj}, where

$$X_{ik}-Y_{jk}+u_{ikj}-v_{ikj}=0,\ \forall(i,j)\in R,\ k=1\ldots p \tag{2}$$

Then minimizing Z becomes equivalent to:

$$\text{Minimize: } \sum_{k=1}^{p}\sum_{(i,j)\in R}(u_{ikj}+v_{ikj})/2$$

The modification entails the use of just one variable u_{ikj} instead of using two variables u_{ikj} and v_{ikj}.

The objective function:

$\sum_{k=1}^{p}\sum_{(i,j)\in R}(u_{ikj}+v_{ikj})/2$ is replaced by

$\sum_{k=1}^{p}\sum_{(i,j)\in R}(u_{ikj})$ to reduce the repetition.

Thus, objective function and necessary constraints can then be formulated as follows:

$$\text{Minimize } \sum_{k=1}^{p}\sum_{(i,j)\in R}(u_{ikj}) \tag{3}$$

Subject to (3) and:

$$\sum_{k=1}^{p} X_{ik}=1 \quad i=1,\ldots, m \tag{4}$$

$$L_c\le\sum_{i=1}^{m} X_{ik}\le U_c,\quad k=1,\ldots,p \tag{5}$$

$$\sum_{k=1}^{p} Y_{jk}=1,\quad j=1,..,n \tag{6}$$

$$L_f\le\sum_{j=1}^{n} Y_{jk}\le U_f,\quad k=1,\ldots,p \tag{7}$$

$$X_{ik}\ge 0,\ i=1,..,m;\ k=1,.....,p \tag{8}$$

$$y_{jk}\ge 0,\ j=1,..,n;\ k=1,....,p \tag{9}$$

$$u_{ikj},\ v_{ikj}\ge 0,\ k=1,.....,p;\ (i,j)\in E \tag{10}$$

Where:

n: number of parts, m: number of machines, p: number of cells, i: index of machine type, i=1,……m, j: index of part type, j= 1,…..n, k: index of cells (families), k = 1,….p, L_c= lower limit on machine cell size, U_c=upper limit on machine cell size, L_f = lower limit on part family size, U_f = upper limit on part family size, A = [a_{ij}], binary PMIM, n_j: Total number of operations required for part j, r : index of operation sequence number r = 1….n_j,

Decision variables:

Y_{jk}: binary variable indicating if part j is assigned to cell k, X_{ik}: binary variable indicating if machine i is assigned to cell k. The objective function (3), is accompanied by the constraints (2) and (4) to (10). Constraint (4) ensures that each machine is assigned to exactly one machine cell. Constraint (5) means that at least L_c machines must be assigned to each cell and at most U_c machines are assigned to each cell. Constraint (6) requires that each part belongs to exactly one part family. Constraint (7) ensures that at least L_f parts must be assigned to each family and at most U_f parts are assigned to each family. Constraints (8) and (9) guarantee the binary solution for machine assignment and part assignment, respectively. Constraint (10) ensures the binary property of continuous variables u_{ikj} and v_{ikj}

6. Computation results and evaluation of the quality of the performance measures of the problems considered

The final block diagonal matrix can be checked to evaluate the quality of the solution relative to the chosen performance measures. For the purpose of comparing the performance of our proposed approach with previously published approaches, thirteen problems with eighty nine solutions resulting from different procedures, were prepared, Table1. The size of the problems ranges from five machines and seven parts to sixteen machines and forty three parts, thus, the ranges represent small problems to comparatively large ones.

The problems were solved by different methods. the solutions of some problems are taken from published papers while other problems are solved for the current work by applying a MATLAB program

to calculate the similarity coefficients and the IMROVE algorithm [11], to obtain final solutions. The performance measures are: grouping index GI, weighted grouping efficacy ω, grouping capability index GCI, modified grouping efficacy τ_2 and grouping efficacy η and number of exceptional elements e_0.

7. Results and Discussion

Table2 presents a summary of computational results regarding comparative performance of the earlier solution procedures and the proposed approach.

It should be noticed that a solution is better when:

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a. It has a higher value of the following measures: grouping index, weighted grouping efficacy, grouping capability index, modified grouping efficacy and grouping efficacy, and

b. It is with minimum number of exceptional elements (e_0).

Because of their dependence on the number of clusters, values of grouping index (GI), weighted grouping efficacy (ω), grouping capability index (GCI), modified grouping efficacy (τ_2) and grouping efficacy (η) were not compared for cases with unequal number of clusters. The comparison of the performance measures resulted in the following:

a. The ω measure has low discriminating capability and weakness sensitivity.

b. The η measure gives the best result for the worst solution, so η has the worst discriminating characteristic, since this method does not consider the weight factor.

c. GCI has high the discrimination compared with other performance measures.

d. GI and τ_2 have the same values for all solutions in all problems because they have the same equation for all problems, since A=0 for all problems. GI and τ_2 show no preference for any solution for all problems even with changing the method or with different number of clusters.

It is worthy to point out that results presented in Table 2 demonstrate that the proposed approach results in solutions of better or equal quality when its solutions are compared with the solutions obtained by conventional algorithms for the test problems.

Due to space limitation, two example problems are given to demonstrate the superiority of the proposed approach.

Example 1[25]

Solution of problem 4/6, Table 1 for three cells, the solution of Kusiak's approach as an input to IMPROVE algorithm, applying ROC approach, and using the proposed approach are given in Figures 3, 4, 5. The proposed approach approach's solution is better in terms of the performance measures, as given in Table2.

	1	2	3	4	5	6	7	8	9	1	1	1
1				1	1	1	1	1			1	1
2						1	1		1			
3				1		1						
4	1	1	1	1								
5	1	1										
6				1		1		1		1	1	
7					1	1	1	1				
8				1			1	1	1	1	1	1
9		1										
1		1		1	1			1		1		1

Figure 2. Machine – part incidence matrix for problem 4 [38].

	1	2	3	6	7	9	4	5	8	1	1	1
4	1	1	1				1					
5	1	1										
9		1										
2				1	1	1						
3				1			1					
7				1	1			1	1			
1				1	1		1	1	1		1	1
6				1			1		1	1	1	
8					1	1	1		1	1	1	1
1		1					1	1	1	1		1

Figure 3. Solution for problem 4/6 of IMPROVE algorithm by using solution of (Kusiak's approach with p=3 as input) [11].

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	1	2	3	4	5	8	1	1	1	6	7	9
4	1	1	1	1								
5	1	1										
9		1										
1		1		1	1	1	1		1			
1				1	1	1		1	1	1	1	
6				1		1	1	1		1		
8				1		1	1	1	1		1	1
2										1	1	1
3				1						1		
7					1	1				1	1	

Figure 4. Solution for problem 4/7 by applying ROC approach [11].

	4	5	6	7	8	1	1	1	1	9	2	3
1	1	1	1	1	1		1	1				
3	1		1									
6	1		1		1	1	1					
7		1	1	1	1							
8	1			1	1	1	1	1		1		
1	1	1			1	1		1			1	
2			1	1						1		
5									1		1	
4	1								1		1	1
9											1	

Figure 5. Solution of the proposed approach [25].

Example 2 [25]

The machine – part incidence matrix for a 16x43 problem [19],is utilized to demonstrate the effectiveness of the proposed approach. The data for problem 6 are given in Figure 6 [19]. In the following section a solution for 3 cells, and applying ROC2 algorithm [3], the solution is given in Figure 7, resulting in 31 exceptional elements and performance measures GI, ω, and GCI as 0.64, 0.25 and 0.76 respectively.

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Table 1: Selected problems, sources, solutions approaches and characteristics of solutions [25].

Problem No./ Solution No.	Source	Approach	m	n	p
1/1, 1/2, 1/3, 1/4, 1/5, 1/6, and 1/7	Waghodekar and Sahu(1984,) Fig. 2(a) [39]	ROC, MACE algorithm, *Kusaik's model, *Viswanathan model, *Islam and Sarker model, *MP1 model, and *MP2 model	5	7	2
2/1	Chandrasekharan and Rajagopalan, (1986) [7]	HGGA algorithm	8	20	2
3/1, 3/2, 3/3, 3/4, 3/5, 3/6, 3/7, 3/8, 3/9, 3/10, 3/11, 3/12, 3/13, and 3/14	James et al.. (2007) [17]	Ideal seed Nonhierarchical, HPH algorithm, ROC2, *Kusiak model, *Viswanthan model, CAN, GRAFICS, *Islam and Sarker model, *MP1 model, *MP2 model, ROC, IMPROVE, HGGA, and ACO-TS	8	20	3
4/1, 4/4, and 4/5	Viswanathan (1996) [38]	Kusiak model, Ben-Arieh and Chang approach, and IMPROVE	10	12	2
4/2, 4/3, 4/6, and 4/7	Viswanathan (1996) [38]	Kusiak model, and Viswanthan model, IMPROVE, and ROC	10	12	3
5/1, 5/2, 5/3, 5/4, 5/5, 5/6, 5/7, 5/8, and 5/9	Chattopadhyay et al. (2011), Fig. 4 (a) [8]	ROC, MACE, *Kusaik's model, *Viswanathan model, *Islam and Sarker model, *MP1 model, *MP2 model, HGGA, and SOM.	5	7	2
6/1, and 6/2	King (1980) [19]	ROC2, and CFP	16	43	3
6/3, 6/4, 6/5, 6/6	King (1980) [19]	ROC2, ROC, IMPROVE ROC, and CFP	16	43	4
6/7, 6/8, and 6/9	King (1980) [19]	ALC, HPH, and CFP	16	43	5
7/1, 7/2, 7/3, 7/4, 7/5, 7/6, 7/7, 7/8, 7/9, 7/10, 7/11	Chattopadhyay et al.(2011) [8]	*Kusiak model, SLINK, ALC, *Viswanthan model, *Islam and Sarker model, *MP1 model, *MP2 model, ROC, IMPROVE, HGGA, and SOM	5	18	2
8/1, 8/2, 8/2, and 8/4	Won (2000) [41]	Kusiak model, *Viswanthan model, *Islam and Sarker model, and *MP2 model	6	10	2
9/1, 9/2, 9/3, 9/4 and 9/5	Agrawal et al. (2011) [1]	ALC, *MP1 model, *Kusiak model, *Viswanthan model, and *Islam and Sarker model	8	12	3
9/6, 9/7, and 9/8	Agrawal et al. (2011) [1]	SAM, HGGA, and ACO-TS,	8	12	4
10/1, 10/2, 10/3, 10/4, 10/5, 10/6, and 10/7	Waghodekar and Sahu(1984), Fig.5(a) [39]	ROC, MACE, *Kusiak model, *Viswanathan model, *MP1 model, *MP2 model, and IMPROVE	5	7	2
11/1, and 11/2	Askine et al.(1991) [3]	ROC2, and HPH	12	19	3
12/1	Chen and Cheng (1995) [9]	ART1	15	15	4
13/1	Sule (1994) [35]	-	11	21	3

Table 2: Summary of computational results

Pro. /sol.	Approach	Problem information			p	Earlier models results									Proposed model results									comp-arison
		m	n	e		e_1	e_o	e_v	B	GI	w	GCI	τ_2	η	e_1	e_o	e_v	B	GI	w	GCI	τ_2	η	
1/1	ROC Fig(2) a	5	7	16	2	14	2	3	17	0.77	0.56	0.88	0.77	0.74	14	2	3	17	0.77	0.56	0.88	0.77	0.74	Equal
1/2	MACE Fig(2) a	5	7	16	2	14	2	3	17	0.77	0.56	0.88	0.77	0.74	14	2	3	17	0.77	0.56	0.88	0.77	0.74	Equal
1/3	*Kusaik's model Fig(2) a	5	7	16	2	14	2	3	17	0.77	0.56	0.88	0.77	0.74	14	2	3	17	0.77	0.56	0.88	0.77	0.74	Equal
1/4	*Viswanathan model Fig(2) a	5	7	16	2	14	2	3	17	0.77	0.56	0.88	0.77	0.74	14	2	3	17	0.77	0.56	0.88	0.77	0.74	Equal
1/5	*Islam and SarkermodelFig(2) a	5	7	16	2	14	2	3	17	0.77	0.56	0.88	0.77	0.74	14	2	3	17	0.77	0.56	0.88	0.77	0.74	Equal
1/6	*MP1 model Fig(2) a	5	7	16	2	14	2	3	17	0.77	0.56	0.88	0.77	0.74	14	2	3	17	0.77	0.56	0.88	0.77	0.74	Equal
1/7	*MP2 model Fig(2) a	5	7	16	2	14	2	3	17	0.77	0.56	0.88	0.77	0.74	14	2	3	17	0.77	0.56	0.88	0.77	0.74	Equal
2/1	HGGA	8	20	91	2	64	27	18	82	0.53	0.34	0.7	0.53	0.59	67	24	29	96	0.59	0.35	0.74	0.59	0.56	Best
3/1	Ideal seed Nonhierarchical	8	20	61	3	52	9	0	52	0.76	0.59	0.85	0.76	0.85	52	9	0	52	0.76	0.59	0.85	0.76	0.85	Equal
3/2	HPH	8	20	61	3	52	9	0	52	0.76	0.59	0.85	0.76	0.85	52	9	0	52	0.76	0.59	0.85	0.76	0.85	Equal
3/3	ROC2	8	20	61	3	46	15	9	55	0.6	0.4	0.75	0.6	0.66	52	9	0	52	0.76	0.59	0.85	0.76	0.85	Best
3/4	*Kusiak model	8	20	61	3	52	9	0	52	0.76	0.59	0.85	0.76	0.85	52	9	0	52	0.76	0.59	0.85	0.76	0.85	Equal
3/5	*Viswanthan model	8	20	61	3	52	9	0	52	0.76	0.59	0.85	0.76	0.85	52	9	0	52	0.76	0.59	0.85	0.76	0.85	Equal
3/6	CAN	8	20	61	3	52	9	0	52	0.76	0.59	0.85	0.76	0.85	52	9	0	52	0.76	0.59	0.85	0.76	0.85	Equal
3/7	GRAFICS	8	20	61	3	52	9	0	52	0.76	0.59	0.85	0.76	0.85	52	9	0	52	0.76	0.59	0.85	0.76	0.85	Equal
3/8	*Islam and Sarker model	8	20	61	3	52	9	0	52	0.76	0.59	0.85	0.76	0.85	52	9	0	52	0.76	0.59	0.85	0.76	0.85	Equal
3/9	*MP1 model	8	20	61	3	47	14	4	51	0.62	0.44	0.77	0.62	0.72	52	9	0	52	0.76	0.59	0.85	0.76	0.85	Best
3/10	*MP2 model	8	20	61	3	52	9	0	52	0.76	0.59	0.85	0.76	0.85	52	9	0	52	0.76	0.59	0.85	0.76	0.85	Equal
3/11	ROC	8	20	61	3	46	15	6	52	0.6	0.41	0.75	0.6	0.69	52	9	0	52	0.76	0.59	0.85	0.76	0.85	Best
3/12	IMPROVE	8	20	61	3	52	9	0	52	0.76	0.59	0.85	0.76	0.85	52	9	0	52	0.76	0.59	0.85	0.76	0.85	Equal
3/13	HGGA	8	20	61	3	52	9	0	52	0.76	0.59	0.85	0.76	0.85	52	9	0	52	0.76	0.59	0.85	0.76	0.85	Equal
3/14	ACO-TS	8	20	61	3	52	9	0	52	0.76	0.59	0.85	0.76	0.85	52	9	0	52	0.76	0.59	0.85	0.76	0.85	Equal

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Pro. /sol.	Approach	Problem information			p	Earlier models results									Proposed model results									comp-arison
		m	n	e		e_1	e_o	e_v	B	GI	w	GCI	τ_2	η	e_1	e_o	e_v	B	GI	w	GCI	τ_2	η	
4/1	Kusiak model	10	12	41	2[a]	34	7	26	60	0.7	0.39	0.83	0.7	0.51	39	2	33	72	0.8	0.49	0.95	0.8	0.53	Best
4/2	Kusiak model	10	12	41	3	29	12	12	41	0.55	0.33	0.71	0.55	0.55	34	7	22	56	0.7	0.4	0.83	0.7	0.54	Best
4/3	Viswanthan model	10	12	41	3	33	8	15	48	0.67	0.41	0.8	0.67	0.59	34	7	22	56	0.7	0.4	0.83	0.7	0.54	Best
4/4	Ben-Arieh and Chang approach	10	12	41	2[a]	29	12	23	52	0.57	0.29	0.71	0.57	0.45	39	2	33	72	0.8	0.49	0.95	0.8	0.53	Best
4/5	IMPROVE	10	12	41	2	39	2	33	72	0.8	0.49	0.95	0.8	0.53	39	2	33	72	0.8	0.49	0.95	0.8	0.53	Equal
4/6	IMPROVE	10	12	41	3	31	10	11	42	0.61	0.38	0.76	0.61	0.6	34	7	22	56	0.7	0.4	0.83	0.7	0.54	Best
4/7	ROC	10	12	41	3	26	15	14	40	0.46	0.26	0.63	0.46	0.47	34	7	22	56	0.7	0.4	0.83	0.7	0.54	Best
5/1	ROC Fig. 4 (a)	5	7	20	2[b]	16	4	9	25	0.67	0.39	0.8	0.67	0.55	17	3	5	22	0.73	0.5	0.85	0.73	0.68	Best
5/2	MACE Fig. 4 (a)	5	7	20	2	17	3	5	22	0.73	0.5	0.85	0.73	0.68	17	3	5	22	0.73	0.5	0.85	0.73	0.68	Equal
5/3	*Kusaik model Fig. 4 (a)	5	7	20	2	17	3	5	22	0.73	0.5	0.85	0.73	0.68	17	3	5	22	0.73	0.5	0.85	0.73	0.68	Equal
5/4	*Viswanathan model Fig. 4 (a)	5	7	20	2	Single cell									17	3	5	22	0.73	0.5	0.85	0.73	0.68	Best
5/5	*Islam and Sarker model Fig. 4 (a)	5	7	20	2	17	3	5	22	0.73	0.5	0.85	0.73	0.68	17	3	5	22	0.73	0.5	0.85	0.73	0.68	Equal
5/6	*MP1 model Fig. 4 (a)	5	7	20	2	14	6	3	17	0.52	0.34	0.7	0.52	0.61	17	3	5	22	0.73	0.5	0.85	0.73	0.68	Best
5/7	*MP2 model Fig. 4 (a)	5	7	20	2	14	6	3	17	0.52	0.34	0.7	0.52	0.61	17	3	5	22	0.73	0.5	0.85	0.73	0.68	Best
5/8	HGGA Fig. 4 (a)	5	7	20	2	16	4	3	19	0.67	0.46	0.8	0.67	0.7	17	3	5	22	0.73	0.5	0.85	0.73	0.68	Best
5/9	SOM Fig. 4 (a)	5	7	20	2	17	3	5	22	0.73	0.5	0.85	0.73	0.68	17	3	5	22	0.73	0.5	0.85	0.73	0.68	Equal
6/1	ROC2	16	43	126	3	96	31	161	260	0.64	0.25	0.76	0.64	0.33										
6/2	CFP	16	43	126	3[a]	96	30	116	212	0.64	0.29	0.76	0.64	0.4	109	(a)17	181	290	0.71	0.3	0.87	0.71	0.36	Best
				126											109	(b)17	186	295	0.71	0.3	0.87	0.71	0.35	Best
				126											109	(c)17	202	311	0.7	0.29	0.87	0.7	0.33	Best
				126											108	(d)18	176	284	0.7	0.3	0.86	0.7	0.36	Best
				126											107	(e)19	150	257	0.7	0.32	0.85	0.7	0.39	Best
				126											106	(f)20	139	245	0.7	0.33	0.84	0.7	0.4	Best
				126											104	(g)22	131	235	0.69	0.32	0.83	0.69	0.4	Best

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Pro. /sol.	Approach	Problem information			p	Earlier models results									Proposed model results									comp-arison
		m	n	e		e_1	e_o	e_v	B	GI	w	GCI	τ_2	η	e_1	e_o	e_v	B	GI	w	GCI	τ_2	η	
6/3	ROC2	16	43	126	4	90	36	83	173	0.58	0.28	0.71	0.58	0.43										
6/4	ROC	16	43	126	4[a]	60	66	116	176	0.4	0.14	0.48	0.4	0.25										
6/5	IMPROVE	16	43	126	4	100	26	77	177	0.66	0.36	0.79	0.66	0.49										
6/6	CFP	16	43	126	4[a]	97	29	76	173	0.64	0.34	0.77	0.64	0.48	105	(a)21	118	223	0.69	0.34	0.83	0.69	0.43	Best
				126											105	(b)21	126	231	0.69	0.33	0.83	0.69	0.42	Best
				126											102	(c)24	97	199	0.68	0.35	0.81	0.68	0.46	Best
				126											102	(d)24	100	202	0.68	0.34	0.81	0.68	0.45	Best
				126											102	(e)24	100	202	0.68	0.34	0.81	0.68	0.45	Best
				126											102	(f)24	106	208	0.67	0.34	0.81	0.67	0.44	Best
6/7	ALC	16	43	126	5	99	27	77	176	0.65	0.35	0.79	0.65	0.49	99									
6/8	HPH	16	43	126	5	95	31	51	146	0.61	0.35	0.75	0.61	0.54	99									
6/9	CFP	16	43	126	5[a]	97	29	54	151	0.63	0.36	0.77	0.63	0.54	99	(a)27	58	157	0.65	0.37	0.79	0.65	0.54	Best
																(b)27	59	158	0.65	0.37	0.79	0.65	0.54	Best
																(c)27	77	176	0.65	0.35	0.79	0.65	0.49	Best
7/1	*Kusiak model	5	18	46	2	39	7	3	42	0.74	0.56	0.85	0.74	0.8	41	5	7	48	0.8	0.6	0.89	0.8	0.77	Best
7/2	SLINK	5	18	46	2	39	7	3	42	0.74	0.56	0.85	0.74	0.8	41	5	7	48	0.8	0.6	0.89	0.8	0.77	Best
7/3	ALC	5	18	46	2	41	5	7	48	0.8	0.6	0.89	0.8	0.77	41	5	7	48	0.8	0.6	0.89	0.8	0.77	Equal
7/4	*Viswanthan model	5	18	46	2	41	5	7	48	0.8	0.6	0.89	0.8	0.77	41	5	7	48	0.8	0.6	0.89	0.8	0.77	Equal
7/5	*Islam and Sarker model	5	18	46	2	41	5	7	48	0.8	0.6	0.89	0.8	0.77	41	5	7	48	0.8	0.6	0.89	0.8	0.77	Equal
7/6	*MP1 model	5	18	46	2	41	5	7	48	0.8	0.6	0.89	0.8	0.77	41	5	7	48	0.8	0.6	0.89	0.8	0.77	Equal
7/7	*MP2model	5	18	46	2	41	5	7	48	0.8	0.6	0.89	0.8	0.77	41	5	7	48	0.8	0.6	0.89	0.8	0.77	Equal
7/8	ROC	5	18	46	2	41	5	7	48	0.8	0.6	0.89	0.8	0.77	41	5	7	48	0.8	0.6	0.89	0.8	0.77	Equal
7/9	IMPROVE	5	18	46	2	41	5	7	48	0.8	0.6	0.89	0.8	0.77	41	5	7	48	0.8	0.6	0.89	0.8	0.77	Equal
7/10	HGGA	5	18	46	2	39	7	3	42	0.74	0.56	0.85	0.74	0.8	41	5	7	48	0.8	0.6	0.89	0.8	0.77	Best
7/11	SOM	5	18	46	2	41	5	7	48	0.8	0.6	0.89	0.8	0.77	41	5	7	48	0.8	0.6	0.89	0.8	0.77	Equal
8/1	Kusiak model	6	10	27	2	23	4	9	32	0.73	0.48	0.85	0.73	0.64	23	4	9	32	0.73	0.48	0.85	0.73	0.64	Equal
8/2	*Viswanthan model	6	10	27	2[a]	23	4	13	36	0.72	0.44	0.85	0.72	0.58	23	4	9	32	0.73	0.48	0.85	0.73	0.64	Best
8/3	*Islam and Sarker model	6	10	27	2	23	4	9	32	0.73	0.48	0.85	0.73	0.64	23	4	9	32	0.73	0.48	0.85	0.73	0.64	Equal

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Pro. /sol.	Approach	Problem information			p	Earlier models results									Proposed model results									comp-arison
		m	n	e		e_1	e_o	e_v	B	GI	w	GCI	τ_2	η	e_1	e_o	e_v	B	GI	w	GCI	τ_2	η	
8/4	*MP2 model	6	10	27	2[a]	22	5	8	30	0.69	0.44	0.81	0.69	0.63	23	4	9	32	0.73	0.48	0.85	0.73	0.64	Best
9/1	ALC	8	12	35	3	28	7	6	34	0.67	0.45	0.8	0.67	0.67	28	7	6	34	0.67	0.45	0.8	0.67	0.67	Equal
9/2	*MP1 model	8	12	35	3	28	7	6	34	0.67	0.45	0.8	0.67	0.67	28	7	6	34	0.67	0.45	0.8	0.67	0.67	Equal
9/3	*Kusiak model	8	12	35	3	28	7	6	34	0.67	0.45	0.8	0.67	0.67	28	7	6	34	0.67	0.45	0.8	0.67	0.67	Equal
9/4	*Viswanathan model	8	12	35	3	28	7	6	34	0.67	0.45	0.8	0.67	0.67	28	7	6	34	0.67	0.45	0.8	0.67	0.67	Equal
9/5	*Islam and Sarker model	8	12	35	3	28	7	6	34	0.67	0.45	0.8	0.67	0.67	28	7	6	34	0.67	0.45	0.8	0.67	0.67	Equal
9/6	SAM	8	12	35	4	25	10	1	26	0.52	0.38	0.71	0.52	0.69	25	10	1	26	0.52	0.38	0.71	0.52	0.69	Equal
9/7	HGGA	8	12	35	4	25	10	1	26	0.52	0.38	0.71	0.52	0.69	25	10	1	26	0.52	0.38	0.71	0.52	0.69	Equal
9/8	ACO-TS	8	12	35	4	25	10	1	26	0.52	0.38	0.71	0.52	0.69	25	10	1	26	0.52	0.38	0.71	0.52	0.69	Equal
10/1	ROC Fig. (5)a	5	7	20	2[b]	15	5	7	22	0.61	0.36	0.75	0.61	0.56	17	3	5	22	0.73	0.5	0.85	0.73	0.68	Best
10/2	MACE Fig. (5)a	5	7	20	2	17	3	5	22	0.73	0.5	0.85	0.73	0.68	17	3	5	22	0.73	0.5	0.85	0.73	0.68	Equal
10/3	*Kusiak model Fig. (5)a	5	7	20	2	17	3	5	22	0.73	0.5	0.85	0.73	0.68	17	3	5	22	0.73	0.5	0.85	0.73	0.68	Equal
10/4	*Viswanathan model Fig. (5)a	5	7	20	2	Single cell									17	3	5	22	0.73	0.5	0.85	0.73	0.68	Best
10/5	*MP1 model Fig. (5)a	5	7	20	2	14	6	3	17	0.52	0.34	0.7	0.52	0.61	17	3	5	22	0.73	0.5	0.85	0.73	0.68	Best
10/6	*MP2 model Fig. (5)a	5	7	20	2	14	6	3	17	0.52	0.34	0.7	0.52	0.61	17	3	5	22	0.73	0.5	0.85	0.73	0.68	Best
10/7	IMPROVE Fig. (5)a	5	7	20	2	17	3	5	22	0.73	0.5	0.85	0.73	0.68	17	3	5	22	0.73	0.5	0.85	0.73	0.68	Equal
11/1	ROC2	12	19	75	3[a]	41	34	35	76	0.38	0.19	0.55	0.38	0.37	56	19	24	80	0.6	0.36	0.75	0.6	0.57	Best
11/2	HPH	12	19	75	3	52	23	24	76	0.53	0.31	0.69	0.53	0.53	56	19	24	80	0.6	0.36	0.75	0.6	0.57	Best
12/1	ART1	15	15	50	4	43	7	13	56	0.74	0.51	0.86	0.74	0.68	43	7	13	56	0.74	0.51	0.86	0.74	0.68	Equal
13/1	-	11	21	73	3	-	-	-	-	-	-	-	-	-	62	11	30	92	0.72	0.46	0.85	0.72	0.6	-

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Because of their dependence on the number of clusters, values of grouping index (GI), weighted grouping efficacy (ω), grouping capability index (GCI), modified grouping efficacy (τ_2) and grouping efficacy (η) were not compared for cases with unequal number of clusters. The comparison of the performance measures resulted in the following:

a) The ωmeasure has low discriminating capability and weakness sensitivity
b) The ηmeasure gives the best result for the worst solution, so η has the worst discriminating characteristic, since this method does not consider the weight factor.
c) GCIhas high the discrimination compared with other performance measures.
d) GIand $\tau_2$have the same values for all solutions in all problems because they have the same equation for all problems, since A=0 for all problems. GIand $\tau_2$show no preference for any solution for all problems even with changing the method or with different number of clusters.

It is worthy to point out that results presented in Table 2 demonstrate that the proposed approach results in solutions of better or equal quality when its solutions are compared with the solutions obtained by conventional algorithms for the test problems.

Due to space limitation, two example problems are given to demonstrate the superiority of the proposed approach.

Example 1[25]

Solution of problem 4/6, Table 1 for three cells, the solution of Kusiak's approach as an input to IMPROVE algorithm, applying ROC approach, and using the proposed approach are given in Figures 3, 4, and 5. The proposed approach approach's solution is better in terms of the performance measures, as given in Table2.

	1	2	3	4	5	6	7	8	9	10	11	12
1				1	1	1	1	1			1	1
2						1	1		1			
3				1		1						
4	1	1	1	1								
5	1	1										
6				1		1		1		1	1	
7					1	1	1	1				
8				1			1	1	1	1	1	1
9		1										
10		1		1	1			1		1		1

Figure 2: Machine – part incidence matrix for problem 4, [38].

	1	2	3	6	7	9	4	5	8	10	11	12
4	1	1	1				1					
5	1	1										
9		1										
2				1	1	1						
3				1			1					
7				1	1			1	1			
1				1	1		1	1	1		1	1
6				1			1		1	1	1	
8					1	1	1		1	1	1	1
10		1					1	1	1	1		1

Figure 3: Solution for problem 4/6 of IMPROVE algorithm by using solution of (Kusiak's approach with p=3 as input) [11].

	1	2	3	4	5	8	10	11	12	6	7	9
4	1	1	1	1								
5	1	1										
9		1										
10		1		1	1	1	1		1			
1				1	1	1		1	1	1	1	
6				1		1	1	1		1		
8				1		1	1	1	1		1	1
2										1	1	1
3				1						1		
7					1	1				1	1	

Figure 4: Solution for problem 4/7 by applying ROC approach [11].

	4	5	6	7	8	10	11	12	1	9	2	3
1	1	1	1	1	1		1	1				
3	1		1									
6	1		1		1	1	1					
7		1	1	1	1							
8	1			1	1	1	1	1		1		
10	1	1			1	1		1			1	
2			1	1						1		
5									1		1	
4	1								1		1	1
9											1	

Figure 5: Solution of the proposed approach [25].

Example 2 [25]

The machine – part incidence matrix for a 16x43 problem [19],is utilized to demonstrate the effectiveness of the proposed approach. The data for problem 6 are given in Figure 6 [19]. In the following section a solution for 3 cells, and applying ROC2 algorithm [3], the solution is given in Figure 7, resulting in 31 exceptional elements and performance measures GI, ω, and GCI as 0.64, 0.25 and 0.76 respectively.

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

Figure 6: Machine – part incidence matrix for problem 6 [19].

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

Figure 7: Solution for problem 6/1 by applying ROC2 algorithm [3].

Figure 8 depicts the solution obtained by the proposed approach where the performance measures increased to 0.71, 0.3 and0.87. Moreover, the proposed approach produces seven alternative solutions with the same number of cells [25] that outperform the previously published solutions.

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	2	4	5	7	8	9	10	12	14	15	16	18	19	21	23	28	29	32	33	37	38	40	41	42	43
1																				1				1	
2	1						1									1		1		1	1	1		1	
4			1			1			1				1	1	1		1								
5			1		1	1			1	1	1		1	1	1		1		1				1		1
6	1			1	1			1	1				1		1			1	1	1		1		1	1
8	1				1	1		1		1			1	1	1	1				1	1		1		1
9	1	1					1					1				1		1		1	1	1		1	
15			1						1				1	1					1				1		1
16	1			1			1					1						1		1	1			1	
3				1																					
7																									
10								1																	
14	1																								
11						1																			
12																									
13																									

	1	6	13	17	25	26	31	34	35	36	39	3	11	20	22	24	27	30
1																		
2																		
4																		
5																		
6	1	1	1	1				1			1							
8	1						1					1	1	1		1	1	
9																		
15																		
16																		
3				1				1	1	1								
7	1		1		1													
10	1		1		1	1	1				1							
14		1		1					1									
11												1		1		1	1	1
12													1		1	1	1	1
13												1				1		

Figure 8: Solution by applying the proposed approach with e_o=17, Lc=3, Uc=9 and Lf=7, Uf=25 [25].

8. Conclusions

The proposed approach seeks to minimize the number of exceptional elements through an integer programming formulation. Machine cells and part families are created simultaneously. The numerical solutions obtained by this approach, to benchmark problems, were superior to solutions obtained by other approaches in forty nine percent of the cases. None of the solutions were of inferior quality.

8.1. Conclusions related to the capability of the approach

These can be summarized as follows

a) The proposed approach permits the designer to set the number of cells.

b) The proposed approach can easily improve, develop, add constraints, change number of cells, puts upper and lower limits on number of machines or parts in each cell, or to cluster machines and parts based on other objectives such as maximization of the actual processing time within each cell.

8.2. Main advantages of the approach

The advantages can be set as follows

a) The proposed approach can be applied for both small and large problems.

b) The proposed approach was prepared to overcome the deficiencies in other approaches with significant advantage where it generates more than one optimal solution with the same objective function values by changing the upper and lower limits for machines and parts allowable in each cell. As a result, this can present more than one choice for the decision maker.

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